USAID | ASIA
FROM THE AMERICAN PEOPLE

BLACK CARBON EMISSIONS IN ASIA:

Sources, Impacts, and Abatement Opportunities

April 2010

BLACK CARBON EMISSIONS IN ASIA:

Sources, Impacts, and Abatement Opportunities

April 2010

This report is made possible by the support of the American People through the United States Agency for International Development (USAID). The contents of this report are the sole responsibility of the International Resources Group (IRG) and do not necessarily reflect the views of USAID or the United States Government. IRG prepared this report as part of its work under the ECO-Asia Clean Development and Climate Program. Contract No. EPP-1-100-03-00013-00: Task Order 9.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

ABC	atmospheric brown cloud
AOD	aerosol optical depth
AWES	automated wood stove emissions sampler
BC	Black carbon
CH_4	methane
CNG	compressed natural gas
CG	compressed gas
CO_2	carbon dioxide
DALY	disability-adjusted life years
DPF	diesel particulate filter
EC/TC	elemental carbon/ total carbon ratio
ffBC	fossil fuel black carbon
GDP	gross domestic product
Gg	gigagram (1000 metric tons)
GHG	greenhouse gas
GWP	global warming potential
GWP_{20}	20-yr global warming potential
GWP_{100}	100-yr global warming potential
I/M	inspection and maintenance
IPCC	Intergovernmental Panel on Climate Change
LPG	liquid petroleum gas
m^3	cubic meter
µg	microgram
µm	micrometer; micron
NO_x	nitrogen oxides
OC	organic carbon
OM	organic matter
PIC	products of incomplete combustion
PM	particulate matter
PM_1	particulate matter with an aerodynamic diameter of 1 µm or less
$PM_{2.5}$	particulate matter with an aerodynamic diameter of 2.5 µm or less
PM_{10}	particulate matter with an aerodynamic diameter of 10 µm or less
pptv	parts per trillion by volume
SOA	secondary organic aerosols
TOA	top of atmosphere
US EPA	United States Environmental Protection Agency
WHO	World Health Organization
Wm^2	watts per square meter

ACKNOWLEDGMENTS

Black Carbon Emissions in Asia: Sources, Impacts and Abatement Opportunities was prepared by the Environmental Cooperation-Asia Clean Development and Climate Program (ECO-Asia CDCP), a program of the US Agency for International Development's Regional Development Mission for Asia (USAID/RDMA).

Timm Kroeger was the principal author of the report. The report was reviewed by a number of technical experts. Among those providing valued comments on the report were Dale Evarts, Marcus Sarofim, and Doug Grano of the US Environmental Protection Agency; Ben Gibson of the International Energy Agency; John Bachmann of Vision Air Consulting; Pamela Baldinger, Bill Butterfield, Tahra Vose, and Leonila Gutierrez of USAID; Tami Bond of the University of Illinois Urbana-Champaign; Danielle Luttenberg Meitiv of the Clean Air Task Force; Suzanne Young of Louis Berger; May Ajero of the Clean Air Initiative-Asia; and Anil Terway of the Asian Development Bank.

The report was prepared under the overall oversight, guidance, and direction of Orestes Anastasia, Regional Environment Advisor, USAID/RDMA, and Peter du Pont, Chief of Party, ECO-Asia CDCP. The study was conceptualized by Pradeep Tharakan, Deputy Chief of Party, ECO-Asia CDCP, who also managed the development of the first draft of the report. Production of the report was overseen by Nick Keyes, Communications Director, ECO-Asia CDCP. The report was designed by John Michael Ymana.

EXECUTIVE SUMMARY

WHY STUDY BLACK CARBON?

Black carbon (BC), the main component of soot, is a product of the incomplete combustion of fossil fuels (primarily coal and diesel fuel), the burning of solid biomass in cook stoves and heating stoves, and the open burning of biomass.

Although black carbon has long been thought to be a contributor to global climate change, its contribution traditionally was estimated to be minor compared to the contribution of the main greenhouse gases (GHGs). However, a number of recent studies have questioned this view, suggesting instead that black carbon is a major contributor to atmospheric warming.

Accompanying this reassessment, black carbon has also been identified as a driver of important regional climate impacts. Several studies have identified Asia as the single-largest source of global black carbon emissions from contained combustion (such as combustion in engines, stoves, and kilns), accounting for more than half of all such emissions. Asia is also a major contributor to global black carbon emissions from open combustion (forest fires, land clearing through fire, and burning of agricultural wastes). However, such combustion also produces emissions of climate-cooling aerosols and by most studies is estimated to have an overall climate neutral or cooling effect.

Because of these new findings, the United States Agency for International Development (USAID) commissioned this report to answer the following key questions:

1) What are the properties of black carbon as a contributor to global warming, and what are the direct and indirect impacts of black carbon with respect to global warming, natural ecosystems, human health, or other considerations?
2) What are the principal sources of black carbon emissions in Asia, both in terms of types of activities generating emissions and the location of these activities?
3) What are the most immediate opportunities (in terms of technological or economic viability) for reducing black carbon emissions in the Asia region and for mitigating the impact of those emissions in Asia, and what are the major obstacles to pursuing these opportunities?

FINDINGS

1) What are the properties of black carbon as a contributor to global warming, and what are the direct and indirect impacts of black carbon with respect to global warming, natural ecosystems, human health, or other considerations?

Black carbon in soot is the dominant anthropogenic absorber of incident solar radiation in the atmosphere – it is approximately 1 million times stronger than CO_2 per mass unit of mass – and contributes to the warming of the atmosphere at the global level. Black carbon also warms the atmosphere by absorbing thermal infrared radiation from the ground and within clouds. Furthermore, because it directly heats surfaces on which it is deposited and changes surface albedo (surface reflectivity), black carbon is a major contributor to the accelerated melting of Arctic sea and land ice, glaciers and seasonal snow covers. However, black carbon has a much shorter average atmospheric residence time than CO_2 and other GHGs (on the order of days to weeks for black carbon versus years to centuries for most GHGs). Because of this mediating factor, the combined global warming impact of one kilogram of black carbon via the multiple warming pathways is estimated to be on average 500-680 times as large as that of one kilogram of CO_2 over a 100-year timeframe, and 1,500-2,200 times over a 20-year timeframe. Recent studies identify black carbon as the second- or third-largest overall contributor to current anthropogenic global warming, surpassed only by carbon dioxide and possibly methane.

Black carbon emissions are also a major contributor to several large regional masses of haze or so-called atmospheric brown clouds (ABCs). One of these, the South Asian ABC covers most of the Arabian Sea, the Bay of Bengal, the Northern Indian Ocean and the South Asian region from at least November through May, and according to some estimates is fuelled by as much as 75 percent by biomass burning and fossil fuel combustion. The South Asian ABC has important regional climate impacts in Asia, with recent research suggesting that its regional radiative impacts at the surface and within the atmosphere exceed those of anthropogenic greenhouse gases by an order of magnitude. These regional climate perturbations cause changes in the hydrological cycle and in monsoon circulation that negatively impact food production in India and China. The South Asian ABC also accelerates the melting of the Hindu Kush-Himalayan-Tibetan glaciers, with projected severe consequences for the freshwater supply for much of Southern and Eastern Asia. Furthermore, several studies suggest that Asian black carbon emissions have long-range impacts on snow and ice, contributing substantially to the accelerated melting of Arctic sea ice and glaciers.

As well as these climate impacts, black carbon emissions from unimproved residential cook stoves and heating stoves that burn coal or solid biomass (i.e., wood and dried animal residues) produce indoor air pollution levels in millions of homes that lead to a variety of severe chronic and acute health impacts. In addition, black carbon emissions from industrial and transport sources are a major contributor to outdoor particulate matter (PM) pollution. In many parts of Asia, particulate matter levels exceed guidelines of the World Health Organization by several-fold. As a result of these indoor and outdoor air quality impacts, black carbon and its co-emitted pollutants are the third-leading contributor to the burden of disease in South Asia and the fifth-leading cause of mortality in Asia as a whole (Ezzati et al., 2006). A disproportionate share of the disease burden associated with black carbon sources is borne by women and young children who spend a larger share of their time indoors and are thus subjected to higher exposures.

2) What are the principal sources of black carbon emissions in Asia, both in terms of types of activities generating emissions and the location of these activities?

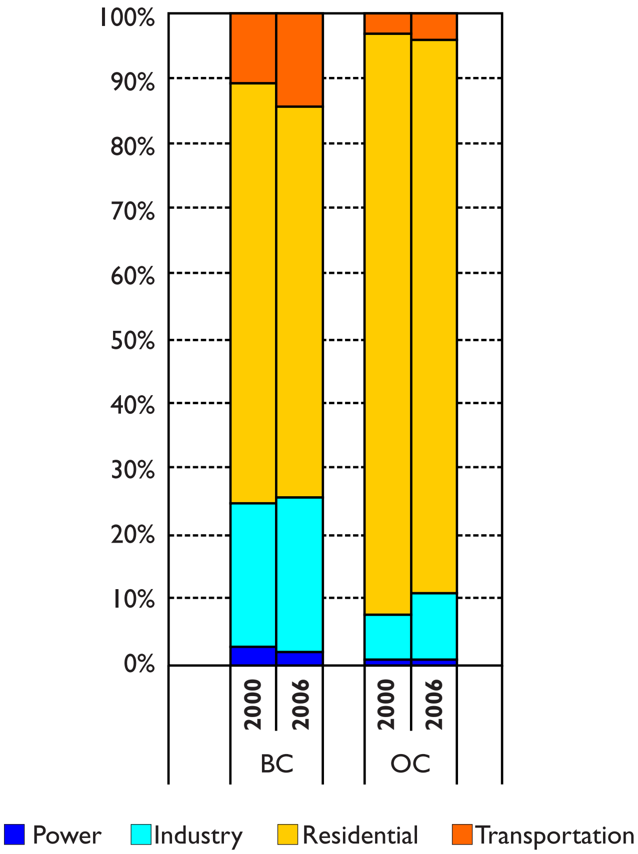
Contained residential combustion of solid biomass (wood, dung) and coal in cook stoves and heating stoves, the burning of coal and petroleum products in the industrial sector, and diesel fuel use in the transport sector are the leading sources of black carbon emissions in developing Asia with global climate impacts (see **Figure ES1**). Within Asia, available estimates indicate that China is the dominant emitter of black carbon from contained combustion, accounting for 61 percent of all Asian black carbon emissions in 2006, followed by India (12 percent) and Indonesia (6 percent).

