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AIR POLLUTION

ASSESSMENT PAPER

Benefits and Costs of the Air Pollution Targets for the Post-2015 Development Agenda

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Post-2015 Consensus

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Highlights

Main conclusions

- PM2.5 air pollution is globally a major cause of premature death and disease. The cost of the health burden is US$ 2.3 trillion per year, based on individuals' willingness to pay for reduced risk of mortality.
- The economic assessment presented here indicates that the global health benefits of reaching a set of proposed PM2.5 control targets amount to US 1.4 trillion per year.
- Benefits by a large magnitude outweigh the costs of controlling household PM2.5 air pollution from the use of solid fuels for cooking and heating.
- Controlling this source of pollution is also important for improved outdoor air quality, especially in Asia.
- Assessment of other options for outdoor PM2.5 abatement suggests that a well prioritized approach be developed, especially in low-income countries.

Health effects

- 6-7 million annual deaths were attributed to PM2.5 outdoor ambient air pollution and household air pollution from solid fuels in 2010-12. This is more than from alcohol and drugs, about the same as from active and passive tobacco smoking, and four times more than from child and maternal undernutrition.
- Over 90% of these deaths occur in the developing countries of Asia, Africa and Latin America and the Caribbean. About 60% occur in China and India alone.

Exposure

- Nearly 90% of the world's population lived in areas with outdoor ambient PM2.5 concentrations exceeding WHO's annual air quality guideline of 10 μg/m3 in 2005. Nearly 1/3rd lived in areas with ambient PM2.5 exceeding WHO's Level 1 Interim Target of 35 μg/m3.
- About 41% of the world's population used mainly solid fuels for cooking in 2012. Over 95% of these people reside in Asia and Sub-Saharan Africa. China and India alone account for nearly 50% of all solid fuel users. About 80% of solid fuel users live in rural areas globally.

Health damage cost

- Annual health cost of outdoor ambient PM2.5 air pollution is estimated at US$ 1.7 trillion. Over US$ 900 billion of this cost is in high income countries when health damages are valued in proportion to GDP per capita. Over US$ 630 billion of the cost is in low- and middle-income countries, and US$140 is in Central and Eastern Europe. Costs are as high as 4.1-4.9% of GDP in some regions.

- Annual health cost of household use of solid fuels is estimated at nearly US$ 650 billion when health damages are valued in proportion to GDP per capita. Costs are as high as 4.2-5.2% of GDP in China, India and South Asia, and 3.3-3.8% of GDP in Sub-Saharan Africa and South East Asia.

Benefits of air pollution targets

- The relationship between health effects of PM2.5 and exposure levels is highly non-linear. Health benefits of air pollution control are therefore initially "small" but increase substantially with stricter targets. Substantial health effects remain, however, even at "low" exposure levels currently experienced by less 10% of the global population.
- Health benefits of globally reaching WHO's interim targets for annual ambient PM2.5 of 35, 25 and 15 μg/m3 are 8%, 19% and 41% of current health effects, respectively. The benefits of reaching WHO's annual air quality guideline of 10 μg/m3 is 67% of current health effects.
- Health benefits of widely advocated and "affordable" improved cooking stoves may only be 25% of current health effects of solid fuel use. Full community conversion to LPG for cooking, while substantially more expensive, may provide a 65% reduction in health effects.

Benefit-cost ratios – household air pollution

- This paper proposes initial targets for household air pollution control using a stove and fuel based approach: 50% adoption rate of improved cookstoves (ICS) and 50% adoption rate of LPG among the household that currently use solid fuels for cooking. A longer term final target is also proposed, with adoption of LPG by those households that initially adopted ICS.
- Global net benefits of the reaching the initial targets are US$ 51-200 billion per year, depending on health valuation measure applied. Additional net benefits of progressing to the final target are US$ 11-116 billion per year, bringing total net benefits to US$ 62-316 billion per year.
- The global benefit-cost ratio (BCR) of improved biomass or coal cookstove (ICS) is in the range of 6-18. The BCRs of LPG adoption are 1.1-2.9, but the net benefits are much greater for LPG than for ICSs suggesting that LPG should be promoted among those that can afford it.
- Benefit-cost ratios increase with higher rates of community conversion to LPG, or improved cookstoves for that matter. This is because of less community pollution from fewer and fewer users of solid fuels (or unimproved cookstoves). It illustrates the importance of household air pollution control promotion activities being community focused with the aim of achieving "solid fuel free" or "unimproved stove free" communities along the lines of "community lead sanitation" programs and "open defecation free" communities.

Benefit-cost ratios – PM2.5 ambient air pollution

- This paper proposes region-specific initial targets for outdoor PM2.5 ambient air quality, corresponding to WHO's interim targets (annual) of 35, 25, and 15 μg/m3 of PM2.5. The initial targets converge over time to a final target equal to WHO's annual air quality guideline (AQG) of 10 μg/m3.
- Household use of solid fuels for cooking and heating contributes substantially to outdoor PM2.5 ambient pollution in Asia. Average benefit-cost ratios (BCR) of improved biomass cookstoves in this region are in the range of 2.5 – 10 in terms of outdoor air pollution benefits from households cooking outdoors or venting out the smoke. BCRs of improved coal cookstoves and LPG are also generally larger than BCRs of other PM2.5 abatement options assessed. A large share of benefits is biomass or coal savings that the interventions provide.
- BCRs of improved solid waste management for minimization of uncontrolled burning and of ultra-low sulfur diesel (ULSD) for road vehicles are relatively similar, albeit with inter-regional variations. They are less than one when health benefits are valued at US$ 1,000 per DALY and mostly larger than one when valued at US$ 5,000 per DALY. BCRs of retrofitting in-use vehicles with diesel particulate filters (DPFs) are generally less than one.
- The often low to moderate BCRs suggest that outdoor PM2.5 abatement in especially low-income countries should be selective and well-targeted. They also suggest that a high priority is to control PM2.5 emissions from household use of solid fuel, be it for indoor and outdoor exposure reduction.

Introduction

The last two decades have seen a large body of evidence of substantial health effects of long term exposure to air pollution – especially fine particulate matter – be it in the form of outdoor ambient air pollution (AAP) or household air pollution (HAP) from the use of solid fuels. The World Health Organization (WHO) consequently revised its Air Quality Guideline (AQG) for outdoor air pollution to an annual average of 10 μg/m3 of PM2.5, with health effects documented at even lower ambient concentrations.

Recent assessments, such as the Global Burden of Disease (GBD) 2010 Project, bring air pollution further to the forefront of global public health and environmental priorities, with estimated magnitudes of global health effects much larger than previously understood (see below). There are therefore compelling arguments that air pollution should feature in a new set of development goals for 2015-2030, currently being determined by the United Nations (UN) as the Millennium Development Goals (MDGs) are coming to a closure in 2015.

The new set of development goals involves specification of targets. The Copenhagen Consensus Center (CCC) has therefore commissioned a paper which objective is to apply economic effectiveness considerations so that targets are not only technically and socio-politically feasible within the time frame, but also reflect an understanding of benefits and costs.

This paper summarizes current estimates of global and regional health effects and levels of exposure to air pollution, provides a discussion of alternative targets, and presents estimates of health benefits of achieving targets based on recent development of new exposure-response functions. This is followed by quantitative estimates of benefits and costs of air pollution control measures and achievements of targets.

Global health effects and exposure to air pollution

Health effects

Nearly 6 million deaths were attributed to AAP and HAP in 2010 according to the GBD 2010 Project (Lim et al, 2012). This is more than from alcohol and drugs, about the same as from active and passive tobacco smoking, four times more than from child and maternal undernutrition, and, of 67 risk factors assessed, is only surpassed by total dietary risk factors and high blood pressure, of which the latter is influenced by air pollution, tobacco smoking and diet. Individually, AAP was associated with 3.2 million deaths, and HAP from solid fuels with 3.5 million deaths.[1]

[1] And jointly caused 5.9 million deaths.

In an update by the WHO, an estimated 7 million were attributed to the joints effects of AAP and HAP in 2012. Individually, AAP was associated with 3.7 million deaths, and HAP from solid fuels with 4.3 million deaths.[2]

The GBD 2010 Project developed an integrated PM2.5 exposure-response (IER) model to estimate these health effects by using relative risk (RR) information from studies of ambient PM2.5 air pollution, second hand tobacco smoke, household solid fuel use, and active tobacco smoking (Burnett et al, 2014). The model was developed for causes of mortality in adults: ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC); and in children under five years: acute lower respiratory infections (ALRI).

The model is applicable to the entire exposure range of PM2.5 concentrations observed globally in the outdoor and household environment. The exposure-response relationships in the IER model are highly non-linear with declining marginal relative risks of health outcomes at higher PM2.5 exposure levels. This has major implications for health benefits that may be expected from controlling air pollution at high exposure concentration levels.

Ambient air pollution exposure

Nearly 90% of the world's population lived in areas with ambient outdoor PM2.5 concentrations exceeding WHO's AQG of 10 μg/m3 (annual average) in 2005, and nearly 1/3rd lived in areas with ambient PM2.5 exceeding WHO's Level 1 Interim Target of 35 μg/m3 according to estimates by Brauer et al (2012).

The highest annual average population weighted PM2.5 concentrations are found in a large belt extending from western Sub-Saharan Africa (SSA-W) and the Middle East and North Africa (MNA) through South Asia (SA) to East Asia (EA) and the High Income Asia Pacific (HI AP) countries. Regional average population weighted exposures were below 10 μg/m3 in most of South America, southern part of Africa, and in Australia and the Pacific Islands (table 2.1).

In South and East Asia, 99% of the population lived in areas with annual average ambient PM2.5 exceeding 10 μg/m3, while 92% did so in Western Europe and 76% in North America according to Brauer et al. In South and East Asia, 26% and 76% of the population, respectively, was exposed to annual average PM2.5 exceeding 35 μg/m3. This represent two-thirds of the global population exposed to such ambient levels.

[2]The WHO used the same methodology as in the GBD 2010 Project. http://www.who.int/phe/health_topics/outdoorair/databases/en/

Table 2.1. Population exposure to ambient PM2.5 air pollution

Regions	Population (millions), 2012	Population weighted PM2.5 (μg/m3), 2005
East Asia (EA)	1,399	55
South Asia (SA)	1,629	28
Middle East and North Africa (MNA)	460	26
High-Income Asia Pacific (HI AP)	183	24
Western Sub-Saharan Africa (SSA-W)	357	24
Central Asia (CA)	85	19
Central Europe (CE)	115	17
South East Asia (SEA)	625	16
Western Europe (WE)	422	16
High-Income North America (HI NA)	349	13
Sub-Saharan Africa – other (SSA-O)	556	12
Eastern Europe (EE)	209	11
Latin America and the Caribbean (LAC)	604	9
Australasia(AA)	27	7
Oceania (OC)	9	6
World	7,044	27

Note: Population weighted PM2.5 is from Brauer et al (2012). See annex 7 for definition of regions. Population is from World Bank (2014). Source: Prepared by the author.

WHO has assembled an AAP database[3] that contains annual average PM2.5 concentrations in over 1,600 city locations in 91 countries.[4] Well over 1,000 are from high-income (HI) countries and well over 500 are from low- and middle-income (LMI) countries. Annual PM2.5 in LMI countries exceeded WHO's AQG of 10 μg/m3 in 98% of locations and WHO'S Level 1 Interim Target of 35 μg/m3 in 44% of locations. Most of the locations in which Level 1 Interim Target was exceeded are in Asia. In HI countries PM2.5 concentrations exceeded 10 μg/m3 in 55% of locations. Level 1 Interim Target was exceeded in 2% of locations.

At ambient PM2.5 concentrations in the range of 35-100 μg/m3, as found in many LMI cities in Asia, the exposure-response relationships are highly non-linear. Only moderate improvements in PM2.5 air quality will therefore give quite small health benefits. Thus air pollution targets must be quite stringent in order to effectively improve health. Stringent targets however increases cost. Moreover, control of ambient outdoor PM2.5 will have limited benefits for households using solid fuels unless solid fuel use is addressed.

[3] http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

[4] For a majority of cities in low- and middle-income countries the PM2.5 concentrations are conversions from PM10 measurements.

Household air pollution exposure

The predominant source of HAP, in terms of global health effects, is the use of solid fuels by households for cooking and other purposes. About 41% of the world's population – or 2.8 billion - used mainly solid fuels for cooking in 2010 (Bonjour et al, 2013). Solid fuel use prevalence declined from 53% in 1990 to 41% of the world's population in 2010 according to the authors. The number of people using solid fuels, however, remained constant over this time period due to population growth. The highest regional prevalence of solid fuel use is found in Sub-Saharan Africa and the developing countries of Asia from Afghanistan to the Pacific.

An update for the purpose of this paper finds that nearly 2.9 billion people used solid fuels in 2012 (table 2.2). Over 95% of these people reside in China and India, Sub-Saharan Africa (SSA), other countries in South Asia (SA) from Afghanistan to Bangladesh, and South East Asia (SEA). China and India alone account for nearly 50% of all solid fuel users (SFUs). Latin America and the Caribbean (LAC) account for 3% of global SFUs, and countries in other regions for about 1.6%.

SFU prevalence varies inversely with GDP per capita. China, however, with an income level similar to SFUs in LAC, has a substantially higher SFU prevalence. On the other hand, countries in the group "others" have a substantially lower SFU prevalence than expected by their income level.

Table 2.2. Populations using solid fuels

	Population (million), 2012	SFU population (million), 2012	SFU (%)
China	1,351	621	46%
India	1,237	767	62%
Sub-Saharan Africa (SSA)	913	752	82%
South East Asia (SEA)1	629	304	48%
South Asia (SA)2	412	306	74%
Latin America and the Caribbean (LAC)	604	83	14%
Others3	878	46	5%
World	7,044	2,878	41%

Note: Estimates of SFU population are based on most recent DHS and MICS household surveys and Bonjour et al (2013). Population is from World Bank (2014). 1Plus Korea DR. 2Excluding India. 3Countries in Central and Eastern Europe, Central Asia, Middle East and North Africa, and Oceania with populations using solid fuels. Source: Prepared by the author.

Globally, about 15% of the urban population uses solid fuels while 67% of the rural population does so, according to analysis conducted in preparation of this paper.[5] About

[5] A database of urban and rural solid fuel use for cooking was assembled from the most recent Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS), the India National Sample Survey, and for a few countries from www.cleancookstoves.org. Almost all the surveys are from the period 2008-2014. The database covers over 95% of global solid fuel users.

25% of the urban population and 79% of the rural population use solid fuels in the main SFU regions (table 2.3). Urban prevalence of solid fuel use is, however, as high as 63% in SSA. In rural areas, however, more than half of the population uses solid fuels in all the regions and as many as 93% do so in SSA and SA (excluding India).