Open biomass burning in the form of forest fires, land clearing through fire, and burning of agricultural wastes is also responsible for large quantities of black carbon emissions. However, unlike contained combustion, open combustion also generates a relatively larger fraction of co-emitted organic matter that produces a climate cooling effect, thus counteracting the warming caused by the emissions of black carbon from these sources. Most studies estimate that open combustion has a neutral or negative overall global warming impact, although several studies do suggest that it contributes to climate warming. In any case, open biomass burning in Asia does have important negative impacts on the regional climate and on human health. China, India and the rest of Asia contribute roughly similar quantities to black carbon emissions from open combustion.

3) What are the most immediate opportunities (in terms of technological or economic viability) for reducing black carbon emissions in the Asia region and for mitigating the impact of those emissions in Asia, and what are the major obstacles to pursuing these opportunities?

Due to the short average residence time of black carbon

Figure ES1. Share of emissions of black and organic carbon from contained combustion in Asia by major sector in 2000 and 2006



Note: BC = black carbon; OC = organic carbon

Source: Zhang et al. (2009)

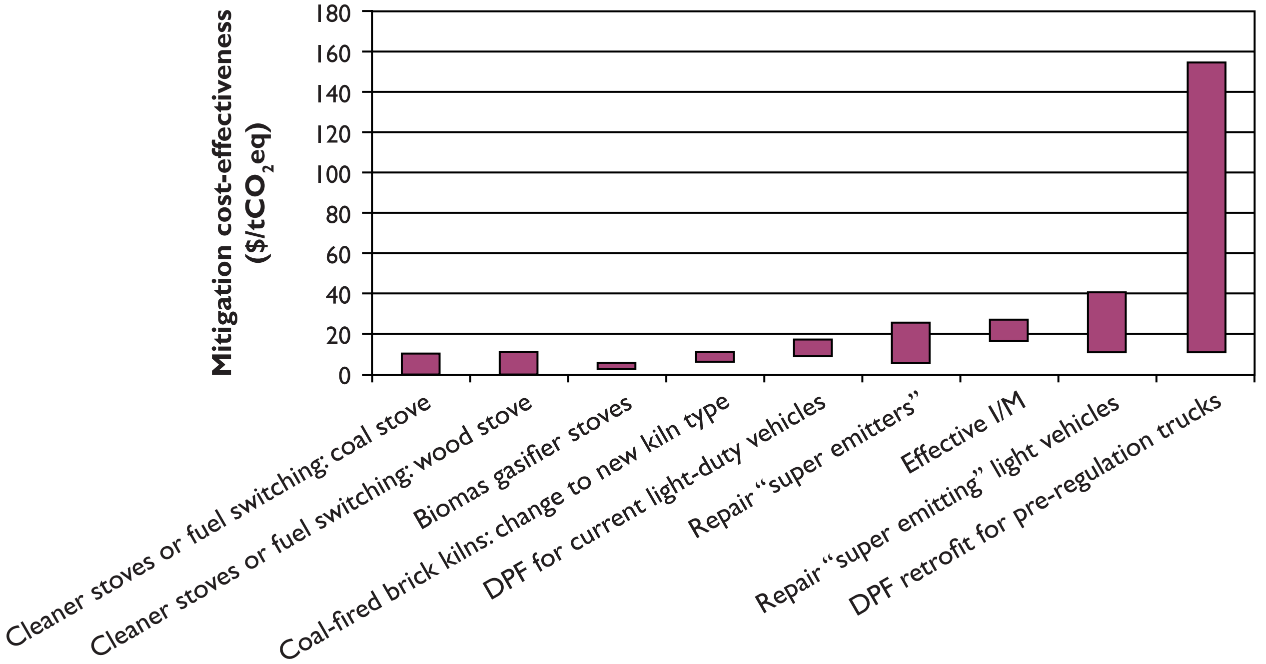
in the atmosphere, which ranges from days to weeks – compared to that of greenhouse gases, which lasts years to centuries – reductions in black carbon emissions produce almost immediate benefits in terms of reduced radiative forcing. Such reductions also produce large co-benefits for public health.

Proven and in many cases readily-available control technologies exist that can substantially reduce emissions from key sources of black carbon in Asia. In the case of households, these include cleaner fuels like biogas, natural gas, LPG or kerosene, or direct solar power, and improved cook stoves that burn fuel more efficiently and result in fewer emissions of black carbon and other climate-relevant pollutants. Overall, changes in particle emissions from the household sector in developing Asia are thought to offer the largest potential for reducing near-term global climate impacts from short-lived global warming pollutants. In the transport sector, the main control options include diesel particle filters (DPFs) combined with ultra low-sulfur diesel fuels, especially in densely populated areas; cleaner fuels such as compressed natural gas (CNG) or liquid petroleum gas (LPG), especially for high-mileage vehicles like taxis, long-distance trucks and buses; a change in the modal split towards mass-transit powered by electricity or clean fuel; more stringent emission standards and programs for in-use vehicle emission inspection and maintenance. Finally, black carbon emissions from the industrial sector can be reduced through improved emission control, process switching, and cleaner fuels (e.g., electricity, LPG).

Though all of these control options achieve reductions in black carbon emissions, the cost-effectiveness and net benefits of the individual measures should be considered in the design of control strategies in order to maximize the reductions achievable by a given intervention budget. The practicality, cost-effectiveness and net benefits of a particular control option all vary depending on the particular local context. Nevertheless, a review of the existing literature on black carbon control options in developing Asia identifies a fairly clear cost-effectiveness hierarchy among the major control measures. **Figure ES2** shows the cost-effectiveness of black carbon control options analyzed in the literature, expressed as the average cost per ton of CO_2-equivalent emissions reduced. About half of the cost-effectiveness estimates in Figure ES2 account for the co-produced changes in GHG emissions that result from the interventions, but none account for the still-uncertain (though probably on balance slightly climate-warming) impacts from reductions in light-scattering (cooling) particles that will accompany black carbon controls.

At the top of this hierarchy sit household fuel and stove interventions, which, if effectively implemented, appear to consistently achieve the highest reduction in black carbon emissions per unit cost. This finding holds true for all stove and fuel interventions examined for this study. Moreover, these interventions are cost-effective not only for control

Figure ES2. Estimated cost-effectiveness (20-year time frame) of key black carbon abatement measures in Asia.



(The more cost-effective measures appear on the left-hand side of the chart. Note: DPF cost-effectiveness includes incremental costs of switching to ultra-low sulfur fuel and reductions in mileage resulting from DPFs, and CNG cost-effectiveness includes increased methane emissions and reduced fuel efficiency of CNG vehicles.) Sources: Based on data in Bond and Sun (2005), Kandlikar et al. (2009), and Mejia (2009).

of black carbon, but also more broadly for abatement of global warming. That is, most are cost-effective compared to most large-scale greenhouse gas abatement options presently considered. Importantly, residential stove and fuel interventions also yield the highest net benefits per unit intervention cost if health benefits are included in the analysis, due to the much higher exposure to fine particles indoors in addition to outdoor exposures. Existing analyses suggest that in many cases, these measures actually will reduce costs for households. Finally, stove and fuel interventions can achieve the largest total reduction in black carbon emissions of all the main control options analyzed in the literature because Asia's household sector is the dominant source of the region's black carbon emissions from contained combustion.

Several past experiences with the large-scale deployment of new cook stove or residential fuel technologies have encountered major implementation challenges in the form of local preferences, cultural norms, and behavior patterns. Several ambitious ongoing initiatives build on the lessons from these past experiences and have the potential to yield cost-effective and large reductions in black carbon emissions as well as massive public health benefits, especially among the poorer sectors of the population. These initiatives, including Project Surya (India); the Shell Foundation and Envirofit's clean cook stoves initiative; Philips and the Appropriate Rural Technology Institute's Chulha project; Grameen Shakti's Improved Cookstove program; and the Partnership for Clean Indoor Air (PCIA, Asia-wide and beyond) present promising opportunities for bilateral and multilateral cooperation and funding assistance that could substantially expand the reach of these initiatives and the speed of their implementation. In addition, there may be opportunities for the provision of assistance to micro-financing schemes aimed at promoting the adoption of improved cook stoves.

The next tier of black carbon abatement measures, in terms of cost-effectiveness, includes a suite of control options directed at the transport sector. These comprise the equipping of new diesel vehicles with DPFs and DPF retrofits for existing heavy-duty vehicles, the repair of high-emissions vehicles, and the implementation of in-use inspection and maintenance (I/M) systems. The literature identifies cost-effectiveness ranges for each of these control options that in many cases are overlapping, indicating that the local context will determine which of these options are the most cost-effective in a particular situation. Nevertheless, equipping new diesels with DPFs and repairing super-emitters generally tend to have lower costs per unit of black carbon reduction. Importantly, even though the findings in this report suggest that switching to transportation fuels with lower black carbon emissions is unlikely to be a cost-effective first step in black carbon control efforts, DPFs may nonetheless be a suitable candidate for inclusion in early-stage black carbon control strategies if reductions achievable by more cost-effective measures are insufficient. Likewise, control measures targeted at vehicles will be important to help achieve overall emission reduction goals in urban areas. The limited information on the cost-benefit performance of these measures also indicates that repairing high-emitting vehicles will generally yield net economic benefits.

It should be noted that effective inspection and maintenance (I/M) programs, although not a necessary precondition for the deployment of DPFs or for repairing high-emissions vehicles, will greatly enhance the effectiveness of both measures, because regular, mandatory and effective vehicle inspections will help ensure the general deployment and adequate maintenance of DPFs as well as the identification of high-emissions vehicles. Thus, these measures should be considered for implementation in parallel. At a minimum, based on a recognition of the substantial institutional capacity required for establishing and maintaining an effective I/M program, such a program should be implemented at some later stage, following the implementation of other emissions control measures for the transport sector.

As demonstrated by past and ongoing efforts, bilateral and multilateral assistance can play an important role in Asia's efforts to control black carbon emissions from the transport sector, with the provision of technical assistance perhaps playing a primary role. Candidates for assistance are the design, implementation and evaluation of I/M programs; the funding of the creation of model tender documents; the establishment of guidelines on conducting the bidding process for private contractors; the selection of contractors; more rigorous program evaluations along with the data collection efforts that would support them; the exploration of "one-stop" government facilities for emission and safety inspections as well as vehicle registration; and the development of I/M test procedures and standards for particulate matter that take advantage of new particulate matter meters.

Donors can also assist policymakers in making sure they have sufficient capacity to carry out their own roles, particularly by engaging independent experts as technical advisors and to develop capacity-building programs.

Deployment of DPFs requires ready availability of ultra-low sulfur diesel (ULSD) fuel. Except for a few metropolitan areas, ULSD currently is not available in developing Asia, although a few countries are considering its introduction in the next two years either nationwide or in metro areas. Reducing the sulfur content of fuels provides substantial and cost-effective reductions in particulate matter, and yields associated health benefits in its own right, in addition to enabling the deployment of DPFs. Thus, there is a critical role for bilateral and multilateral assistance in promoting desulfurization both in countries in Asia that are considering the measure as well as in the majority of other countries that currently are not planning to do so in the coming years. Assistance should focus on facilitating technology transfer and providing technical expertise both in the development of fuel standards and desulfurization technologies and policy measures.

Controlling black carbon emissions from industrial sources will form part of any comprehensive control strategy, given that industrial emissions are estimated to account for almost one quarter of black carbon emissions from contained combustion in Asia (Figure ES1). Currently, however, there is very little data on the cost-effectiveness of control measures in this sector for developing Asia, although experience with particulate matter controls from industrial sources in developed countries shows that they generally are highly cost-effective. Emissions from one important black carbon source, coal-fired brick kilns, are thought to be controllable comparatively cost-effectively, but the uncertainty associated with this assessment is large. Thus, there is an important role for bilateral and multilateral assistance in promoting and supporting studies of the impact and cost-effectiveness of black carbon control measures from industrial sources.

In short, the cost-effectiveness of many black carbon control options appears to exceed or at least be competitive with that of many of the main conventionally-proposed greenhouse gas abatement measures. Control of black carbon emissions appears to be a particularly attractive near-term global warming strategy in Asia.

This cost effectiveness, coupled with the large externalities associated with pollutant emissions that cause global warming, means that international and bilateral approaches aimed at reducing these emissions in Asia through technology transfer or financing of control options are likely to generate net benefits for the donor countries. These benefits will be dominated by the avoided national security risks that would result from severe disruptions of the water and associated hydro-energy supply for 40 percent of the world's population. Likewise, the negative externalities of black carbon emissions at local and national levels in many countries argue for well-designed government intervention in the form of technology subsidies, emissions standards, or fiscal measures such as taxes on emissions.

That said, control strategies will require careful design, including financial incentives and in many cases some form of transitional financial assistance, as many of the important black carbon sources include households and small businesses operating at the subsistence level.

SECTION I

INTRODUCTION

Black carbon (BC) is the main component of soot (Jacobson, 2004a) and is produced through the incomplete combustion of coal, diesel fuel, solid biomass, and through the burning of outdoor biomass (Novakov et al., 2000; Mayol-Bracero et al., 2002).[1] Black carbon, in a mixture that also includes anthropogenic sulfate, nitrate, organics, dust, and fly ash particles and natural aerosols such as sea salt and mineral dust, produces several large regional brownish hazes or Atmospheric Brown Clouds (ABCs) (Ramanathan and Crutzen, 2003). One of these, the South Asian ABC covers most of the Arabian Sea, the Bay of Bengal, the Northern Indian Ocean and the South Asian region and extends from at least November through May, and is fuelled by as much as 75 percent by biomass burning and fossil fuel combustion (Ramanathan and Crutzen, 2003).

The South Asian ABC has important regional climate impacts, with the regional radiative perturbations by the anthropogenic aerosols at the surface and within the atmosphere an order of magnitude greater than those caused by anthropogenic greenhouse gases (GHG), and with resulting strong impacts on the hydrological cycle and monsoonal circulation (Ramanathan and Crutzen, 2003). Studies have linked the South Asian ABC to reduced crop production in India and China and to rapid increases in the melting of the Hindu-Kush-Himalayan-Tibetan glaciers, with projected severe consequences for the freshwater supply for much of Southern and Eastern Asia (Ramanathan et al., 2008). Furthermore, the impacts of black carbon on snow and ice are not just local or regional, but long-range, with emissions from Europe and Asia contributing substantially to the accelerated melting of Arctic sea ice and glaciers (Ramanathan and Carmichael, 2008; Ramanathan and Feng, 2009; Flanner et al., 2009; Hadley et al., 2007; Hansen and Nazarenko, 2004; Ramanathan et al., 2007a; Zhu et al., 2007; Koch and Hansen, 2005). Recent scientific research also has identified black carbon as a much larger contributor to global climate change than previously anticipated (Sato et al., 2003). In fact, recent estimates identify black carbon as the second- or third-largest contributor to global excess radiative forcing, surpassed only by carbon dioxide (CO_2) and possibly methane (CH_4) (Ramanathan and Carmichael, 2008; Jacobson, 2002, 2004a) (**Figure 1**).

Emissions of black carbon thus present a classic technological externality case, in the sense that part of the impacts caused by black carbon emitters are borne by others. Emitters therefore do not have an incentive to take these impacts into account. Such externalities create economic inefficiencies.

In addition to these climate impacts, black carbon also has significant health impacts because its small size – much of it being $<1\,\mu m$ (PM_1) in aerodynamic diameter – allows it to deeply penetrate into lungs (Jacobson, 2007; Cohen et al., 2005). Small aerosols (solid and liquid droplets suspended in a gas) like black carbon are the third-leading contributor to the burden of disease in South Asia and the fifth-leading cause of mortality in Asia as a whole (Ezzati et al., 2006).[2]

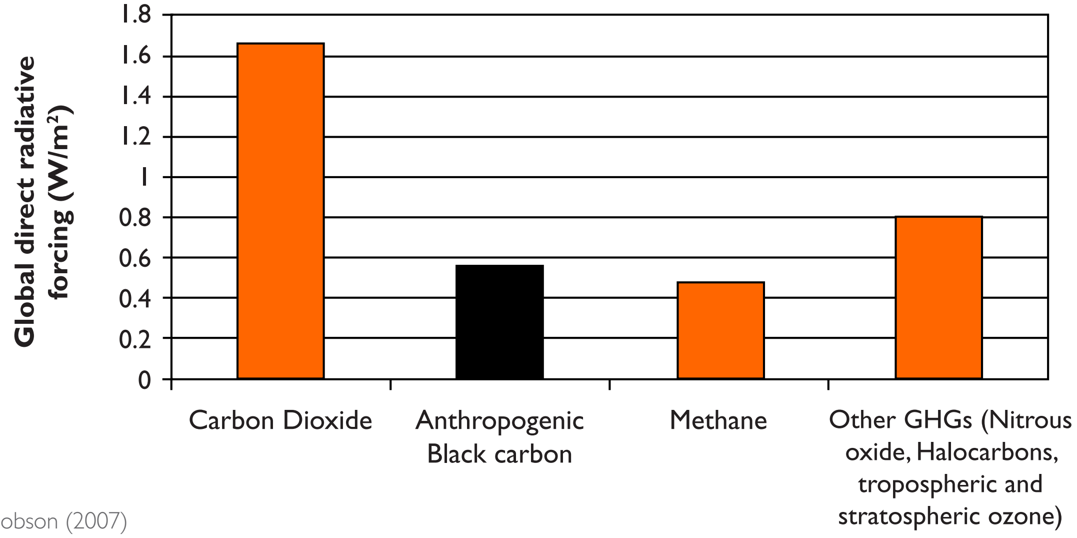
Because of the short atmospheric residence time of black

---

[1] For analyzing radiative effects, black carbon is defined as the mass of elemental carbon that absorbs the same amount of light as the emitted particles, although carbon that absorbs light may not be black and its molecular form may differ from that of elemental carbon (Streets et al., 2001).

[2] Recent assessments incorporating the latest scientific evidence indicate even larger health impacts (Bachmann, 2009).

Figure 1. Contributions of anthropogenic greenhouse gas and black carbon emissions to direct radiative forcing at the top of the atmosphere



Source: Jacobson (2007)

carbon particles compared to other global warming (GW) pollutants and because of black carbon's strong warming effect, reductions in black carbon emissions yield almost immediate benefits in terms of reduced atmospheric forcing. Recent studies estimate that eliminating all fossil fuel black carbon and organic matter (OM) could eliminate 20-45 percent of net global warming within 3-5 years if no other change occurred (Jacobson, 2002). Reducing CO_2 emissions by a third would have the same effect, but only after 50-200 years (Jacobson, 2002). Thus, controlling black carbon emissions simultaneously with controlling CO_2 emissions can be an effective tool for slowing global warming for a specific period (Jacobson, 2004a). If black carbon emissions from biomass combustion in cook- and heating stoves are included in the analysis, the potential climate benefits increase substantially.