Overall, 80% of the world's solid fuel users reside in rural areas and only 20% reside in urban areas. In India and the rest of SA as many as 88-90% of solid fuel users reside in rural areas, due to low SFU prevalence in urban areas and/or high rural population shares.

Table 2.3. Urban and rural solid fuel use, 2012

	SFU prevalence			SFU distribution	
	Total	Urban	Rural	Urban	Rural
China	46%	22%	71%	25%	75%
India	62%	19%	82%	10%	90%
SSA	82%	63%	93%	27%	73%
SEA1	48%	26%	65%	23%	77%
SA2	74%	31%	93%	12%	88%
LAC	14%	4%	53%	25%	75%
Sub-total	55%	25%	79%	20%	80%

[1]Plus Korea DR. 2Excluding India. Source: Prepared by the author from recent DHS, MICS and other surveys.

Wood is the most widely used solid cooking fuel in developing countries. Agricultural residues, straws and dung are only widely used in a few countries, including rural China. Use of coal is quite widespread in China and Mongolia for both cooking and heating. Kerosene is not a major fuel in any developing country, and is used by 5-15% of the population as a primary cooking fuel in only a handful of countries. Charcoal is largely a "transition fuel" from wood, straw and dung to modern fuels such as LPG. It is mainly used by households in the middle income quintiles in mostly urban areas in many Sub-Saharan African countries, several East Asian countries, and a few Latin American countries. It is not included as a fuel target in this paper.

Concentrations of PM2.5 in the household environment from cooking with wood or agricultural residues, straw or dung on open fire or in a traditional, unimproved stove are often several hundred μg/m3 (annex 2). Concentrations from use of coal are on average about half the levels of wood according to studies in China (Mestl et al, 2007; Jin et al, 2005; annex 2). Use of coal does however tend to be more carcinogenic than biomass. Concentrations from use of charcoal are also substantially lower than wood, but charcoal production often has its own problems.

Using an improved biomass cookstove with chimney or hood for venting of smoke often substantially reduces PM2.5 concentrations. Studies have typically found that personal exposure declines from several hundred to 75-125 μg/m3 (annex 2). Thus exposure levels remain relatively high, and reductions in health effects of switching from an open fire or traditional stove to an improved cookstove may "only" be on the order of 20-30% due to the highly non-linear exposure-response relationships for major health outcomes.

One should also bear in mind that 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.

Bottled LPG is by far the most common modern energy used for cooking in LMI countries. Electricity is commonly used in a few LMI countries in Sub-Saharan Africa and Asia, and in some countries of the former Soviet Union and former Yugoslavia. Natural gas is used in some LMI countries, including many countries of the former Soviet Union. Kerosene is commonly used in several Sub-Saharan countries and in a few other 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 μg/m3, presumably mainly due to the community effects of neighboring households using solid fuels. Thus reductions in health effects for individual households switching from an open fire or traditional biomass stove to LPG may be on the order of 40-50% in the presence of community effects of solid fuel use. If however all households in a community switch to LPG, reductions in health effects of PM pollution are likely greater than 65% depending on the AAP levels from sources other than HAP.

While benefit-cost ratios of improved cookstoves may still be higher than for switching to LPG, LPG or other clean energies is the time tested option for effectively combatting health effects of solid fuels, especially when achieved community-wide. In other words, improved cookstoves may continue be the efficient but not a very effective solution.

Switching to an improved cookstove or to modern fuels and stove also has non-health benefits. Main benefits are reduced biomass consumption, whether self-collected or purchased, and reduced cooking time requirements. 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.

Targets

Domains of targets

Air pollution targets can be defined in three domains:

1) Reductions in health effects of air pollution (deaths, DALYs, etc.);
2) Improvements in air quality (ambient and household air quality)
3) Reductions in sources of pollution (use of solid fuels, cookstoves, mobile and stationary sources of outdoor AAP)

Targets should be reasonably measurable and effective in achieving health benefits. Targets should also be reasonably ambitious but feasible and affordable to achieve. And they should be defined so that benefits of achieving them exceed the cost.

Reductions in health effects

The advantage of targets in terms of reduction in health effects of air pollution at regional or national levels is the flexibility they provide in achieving the targets. This is because such targets allow a focus on reducing health effects in locations and from pollution sources where such reductions can be achieved at lower cost than in other locations. Equity in air quality and exposure within a nation may however be compromised to the extent of being socially unacceptable.

Targets in terms of reduction in health effects are difficult to monitor. Reductions in health effects are not directly observable and can only be estimated based on multiple parameters, some of which change over time such as the evolving understanding of exposure-response relationships. Progress towards achieving such targets is therefore difficult to verify and subject to disagreements over evidence base and methodologies.

Improved air quality

Targets in terms of improved air quality are easier to measure and verify for AAP if and when good monitoring equipment capable of measuring PM2.5 is in place at sufficient locations in cities. This is however presently not the case in a majority of cities in LMI countries in which 85-90% of AAP health effects occurs. A disadvantage of air quality targets is their economic inefficiency if targets are nationally or regionally uniform. This is because benefits and costs of air quality improvements are likely to vary substantially across locations. One approach could be to establish interim and time-bound city-specific air quality targets that converge over time to a singular national target.

As to HAP, air quality is household specific and varies during day and night, across locations within a household, and seasonally. Monitoring of improvements in household air quality nationwide is therefore costly and impractical, and requires decisions as to how, where and when in a household monitoring should take place.

Reductions in sources of pollution

The advantage of targeting sources of pollution is the relative ease with which many sources can be monitored and costs be estimated of achieving the targets. Thus targeting of pollution sources can provide a high degree of cost effectiveness per unit of pollution reduction. For AAP however, health benefits of pollution reductions vary greatly across type of pollution source, and the spatial distribution of each source, due to differences in exposure impacts. Thus the economic efficiency of such targets is not very tractable. Moreover, the sources of AAP are impractically many and ambient air quality improvements of source specific pollution reductions are difficult to discern.

For HAP, targets in terms of sources of air pollution are more palatable. Type of energy and cookstoves can easier be monitored through regularly administered household surveys, although mostly relying on household self-reporting. Behavioral determinants of HAP, such as cooking location and ventilation practices, can also at least to some extent be influenced through HAP control programs, campaigns, and community projects.

"Zero" targets

"Zero" targets are targets that would eliminate outdoor and indoor air pollution (PM2.5), or at least bringing anthropogenic PM2.5 concentrations outdoors and indoors below the level known to cause health effects. Presently this level is about 5.8 μg/m3 (Lim et al, 2012). In some geographic areas PM2.5 concentrations would still exceed this level due to the influence of natural dust from deserts and other non-anthropogenic sources that are difficult to control.

"Zero" targets may only be achieved if outdoor air pollution sources and household use of solid fuels were simultaneously eliminated, as outdoor and indoor sources of pollution affect both environments. For instance, an estimated 12% of combustion derived outdoor PM2.5 pollution was attributable to household cooking with solid fuels in 2010, with attributable fraction as high as 26% in South Asia and 37% in southern Sub-Saharan Africa (Smith et al, 2014).

Achieving "zero" targets would involve practically all households substituting to modern energy for cooking and other purposes, such as bottled LPG or electricity. It would also involve controlling mobile, stationary, and area wide sources of PM2.5 at an unprecedented scale. In WHO's AAP database no locations in LMI countries and only 8% of locations in HI countries meet a "zero target" of 5.8 μg/m3 of ambient annual PM2.5, and almost all of these locations are small, pristine areas in Australia, Canada, New Zealand and the United States.

Selected targets

Targets for ambient air pollution

Air quality targets for AAP are more attractive – as they are easier to measure and verify - than targets that specifies reductions in health effects or pollution sources. This type of targets is therefore assessed in more detail in this paper. Considerations can be given to allowing interim and time-bound regional, national, and city-specific air quality targets that converge over time to a singular target, this in order to improve the economic efficiency of targets and thus achieve greatest benefits at least cost.

WHO has established interim air quality targets for annual outdoor PM2.5. Level 1, 2, and 3 Interim Targets are 35, 25 and 15 μg/m3 respectively, and the annual air quality guideline (AQG) is 10 μg/m3. The health benefits of these targets can be estimated using the methodology of the GBD 2010 Project.

As population weighted PM2.5 exposure levels vary greatly across and within regions, variation in initial regional and even national targets may be sensible. Reasonable targets for most HI countries in the Americas, Europe and Asia/Pacific would be the annual AQG of 10 μg/m3. The interim targets of 15-25 μg/m3 may be the initial aim for Latin America and the Caribbean and much of Eastern Europe. The interim targets of 25-35 μg/m3 may initially be more realistic for many of the LMI countries in Western Africa and Asia.

Targets for household air pollution

The most attractive targets for household air pollution center on stoves and cooking fuels. Such targets are relatively easy to monitor, and are in principle relatively simple to convey and promote to communities and individual households. This type of targets is therefore assessed in more detail in this paper.

Targets may be community focused. A household's use of solid fuels influences both outdoor and indoor community air quality. To achieve the maximum benefits per dollar spent 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.

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.

Benefits and costs of household air pollution control

Targets

Two interim (IT) and one final (FT) household air pollution control targets are selected for the purpose of assessing benefits and costs. All targets are fuel and stove based. The targets are assessed in terms of PM2.5 exposure levels, health benefits, non-health benefits and benefit-cost ratios.

The first interim target (IT-1) involves the adoption of improved cookstoves, as most households that currently cook with biomass (or coal) do so with unimproved stoves. The second interim target (IT-2) involves adoption of LPG or other gaseous fuel. The interim targets stipulate a 50% adoption rate of improved cookstoves and 50% adoption rate of LPG stoves among households that currently use biomass or coal. The interim targets can be pursued concurrently. The interim targets are contrasted with a longer term final target (FT) of 100% adoption rate of LPG (or other gaseous fuels or clean cooking (and heating) options).

The interim target is expected to reduce personal PM2.5 exposure from an average of 250 μg/m3 to 100 μg/m3 with adoption of improved stoves and from 250 μg/m3 to 50 μg/m3 with adoption of LPG stoves (table 4.1). At final target, PM2.5 exposure is expected to decline to < 25 μg/m3. The difference in exposure from the use of LPG at interim (50 μg/m3) and final (25 μg/m3) target is due to community pollution from households using biomass or coal at interim target (table 4.1). PM2.5 exposure levels in relation to targets are discussed below.

Table 4.1. Household air pollution control targets

Control option	Target	Average PM2.5 exposure (μg/m3)	
		Interim Target (IT) 50% adoption	Final Target (FT) 100% adoption
Improved cookstoves	Adoption of improved cookstoves by households currently using unimproved biomass or coal stoves	100	
LPG stoves	Adoption of LPG stoves by households currently using biomass or coal	50	< 25

Source: Selected by the author.

Average levels of household members' long term exposure to PM2.5 applied in the GBD 2010 project are presented in table 4.2. These exposure levels are based on monitoring studies such as those reported in annex 2. Men's exposure levels are lower than women's due to different 24-hour activity patterns. The use of biomass - largely on open fire or in unimproved stoves – results in an average long term PM2.5 exposure of 200-300 μg/m3. The average exposure levels in a household using a mix of gas (e.g., LPG) and biomass in chimney stove - or only gas - are still substantial at 46-100 μg/m3. This reflects "community effects" of pollution from nearby households using biomass fuels.

Table 4.2. Long term personal exposure to PM2.5 from household fuel use (μg/m3)

	Women	Men
Biomass	300	200
Mix of gas and biomass in chimney stove	100	65
Gas	70	46

Source: Produced by the author from Burnett et al (2014).

Levels of personal exposure to PM2.5 applied in this paper to estimate health benefits of interventions are presented in table 4.3. The exposure levels represent the type of stove or fuel used by a household living in a community in which other households may continue to use biomass fuels 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. The levels are average exposures of men and women. Exposure levels of children are assumed to be the same as the average of men and women.[6]

[6] Balakrishnan et al (2012) report children's exposure level to be somewhere in the neighborhood of the average of exposure levels of men and women.

Level 1 – biomass used largely on open fire or in unimproved stove – corresponds to the baseline in Burnett et al (2014). This represents the average exposure level of the 2.8 billion people in the world using solid fuels for cooking and other purposes. Level 2 – chimney stove or other improved stove – has an exposure level somewhat higher than level 3.[7] Levels 3 & 4 – mix of gas and of biomass in improved stove, and gas with community pollution from other biomass users - closely corresponds to the intermediate and lowest level of exposure in Burnett et al. The exposure levels are slightly lower than the average level of men and women in Burnett et al, assuming that community pollution is to some extent addressed by reducing emissions at source by choice of smoke efficient improved stoves among biomass users. Level 5 reflects household conversion to gas in communities in which all or nearly all households use or convert to gas and in which there is limited community pollution from sources other than household fuels. Level 6 reflects household conversion to gas in communities in which all households use or convert to gas and in which there is very little community pollution from sources other than household fuels. Levels 1-5 pertain to both urban and rural areas with varying prevalence of biomass users and other sources of pollution. Level 6 is most relevant in rural areas, given that PM2.5 levels in urban areas mostly exceed 7.3 μg/m3 even in the absence of household biomass use.

The three targets selected for assessment of benefits and costs correspond to exposure levels 2, 4 and 5.

Table 4.3. Levels of long term personal exposure to PM2.5 from household fuel use (μg/m3)

Exposure levels		**PM2.5 (μg/m3)**
1	Biomass largely used on open fire or in unimproved stove	250
2	Chimney stove or other improved biomass or coal stove with community pollution	100
3	Mix of gas and biomass or coal in chimney stove or other improved stove with community pollution	75
4	Gas (e.g., LPG) with community pollution	50
5	Gas (e.g., LPG) with limited community pollution	25
6	Gas (e.g., LPG) with very limited community pollution	< 7.3

Source: The author.

Health effects

Health benefits of progressively moving from exposure level 1 to 6 - can be estimated by using the integrated PM2.5 exposure-health response methodology in annex 1 and risk ratios presented in Burnett et al (2014). Health benefits are presented in table 4.4 relative to baseline PM2.5 exposure level of 250 μg/m3 at which level health effects are indexed to 1.0.

As clearly seen in the table and figure 4.1, health benefits of exposure reductions are highly non-linear with progressively higher marginal benefits as exposure approaches < 7.3

[7] The difference in exposure between levels 2 &3 is the same as between levels 3 & 4.