Major reductions in black carbon emissions thus could slow the effects of climate change for a decade or two (Ramanathan, 2007). In addition to these climate benefits, substantial reductions in black carbon emissions also would yield massive co-benefits for human health by reducing indoor and outdoor exposure to respirable particulate matter.

1.1 MOTIVATIONS FOR THE STUDY AND MAIN OBJECTIVES OF THE REPORT

As a result of the recent findings regarding the scale of black carbon climate impacts and the increasing interest in the possibility of incorporating black carbon control measures into a comprehensive climate change abatement strategy, the United States Agency for International Development (USAID) commissioned the present report to answer the following key questions:

1) What are the properties of black carbon as a contributor to global warming (e.g., in terms of radiative forcing), and what are the direct and indirect impacts of black carbon with respect to global warming (e.g., glacial melt), natural ecosystems, human health, or other considerations?
2) What are the principal sources of black carbon emissions in Asia, both in terms of types of activities generating emissions and the location of these activities?
3) What are the most immediate opportunities (in terms of technological or economic viability) for reducing black carbon emissions in the Asia region and for mitigating the impact of those emissions in Asia,

and what are the major obstacles to pursuing these opportunities?

1.2 STRUCTURE OF THE REPORT

Section 2 presents a brief overview of the main sources of black carbon emissions both globally and in Asia. Section 3 presents a summary of the main impacts of black carbon emissions on regional and global climate, food and water, and human health. Sections 4 and 5 present overviews of the main options for controlling black carbon emissions and their economic performance as measured by cost-effectiveness and benefit-cost metrics, respectively. Section 6 examines technological considerations, institutional capacity needs, persistent barriers, and examples of innovations and ongoing initiatives for black carbon control. Section 7 concludes and highlights opportunities for bilateral and multilateral cooperation in implementing black carbon control measures.

SECTION 2

SOURCES OF BLACK CARBON EMISSIONS

Black carbon emissions result from the incomplete combustion of carbonaceous fuels. The four major source types of black carbon emissions are 1) diesel engines for transportation or industrial use; 2) residential combustion of solid fuels such as coal or wood, using traditional technologies; 3) outdoor burning of biomass, both human-caused (crop residues, burning of forests and savannas for land clearing,) and natural (forest fires); and 4) industrial processes, usually from smaller boilers burning coal or petroleum products (Bond, 2007a; Mayol-Bracero et al., 2002; Novakov et al., 2000).

The relative contribution of the black carbon fraction to the total aerosol produced during combustion varies considerably with source type (Bond et al., 2004). Generally, the blacker the soot, the higher the black carbon content and the more of a warming agent it is (Pew Center on Global Climate Change, 2009). Open combustion (agricultural burning, forest fires, land clearing by fire) generally produces more of a brownish soot whose carbon content is dominated by organic carbon, while contained combustion (cooking and heating stoves, internal combustion engines, industrial and commercial boilers) produces carbon emissions with a higher share of black carbon (Bachmann, 2009; Kandlikar et al., 2009). Organic carbon compounds and sulfates produced by open burning sources scatter direct light and interact with clouds to produce a cooling effect (Ramanathan and Carmichael, 2008).

Although some organic carbon also absorbs sunlight and can be a net warming agent (Bond et al., 2004; Bond, 2007a), due to the relative strength of their cooling and warming effects, black carbon-emitting open-burning sources likely are not net contributors to global climate warming. In fact, most research estimates that open burning sources have a net cooling effect (Bond et al., 2004), though some studies hypothesize a small net warming effect (Naik et al., 2007), and the net effect may have different signs depending on where and when the emissions occur. Nevertheless, even organic carbon-dominated sources have serious regional climate effects by contributing to atmospheric brown clouds (ABC) (Ramanathan and Carmichael, 2008), which have been shown to reduce monsoon precipitation over the Indian subcontinent (Menon et al., 2002) and to negatively impact agricultural yields in both China and India (Aufhammer et al., 2006; Chameides et al., 1999). By contrast, sources that produce emissions with a higher black carbon content, like residential cooking and heating stoves using solid fuels, and especially high-emitting diesel engines, produce a net warming effect (Bond, 2007b).

2.1 GLOBAL ESTIMATES OF BLACK CARBON SOURCE STRENGTHS

Information about the relative and absolute strength of different black carbon sources is essential for the development of effective control strategies. The two methodologies used to assess black carbon source strengths – emission inventories and composition analysis using some form of marker – often yield different source apportionments (Szidat, 2009).

Emission inventories (e.g., Bond et al., 2004; Koch et al., 2007a) estimate black carbon emissions by combining source-specific estimates of carbonaceous fuel consumption and black carbon emission factors. Unlike carbon dioxide emissions, black carbon emissions are difficult to determine because of the uncertainty in the fraction of total particulate matter emissions that is elemental carbon of less than 1 μm, which is the black carbon fraction that is climate-relevant (Streets et al., 2001). This fraction is very sensitive to fuel type, combustion and emission control technology, and the state of maintenance of sources (Bond et al., 2004; Wehner et al., 1999). Therefore, the construction of black carbon emission inventories necessitates a detailed treatment of emissions factors by fuel, sector, and degree of emission control, information that is often lacking for many sources in developing countries (Streets et al., 2001). Consequentially, estimates of black carbon emission source strengths are characterized by a significant degree of uncertainty of about 2 to 5 (Bond et al., 2007), introducing substantial uncertainties even in the most sophisticated aerosol emission inventories that utilize the best available, up-to-date data (Shindell et al., 2008; Bond et al., 2004; Koch et al., 2007a).

Concentration-based estimates of black carbon source strengths are based on analyses of the atmospheric content of aerosols. These estimates utilize either receptor-based techniques that employ organic marker compounds indicative of certain black carbon sources (Stone et al., 2007; Hegg et al., 2009), ratios of black carbon to other aerosols (e.g., Mayol-Bracero et al., 2002; Novakov et al., 2000), measurements of aerosol optical depth (the amount of aerosols in a vertical column of air; e.g., Sato et al., 2003), or radiocarbon-based analysis of carbon isotopes (e.g., Gustafsson et al., 2009). The latter is considered the most accurate source strength estimation methodology (Szidat, 2009) because it minimizes the potentially large impacts on estimates that may be caused by atmospheric processes such as the formation of secondary organic aerosols (Stone et al., 2007) and inaccurate source emission factors. Radiocarbon-based analysis must be combined with other approaches as it can only identify fossil or biofuels as the source but not particular source types within those categories (Bond, 2010).

Globally, in 1996, emissions from open biomass burning exceed those from fossil and solid biomass combustion, accounting for an estimated 42 percent versus 38 percent and 20 percent, respectively, of black carbon emissions and 74 percent versus 7 percent and 19 percent, respectively, of organic carbon emissions (Bond et al., 2004). At the global level, an estimated two-thirds of black carbon emissions from energy-related combustion in 2000 were from fossil fuel combustion (Bond et al., 2007; Junker and Liousse, 2008), with diesel combustion emerging as the leading source of black carbon emissions globally since around 1985 (Bond et al., 2007).[3] Conversely, about three-quarters of emissions of organic carbon were from solid biomass (Bond et al., 2007).

Household combustion of both solid fossil (coal) and biomass fuels (wood, charcoal, crop residues, dung) probably represents the second-largest source of global black carbon emissions, after open biomass burning, contributing about one-fifth to total global black and organic carbon emissions (Aunan et al., 2009). In 2000, Asia accounted for slightly over half of global energy-related emissions of both black carbon and organic carbon (Bond et al., 2007), and South Asia for an estimated 44 percent of global industrial (fossil fuel) black carbon emissions (Koch and Hansen, 2005). Importantly, low-technology combustion contributes greatly to both the emissions and the uncertainty of these estimates, which in some cases are of a factor of two overall (Bond et al., 2004).

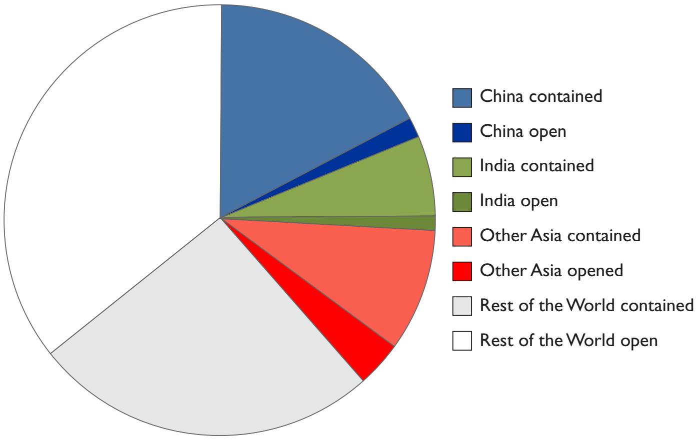
On average, black carbon emissions in developed (Kyoto Annex I) countries are dominated by road transport (Bond and Sun, 2005), with the climate forcing from black carbon far smaller than that from greenhouse gas emissions (Bond and Sun, 2005). Most of the global emissions of black carbon are emitted in developing (Kyoto non-Annex I)

---

[3] Energy-related combustion refers to the burning of fossil or biomass fuels for the purpose of heating, cooking, or power generation in internal and external combustion processes.

countries (Bond and Sun, 2005). In 1996, China and India together accounted for an estimated 26 percent of global black carbon emissions, while Asia as a whole (excluding Japan) accounted for almost 40 percent of overall black carbon emissions and over half of worldwide emissions from contained combustion (**Figure 2**).

Figure 2. Asia's share in global black carbon emissions by combustion type, 1996



Source: Bond et al. (2004). See Appendix Table A1

Despite the dominance of Asia, and especially China and to a lesser degree India, in global black carbon emissions, it should be noted that per-capita emissions in these countries generally are not higher than those in developed countries (Bond, 2007b; Ramanathan and Feng, 2009).

The East Asian, South Asian, and Southeast Asian residential sectors (dominated by China, India, and Indonesia, respectively) are the primary sources of present-day black carbon in the northern hemisphere, with the global transport and industrial sectors also contributing substantial amounts (Koch et al., 2007a). By contrast, biomass burning is the dominant source of black carbon in the southern hemisphere (Koch et al., 2007a).

Before the industrial revolution, black carbon depositions in the Arctic were dominated by biomass combustion sources, but since around 1850, fossil fuel combustion has dominated arctic black carbon deposition (McConnell et al., 2007). Until around 1950, high northern hemisphere latitudes (>40° N) were the primary source of most black carbon deposited in the Arctic. Today, industrial emissions in Asia appear to be a major driver of climate forcing in the Arctic (McConnell et al., 2007), with South Asian industrial and solid biomass emissions contributing substantially (20-40 percent) to Arctic black carbon concentrations and forcing, together with northern hemisphere open biomass burning (forest fires), primarily from Russia (Koch and Hansen, 2005). Low-latitude (<40° N) biomass emissions, which account for an estimated 60 percent of total global biomass black carbon emissions, contribute an estimated further 10-20 percent to Arctic black carbon concentrations and forcing (Koch and Hansen, 2005). Corroborating these estimates, Hegg et al. (2009) found that most black carbon deposition at their 36 Arctic sampling sites appeared to be from biomass combustion, both open (agricultural residue and vegetation clearing burning and forest fires) and contained (household), followed by industrial emissions.

2.2 SOURCE STRENGTH OF BLACK CARBON EMISSIONS IN ASIA

In Asia, high concentrations of black carbon extend from the industrial centers into more rural areas in southern India and Southeast Asia, reflecting the importance of both fossil fuel combustion (industrial and urban areas) and solid biomass and open biomass burning (rural areas) as contributors to black carbon loadings (Carmichael et al., 2009). Thus, the source contribution to black carbon and other small aerosol concentrations varies throughout the region.

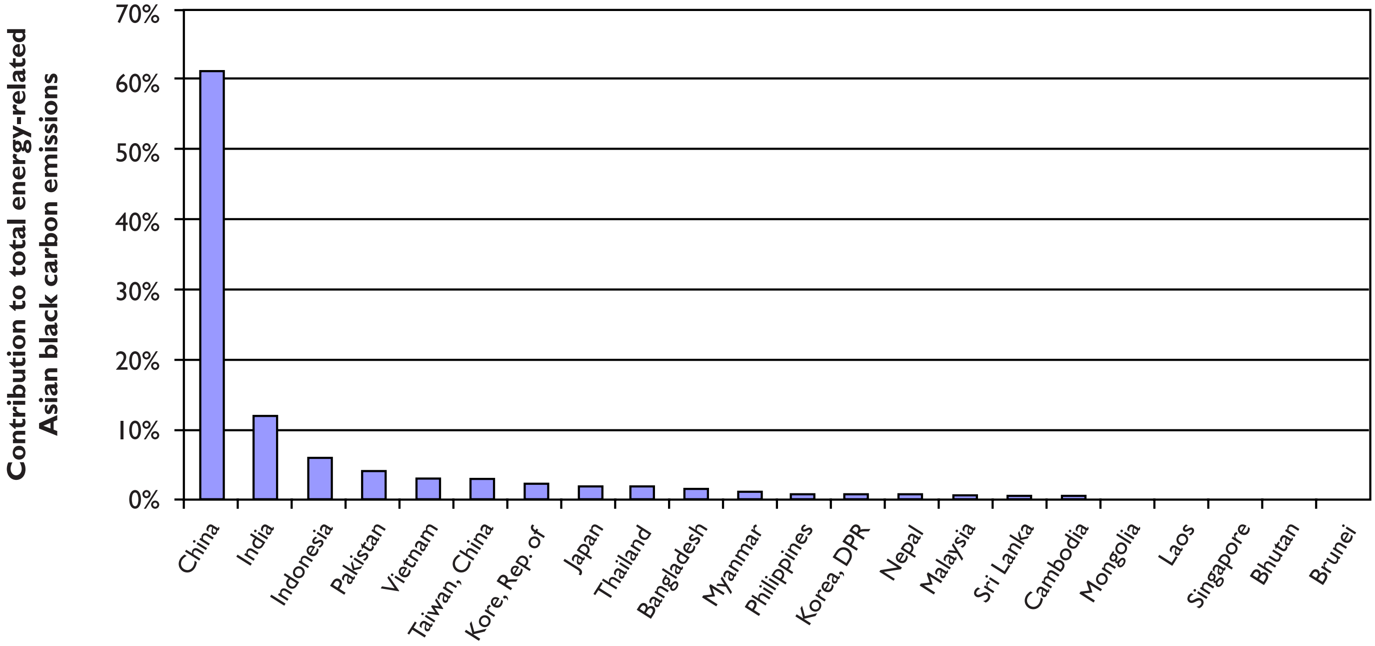
Biomass is the dominant household fuel in Asia, accounting for about 70 percent of total household fuel use. Coal accounts for about 10 percent of household fuel in Asia, with almost all of it used in China (Aunan et al., 2009).

Source strength estimates for Asia vary with the particular estimation methodology employed. Emission inventory-based studies commonly yield lower estimates (10-30 percent) of the share of black carbon in the atmospheric brown cloud (ABC) over southern Asia that is attributable to fossil fuel combustion (Szidat, 2009), while studies using ambient concentration ratios of black carbon to other particle fractions (elemental carbon, total organic carbon, soot carbon) attribute 50-90 percent of ABC black carbon to fossil fuel sources (Gustafsson et al., 2009).

Emission inventories suggest that household emissions account for about two-thirds each of Asia's anthropogenic black and organic carbon emissions (Aunan et al., 2009). However, emission factors in Asia are characterized by large uncertainties, especially for India, the rest of South Asia and Southeast Asia, and these uncertainties are especially large for open biomass burning in India (Streets et al., 2003). This, together with the seasonality of open burning, makes it extremely difficult to accurately assign source contributions for India (Streets et al., 2004a). In China, the industrial and residential sectors are the largest black carbon-emitters (solid biomass and coal), while the major contributors in India are residential solid biomass, road transport, and industry (Bond et al., 2004).[4]

China is by far the largest emitter of black carbon (Bond et al., 2004), accounting for an estimated 30 percent of global emissions from contained combustion, and nearly 20 percent of contained and open combustion combined (Figure 2). Moreover, China's emissions are estimated to have been increasing rapidly since the 1990s, reaching over 40 percent of total (energy-related and open biomass burning) Asian black carbon emissions in 2000 (Figure A3). The most recent study (Zhang et al., 2009) puts China's share in Asian energy-related black carbon emissions (excluding biomass burning) at over 60 percent in 2006, with the three main emitting countries together accounting for nearly 80 percent of energy-related black carbon emissions (**Figure 3**).

Figure 3. Contributions of countries to total Asian black carbon emissions from contained combustion in 2006



Source: Zhang et al., 2009

---

[4] In 2003, approximately 80 percent of the energy consumed by rural households in China was in the form of biomass and almost 10 percent as coal (Zhang and Smith, 2007), residential burning of both of which produces fine particles with a high carbon content (Streets et al., 2001).

Streets et al. (2001), one of the most comprehensive early analyses of China's black carbon emissions, estimated that the residential sector accounted for over four-fifths of total black carbon emissions in the country in 1995, with industry and open biomass burning distant second- and third-strongest sources. Residential black carbon emissions from coal are estimated to account for fully 45 percent of total national black carbon emissions, with solid biomass accounting for another 38 percent.[5] This dominance was due to the simple combustion designs used that result in very high emission factors for bituminous and raw coal (Zhang et al., 2009) and the almost complete lack of emission control. The dominant emitters in the industrial sector are iron and steel production, mostly from coal combustion due to the dominance of the fuel. Due to effective control, power generation in China generally has low black carbon emission factors, except for fuel-oil-based power generation, which has much higher emission factors than the typical pulverized coal; however, the use of fuel oil in power production was comparatively small (Streets et al., 2001). Emissions from the transport sector were dominated by diesel fuel and were expected to increase sharply due to expansion of diesel's share (Streets et al., 2001).

The most recent estimates of black carbon emissions in China use fuel consumption data from the years 2000 (Guoliang et al., 2007) and 2006 (Zhang et al., 2009), respectively, a finer spatial scale and updated, empirically-based black carbon emission factors for some sources for which previously few or no estimates were available. The findings of these studies show the same ranking of the major sources, but they do show substantial differences from Street et al.'s (2001) estimates. Specifically, the estimated contribution of the residential sector falls by almost 30 percent (absolute value) to over 55 percent of total emissions, while that of industry increases five-fold to 32-36 percent (**Table 1**). Zhang et al. (2009) also shows

Table 1. Estimated black carbon emissions in China in 2000 and 2006

Sector	Fuel	BC emissions (Gg)		Sector share in total BC emissions	
		Guoliang et al. (2007)	Zhang et al. (2009)	Guoliang et al. (2007)	Zhang et al. (2009)
Residential	Agric. residues	186.6	1002	55%	55%
	Fuelwood	109.2			
	Coal-Rural	487.1			
	Oil-Rural	0.4			
	Coal-Urban	33.7			
	Oil-Urban	0.6			
	Coal-Urban	122.4			
	Oil-Urban	15			
Industry	Coal-Rural	374.7	575	36%	32%
	Oil-Rural	10.5			
	Biomass	21.3			
Power Generation	Coal	7.8	36	1%	2%
	Oil	0.1			
Transportation	Diesel	25.5	198	2%	11%
	Gasoline	1.3			
Biomass burning	Agric. waste	100.1	Not included	7%	Not included
	Forest fires	2.7			
	Grassland fires	0.4			

Sources: Guoliang et al. (2007); Zhang et al. (2009).