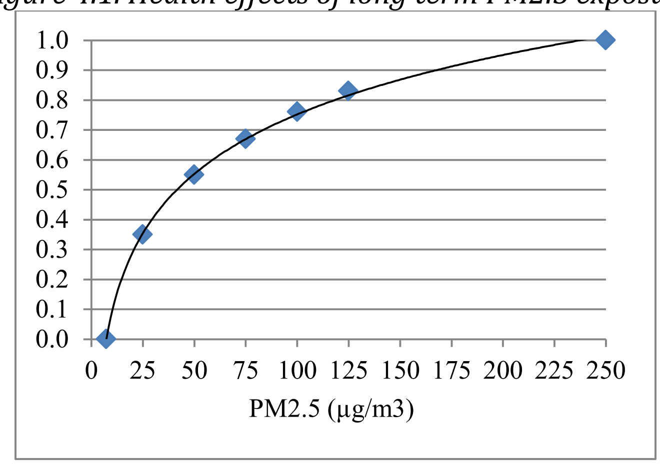
μg/m3. Health benefits of reducing long term exposure from 250 to 25 μg/m3 are 65% of the baseline health effects. Only somewhat over one-third of these benefits are realized from reducing exposure from 250 to 100 μg/m3. Nearly two-thirds of the benefits are realized from reducing exposure from 100 μg/m3 to 25 μg/m3. And, still, at 25 μg/m3 of PM2.5, one-third of baseline health effects of HAP remain.[8]

Table 4.4. Health effects of long term PM2.5 exposure

PM2.5 exposure (μg/m3)	Index of health effects	Health benefits of exposure reduction
250	1.00	-
100	0.76	24%
75	0.67	33%
50	0.55	45%
25	0.35	65%
<7.3	0.00	100%

Source: The author based on Burnett et al (2014) and Shin et al (2013).

Figure 4.1. Health effects of long term PM2.5 exposure



Source: The author.

An estimated 3.5 million people died and 19.7 billion disease days occurred globally in 2012 from household air pollution (HAP) (table 4.5). Almost 900 thousand deaths and 4.8 billion disease days could be avoided annually if all households used an improved biomass or coal stove (exposure level 2; 100 μg/m3 of PM2.5). If all households used LPG or other clean fuels, over 2.3 million deaths and 12.8 million disease days could be avoided annually (exposure level 5; 25 μg/m3 of PM2.5). Partial conversions to improved stoves or clean fuels would result in lower benefits.

[8] Relative risk functions in Burnett et al (2014) are mortality cause specific. The exposure reduction – health benefit relation presented here therefore varies slightly across countries in relation to the structure of mortality.

Table 4.5 Estimated annual health effects of household air pollution exposure

	PM2.5	China	India	SSA	SEA1	SA2	LAC	Other3	World
Deaths from PM2.5 (thousands)	Current levels	1,049	1,048	490	400	279	90	193	3,549
Avoided deaths (thousands) from PM2.5 reductions	100 μg/m3	263	254	118	96	67	22	46	865
	25 μg/m3	722	672	318	260	181	58	125	2,337
Disease days (millions) from PM2.5	Current levels	3,605	6,730	3,249	2,641	2,265	498	666	19,654
Avoided disease days (millions) from PM2.5 reductions	100 μg/m3	903	1,629	780	634	544	120	160	4,769
	25 μg/m3	2,481	4,314	2,112	1,717	1,472	324	433	12,852

Notes: 1Plus Korea DR. 2Excluding India. 3Countries in Central and Eastern Europe, Central Asia, Middle East and North Africa, and Oceania. Source: Author's estimates.

Monetized values of health effects

The health effects of PM2.5 exposure from solid fuel use, as well as health benefits of adopting improved stoves and clean fuels can be valued using standard economic valuation techniques. Two alternative measures are applied to value the loss of a life or the benefit of avoiding a death.

The first measure values a death in the range of US$ 52 – 323 thousand in the major solid fuel using countries and regions in table 4.6, using values of statistical life (VSL) estimated by a benefit transfer function (see annex 3). VSL is a measure based on people's willingness to pay for a reduction in the risk of death and is widely applied in benefit-cost analysis around the world. The VSLs applied here are equivalent to 50 times GDP per capita in each of the countries and regions. VSL can be converted to a value of statistical life year (VSLY) by dividing VSL by the number of years prematurely lost to death. VSLYs are thus in the range of US$ 1-16 thousand.[9]

The second measure uses a uniform value of US$1,000 and US5,000 per year of life lost (YLL). The VSLs and VSLYs are within this range for India, SSA, SEA and SA, but much higher for China and LAC which have substantially higher income levels than the former groups.

[9] The number of years of life lost (YLL) per premature death from PM2.5 exposure in the household environment range from about 20 in China to about 54 in SSA. These figures are based on the Global Burden of Disease (GBD) 2010 Project results. YLL per death is high in countries and regions with high child mortality rates. No age-weighting or discounting is applied in the calculation of YLLs.

Table 4.6. Valuation of mortality, 2012 (US$)

	China	India	SSA	SEA1	SA2	LAC
Value of statistical life (VSL)	307,000	76,000	52,000	130,000	52,000	323,000
Value of statistical life year (VSLY)	16,095	2,705	968	5,086	1,440	12,445
Value of a year of life lost (YLL) - lower	1,000	1,000	1,000	1,000	1,000	1,000
Value of a year of life lost (YLL) - upper	5,000	5,000	5,000	5,000	5,000	5,000

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Two alternative measures are also applied to value morbidity. The first measure values a day of avoided illness as equivalent to 50% of daily wages (see annex 4).[10] This is converted to a value of disability weighted year of disease in the range of US$ 4 – 21 thousand (table 4.7).[11] The second measure values a year lost to disease (YLD) at US$ 1,000 and US$ 5000, as for years lost to premature mortality.[12]

Table 4.7. Valuation of morbidity, 2012 (US$)

	China	India	SSA	SEA1	SA2	LAC
Value of a day of disease (50% of wage rates)	6.8	2.7	1.8	3.3	1.7	8.6
Value of a disability weighted year of disease (50% of wage rates)	16,657	6,455	4,377	8,040	4,156	21,038
Value of a year lost to disease (YLD) - lower	1,000	1,000	1,000	1,000	1,000	1,000
Value of a year lost to disease (YLD) - upper	5,000	5,000	5,000	5,000	5,000	5,000

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

The global cost of household solid fuel use in 2012 is estimated at US$ 646 billion, applying VSL for mortality and a fraction of wage rates for morbidity. Nearly 90% of this cost is from mortality. The cost ranged from 0.9% of GDP in Latin America and the Caribbean (LAC) to 4.3% in South Asia (SA) and China, and 5.2% in India. The cost in Sub-Saharan Africa (SSA) and South East Asia (SEA) was 3.3 and 3.8% of GDP respectively.[13]

The global cost of household solid fuel use is estimated at US$ 111-555 billion in the same year when applying US$ 1,000 to US$ 5,000 per DALY (YLL and YLD) (table 4.8).

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[10] Rural wages are applied as 80% of the world's users of solid fuels for cooking live in rural areas.

[11] Applying an average disability weight of 0.15.

[12] YLD is a disability weighted measure of disease burden. If the disability weight is 0.15 then 2,433 days of disease is equivalent to one YLD.

[13] Regional GDPs are calculated by weighing by the solid fuel using population in each country.

Table 4.8. Annual cost of health effects of household air pollution exposure, 2012 (US$ billion)

Valuation measure	China	India	SSA	SEA1	SA2	LAC	Other	World
VSL	347	98	31	61	18	33	58	646
DALY=US1,000	21	32	28	11	11	3	5	111
DALY=US$5,000	107	161	138	57	55	13	24	555

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Non-health benefits

Non-health benefits of interventions included in this paper are fuel and cooking time savings. Fuel savings from the use of an improved biomass or coal cookstove instead of an unimproved stove or open fire are 30%. Use of LPG results in 100% savings of biomass fuels or coal. Fuel savings are valued as the time that households spend on fuel collection, and time is valued at 50% of wage rates (table 4.9 and annex 4).

Improved cook stoves and LPG stoves tend to provide cooking time savings. This paper applies a cooking time saving of 10 minutes from the use of an improved cookstove and 40 minutes from the use of LPG compared to an unimproved cook stove or open fire. The time savings are valued at 50% of wage rates (table 4.10 and annex 4).

Table 4.9. Value of solid fuel savings of switching to improved cookstove or LPG, 2012 (US$/household/year)

	China	India	SSA	SEA1	SA2	LAC
Improved cookstove (biomass/coal)	52	23	18	18	28	57
LPG (switching from unimproved stove)	175	77	59	60	94	189
LPG (switching from improved stove)	123	54	41	42	66	132

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Table 4.10. Value of cooking time savings, 2012 (US$/household/year)

	China	India	SSA	SEA1	SA2	LAC
Improved cookstove (biomass, coal)	42	16	11	20	10	53
LPG (switching from unimproved stove)	167	65	44	80	42	210
LPG (switching from improved stove)	125	49	33	60	32	157

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Costs of pollution control options

Cost of improved biomass and coal cookstoves (ICS) varies tremendously depending on fuel and emission efficiency, durability, materials, and technology. Basic improved stoves cost in the range of US$2-10 and include basic portable stoves, basic chimney stoves, and basic vented coal stoves. 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 and efficient coal stoves. These stoves can provide up to 50% fuel savings and substantial emission reduction benefits. Advanced improved stoves such as natural or forced draft gasifier stoves cost US$20-75. LPG stoves typically cost US$30-100 depending on size and durability (Dalberg, 2013).

The situation is somewhat different in China than in most other regions of the developing world. Heating is required for at least 3-5 months in the northern regions and 0-3 months in the southern regions (World Bank, 2013). Tackling household air pollution therefore often implies improved or clean stoves and fuels for both cooking and heating. Clean biomass and coal cookstoves are available for US$80-125 in China with a thermal efficiency of as high as 35-45%. Clean combined cooking and heating stoves are available for US$ 100-160 with a thermal efficiency of as high as 70% (World Bank, 2013).

A price of an improved biomass stove of US$30 is applied to most regions where heating is uncommon. This is the mid-point cost estimate of an intermediate improved cookstove. A price of US$ 60 per stove is applied to Latin America and the Caribbean (LAC) where stove requirements and preferences, especially in the highlands of several countries, are different than in South (SA) and South East Asia (SEA). A price of US$115 is applied to China reflecting an average of efficient cookstoves and combined cooking and heating stoves. The useful life of improved stoves is assumed to be 3-5 years. With such a short life the annualized cost is highly insensitive to discount rate.

A price of an LPG stove of US$60 is applied to all regions and countries. The stove is for cooking only, and not heating. Useful life is assumed to be 7 years. Annualized cost is somewhat sensitive to discount rate, but stove cost is only a small fraction of LPG fuel cost and has therefore very little influence on total cost.

LPG fuel to replace solid fuels is applied at a rate of 30-40 kg per person per year, depending on average household size. This is roughly the same as the 35 kg proposed by Goldemburg et al (2004), but higher than the estimated consumption of 22 kg among LPG users in India (D'Sa and Murthy, 2004) and 28 kg among LPG users in Sri Lanka (Tennakoon, 2008). A per person consumption of 30-40 kg of LPG implies a household consumption of 120 to 215 kg per year in the main solid fuel using regions and China and India, based on average household size in rural areas. This compares to a consumption of 80-132 kg per rural household per year in eight countries in Asia, Latin America and Africa (Kojima et al, 2011).[14] It should be noted, however, that the estimated LPG consumption per person or household is likely less than actual fuel consumption for cooking because many households also use secondary fuels.

A price of US$ 1.3 per kg is applied as the economic cost of LPG in order to estimate the cost of switching to LPG for cooking. This price is regional and reflects current world prices of LPG and average distribution costs. The actual price in an individual country may differ, and sometimes substantially, due to various market factors as well as regulatory, taxation and subsidy policies.

[14] Guatemala, India, Indonesia, Kenya, Pakistan, Sri Lanka, Brazil, Peru.

Table 4.11. Estimates of unit costs, 2012

	China	India	SSA	SEA1	SA2	LAC
Average household size (rural)	3	4.9	4.9	4.2	5.5	4.2
Cost of improved stove (US$)	115	30	30	30	30	60
Discount rate	5%	5%	5%	5%	5%	5%
Useful life of stove (years)	5	3	3	3	3	5
Annualized cost of stove (US$)	25.30	10.49	10.49	10.49	10.49	13.20
Cost of LPG cookstove (US$)	60	60	60	60	60	60
Discount rate	5%	5%	5%	5%	5%	5%
Useful life of stove (years)	7	7	7	7	7	7
Annualized cost of stove (US$)	9.88	9.88	9.88	9.88	9.88	9.88
LPG fuel (kg/person/year)	40	32	32	35	30	35
LPG fuel (kg/household/year)	120	157	157	147	165	147
LPG cost (US$/kg)	1.30	1.30	1.30	1.30	1.30	1.30
LPG fuel cost (US$/household/year)	156	204	204	191	215	191

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Benefit-cost ratios

Benefits and costs are assessed for four cases of household air pollution control. Cases 1-2 refer to reaching the initial targets (IT): 50% of households adopting improved cookstoves (ICS) and 50% adopting LPG instead of using unimproved cookstoves (UCS). Case 3 is an assessment of reaching the final target (FT), i.e., adopting LPG in the longer term by those households that initially adopted ICSs. Case 4 is presented for comparison of benefit-cost ratios in Case 2 vs. Case 4 to demonstrate the effect of community pollution on households switching to LPG in the presence of other households continuing to use solid fuels. Health benefits, net benefits and benefit-cost ratios are calculated using three alternative health valuation measures (table 4.12).

Global benefits

The global benefits of reaching the initial targets for ICSs and LPG are US$ 120-270 billion per year. In the range of 40-80% of the benefits of ICSs and 25-65% of the benefits of LPG are health improvements. The remaining benefits are solid fuel savings and cooking time savings. The lower bounds reflect health valuation using US$ 1,000 per DALY. The upper bounds reflect valuation using VSL.

The global cost of ICS is estimated at nearly US$ 20 billion, with an annualized cost of US$ 5 billion. The global cost of LPG stoves is also estimated at about US$ 20 billion. The global cost of LPG fuel is estimated at a little over US 60 billion per year for the initial target.
The net benefits of the reaching the initial targets (Case 1+2) are US$ 51-200 billion per year, depending on health valuation measure. Additional net benefits of progressing to the final target (Case 3) are US$ 11-116 billion per year, bringing total net benefits to US$ 62-316 billion per year.

Global benefit-cost ratios

Globally, the benefit-cost ratio (BCR) of improved biomass or coal cookstove (ICS) is in the range of 6-18. The BCRs of LPG adoption (Cases 2 & 3) are much smaller than the BCR for ICS, but the net benefits are greater for LPG suggesting that LPG should be promoted among those that can afford it.