---

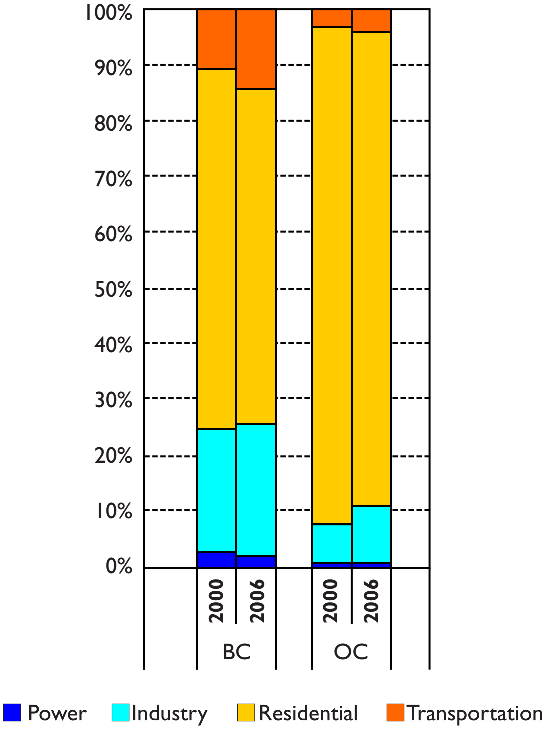
[5] Woody fuel combustion accounts for approximately two-thirds of China's estimated 430 Gg of black carbon emissions from household biofuel combustion in 2005 (Li et al., 2009).

a significantly larger contribution of the transport sector. Despite these substantial differences, all three studies identify the same priority sources (residential, industrial, and transport sectors) for black carbon control in China.

Using satellite-based analysis of aerosol optical depth (AOD), Carmichael et al. (2009) estimate that fossil fuel sources (industrial, transport, and households) are the major black carbon source (~60 percent) in China, and are the second-leading contributor to black carbon emissions in Southeast (>40 percent) and South Asia (>30 percent). Solid biomass used for domestic purposes (heating and cooking) currently is the largest source (~50 percent) of black carbon emissions in South Asia and contributes about one-third of black carbon emissions in Southeast and East Asia (Carmichael et al., 2009). However, the contribution of energy-related biomass burning to surface concentrations often is larger than indicated by AOD analysis, reaching up to 70-90 percent in India and 20-80 percent in China (Carmichael et al., 2009).

This dominance of biomass sources in South Asian black carbon emissions mirrors findings from emission inventory-based analyses which estimate that solid biomass combustion in the residential sector and open biomass burning are the main black carbon sources in India (Koch and Hansen, 2005; Bond et al., 2004). It also matches findings of analyses of air masses advected from the Indian subcontinent that indicate a strong impact of solid biomass burning in India (Guazzotti et al., 2003). Similar results were obtained by the potentially most reliable methodology for source identification which uses radiocarbon analysis to apportion black carbon in the ABC to biomass and fossil fuel sources (Gustafsson et al., 2009). The results of that analysis indicate that two-thirds of the bulk carbonaceous aerosols in the ABC are from biomass sources, and elemental and soot carbon in the ABC suggest that between one-half and two-thirds of ABC black carbon are from biomass combustion. These findings correspond broadly to the latest emission-inventory based estimate compiled for Asia on the basis of 2006 fuel consumption estimates (Zhang et al., 2009), which attributes around 61 percent of black carbon emissions to the residential sector, dominated by energy-related biomass combustion but also from coal (mostly in China) and diesel (mostly in India), with the industrial, transport and power sectors accounting for approximately 23 percent, 14 percent and 2 percent, respectively.

Figure 4: Share of emissions of black and organic carbon from contained combustion in Asia by major sector in 2000 and 2006



Source: Zhang et al. (2009)

These results, however, contrast with findings from a few other concentration-analysis studies. Stone et al. (2007) applied a receptor-based attribution model to fine particulate matter trace metal measurements at two Maldives sites in the northern Indian Ocean, located downwind of the major continental outflow from South and Southeast Asia. Their results suggest that solid biomass burning (30-40 percent) and fossil fuel combustion (40-50 percent) were almost equally-important sources of elemental carbon during the polluted dry season. Mayol-Bracero et al. (2002) estimated that fossil fuel combustion accounted for an even higher share – between 60 and 90 percent – of the measured total aerosol pollution during the Indian Ocean Experiment (1999), with the remainder from biomass and biofuel combustion. However, Mayol-Bracero et al. probably overestimate the fossil fuel contribution because their source strength estimates are derived by comparing measured elemental carbon/ total carbon concentrations during the study with EC/TC ratios of biomass burning, which are quite different from those of biofuel burning in residential stoves.[6]

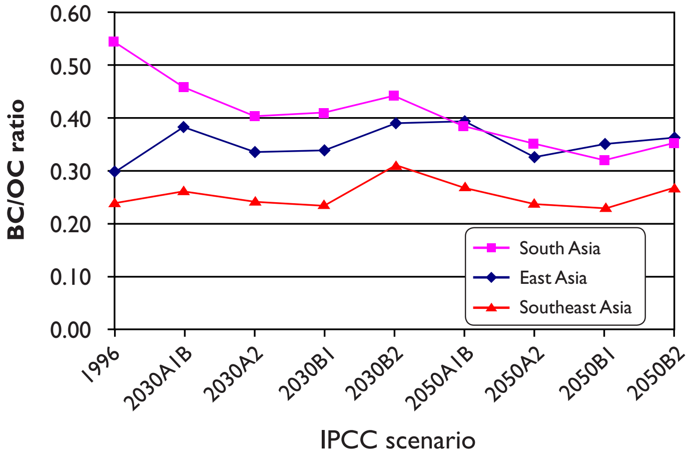
Notwithstanding disagreements among studies about relative source strengths, all studies identify household combustion of both fossil fuels and biomass and open biomass burning as major sources of black carbon emissions in Asia, with additional substantial contributions from uncontrolled or little controlled fossil fuel combustion in the industrial and transport sectors.

2.3 PROJECTED BLACK CARBON EMISSIONS

Estimates of future black carbon emissions in Asia depend on the particular scenario assumptions. Detailed analyses (Streets et al., 2004a; 2007) using IPCC fuel use scenarios A1B, A2, B1 and B2 (Nakicenovic and Swart, 2000) suggest that black carbon emissions in East Asia are expected to decline from their 1996 levels by 2030 and 2050, primarily due to a switch away from coal for residential use. On the other hand, emissions in South Asia and Southeast Asia are expected to increase by 2030 in some scenarios, but generally to fall below 1996 levels by 2050 (Streets et al., 2004a). Black carbon emissions from transport increase in the near term (2030) due to greatly increased numbers of vehicles with less-than-optimal emission performance, especially in South Asia (Koch et al., 2007b), but are expected to decrease by 2050 (Streets et al., 2004a). A follow-up analysis (Koch et al., 2007a) incorporating updated technological projections for scenarios A1B and B1 also predicts that future (2030 and 2050) residential emissions will decrease due to reduction in solid fuel combustion. In both scenarios, industrial black carbon emissions in Asia decrease largely due to fuel switching (Koch et al., 2007b). The most recent analysis (Carmichael et al., 2009) suggests that South Asian emissions may show anything from a slight increase to a considerable decrease compared to 2004 values depending on the scenario, while Southeast and especially East Asian emissions decrease in all scenarios.

These scenarios already incorporate a variety of fuel-switching and technology assumptions. These include the gradual replacement in the residential sector of traditional fossil fuel and biomass stoves by higher-grade fuels (biogas, natural gas, electricity) and cleaner technologies (improved cook stoves etc.); a gradual banning in many parts of open biomass burning and crop residue burning due to pressure from local and household air quality concerns to restrict open and domestic solid biomass burning; slower increases for forest and savanna burning due to slowing population growth; reduced pressure for additional agricultural land as a result of increased food supplies (Streets et al., 2004a). All of these assumptions carry associated uncertainties. By selecting the full range of scenarios as done by Streets et al. (2004a) and Koch et al. (2007a), one can span the full range of assumptions and thus the likely range of future emissions (Streets et al., 2004a). The projected emission trends are generally similar but show larger declines for organic carbon, due primarily to the gradual slowdown in open biomass burning (Streets et al., 2004a). As a result of this, in South and Southeast Asia, black carbon/ organic carbon (BC/OC) emission ratios are projected to increase for several IPCC scenarios (Streets et al., 2004a) (**Figure 5**), indicating increases in radiative forcing.

Figure 5: Projected BC/OC ratios for three Asian subregions, based on Streets et al. (2004a)



---

[6] Mayol-Bracero et al. (2002, p. 18) themselves state that their measured sulfur/BC ratios seem to suggest a much larger contribution from biofuel emissions.