The BCR of switching to LPG from UCS (initial target) or from ICS (final target) are quite similar and all greater than one. That the BCR in Case 3 is as high as in Case 2, despite different pre- and post-adoption PM2.5 exposure levels, stems from there being external health benefits from Case 3: In Case 2, households switching to LPG are affected by community pollution from the households that continue to use solid fuels, thus the post-adoption PM2.5 exposure level is 50 μg/m3. Once these solid fuel using households also switch to LPG (Case 3) post-adoption PM2.5 exposure levels drop to 25 μg/m3 among these households as well as among the households in Case 2 because of reduced community pollution.

Comparing Cases 2 & 4 it can be seen that the BCR in Case 4 is 15-25% higher than in Case 2. This is because the post-adoption PM2.5 exposure level in Case 2 is higher than in Case 4 due to community pollution in Case 2. The increasing benefit-cost ratios with higher rates of community conversion to LPG, or improved cookstoves for that matter, illustrates the importance of household air pollution control promotion activities being community focused with the aim of achieving solid fuel free or unimproved stove free communities along the lines of community lead sanitation programs and open defecation free communities. Promotion program cost per household is, however, likely to increase with the intensity and/or duration of programs to achieve higher rates of adoption of LPG or improved stoves. This increasing marginal cost must be weighed against expected increase in adoption rates.

Table 4.12. Global benefit-cost ratios of household air pollution control targets

Case	(1)	(2)	(3)	(4)
Pre-adoption stove or fuel	UCS	UCS	ICS	UCS
Post-adoption stove or fuel	ICS	LPG	LPG	LPG
Target	Initial target	Initial target	Final target	
Adoption rate	50%	50%	all in (a)	100%
PM2.5 (μg/m3) pre-adoption	250	250	100	250
PM2.5 (μg/m3) post-adoption	100	50	25	25
Benefit-cost ratios:				
Using VSL	18	2.6	2.7	3.3
Using DALY=US$1,000	6	1.3	1.1	1.5
Using DALY=US$5,000	16	2.6	2.9	3.2
Net global benefits (US$ billion/year)				
Using VSL	87	113	116	316
Using DALY=US$1,000	28	23	11	62
Using DALY=US$5,000	76	110	124	310

Notes: UCS=unimproved biomass or coal cookstove. ICS=improved biomass or coal cookstove. Source: The author.

Regional benefit-cost ratios

Tables 4.13-15 present BCRs and net benefits for each major solid fuel using region by each valuation measure of health benefits. The main conclusions are the same regionally as globally. The main difference is that the BCRs are slightly < 1 for SSA for adoption of LPG when VSL or US$1,000 per DALY is used for valuation of health benefits. When using US$5,000 per DALY, the BCR is in the range of 2.4-2.9 in Cases 2 & 3. The latter may better reflect urban households and better-off rural households with higher incomes than national averages.

As heating in rural China in the foreseeable future is likely at best to be met from improved heating stoves using biomass fuels and/or coal, health benefits of LPG for cooking are conservatively estimated using exposure level 4 (50 μg/m3) instead of 5 (25 μg/m3), and improved heating stoves are added to the cost of stoves.[15] This is reflected in the BCRs for China in the tables below.

[15] The number of households with unimproved, inefficient heating stoves is unknown. It is here assumed to be the same as the number of households using solid fuels for cooking.

Table 4.13. Benefit-cost ratios of household air pollution control targets using VSL for health valuation

Case	(1)	(2)	(3)	(4)
Pre-adoption stove or fuel	UCS	UCS	ICS	UCS
Post-adoption stove or fuel	ICS	LPG	LPG	LPG
Target	Initial target	Initial target	Final target	
Adoption rate	50%	50%	all (a)	100%
PM2.5 (μg/m3) pre-adoption	250	250	100	250
PM2.5 (μg/m3) post-adoption	100	50	25	25
Benefit-cost ratios:				
China	20	4.8	4.3	5.9
India	18	2.0	2.2	2.5
SSA	7	0.9	0.9	1.1
SEA1	23	2.6	3.1	3.4
SA2	11	1.3	1.3	1.6
LAC	39	5.8	6.6	7.5
Total	18	2.6	2.7	3.3
Net benefits (US$ billion)	87	113	116	316

Notes: 1 Plus Korea DR. 2 Excluding India. UCS=unimproved biomass or coal cookstove. ICS=improved biomass or coal cookstove. Source: The author.

Table 4.14. Benefit-cost ratios of household air pollution control targets using DALY=US$1,000 for health valuation

Case	(1)	(2)	(3)	(4)
Pre-adoption stove or fuel	UCS	UCS	ICS	UCS
Post-adoption stove or fuel	ICS	LPG	LPG	LPG
Target	Initial target	Initial target	Final target	
Adoption rate	50%	50%	all (a)	100%
PM2.5 (μg/m3) pre-adoption	250	250	100	250
PM2.5 (μg/m3) post-adoption	100	50	25	25
Benefit-cost ratios:				
China	5	2.0	1.5	2
India	9	1.1	1.1	1.3
SSA	7	0.9	0.9	1.0
SEA1	7	1.1	1.0	1.2
SA2	8	1.0	1.0	1.2
LAC	11	2.3	1.8	2.4
Total	6	1.3	1.1	1.5
Net benefits (US$ billion)	28	23	11	62

Notes: 1 Plus Korea DR. 2 Excluding India. UCS=unimproved biomass or coal cookstove. ICS=improved biomass or coal cookstove. Source: The author.

Table 4.15. Benefit-cost ratios of household air pollution control targets using DALY=US$5,000 for health valuation

Case	(1)	(2)	(3)	(4)
Pre-adoption stove or fuel	UCS	UCS	ICS	UCS
Post-adoption stove or fuel	ICS	LPG	LPG	LPG
Target	Initial target	Initial target	Final target	
Adoption rate	50%	50%	all (a)	100%
PM2.5 (μg/m3) pre-adoption	250	250	100	250
PM2.5 (μg/m3) post-adoption	100	50	25	25
Benefit-cost ratios:				
China	9	2.7	2.2	3.1
India	28	2.8	3.4	3.3
SSA	23	2.4	2.9	3.2
SEA1	22	2.4	2.9	3.2
SA2	26	2.6	3.1	3.5
LAC	20	3.4	3.4	4.1
Total	16	2.6	2.9	3.2
Net benefits (US$ billion)	76	110	124	310

Notes: 1 Plus Korea DR. 2 Excluding India. UCS=unimproved biomass or coal cookstove. ICS=improved biomass or coal cookstove. Source: The author.

Benefits and costs of outdoor ambient air pollution control

Targets

WHO has issued air quality guidelines (AQG) and three levels of interim targets (IT) for outdoor ambient particulate matter. The AQG for annual PM2.5 is 10 μg/m3 and the annual values for the three targets are 35, 25 and 15 μg/m3. These interim targets and AQG are used in this paper for the purpose of estimating benefits and costs of PM2.5 ambient air pollution control. The AQG with interim targets allow geographic flexibility as to the time path of globally achieving the AQG.

Regional targets are proposed in table 5.1. These targets progress towards WHO's annual AQG over time. The targets reflect the large differences in regional ambient concentrations of PM2.5 today, and regions are grouped accordingly (Group 1-3). A first target for Group 1 (East Asia) would be to reach WHO's Interim Target-1 (IT-1) for the entire population. Annual ambient concentrations currently exceed this target for 76% of the population in East Asia according to Brauer et al (2012). For Group 2, in which a substantial share of the population is exposed to PM2.5 exceeding 25 μg/m3, a first target would be to reach IT-2. For Group 3, in which the population is generally exposed to lower PM2.5 concentrations than in the former groups, a first targets would be to reach IT-3. All regions would, with the proposed targets, eventually reach WHO's annual AQG of 10 μg/m3 or less.

These progressive targets may also be made country specific. Thus the targets for a country in Group 2 with lower PM2.5 concentrations than the regional average in Group 2 may be the targets of Group 3. Targets may also be differentiated within a country reflecting intra-country geographic differences in PM2.5 concentrations.

Table 5.1. Regional PM2.5 ambient air pollution targets (annual maximum)

	Target	IT-1	IT-2	IT-3	AQG
	max annual PM2.5	35 µg/m3	25 µg/m3	15 µg/m3	10 µg/m3
Regions	Regions				
Group 1	EA				
Group 2	SA, MNA, HI AP, SSA-W, CA, CE, SEA				
Group 3	WE, HI NA, SSA-O, EE, LAC, AA, OC				

Source: The author.

Health effects

Health benefits of progressively moving from current exposure levels to the interim targets and WHO's AQG can be estimated by using the integrated PM2.5 exposure-health response methodology in annex 1 and risk ratios presented in Burnett et al (2014).

Health benefits are presented in table 5.2 relative to health effects at current exposure levels. The benefits, in percentage terms, are largest for the regions currently furthest away from the final target (AQG). Percentage benefits per 1 µg/m3 improvement in ambient concentrations of PM2.5 increases as ambient concentrations decline. This is due to the highly non-linear relationship between exposure and health effects.

As much as one-third of current health effects remain globally after reaching the AQG. This is due to the rapidly increasing relative risks of health effects from very low exposure levels.[16]

[16] The remaining health effects after reaching the AQG and the interim targets are likely to be lower than presented here. This is because it is assumed that air quality improvements only take place among the population with PM2.5 exposures exceeding the targets. In reality, air pollution control interventions aimed at areas with high PM2.5 concentrations will also benefit some of the areas with low concentrations, and thus also reduce health effects in these areas.

Table 5.2. Health benefits of meeting PM2.5 ambient air quality targets (% reduction in current health effects)

	Target	IT-1	IT-2	IT-3	AQG
	max annual PM2.5	35 μg/m3	25 μg/m3	15 μg/m3	10 μg/m3
Regions	Regions				
Group 1	EA	20%	34%	59%	80%
Group 2	SA, MNA, HI AP, SSA-W, CA, CE, SEA		13%	37%	66%
Group 3	WE, HI NA, SSA-O, EE, LAC, AA, OC			7%	39%
World	All	8%	19%	41%	67%

Source: Author's estimates.

An estimated 3.3 million people died and 9.4 billion disease days occurred globally in 2012 from PM2.5 ambient air pollution (AAP) (table 5.3). Almost 2.2 million deaths and 6.3 billion disease days could be avoided annually if all regions reached the annual PM2.5 AQG of 10 μg/m3.

Table 5.3. Estimated annual health effects of PM2.5 ambient air pollution exposure

	PM2.5	Group 1	Group 2	Group 3	World
Deaths from PM2.5 (000)	Current levels	1,276	1,452	542	3,269
Avoided deaths from reaching targets (000)	35 μg/m3	261			261
	25 μg/m3	439	182		621
	15 μg/m3	755	539	38	1,331
	10 μg/m3	1,022	962	212	2,196
Disease days from PM2.5 (million)	Current levels	3,270	4,481	1,621	9,372
Avoided disease days from reaching targets (million)	35 μg/m3	670			670
	25 μg/m3	1,125	571		1,696
	15 μg/m3	1,936	1,694	127	3,757
	10 μg/m3	2,620	2,998	662	6,280

Note: Groups are defined as in previous tables. Source: Author's estimates.

Monetized values of health effects

As for household air pollution, two alternative measures are applied to value the loss of a life or the benefit of avoiding a death associated with outdoor ambient PM2.5 air pollution. By the first measure using values of statistical life (VSL) a death is valued in the range of US$ 58 – 451 thousand in developing regions or the world, US$ 510 – 544 thousand in Central (CE) and Eastern Europe (EE), and US$ 1.9 - 3.2 million in the high income regions. The VSLs are equivalent to 50 times GDP per capita in each of the countries and regions. VSL can be converted to a value of statistical life year (VSLY) by dividing VSL by the number of years prematurely lost to death. VSLYs are thus in the range of US$ 1.2 – 224 thousand.[17] By the second measure, a uniform value of US$1,000 and US5,000 per year of life lost (YLL) is applied. The VSLYs are within this range for the lowest income regions of the world, but are much higher for middle- and high-income regions (table 5.4).

Two alternative measures are also applied to value morbidity. By the first measure a day of avoided illness is valued as the equivalent of 50% of daily wages (see annex 4). This is converted to a value of disability weighted year of disease in the range of US$ 6 – 343 thousand (table 5.4).[18] The second measure values a year lost to disease (YLD) at US$ 1,000 and US$ 5,000 as for years lost to premature mortality.[19]

Table 5.4. Valuation of mortality and morbidity, 2012 (US$)

	Value of statistical life (VSL)	Value of a statistical life year (VSLY)	Value of a day of disease (50% of wage rates)	Value of YLD (50% of wage rates)	DALY lower value	DALY upper value
EA	309,000	15,912	8.0	19,378	1,000	5,000
SA	71,000	2,514	2.7	6,662	1,000	5,000
MNA	369,000	14,327	16.3	39,783	1,000	5,000
HI AP	2,042,000	149,253	89.6	218,093	1,000	5,000
SSA-W	58,000	1,211	2.4	5,893	1,000	5,000
CA	250,000	10,052	7.9	19,238	1,000	5,000
CE	544,000	32,467	22.7	55,203	1,000	5,000
SEA	166,000	7,131	4.7	11,517	1,000	5,000
WE	1,935,000	143,042	86.7	210,931	1,000	5,000
HI NA	2,609,000	164,705	113.6	276,415	1,000	5,000
SSA-O	69,000	1,791	2.5	6,138	1,000	5,000
EE	510,000	26,918	14.8	35,898	1,000	5,000
LAC	451,000	20,686	14.7	35,655	1,000	5,000
AA	3,161,000	223,794	140.8	342,582	1,000	5,000
Oceania	142,000	4,400	5.3	12,923	1,000	5,000

Source: Author's estimates.

The global cost of outdoor ambient PM2.5 exposure in 2012 is estimated at US$ 1.7 trillion, applying VSL for mortality and a fraction of wage rates for morbidity. Over US$ 0.9 trillion of this cost is in the high income regions of Western Europe (WE), High Income North America (HI NA), High Income Asia Pacific (HI AP) and Australasia (AA). The high cost in these regions is associated with valuation of health effects in proportion to these regions' GDP per capita, although these regions only account for 11% of global deaths from PM2.5.

[17] The number of years of life lost (YLL) per premature death from outdoor ambient PM2.5 range from about 14-16 in the high income regions to 48 in western Sub-Saharan Africa (SSA-W). These figures are based on the Global Burden of Disease (GBD) 2010 Project results. YLL per death is high in countries and regions with high child mortality rates. No age-weighting or discounting is applied in the calculation of YLLs.

[18] Applying an average disability weight of 0.15.

[19] YLD is a disability weighted measure of disease burden. If the disability weight is 0.15 then 2,433 days of disease is equivalent to one YLD.

About US$ 637 billion of the cost is in the developing regions of Asia (EA, SA), Oceania (OC), Africa (SSA-W, SSA-O), Middle East and North Africa (MNA), Central Asia (CA) and Latin America and the Caribbean (LAC). This is similar to the cost of household air pollution (HAP) in these regions. The regions account for 81% of total deaths. The remaining US$230 billion of the cost is in Central (CE) and Eastern Europe (EE) and accounts for 8% of global deaths (table 5.5).

The cost ranged from 0.2-0.5% of GDP in Oceania (OC), Australasia (AA), Latin America and the Caribbean (LAC), and non-western Sub-Saharan Africa (SSA-O) to 4.1-4.9% in Eastern Europe (EE), Central Europe (CE) and East Asia (EA). The high cost in EE and CE is due to the high number of deaths and disease days per μg/m3 of exposure associated with baseline health conditions.

The global cost of outdoor ambient PM2.5 is estimated at US$ 78-388 billion in the same year when applying US$ 1,000 to US$ 5,000 per DALY (YLL and YLD) (table 5.5).

Table 5.5. Annual cost of health effects of outdoor ambient PM2.5 exposure, 2012 (US$ billion)

Valuation measure	VSL	DALY= US$1,000	DALY= US$5,000
EA	420	26	131
SA	63	23	116
MNA	76	4.9	25
HI AP	213	1.4	6.8
SSA-W	5.4	4.0	20
CA	14	1.3	6.7
CE	54	1.6	8.1
SEA	30	4.1	21
WE	372	2.5	12
HI NA	346	2.0	10
SSA-O	3.9	2.0	10
EE	86	3.2	16
LAC	24	1.1	5.6
AA	6.7	0.03	0.14
Oceania	0.05	0.01	0.05
World	1,714	78	388

Source: Author's estimates.

Pollution control options and costs

Ambient PM2.5 air pollution in the outdoor environment stems from many sources. These sources differ greatly inter- and intra-regionally. The road transport sector is generally a major contributor to ambient PM2.5, and so is often power generation and industry. Household use of solid fuels for cooking and heating is also a major contributor in some regions. Solid waste burning contributes substantially in some countries, as does seasonal agricultural field burning, and forest fires.

Secondary particulate formation (sulfates and nitrates) from sulfur dioxide and nitrogen oxide emissions are also important contributors to outdoor ambient PM2.5. Coal burning is often the major source of sulfur dioxide emissions, as can be combustion of high-sulfur oil products. Road vehicles are often a major source of nitrogen oxides.

Countries and regions are also at different stages of PM2.5 emission abatement, influenced by transport policy (e.g., transport modes), industrial development, regulatory policies and enforcement, pricing and taxation policies, demand management (e.g., energy, road vehicles), and adoption of effective abatement technologies. Countries and regions also differ in energy mix in terms of coal, gas, oil products, renewables and nuclear energy, which can have great implications for outdoor ambient PM2.5 air quality.

With such diversity in sources of emissions and stages of abatement, each region and country will have their own unique marginal cost curve of PM2.5 emission reductions, with different starting points (i.e., lowest currently available abatement cost) and different incremental costs of abatement. As high-income countries (HIC) have generally taken more measures to control PM2.5 than low- and middle-income countries (LMIC), costs of PM2.5 abatement are generally higher in the former group of countries.

This paper cannot hope to assess the cost of PM2.5 abatement from all these diverse sources. Two policy dimensions of abatement are briefly discussed: (i) energy subsidies; and (ii) taxation policies. This is followed by estimates of cost of abatement from four sources of PM2.5: (i) household use of solid fuels for cooking and heating; (ii) solid waste management; (iii) fuel quality; and (iv) road vehicle technologies.

Energy subsidies

World energy subsidies contribute to energy waste and pollution. Energy consumption subsidies averaged over US$ 400 billion per year during 2007-2010 and US$520-540 billion per year during 2011-2012 according to the International Energy Agency (IEA). These subsidies are concentrated in 39 countries responsible for over half of world fossil fuel consumption.[20] About half of the subsidies are to petroleum products, a quarter to natural gas, and a quarter to electricity. Subsidies to coal amount to less than one percent of total global subsidies. Eliminating these subsidies would provide economic efficiency gains and thus PM2.5 emission reductions at a negative marginal cost (i.e., positive economic benefit). Additionally, OECD has identified over 550 measures that subsidize and support fossil fuel production and use in its 34 member countries, amounting to US$ 55-90 billion per year from 2005 to 2011.[21] The majority of these subsidies and supports are to petroleum products, placing renewables and less polluting energies at a disadvantage.

Taxation policies

Taxation policies are important instruments for demand management and internalization of externalities. While direct tax instruments for PM2.5 abatement often are difficult to design, indirect instruments can provide PM2.5 emission reductions at lower cost to society than regulatory, command-and-control options. This is because these instruments

[20] http://www.worldenergyoutlook.org/resources/energysubsidies/
[21] http://www.oecd.org/site/tadffss/Fossil%20Fuels%20Inventory_Policy_Brief.pdf

allow polluters to identify and select lowest cost options, including reducing polluting behavior (e.g., drive less). Indirect instruments include fuel taxes, vehicle taxes, and tax rebates on PM2.5 control technology. As PM2.5 emissions often are correlated with other externalities of energy combustion and transportation, PM2.5 emission reductions can be achieved as a co-benefit of tax policies addressing congestion, cost recovery of wear-and-tear of transport infrastructure, and/or climate change emissions. These instruments are particularly effective in the long run for shaping transport demand and modals, encouraging smaller and more fuel efficient transport vehicles, and development and use of cleaner energies.

Household use of solid fuels

Household use of solid fuels does not only cause serious air pollution in the immediate household environment, but also contributes to outdoor ambient PM2.5 pollution. This is particularly the case if households use unimproved, inefficient stoves and cook outdoors or vent the smoke out of the dwelling. These emissions can impact a large number of people especially in the urban environment. In 2010, household cooking fuels contributed 7 μg/m3 of outdoor ambient PM2.5 in East Asia (incl. China) and nearly 9 μg/m3 in South Asia (incl. India) (Smith et al, 2014).

Two options for abating PM2.5 emissions from household use of solid fuels are assessed: i) improved cookstoves; and ii) switching to LPG. These two options are evaluated for both biomass and coal and for East Asia (EA), Latin America and the Caribbean (LAC), and other regions separately due to differences in cost of improved stoves.[22] The biomass assessment is particularly relevant for cities in South Asia (SA), South East Asia (SEA) and Sub-Saharan Africa where a substantial share of the population still uses solid fuels in urban areas. The coal assessment is particularly relevant for China.

Improved cookstoves provide cheaper PM2.5 abatement than switching to LPG, but LPG is far more effective in reducing PM2.5 emissions (table 5.6). Abatement of PM2.5 from using an improved biomass or coal cookstove can be achieved at a negative (positive net benefits) or very low positive cost when accounting for the value of fuel savings that the improved stove provides. The cost of switching to LPG from unimproved cookstoves is the range of US$ 8-13 thousand net of fuel savings with somewhat lower cost from biomass stoves than from coal stoves. The cost of switching to LPG from improved coal stoves is as high as US$ 50 thousand. These costs estimates are for households cooking outdoors or who vent the smoke out of their dwelling. The costs are higher when a share of PM2.5 emissions is retained indoors.

[22] The improved stove costs applied are the same as for household air pollution. East Asia is mainly China.

Table 5.6. Cost of PM2.5 abatement from household energy (US$/ton of PM2.5)

	FS not included			Including FS		
	EA	LAC	Other	EA	LAC	Other
Improved biomass cookstove	7,000	3,700	2,900	1,300	-2,100	-2,800
Improved coal cookstove	12,800			-1,500		
LPG instead of biomass for cooking	13,800	13,800	13,800	8,100	8,100	8,100
LPG instead of unimproved coal stove	27,700			13,400		
LPG instead of improved coal stove	64,500			50,300		

Note: FS = biomass or coal savings from switching to improved stove or LPG. Source: Estimates by the author.

Solid waste management

Uncontrolled burning of solid waste by households and scavengers contributes to urban ambient PM2.5 pollution. This is particularly the case in South Asia (SA) and Sub-Saharan Africa (SSA), but also in poor neighborhoods in other parts of the world. Improved municipal solid waste management can reduce waste burning. The cost of improved management per ton of waste increases with GDP per capita, e.g., higher costs of labor and land, but declines as a percentage of GDP per capita (table 5.7). The cost estimates are based on cost per ton of waste collection, city cleaning from littering, and sanitary disposal. The costs translate to US$ 10-12 thousand per ton of PM2.5 abatement from avoided burning of waste in the lowest income regions of the world, somewhat higher in South East Asia (SEA) at US$ 16-17 thousand, and US$ 24-28 in East Asia (EA) and Latin America and the Caribbean (LAC) (table 5.7).

Table 5.7. Cost of PM2.5 abatement from improved solid waste management

	SSA-W	SSA-O	SA	SEA	EA	LAC
GDP per capita, US$, 2012	1,153	1,367	1,414	3,299	6,128	8,936
Waste generation (kg/capita/day)	0.6	0.6	0.6	0.8	0.9	1.00
Waste generation (tons/capita/year)	0.22	0.22	0.22	0.29	0.33	0.37
Cost of waste management (% of GDP)	1.3%	1.3%	1.3%	1.0%	0.9%	0.8%
Cost of waste management (US$/ton)	68	81	84	113	168	196
PM2.5 per ton of waste burning (kg)	7	7	7	7	7	7
Cost of PM2.5 emission reductions (US$/ton)	9,800	11,600	12,000	16,100	24,000	28,000

Source: Estimates by the author.

Fuel quality

Quality of fuels greatly influences PM2.5 emissions, directly or indirectly. Low sulfur coal and petroleum products reduce the formation of secondary particulates (sulfates). Cleaner coal can also reduce the amount of fly ash. Low sulfur diesel, discussed below, directly reduces PM2.5 emissions and allows installation of efficient particulate control technology on diesel vehicles.

The majority of primary PM2.5 emissions from vehicle fuel combustion come from diesel vehicles. According to OECD energy balance statistics, diesel fuel constituted 44% of global road transport fuel consumption in 2012, but with large inter- and intra-regional differences.[23] Regionally, the highest rate of road transport dieselization is found in OECD Europe (65%) or the European Union (65%), followed by non-OECD Asia (56%), Africa (52%), non-OECD Americas (45%), Middle East (43%), OECD Asia-Oceania (40%), non-OECD Europe-Eurasia (approx. 35%), and North America (28%).

With ultra-low sulfur diesel and modern particulate control technologies, such as diesel particulate filters (DPF), PM2.5 emissions from new diesel vehicles or older vehicles retrofitted with DPFs are very low and comparable to gasoline vehicles. However, nationwide fuel quality (e.g. high sulfur diesel) in most developing countries is not good enough for effective functioning of DPFs, and vehicle fleets are often old with no or minimal PM emission controls.

Among major countries of non-OECD Asia - the region in which 68% of all deaths from ambient PM2.5 occurs - road transport dieselization range from 39-40% in Indonesia and Malaysia and 52-60% in Pakistan, Vietnam, China, Thailand, the Philippines and Bangladesh to as high as 74% in India.

Lowering of sulfur in diesel directly results in less PM2.5 emissions per km driven, and, importantly, allows introduction of diesel vehicles with effective PM control technologies as well as retrofitting of in-use diesel vehicles.

In recognition of the road transport sector's contribution to air pollution, there is globally a major push for ultra-low sulfur (<50 ppm) diesel for road vehicles. According to global data by UNEP, most high-income OECD countries allow a maximum of 15 ppm sulfur in diesel. A handful of developing countries have reached a maximum of 50 ppm, compatible with EURO 4 vehicle emissions standards. A substantial number of developing and transition economies have below 500 ppm, compatible with EURO 2 standards. However, many countries continue to use diesel with up to 2000 ppm sulfur (EURO 1) and above, especially in the Middle East and North Africa, Central and Western Sub-Saharan Africa, Central Asia, and to some extent also in Latin America and the Caribbean (LAC).[24]

The cost of PM2.5 abatement by reducing sulfur in diesel depends on several factors including initial sulfur content, incremental refinery costs or market price differentials, and vehicle characteristics. Reducing sulfur from around 2000 ppm to 50 ppm is estimated to cost US$3-6 per barrel of diesel. Reduction from 500 ppm to 50 ppm is estimated to cost US$1.5-2.0 per barrel.[25] These costs translate to roughly US$14-29 thousand per ton of PM2.5 abatement (table 5.8). The upper bound reflects high refinery investment requirements in many refineries in SSA (ICF International, 2009). Lower costs may be

[23] http://www.iea.org/statistics/statisticssearch/report/?country=WORLD&product=balances&year=2012

[24] http://www.unep.org/transport/new/pcfv/

[25] These cost figures are largely based on refinery sector studies of continental Sub-Saharan Africa (ICF International, 2009) and Brazil, China and India (Hart Energy and MathPro, 2012), as well as petroleum product market information.

achieved by importing ultra-low sulfur diesel, either from efficient refineries in SSA or elsewhere.

Table 5.8. Cost of PM2.5 abatement from using ultra-low sulfur diesel (50 ppm) for road vehicles

	US$/bbl of diesel	US$/ton of PM2.5
Sulfur from 2000 ppm to 50 ppm	3	14,650
	6	29,300
Sulfur from 500 ppm to 50 ppm	1.5	14,000
	2	18,600

Source: Estimates by the author.

Road vehicle technologies

Technical control options are available to reduce emissions from major sources of PM2.5 such as road transport, power generation and industry. These options are available in multiple forms: (i) production process technology and engine technology; (ii) end-of-pipe technology installed at the time of manufacturing of industrial equipment or vehicles; (iii) end-of-pipe technology for retrofitting of in-use equipment or vehicles; and (iv) change of technology in in-use equipment or vehicles. Options (i) and (ii) can often be achieved at lower cost than retrofitting or change of technology in in-use equipment or vehicles. Retrofitting or technology change is often the only options for equipment stocks or vehicle fleets with substantial remaining life.

The option assessed here is retrofitting of in-use diesel vehicles with diesel particulate filters (DPFs). These retrofit DPFs cost several thousand US dollars and can reduce PM emissions by over 90% once ultra-low sulfur diesel (S < 50 ppm) is available. Cost per ton of PM2.5 abatement is in the range of US 30-100 thousand for relatively high usage vehicles (40-60 thousand km/year) used primarily within cities (table 5.9). The cost of this abatement option is substantially higher than the previous options assessed, but highly effective. The cost of diesel oxidation catalysts (DOCs) is substantially lower than the cost of DPFs, but DOCs' abatement efficiency is also substantially lower.