SECTION 3

IMPACTS OF BLACK CARBON

3.1 CLIMATE IMPACTS: OVERVIEW

Black carbon affects climate through several pathways. Airborne black carbon in soot is the dominant anthropogenic absorber – approximately 1 million times stronger per unit mass than carbon in CO_2 (Jacobson, 2002, 2009)[7] – of incident solar radiation in the atmosphere (Haywood and Ramaswamy, 1998; Jacobson, 2004a; Ramanathan and Carmichael, 2008), which it stores in the form of thermal energy and then re-emits, warming surrounding air molecules. These warmer molecules have long lifetimes and travel longer distances than the black carbon particles themselves, contributing to the warming of the atmosphere at the global level (Jacobson, 2004a). Black carbon also absorbs thermal infrared radiation from the ground (Ramanathan et al., 2007b; Jacobson, 2004a) and within clouds (Jacobson, 2006). Furthermore, black carbon directly heats surfaces on which it is deposited. In the case of snow and ice, this leads to additional melting. Finally, black carbon changes the albedo (surface reflectivity) of ice and snow, leading to additional warming of the surface and melting (Hansen and Nazarenko, 2004). This reduced reflection of radiative energy can extend the warming of a site by several months (Kandlikar et al., 2009), making black carbon a particularly powerful contributor to the observed accelerated melting of glaciers and Arctic sea and land ice (Hansen and Nazarenko, 2004; Shindell and Faluvegi, 2009) and to associated impacts like sea level rise and loss of glacier-fed freshwater supplies. The impacts of black carbon on seasonal snow covers are even larger, because additional warming leads to earlier exposure of low-albedo underlying rock, soil, vegetation and sea ice (McConnell et al., 2007). Because of these multiple impacts, the "efficacy" of black carbon forcing via snow and ice albedos is two (Hansen and Nazarenko, 2004) to three times (Flanner et al., 2007) that of CO_2. That is, for a given forcing, black carbon deposited on snow and ice alters global air surface temperature by two or three times as much as CO_2.

Because of these multiple warming pathways, black carbon has a comparatively large impact on global warming. For greenhouse gases, this global warming impact is commonly expressed in the form of global warming potentials (GWPs), which quantify the integrated radiative forcing of a unit mass pulse of a greenhouse gas over a specified time period (usually 20 or 100 years) relative to that of CO_2 (Forster et al., 2007). GWPs have also been estimated for black carbon, although their use for such short-lived species is controversial (Bond, 2007b). Several estimates of the GWP of black carbon are shown in **Table 2** for time frames of 20 and 100 years. Because of the short lifetime of black carbon emissions (ranging from days to weeks) compared to CO_2 (decades to centuries), the warming impact of a unit of black carbon emissions relative to that of a unit of CO_2 is larger over shorter periods. These estimates imply that one kilogram of black carbon heats the atmosphere 500-680 times as much as one kilogram of CO_2 over a 100-year timeframe, and 1500-2200 times over a 20-year timeframe. Note that the 100-year GWP of fossil fuel soot (GWP100 ffBC+OM) is smaller than that of the black carbon in soot (GWP100 BC in ff-soot). This is due to the fact that the soot also contains organic carbon and sulfate (Jacobson, 2007) which produce net cooling effects.

---

[7] This figure is based on the relative surface temperature response per unit mass (STRM) of continuous emissions over a 100-year time frame. This differs from the standard way of expressing GWP, which gives the warming caused by a single unit "pulse" of BC emitted, say, today. The large difference between the standard GWP reported for BC (between 500 and 680 over 100 years) and the 1 million estimate from Jacobson is due to the comparatively very short life time of BC relative to CO_2. Thus, the GWP of a single unit of BC over a 100-year timeframe is very small compared to that of one unit of continuous emissions of BC.

Table 2. Global warming potential of black carbon, fossil fuel soot, and black carbon in fossil fuel soot

GWP$_{20}$ BC	GWP$_{100}$ BC	GWP$_{100}$ of ffBC+OM	GWP$_{20}$ BC in ff-soot	GWP$_{100}$ BC in ff-soot	Source
2200 (690-4700)	680 (210-1500)				Bond and Sun (2005)[1]
		330-700			Jacobson (2005)
			4470	1500-2240	Jacobson (2007)
		500			Hansen et al. (2007)

Notes: [1] Synthesis of pre-2005 published studies. Values in brackets give the ranges reported in studies. BC-black carbon; ffBC- fossil fuel black carbon; ff-fossil fuel; OM-organic matter (mostly organic carbon).

Because of the combination of high absorption and a regional distribution roughly aligned with solar irradiance (concentrated in the tropics where solar irradiance is highest), anthropogenic emissions of black carbon are considered to be the second- or third-strongest contributor to current anthropogenic global warming, after carbon dioxide emissions and possibly methane (Ramanathan and Carmichael, 2008; Hansen et al., 2005; Jacobson, 2002), contributing approximately 0.3°C of the 2°C increase in global mean temperatures since circa 1760 (Jacobson, 2004a; Bice et al., 2009), or about one quarter of observed warming between 1880 and 2000 (Hansen and Nazarenko, 2004).

Soot from carbonaceous fuel combustion contains both black carbon and organic carbon (Jacobson, 2004b), with the ratio of the two species depending on the particular emission source (Bond et al., 2004). The overall warming impact of a particular soot depends on the balance of the individual climate forcings of each of its constituent components (Ramanathan et al., 2008; Hansen et al., 2005). With black carbon having a strong positive forcing and most organic carbon and other aerosols having a negative forcing (due to their light-scattering or "dimming" effect), the higher the share of black carbon in soot, the higher the warming effect of the soot.[8,9] Thus, fossil-fuel soot warms more than solid biomass soot per unit mass because of its greater fraction of black carbon (Jacobson, 2007), and the two combined have a strongly positive net global forcing (Flanner et al., 2009), while biomass soot from agricultural burning and forest and savanna fires has a net negative global forcing (Hansen et al., 2005; Jacobson, 2004b).

The GWP expresses the warming caused by a greenhouse species during a given time period relative to that of CO_2. The absolute radiative effect of a global warming substance is typically expressed in terms of "forcing", that is, the change in net energy flux at the tropopause, measured in watts per square meter (Wm^2). Estimates of black carbon forcing are presented in **Table 3**. Note that the values shown in the table are average values. Some fossil fuel soot sources (e.g., coal and diesel engines) have a much higher BC/OC ratio and thus higher warming (Hansen et al., 2005).

Comparing the average of the global mean black carbon forcing estimates in the table (indicated in bold face), 0.64 Wm^2, to the global average forcing from CO_2 of 1.66 Wm^2 shows that the impact of black carbon on global temperatures is at least 25 percent (Bond, 2007b) and possibly as much as 55 percent of the anthropogenic CO_2 forcing (Ramanathan and Carmichael, 2008).[10]

---

[8] Globally, the forcing of snow darkening from black carbon and organic matter combined is estimated to be six-fold the forcing from aerosol-related dimming, resulting in a strong net positive forcing from fossil and biofuel combustion (Flanner et al., 2009).

[9] The surface dimming from ABCs is accompanied by a positive forcing at the top of the atmosphere (TOA) and thus, unlike for sulfates and other non-black carbon aerosols, black carbon-related dimming does not necessarily result in surface cooling (Ramanathan and Feng, 2009). For this reason, the overall TOA forcing from ABCs (-1.4 Wm^2) is much smaller than the large negative surface forcing from ABC-caused dimming (-4.4 Wm^2) (Ramanathan and Feng, 2009).

values. Hansen et al.'s (2005) "industrial BC" refers to BC from fossil fuel combustion; soot includes BC and other aerosols.

[10] To calculate this average value, Hansen et al.'s (2005) industrial and biomass black carbon forcings were weighted by the contribution of fossil (two-thirds) and biofuel (one-third) black carbon to total anthropogenic black carbon emissions (based on Bond et al., 2007).

Table 3. Global mean net radiative forcing from black carbon and soot*

Species	Forcing (Wm^2)	Effective forcing[2] (Wm^2)	Source
Fossil fuel soot[1]	0.48	0.25 (±0.20)	Hansen et al. (2005)
Biomass soot	0.1	-0.23 (±0.17)	Hansen et al. (2005)
Industrial BC	0.48	0.38 (±0.12)	Hansen et al. (2005)
Biomass BC	0.17	0.1 (±0.05)	Hansen et al. (2005)
BC	0.3[3]	0.6[3]	Hansen and Nazarenko (2004)
Fossil fuel BC	0.2 (±0.15)		Forster et al. (2007)
BC	0.34 (±0.25)		Forster et al. (2007)
BC	0.9		Ramanathan and Carmichael (2008)
BC in Arctic	0.53[4]		Quinn et al. (2008)
BC	1.0 (±0.5)		Sato et al. (2003)
BC	0.55[4]		Jacobson (2001)
BC	0.5-0.8		Chung and Seinfeld (2002)

Notes:* Except for values from Hansen et al. (2005) and Hansen and Nazarenko (2004) that account for BC impacts on snow and ice albedos, the forcings shown are those from the direct effect of BC in the atmosphere only. Thus, they do not include indirect impacts of BC on snow and ice albedo and clouds.

[1] Sum of industrial black and organic carbon (-0.1 Wm^2) and snow BC forcings (0.1 Wm^2) (Hansen et al., 2005). [2] Includes aerosol indirect effect and adjustments for efficacies of individual forcings. [3] Northern Hemisphere forcing. [4] Direct forcing only. All forcings shown are top-of-atmosphere. Hansen et al.'s (2005) "industrial BC" refers to BC from fossil fuel combustion; soot includes BC and other aerosols.

3.2 CLIMATE, WEATHER, AND HYDROLOGICAL IMPACTS OF ASIAN BLACK CARBON EMISSIONS: ASIA

In addition to its impact on global warming, black carbon aerosols have important regional climate, weather, and hydrological impacts. These include a decrease in the Indian summer monsoon rainfall, a north-south shift in rainfall patterns in eastern China, the accelerated retreat of the Hindu Kush-Himalayan-Tibetan glaciers and decrease in snow packs, and a rapid increase in the loss of Arctic sea and land ice.