Table 5.9. Cost of PM2.5 abatement from DPF retrofitting of in-use diesel vehicles (US$/ton)

	Low	High
Heavy duty vehicles	32500	77500
Light duty vehicles	57500	102500

Source: Estimates by the author.

Benefit-cost ratios

Global benefits

Global benefits of reaching the final target, i.e., annual AQG of 10 μg/m3 of PM2.5, are US$ 52 – 971 billion per year (table 5.10). The marginal or incremental benefits increase substantially as the world progresses from the interim targets to the AQG due to the non-linear relationship between exposure and health effects. About 87% of the avoided deaths are in low- and middle-income countries.

Table 5.10. Annual global benefits of reaching the PM2.5 targets, 2012 (billion US$)

Interim and final targets (PM2.5)	Benefits by alternative health valuation measures		
	VSL	DALY=US$1,000	DALY=US$5,000
IT-1: 35 µg/m3	86	5	27
IT-2: 25 µg/m3	200	14	71
IT-3: 15 µg/m3	485	32	158
AQG: 10 µg/m3	971	52	262

Note: Groups are defined as in previous tables. Source: Author's estimates.

Benefits per ton of PM2.5 emissions

Health benefits must be estimated per ton of PM2.5 emission reductions in order to estimate benefit-cost ratios of PM2.5 pollution control. This is undertaken by using geographic-specific intake fractions (see annex 5). An intake fraction is a measure of how much of a ton of emissions in a geographic area is breathed in by the exposed population. The higher the intake fraction the larger are the health damages and thus the health benefits of emissions reductions.

Apte et al (2012) estimate the intake fraction of distributed ground-level emission sources in over 3,600 cities of the world with a population greater than 100 thousand in year 2000 based on geographic, meteorological, and demographic location specific data. Population weighted intake fractions by country range from less than 10 to over 100 ppm, and by major city from less than 5 to over 250.

Benefits per ton of PM2.5 emissions reductions are very location specific and will depend on PM2.5 ambient concentrations and intake fractions (see annex 5). Benefits per ton are here estimated for cities with locations in which PM2.5 concentrations exceed initial regional targets. Intake fractions for these cities are derived from Apte et al (2012). Estimated benefits are presented in table 5.11. These benefits per ton are applied to estimate benefit-cost ratios (BCRs) of PM2.5 emission control interventions.

Regional variations in benefits per ton are mainly explained by variations in intake fractions, initial PM2.5 concentrations, baseline health conditions, and valuation of health effects. Benefits per ton will increase intra-regionally as regions progress from the interim targets to the AQG due to the non-linear relationship between exposure and health effects.

Table 5.11. Benefits of PM2.5 emissions reductions (US$/ton)

			Benefits (US$/ton) by alternative valuation measures		
		Intake fraction (iF)	VSL	DALY= US$1,000	DALY= US$5,000
Group 1 (IT-1: max 35 μg/m3)	EA	100	52,000	3,230	16,150
Group 2 (IT-2: max 25 μg/m3)	SA	100	15,700	5,800	29,000
	MNA	70	48,400	3,140	15,700
	SSA-W	80	7,400	5,500	27,500
	CA	30	30,100	2,920	14,600
	SEA	90	40,500	5,510	27,550
Group 3 (IT-3: max 15 μg/m3)	SSA-O	50	8,400	4,270	21,350
	LAC	70	80,600	3,740	18,700
	Oceania	15	5,800	1,230	6,150
IT-2: max 25 μg/m3)	CE	30	99,000	2,970	14,850
IT-3: max 15 μg/m3)	EE	40	288,400	10,620	53,100
High income regions	HI AP	60	361,300	2,310	11,550
	WE	45	404,800	2,710	13,550
	HI NA	40	533,000	3,030	15,150
	AA	20	186,500	790	3,950

Source: Author's estimates.

Regional benefit-cost ratios

As an estimated 81% of global deaths from outdoor ambient PM2.5 occur in low- and middle-income countries, the benefit-cost analysis in this paper concentrates on these regions.

Benefit-cost ratios (BCRs) of controlling PM2.5 emissions to the outdoor environment from household use of solid fuels are larger than the BCRs of other abatement options assessed. This is mainly due to the biomass or coal savings that the interventions provide. BCRs of improved solid waste management for minimization of uncontrolled burning and of ultra-low sulfur diesel for road vehicles are relatively similar, albeit with inter-regional variations.

Regional benefit-cost ratios (BCRs) of improved biomass cookstoves range from 1.3 to 23.3. They are all greater than one even for health valuation of US$1,000 per DALY. In East Asia (i.e., mainly China), BCRs of improved coal cookstoves are in the range of 1.4-5.2. Regional BCRs for using LPG instead of biomass cookstoves or unimproved coal cookstoves in East Asia are mostly greater or equal to one for health valuation using VSL or US$5,000 per DALY (tables 5.12-13). The BCRs are for households cooking outdoors or who vent the smoke out of the dwellings. They are conservative insofar as they do not include the benefits of household air pollution reduction.

Table 5.12. Benefit-cost ratios of household use of improved biomass cookstoves (ICS) and LPG, 2012

	ICS (biomass)			LPG (from biomass)		
Region/valuation measure	VSL	DALY= US$1,000	DALY= US$5,000	VSL	DALY= US$1,000	DALY= US$5,000
EA	8.2	1.3	3.1	4.2	0.6	1.6
SA	7.4	4.0	12.0	1.6	0.8	2.5
SEA	15.9	3.9	11.5	3.3	0.8	2.4
SSA-W	4.5	3.9	11.5	1.0	0.8	2.4
SSA-O	4.9	3.4	9.3	1.0	0.7	2.0
LAC	23.3	2.6	6.6	6.3	0.7	1.8
Oceania	3.1	1.9	3.2	0.8	0.5	0.9

Note: ICS=improved cookstove. Source: Author's estimates.

Table 5.13. Benefit-cost ratios of household use of improved coal cookstoves (ICS) and LPG in East Asia, 2012

	VSL	DALY= US$1,000	DALY= US$5,000
ICS (coal)	5.2	1.4	2.4
LPG (from UCS with coal)	2.4	0.6	1.1
LPG (from ICS with coal)	1.0	0.3	0.5

Note: ICS=improved cookstove. UCS=unimproved cookstove. Source: Author's estimates.

Regional BCRs of improved municipal solid waste management to minimize uncontrolled burning of waste range from 0.13 to 2.88. They are mostly greater than one when using VSL or US$ 5,000 per DALY for health valuation, but less than one in all regions for US$ 1,000 per DALY. They are less than one in Oceania for all three health valuation measures, reflecting low intake fractions (table 5.14). The BCRs do however not include co-benefits associated with a cleaner urban environment.

Table 5.14. Benefit-cost ratios of improved solid waste management, 2012

	VSL	DALY= US$1,000	DALY= US$5,000
EA	2.17	0.13	0.67
SA	1.31	0.48	2.42
SEA	2.52	0.34	1.71
SSA-W	0.76	0.56	2.81
SSA-O	0.72	0.37	1.84
LAC	2.88	0.13	0.67
Oceania	0.37	0.08	0.39

Source: Author's estimates.

Regional BCRs of ultra-low sulfur diesel (ULSD) fuel for road vehicles range from 0.1 to 5.0. They are mostly greater than one when valuing health benefits using either VSL or US$

5,000 per DALY. They are less than one for US$ 1,000 per DALY. They are quite similar for sulfur reduction from 2000+ to 50 ppm and from 500 to 50 ppm (table 5.15).

The BCRs are for ULSD consumed primarily within the cities targeted for PM2.5 abatement. BRCs for nationwide use of ULSD are lower than presented in table 5.15. However, as ULSD is a prerequisite for effective PM2.5 emission controls from diesel vehicles, there are indirect benefits not captured in the BCRs here.

Table 5.15. Benefit-cost ratios of ultra-low sulfur diesel fuel (ULSD) for road vehicles, 2012

	ULSD (2000+ to 50 ppm)			ULSD (500 to 50 ppm)		
Region/valuation measure	VSL	DALY= US$1,000	DALY= US$5,000	VSL	DALY= US$1,000	DALY= US$5,000
EA	3.1	0.19	1.0	3.3	0.20	1.0
SA	0.9	0.35	1.7	1.0	0.36	1.8
SEA	2.4	0.33	1.6	2.5	0.34	1.7
SSA-W	0.3	0.23	1.2	0.5	0.34	1.7
SSA-O	0.4	0.18	0.9	0.5	0.27	1.3
LAC	4.8	0.22	1.1	5.0	0.23	1.2
Oceania	0.3	0.07	0.4	0.4	0.08	0.4
CA	1.8	0.17	0.9	1.9	0.18	0.9
MNA	2.9	0.19	0.9	3.0	0.20	1.0

Source: Author's estimates.

Regional BCRs of retrofitting in-use diesel vehicles with diesel particulate filters (DPFs) range from 0.02 to 1.47. BCRs are less than one in most regions and for all three health valuation measures (table 5.16). Cost of DPFs for vehicle retrofitting is declining, however, and installation of DPFs on new vehicles is cheaper than retrofitting of in-use vehicles.

Table 5.16. Benefit-cost ratios of DPF retrofitting of in-use vehicles, 2012

	DPF for LDVs			DPF for HDVs		
Region/valuation measure	VSL	DALY= US$1,000	DALY= US$5,000	VSL	DALY= US$1,000	DALY= US$5,000
EA	0.65	0.04	0.20	0.95	0.06	0.29
SA	0.20	0.07	0.36	0.29	0.11	0.53
SEA	0.51	0.07	0.34	0.74	0.10	0.50
SSA-W	0.09	0.07	0.34	0.13	0.10	0.50
SSA-O	0.11	0.05	0.27	0.15	0.08	0.39
LAC	1.01	0.05	0.23	1.47	0.07	0.34
Oceania	0.07	0.02	0.08	0.11	0.02	0.11
CA	0.38	0.04	0.18	0.55	0.05	0.27
MNA	0.61	0.04	0.20	0.88	0.06	0.29

Note: DPF=diesel particulate filter. LDV=light duty vehicles. HDV=heavy duty vehicles. Source: Author's estimates.

The estimated BCRs suggest that outdoor PM2.5 abatement in especially low-income countries should be selective and well prioritized. They also suggest that a high priority is to control PM2.5 emissions from household use of solid fuel, be it for indoor and outdoor exposure reduction.

Only ground level distributed PM2.5 abatement options have been assessed in this paper. Options are also available to reduce PM2.5 emissions from power plants and industrial facilities. The PM2.5 intake fractions associated with these sources are often substantially lower than the fraction from ground level sources, but abatement cost per ton of PM2.5 is also often lower. Development of a least cost abatement strategy per unit of health benefit would need to include an assessment of these PM2.5 sources.

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Annex 1. Health effects of particulate matter pollution

Particulate matter (PM) is the air pollutant that globally is associated with the largest health effects. It is a major outdoor air pollutant and a major household air pollutant from the burning of solid fuels for cooking and, in cold climates, heating. 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 (μg/m3) 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[26] 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 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.

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

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 (PM2.5) both in the outdoor and household environments:

$$RR(x)_{kl} = 1 \qquad \text{for } x < xcf \qquad \text{(A1a)}$$
$$RR(x)_{kl} = 1 + \alpha_{kl}(1 - e^{-\beta_{kl}(x - x_{cf})^{\rho_{kl}}}) \qquad \text{for } x \geq xcf \qquad \text{(A1b)}$$

where x is the ambient concentration of PM2.5 in μg/m3 and xcf 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 PM2.5 concentrations, with RR(xcf+1) ~ 1+αβ and RR(∞) = 1 + α 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 PM2.5 concentrations around the world as well as to high household air pollution levels of PM2.5 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). 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 xcf = 7.3 μg/m3 is applied here based on bounds of 5.8 to 8.8 μg/m3 used in the GBD 2010 Study (Lim et al, 2012).

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

$$AF = \sum_{i=1}^{n} P_i[RR\left(\frac{x_i + x_{i-1}}{2}\right) - 1]/(\sum_{i=1}^{n} P_i[RR(\frac{x_i + x_{i-1}}{2}) - 1] + 1) \qquad \text{(A2)}$$

where Pi is the share of the population exposed to PM2.5 concentrations in the range xi-1 to xi. 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:

$$B = \sum_{k=1}^{t} \sum_{l=1}^{s} D_{kl} AF_{kl} \qquad \text{(A3)}$$

where Dkl is the total annual number of cases of disease, k, in age group, l, and AFkl is the attributable fraction of these cases of disease, k, in age group, l, due to PM2.5 exposure.

Annex 2. Exposure from household use of solid fuels

PM2.5 concentrations in households cooking with solid fuels 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.

Concentrations of PM2.5 often reach several hundred micrograms per cubic meter (μg/m3) in the kitchen, and well over one hundred μg/m3 in the living and sleeping environments. In rural Mexico, mean PM2.5 concentrations (> 24 hours) were found to average 600-1200 μg/m3 in kitchens using wood over open fire, and 250-330 μg/m3 in the same kitchens after switching to an improved wood stove (Zuk et al, 2007; Cynthia et al, 2008). In rural Guatemala, mean PM2.5 concentrations (> 24 hours) were 900 μg/m3 in kitchens using wood over open fire and 340 μg/m3 in kitchens using an improved chimney stove (Northcross et al, 2010). Balakrishnan et al (2013) report similar PM.2.5 kitchen concentrations (24 hours) in several other countries, generally in the range of 200-300 μg/m3 to 1,100-1,300 μg/m3.

PM2.5 concentrations from solid fuel use are also high in other parts of the household environment. Zuk et al (2007) in rural Mexico found concentrations of around 100 μg/m3 at the outdoor patio of the dwellings cooking over open fire and after switching to an improved wood stove. In households using solid cooking fuels in four states in India, PM2.5 concentrations (24 hours) averaged over 160 μg/m3 in the living area and over 600 μg/m3 in the kitchen (Balakrishnan et al, 2013).

Personal PM2.5 exposure is high as a result of these high indoor concentrations. In Guatemala, 24-hours personal PM2.5 exposure among women using open wood fire was over 260 μg/m3, and over 100 μg/m3 among women using an improved chimney wood stove (McCracken et al, 2007). In Honduras, 8-hours daytime personal PM2.5 exposure among women using open wood fire or traditional stoves was about 200 μg/m3, and 74 μg/m3 among women using an improved chimney wood stove. Kitchen concentrations over the same time period and groups of women were about 1000 μg/m3 and 266 μg/m3 respectively (Clark et al, 2009).

Balakrishnan et al (2012) estimate a nationwide long-term personal exposure in households using solid fuels in India of 338 μg/m3 among women, 285 μg/m3 among children, and 205 μg/m3 among men.

Mestl et al (2006) models annual average rural population weighted exposure (PWE) to household air pollution by using monitoring data from Chinese studies, the share of the population using solid fuels, and household member activity patterns. PWE to PM10 is estimated at 360 μg/m3 for households using coal and 810 μg/m3 for households using biomass.

Jin et al (2005) report on monitoring in rural households in four provinces in China. Average PM4 levels in living/bedrooms and kitchens were in the range of 350-720 μg/m3 in households using predominantly biomass and 185-360 μg/m3 in households using predominantly coal.

Edwards et al (2007) report indoor air quality monitoring in three provinces in China. PM4 concentrations in 75 percent of kitchens and 73 percent of living rooms during the winter - and 48 percent of kitchens and 46 percent of living rooms during the summer - exceeded 150 μg/m3 for a 24 hour average. Edwards et al conclude that PM4 concentrations are substantially lower in the homes with improved stoves (chimney) -- 152 μg/m3 compared to 268 μg/m3 in homes with unimproved stoves (no chimney).

Annex 3. Valuation of health benefits

The benefit of avoided illness is in this paper valued based on two measures: i) a day of disease is valued as 50% of average labor income per day (see annex 4); or ii) a year lost to disease (YLD) is valued at US$ 1,000 and US$ 5,000.

The benefit of an avoided death (or cost of a death) is in this paper valued based on two measures: i) the value of statistical life (VSL); or ii) a year of life lost (YLL) to premature mortality is valued at US$ 1,000 and US$ 5,000.

Country specific and regional VSLs are 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:[27]

$$\ln VSL = 0.23 + 1.0 \ln(gdp) - 0.445 \ln(r) \qquad \text{(A1)}$$

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.[28] The VSL is then converted to a country's currency by multiplying by the PPP rate as reported in World Bank (2014), which is the ratio "GDP in local currency / PPP adjusted GDP in dollars".

[27] 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.

[28] This BT function implies that the income elasticity is 1.022, meaning that VSL varies across countries in proportion to their PPP adjusted GDP per capita level.

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.

VSL is about 50 times GDP per capita and ranges from US$50-75 thousand in much of Sub-Saharan Africa (SSA) and South Asia (SA) to US$ 1.9-3.2 million in high income regions.

Annex 4. Valuation of time savings

In this paper, the assessed benefits of improved ambient PM2.5 air quality are health improvements. For clean household fuels and improved cookstoves the assessed benefits also include biomass fuel savings and cooking time savings. These three categories of benefits involve time savings from avoided illness, reduced biomass collection, and improved cooking efficiency. These time savings are valued at a fraction of wage rates.
Country specific average wage rates are estimated as follows:

$$W = gdp * s / L \qquad \text{(A1)}$$

where W is annual wages per person, gdp is GDP per capita, s is labor income share of GDP, and L is labor force as a percent of total population. Labor income share of GDP is not readily available for most developing countries, and is therefore roughly estimated by a simple procedure using wage data from the Global Wage Database of the International Labour Organization (ILO).

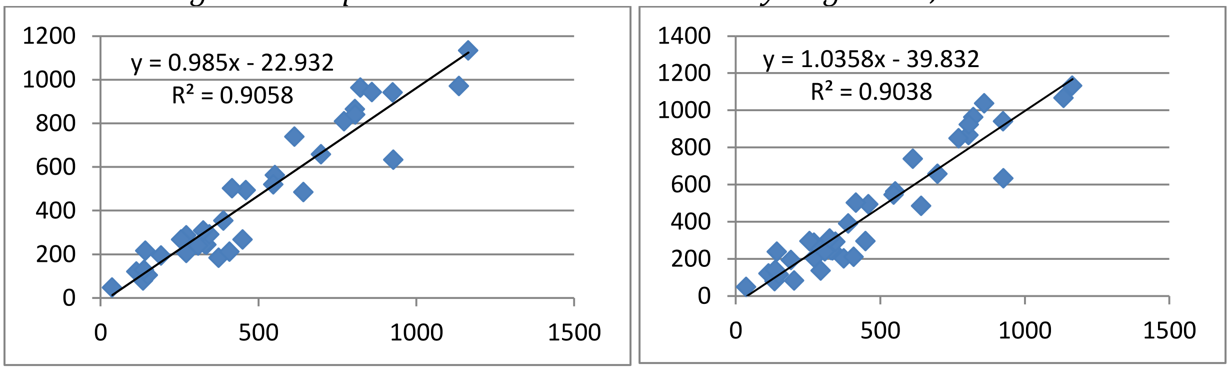
The ILO database includes monthly wage data in local currency in 2010-2011 for well over 40 developing countries and countries of the former Soviet Union (Eastern Europe and Central Asia regions). Wages are reported as nationwide and for all sectors in two-thirds of the countries and for urban or the manufacturing sector in the remaining countries.

The reported wage data were plotted against estimated monthly wages using equation A1 (figure A1).[29] Monthly wages from equation A1 were estimated by selecting a labor income share of GDP of 0.4. This is the labor income share that provides the best fit between reported and estimated wages.[30] The correlation coefficient for reported versus estimated wages is 0.95.

[29] Ten countries with widely and improbably divergent estimated versus reported wages were removed from the plot (ratios < 0.5 and > 1.55).

[30] This share may better be interpreted as the adjustment factor that regionally best describes the relationship between GDP per capita and average wage rates. The ILO Global Wage Database reports unadjusted labor income shares (unadjusted wage shares of GDP) for some developing countries. The shares are generally in the range of 0.25-0.45. Adjusted shares are not reported for these countries. The average unadjusted and adjusted share in high-income OECD countries reported in the ILO database is 0.48 and 0.55 respectively.

Figure A1. Reported versus estimated monthly wage rates, 2010-2011



Notes: Reported nationwide monthly wages (ILO Global Database) on x-axis and estimated monthly wages on y-axis. Estimated monthly wages in the figure to the right are adjusted by a factor of 1.1 when reported wages are for urban or manufacturing sector.

The labor income share of 0.4 is uniformly applied to all developing regions and countries of the former Soviet Union (Eastern Europe and Central Asia) to estimate regional wage rates. Labor income shares in Western Europe (WE), Central Europe (CE), High Income Asia Pacific (HI AP), High Income North America (HI NA), and Australasia (AA) are calculated from reported country specific adjusted labor income shares in the ILO database and range from 0.52 in CE to 0.63 in AA (table A1).

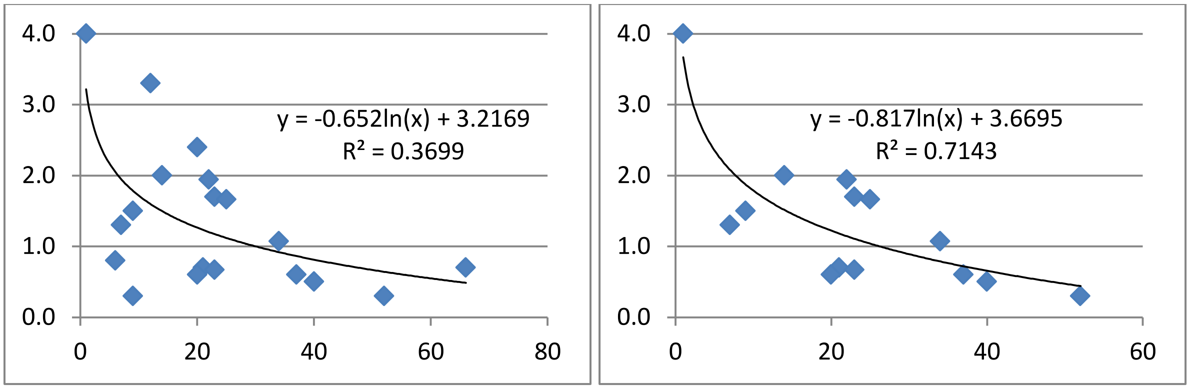
As the vast majority of solid fuel users live in rural areas, a rural hourly wage rate is estimated by applying an urban/rural wage ratio of 1.30. As women are often the beneficiary of reduced fuel collection and cooking time, and with average salaries lower than males', a rural female hourly wage is estimated by applying a female to average wage ratio of 0.80.

Improved cookstoves and modern fuel stoves provide fuel savings. These fuel savings are mainly in the form of biomass fuels (e.g., wood, agricultural residues and straws, animal dung) and sometimes coal (e.g., China).

A majority of urban households purchases some or all of the biomass fuels they use for cooking while the majority of rural households collects these fuels themselves. As about 80% of the world's solid fuel users live in rural areas, it is important to impute a value to these self-collected fuels. A common approach to doing so is to value the time households spend on biomass fuel collection.

Hutton et al (2006) report firewood collection times in fifteen countries in Sub-Saharan Africa (SSA), and in China, India, Nepal, and Indonesia. These collection times are plotted against national forest cover. A logarithmic function provides the best data fit (figure A2).

Figure A2. Household firewood collection time (hours per day) in relation to national forest cover



Note: X-axis is forest cover (% of land area). Y-axis is hours of collection time per household per day. The figure to the right excludes five outliers.

Predicted collection times using the logarithmic function are presented in table A1. The predicted values for India and Indonesia are much higher than the collection times reported in Hutton et al (2006). The collection times applied in this paper are therefore scaled downwards relative to predicted values in all regions to range from 0.5 hours in South East Asia (SEA) to 1.5 hours in South Asia (SA). The applied value for China is also adjusted downwards given that 2/3rd of household biomass consumption in rural China is straw, mostly collected on-farm (World Bank, 2013).

Table A1. Estimated average household firewood collection time by region (hours/household/day)

	Household firewood collection time			
	All observations	Excluding five outliers	Applied	Forest cover (% of land area)
China	1.20	1.14	0.70	22%
India	1.17	1.11	0.80	23%
SSA	1.33	1.31	0.90	24%
SEA1	0.76	0.59	0.50	45%
SA2	2.08	2.25	1.50	9%
LAC	0.96	0.85	0.60	39%

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates. Forest cover is from World Bank (2014).

These collection times can be applied to estimate the value of biomass fuels used by households. Arguably they are likely to somewhat understate the value of biomass fuels as households also spend time on collecting and preparing fuels such as agricultural residues, straws and animal dung, although these latter fuels are used less and less frequently. Some households, even in rural areas, also purchase some of their fuel needs, which value is not reflected in fuel collection.

Applying the estimated collection times, rural female wages rates, and a value of time equal to 50% of wage rates, the value of fuel collection is estimated in the range of US$59-189 per household per year (table A2). Rural female wage rates were applied as 80% of solid fuel users live in rural areas and most fuel collection is carried out by women (or children).

The estimated value of fuel collection in India of US$77 per household per year is the same as the rural household expenditure on cooking fuel in 2009-10 reported in Dalberg (2013) from the National Sample Surveys. The estimated value for South Asia (SA) is just below rural household expenditure on fuels (excl. electricity) in Pakistan according to the Household Integrated Economic Survey 2010-11. The estimated value of fuel collection in China is likely to underestimate the actual value of household fuel use because of substantial amounts of coal used for both cooking and heating.

Use of an improved cookstove instead of an unimproved stove or open fire can bring substantial 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 more than double depending on type of stoves, cooking practices and type of food cooked. Efficiency of coal cookstoves are found in the range of 7% for unprocessed (coal power) metal vented stoves to 47% for honeycomb coal briquette improved stoves (Malla and Timilsina, 2014. Consequently, biomass fuel savings therefore generally exceed 20% and can be as high as 53% using agricultural residues and 68% using wood. Coal savings can be as high as 85%.

In this paper it is assumed that fuel savings from the use of an improved biomass or coal cookstove instead of an unimproved stove or open fire are on average 30%. Use of LPG results in 100% savings of biomass fuels or coal. The value of fuel savings from an improved cookstove or LPG is estimated as 30% or 100%, respectively, of the value of fuel collection. The value of fuel savings of switching from an improved cookstove to LPG is 70% of the value of fuel collection. These calculations implicitly assume that households currently use unimproved cookstoves or open fire, which according to recent household surveys is the case for the vast majority of households in developing countries.

Table A2. Estimated value of household fuel collection, 2012

	China	India	SSA	SEA1	SA2	LAC
Fuel collection time (hours/day)	0.70	0.80	0.90	0.50	1.50	0.60
Female rural wage rate (US$/hour)	1.37	0.53	0.36	0.66	0.34	1.73
Value of time (% of wage rate)	50%	50%	50%	50%	50%	50%
Value of fuel collection (US$/year)	175	77	59	60	94	189

Notes: 1 Plus Korea DR. 2 Excluding India. Source: Author's estimates.

Improved cook stoves and LPG stoves tend to provide 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, could effectively be considered time savings, 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.

This paper applies a cooking time saving of 10 minutes from the use of an improved cookstove and 40 minutes from the use of LPG compared to an unimproved cook stove or open fire. As for fuel collection time savings, rural female wages rates and a value of time equal to 50% of wage rates are applied to estimate the value of cooking time savings.

Annex 5. Intake fractions

Health benefits per ton of emission reductions in a geographic area are:

$$B = \frac{h(\delta C)}{\delta E} = m\frac{\partial AF}{\delta E} \qquad \text{(A1)}$$

where $h(\delta C)$ is the change in health effects associated with a change in annual ambient PM2.5 concentrations δC (μg/m3); E is emissions of PM2.5 (tons/year); δAF is the change in the population attributable fraction of health outcomes associated with δE; and m is baseline annual cases of the health outcomes.

To solve for B we need a relation between emissions (E) and concentrations (C). The change in the quantity of PM2.5 that a population in a geographic area breathes into the lungs in a year is given by:

$$\partial\, iP = P * Q_d * 365 * 10^{-12} * \partial C \qquad \text{(A2)}$$

where iP is population intake of PM2.5 (tons/year), P is population, Qd is breathing rate of air (m3/day). The change in population intake (tons/year) is also given by:

$$\delta\, iP = \delta E * iF * 10^{-6} \qquad \text{(A3)}$$

where E is emissions of PM2.5 (tons/year), iF is the so called intake fraction in parts per million (ppm), or the fraction of emissions that the population breathes into their lungs.[31] From A2 and A3 follows:

[31] The single compartment intake fraction (ppm) is $iF = Q_s * P * 10^6/(u * H * \sqrt{A})$ where Q_s is breathing rate of air (m^3/s), P is population, u is wind speed (m/s), H is mixing height (m), and A is the geographic area (m^2).

$$\partial E = P * Q_d * 365 * 10^{-6} * iF^{-1} * \partial C \qquad \text{(A4)}$$

This can simply be written as:

$$\delta E = K \frac{P\, \delta C}{iF} \qquad \text{(A5)}$$

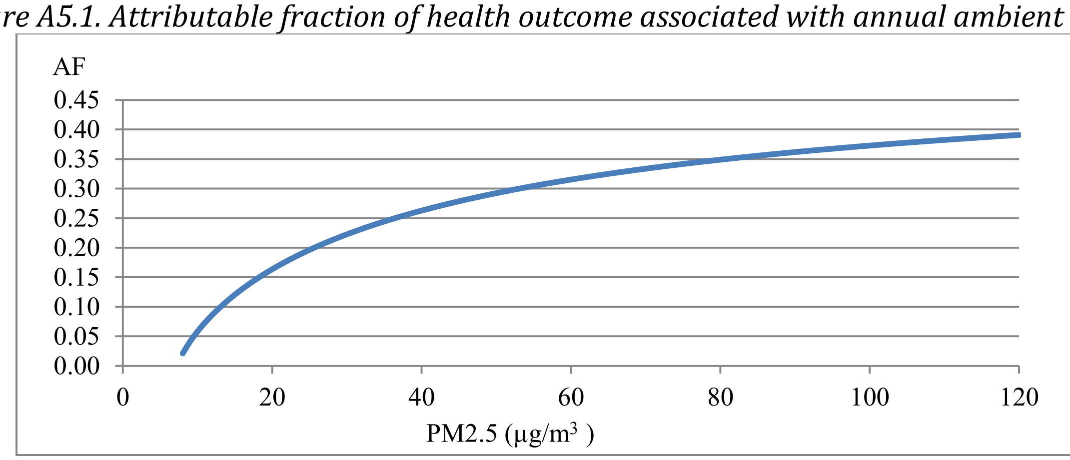
from which can be seen how changes in emissions and concentrations are related for a known population and intake fraction, and K is a constant ($Q_d * 365 * 10^{-6}$). Equation A1 then becomes:

$$B = \frac{m}{KP}\, iF \frac{\delta AF}{\delta C} \qquad \text{(A6)}$$

which says that health benefits per ton of emission reductions in a geographic area are a function of the product of the intake fraction and the change in the attributable fraction of health outcomes per change in PM2.5 concentrations. The latter is estimated using the methodology in annex 1 and its magnitude is a function of initial or pre-change concentration level as seen by the non-linear relationship between the attributable fraction and annual PM2.5 concentrations in figure A5.1.

The non-linear relationship demonstrates that the change in the attributable fraction rapidly declines with higher PM2.5 concentrations. The implications of this decline is that benefits per ton of emission reductions (B) start out "low" at high concentration levels and increases as air quality improves. In the East Asia (EA) region the estimated benefits per ton of emission reductions in a given geographic area increases by 21 times as air quality improves from 120 to 10 μg/m3 (figure A5.2).[32]

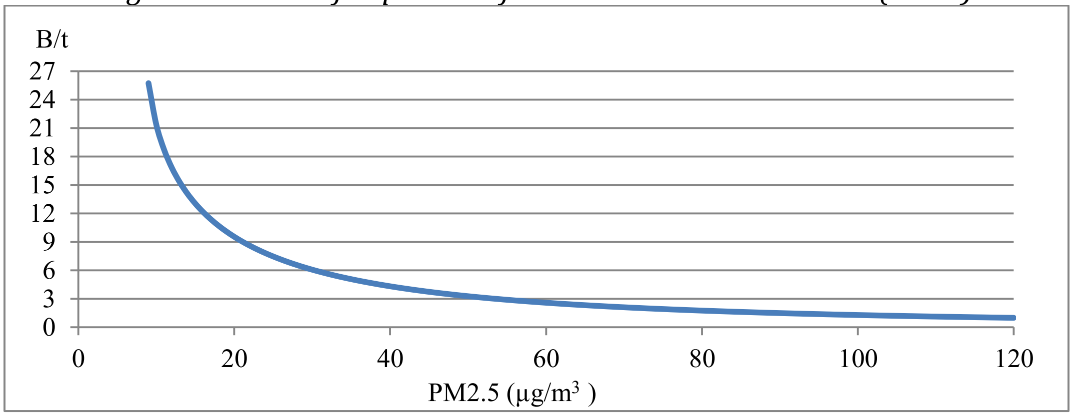
Figure A5.1. Attributable fraction of health outcome associated with annual ambient PM2.5



Note: AF of a weighted average of five health outcomes in the EA region. Source: Author's estimates.

[32] The intake fraction is assumed constant as air quality improves, i.e., there is no change in population and other factors that determine the intake fraction.

Figure A5.2. Benefits per ton of PM2.5 emission reductions (index)



Note: B/t in the EA region indexed to 1 at ambient PM2.5=120 μg/m3. Source: Author's estimates.

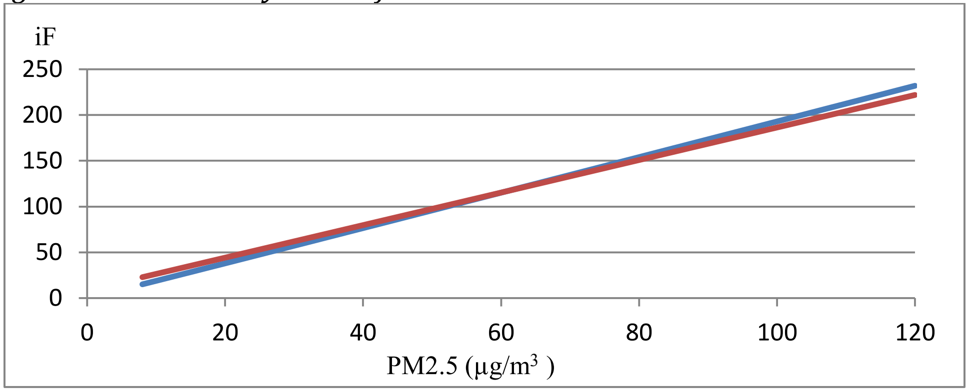
The relationship observed in figure A5.2 does usually not hold across geographic locations or cities. Intake fractions tend to be higher in more polluted cities. A regression analysis was here undertaken of 70 major cities around the world for which intake fractions were reported in Apte et al (2012) and annual ambient PM2.5 was reported in WHO's air pollution database. About half of these cities are in high-income and half in low- and middle-income countries. Intake fractions varied from 3 to 262 ppm and annual PM2.5 from 5 to 86 μg/m3. The analysis yielded the following two equations:

$$iF = 1.8413\, X^{1.0102} \qquad \text{R2=0.53} \qquad \text{(A7)}$$

$$iF = 8.6238 + 1.7779\, X \qquad \text{R2=0.49} \qquad \text{(A8)}$$

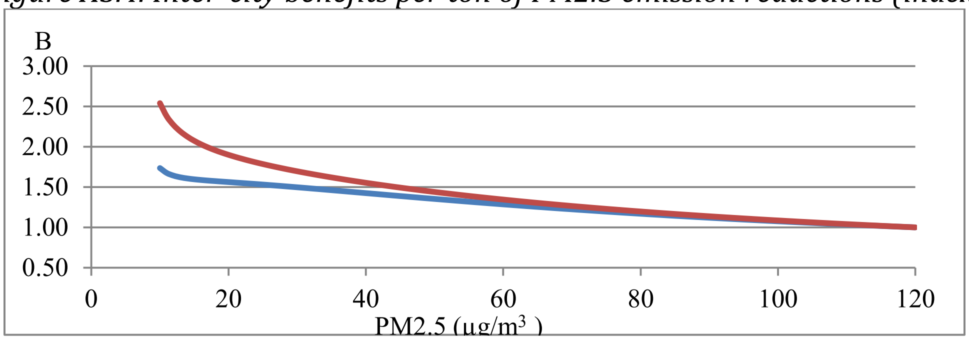
which are fairly similar for PM2.5 ranging from 10 to 120 μg/m3 (figure A5.3). This means that benefits per ton of emission reductions across cities are not as disparate as suggested by figures A5.1-2. In the East Asia (EA) region the estimated inter-city average benefits per ton of emission reductions vary "only" by a factor of 1.8-2.6 between cities with annual ambient PM2.5 of 10 vs. 120 μg/m3 (figure A5.4). However, as emission abatement is undertaken and air quality improves in a given city, benefits per ton of reductions increases as indicated in figure A5.2.

Figure A5.3. Inter-city intake fractions in relation to annual ambient PM2.5



Source: Author's estimates.

Figure A5.4. Inter-city benefits per ton of PM2.5 emission reductions (index)



Note: B in the EA region indexed to 1 at ambient PM2.5=120 µg/m3. Source: Author's estimates.

Annex 6. Countries and regions

The four regions and two countries used for household air pollution (HAP) analysis in this paper account for over 98% of the world's users of solid fuels for cooking, based on solid fuel use prevalence reported in Bonjour et al (2013) and the most recent DHS and MICS national household surveys assembled for the purpose of this paper. The countries of each region are presented in table A1.

Table A1. Major solid fuel using regions, 2012

Region, country	SFU	Region, country	
China	621,319,700	**South East Asia (SEA) and Korea DR**	**SFU**
India	766,745,774	Cambodia	13,229,535
		Indonesia	93,808,393
Sub-Saharan Africa (SSA)	**SFU**	Korea, DR	22,534,501
Angola	11,451,289	Lao PDR	6,379,994
Benin (SSA-W)	9,146,139	Malaysia	0
Botswana	741,447	Maldives	27,075
Burkina Faso (SSA-W)	15,143,330	Myanmar	49,629,480
Burundi	9,652,578	Philippines	58,991,126
Cameroon (SSA-W)	16,274,723	Thailand	17,364,100
Cape Verde (SSA-W)	158,208	Timor-Leste	1,113,414
Central African Republic	4,344,201	Vietnam	40,835,534
Chad (SSA-W)	12,074,730		
Comoros	509,427	**South Asia (SA) excluding India**	**SFU**
Congo, DR	63,733,940	Afghanistan	25,350,856
Congo, Rep.	3,339,529	Bangladesh	133,038,016
Cote d'Ivoire (SSA-W)	15,475,005	Bhutan	296,729
Djibouti	111,755	Nepal	20,605,783
Equatorial Guinea	566,948	Pakistan	111,079,269
Eritrea	3,678,553	Sri Lanka	15,246,000
Ethiopia	87,142,407		
Gabon	424,469	**Latin America and the Caribbean (LAC)**	**SFU**
Gambia, The (SSA-W)	1,630,015	Antigua and Barbuda	0
Ghana (SSA-W)	20,546,834	Argentina	0
Guinea (SSA-W)	11,107,735	Bahamas	11,159
Guinea-Bissau (SSA-W)	1,630,287	Barbados	0
Kenya	36,269,638	Belize	38,887
Lesotho	1,251,442	Bolivia	3,043,923
Liberia (SSA-W)	4,106,626	Brazil	11,919,361
Madagascar	21,848,036	Chile	1,047,889
Malawi	15,429,289	Colombia	6,678,620
Mali (SSA-W)	14,556,501	Costa Rica	288,318
Mauritania (SSA-W)	2,201,762	Cuba	1,014,386
Mauritius	0	Dominica	717
Mozambique	23,943,225	Dominican Republic	719,363
Namibia	1,242,666	Ecuador	309,845
Niger (SSA-W)	16,470,760	El Salvador	1,385,427

Nigeria (SSA-W)	138,443,696	Grenada	0
Rwanda	11,228,645	Guatemala	8,597,214
Sao Tome and Principe (SSA-W)	133,550	Guyana	55,676
Senegal (SSA-W)	7,000,271	Haiti	9,258,135
Seychelles	0	Honduras	4,047,281
Sierra Leone (SSA-W)	5,859,152	Jamaica	297,859
Somalia	9,685,377	Mexico	16,918,647
South Africa	7,841,242	Nicaragua	3,235,536
South Sudan	8,561,646	Panama	684,411
Sudan	29,384,326	Paraguay	3,276,807
Swaziland	677,042	Peru	9,895,974
Tanzania	44,916,121	St. Lucia	0
Togo (SSA-W)	6,244,352	St. Vincent and the Grenadines	3,281
Uganda	34,892,026	Suriname	64,145
Zambia	11,682,332	Trinidad and Tobago	0
Zimbabwe	9,058,049	Uruguay	0
		Venezuela	0

Source: Author's estimates based on Bojour et al (2013) and most recent DHS and MICS national household surveys.

For ambient air pollution (AAP), the regions follow the outdoor ambient PM2.5 exposure maps in Brauer et al (2012). China and India are not presented separately. China is included in the East Asia (EA) region with Korea DR and India is included in the South Asia (SA) region. The regions of LAC, SA, and SEA are otherwise the same as used for HAP. The Sub-Saharan Africa (SSA) region is divided into Western SSA (SSA-W) and the rest of SSA (SSA-O) as indicated in table A1.[33] Other regions for purposes of AAP assessment are as presented in table A2.

[33] Brauer et al (2012) use five LAC sub-regions and four SSA sub-regions. These are aggregated into one LAC region and two SSA regions (SSA-W and SSA-O) in this paper.

Table A2. Additional regions used for AAP assessment

Middle East and North Africa (MNA)	**Central Europe (CE)**	**Western Europe (WE)**
Algeria	Albania	Andorra
Bahrain	Bosnia and Herzegovina	Austria
Egypt	Bulgaria	Belgium
Iran	Croatia	Cyprus
Iraq	Czech Republic	Denmark
Jordan	Hungary	Finland
Kuwait	Macedonia	France
Lebanon	Montenegro	Germany
Libya	Poland	Greece
Morocco	Romania	Iceland
Oman	Serbia	Ireland
Palestine	Slovakia	Israel
Qatar	Slovenia	Italy
Saudi Arabia		Luxembourg
Syria	**Eastern Europe (EE)**	Malta
Tunisia	Belarus	Netherlands
Turkey	Estonia	Norway
United Arab Emirates	Latvia	Portugal
Yemen	Lithuania	Spain
	Moldova	Sweden
Oceania (OC)	Russia	Switzerland
Fiji	Ukraine	United Kingdom
Kiribati		
Marshall Islands	**Central Asia (CA)**	**High-Income North America (HI NA)**
Micronesia	Armenia	Canada
Papua New Guinea	Azerbaijan	United States
Samoa	Georgia	
Solomon Islands	Kazakhstan	**High-Income Asia Pacific (HI AP)**
Tonga	Kyrgyzstan	Brunei
Vanuatu	Mongolia	Japan
	Tajikistan	Korea, Rep
Australasia (AA)	Turkmenistan	Singapore
Australia	Uzbekistan	
New Zealand		

Source: The author.

This paper was written by Bjorn Larsen, economist and consultant to international and bilateral development agencies, consulting firms, and research institutions. The project brings together 60 teams of economists with NGOs, international agencies and businesses to identify the targets with the greatest benefit-to-cost ratio for the UN's post-2015 development goals.

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