Black carbon is often transported over long distances, mixing with other aerosols along the way. This aerosol mix can form transcontinental plumes of ABCs, with vertical extents of 3 to 5 km (Hansen and Nazarenko, 2004). Asia has been identified as a regional ABC hotspot (Ramanathan et al., 2008).

ABCs intercept solar radiation, causing surface dimming with important implications for the hydrological cycle, specifically, reduced evaporation and precipitation and changes in the sea-land temperature gradients (Ramanathan and Carmichael, 2008; Ramanathan and Feng, 2009). Because the concentration of dimming is largest in the tropics and the precipitation-increasing warming from greenhouse gases is larger in the extra-tropics than the tropics, ABCs are likely to lead to net precipitation reductions in the tropics (Ramanathan and Feng, 2009).

Evidence of localized climate forcing in Asia consists of decreases Indian and Southeast Asian summer monsoon rainfall (Ramanathan et al., 2005; Ramanathan ate al., 2008; Ramanathan and Feng, 2009), resulting in a weaker hydrological cycle and reduced freshwater availability (Ramanathan and Feng, 2009); a north-south shift in eastern China rainfall over the past several decades, leading to increased summer floods in south China and increased drought in northern China (Menon et al., 2002; Ramanathan et al., 2005); and reduced surface temperatures coupled with increased atmospheric warming during the dry season (Ramanathan et al., 2008). The rising air temperatures have been identified as the main driver behind the accelerated retreat of the Hindu Kush-Himalayan-Tibetan glaciers since the 1970s (Ramanathan et al., 2008). Their impact is exacerbated by the strong snow and ice albedo effects from black carbon deposition

(Hansen and Nazarenko, 2004). Research shows that black carbon concentrations are sufficiently high in northeast China to substantially lower snow albedo, and instantaneous concentrations are highest over the Tibetan Plateau, exceeding 20 Wm^2 in some places (Flanner et al., 2007). Thus, in the Hindu Kush-Himalayan-Tibetan glaciers, solar heating at high elevations from ABC black carbon may be just as important as carbon dioxide in the melting of the snowpacks and glaciers upon which some 40 percent of the world's population depends for freshwater (Ramanathan and Carmichael, 2008; Ramanathan et al., 2008).

3.3 CLIMATE IMPACTS OF ASIAN BLACK CARBON EMISSIONS: ARCTIC AND EURASIA

The Arctic is particularly susceptible to regional forcings, including from snow albedo change (Hansen et al., 2005). The deposition of black carbon darkens snow and ice surfaces and can contribute to melting, in particular of Arctic sea ice. Black carbon forcing may be responsible for more than 30 percent of recent warming in the Arctic (Shindell and Faluvegi, 2009), and for perhaps as much as half of the observed retreat of Arctic sea ice (Ramanathan and Carmichael, 2008; Hansen and Nazarenko, 2004; Flanner et al., 2007). South Asian industrial fossil fuel (McConnell et al., 2007) and residential biomass and open biomass burning emissions (Koch and Hansen, 2005) are considered to be major drivers of Arctic black carbon forcing. Fossil fuel and energy-related biomass emissions, primarily from Asia, also induce strong snow cover loss in Eurasia from strong snow-albedo feedacks (Flanner et al., 2009).

3.4 IMPACTS ON AGRICULTURE AND WATER SUPPLIES

The cooling and moisture-absorbing properties of the ABC haze layer reduce rain events in the dry season (Ramanathan and Crutzen, 2003), with black carbon cloud absorption in particular decreasing precipitation (Jacobson, 2006). This reduction in rainfall is negatively impacting rice harvests in India (Aufhammer et al., 2006).

Furthermore, ABC-caused local dimming, that is, the reduction in the amount of solar radiation reaching the earth, has been shown to reduce crop yields in China. Using modeled reductions in solar irradiance (which are smaller than measured reductions) and empirically-observed solar irradiance-yield relationships, Chameides et al. (1999) conservatively estimate that regional haze in China in the late 1990s was depressing optimal yields of 70 percent of the crops (rice and wheat) grown in China by at least 5–30 percent.

A number of studies have documented decreases in rainfall over northern India coupled with an increased severity of flood events, and a southward shift in rainfall in eastern China, all of which are attributed in part to ABC-induced dimming (Ramanathan et al., 2008). Black carbon also is a major contributor to the accelerated retreat of the Hindu Kush-Himalayan-Tibetan glaciers and snow packs that feed all of the major Asian river systems (Ramanathan et al., 2008). All of these impacts threaten water security in East and South Asia. Large parts of South and East Asia are projected to be water stressed by 2050 as a result of climate change and other development impacts, and black carbon is expected to further exacerbate the severity of these water shortages (Ramanathan et al., 2008).

3.5 HUMAN HEALTH IMPACTS

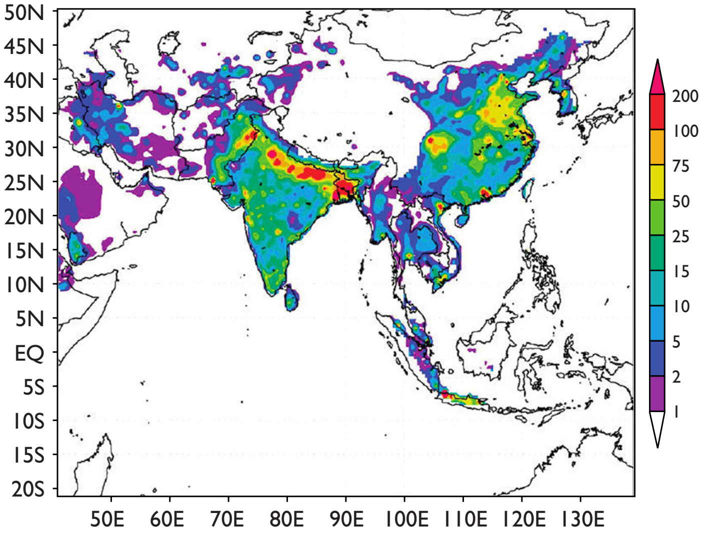
Black carbon emissions contribute to both indoor and outdoor air pollution. Black carbon emissions in soot are small enough to remain airborne for days to weeks and in many regions of the world form an important part of airborne particulate matter (PM).[11] Vast regions of

---

[11] In the environmental health and epidemiological literatures, particulate matter (PM) is commonly distinguished into size fractions that are of particular relevance for health effects. In general, the smaller a particle's size, the deeper it can penetrate into the lungs and the more serious its health effects (Pope and Dockery, 2006). Total particulate matter contains a coarse fraction that is made up of particles too large to enter deeply into airways and that is not a primary health concern. Particles of less than 10 micrometers in aerodynamic diameter in size (PM_{10}) are small enough to enter the lungs and thus make up the respirable fraction that has formed the basis for many early health effects research of particulate air pollution. More recent studies suggest that the observed health effects are primarily due to the smaller particles within the PM_{10} fraction, and most studies now focus on $PM_{2.5}$.

Asia are characterized by high aerosol loadings due to ABCs with significant contributions (60-80 percent) from anthropogenic aerosols, and with more than 80 percent of the region's population exposed to $PM_{2.5}$ concentrations that exceed the World Health Organization's annual mean guideline (10 μg/m^3), often by factors of 2-5 (Carmichael et al., 2009). Black carbon emissions are an important contributor to the high loadings, with black carbon accounting for 5-10 percent of aerosol optical depth (Carmichael et al., 2009). Population-weighted black carbon surface concentrations in Asia are shown in **Figure 6**.

Figure 6: Population-weighted exposure to $PM_{2.5}$ levels greater than the WHO guideline of 10 μg/m^3 (for grid cells with concentrations >10 μg/m^3 the $PM_{2.5}$ concentration is multiplied by the population in that grid.) Units: millions of people-μg/m^3 of $PM_{2.5}$.



Source: Carmichael et al. (2009).

Particulate matter pollution (PM_{10}) and especially its smaller fractions ($PM_{2.5}$) including black carbon (<1μm, or PM_1) causes a number of severe cardiovascular and pulmonary effects that lead to acute symptoms, chronic diseases and death (Pope and Dockery, 2006). High concentrations of black carbon and associated organic compounds like those found in South Asia contribute significantly to these effects (Knaapen et al., 2004; Bachmann, 2009).[12]

Exposure to indoor air particulate matter pollution from incomplete combustion of low-quality solid fuels, is the fourth-leading contributor to the global burden of disease in poor developing countries, as measured by the common metrics of disability-adjusted life years (DALY) (Ezzati et al., 2002), killing an estimated over 1.8 million people per year in those countries (Ezzati et al., 2006). It is the third-leading contributor to the burden of disease in South Asia, and the fifth-leading cause of mortality in Asia as a whole (Ezzati et al., 2006).

Globally as well as in Asia, the burden of disease that is attributable to the use of household solid fuels is dominated by the burdens from acute lower respiratory infections especially in children and chronic obstructive pulmonary disease, especially in women, with lung cancer a relatively minor contributor (Smith et al., 2004; Smith, 2000). Young children, girls, and women bear a disproportionate share of the disease burden because they spend a large proportion of their time indoors (Smith et al., 2004). Two-thirds of global deaths and over half of the global burden of disease (DALY) from indoor air pollution from solid fuel combustion falls on Asia (Smith et al., 2004). China and India, due to their large populations and widespread reliance on household biomass and coal (in China) burning, dominate Asian impacts.

In Asia as a whole, the total number of deaths from indoor air pollution exceeds 1 million per year (Cohen et al., 2005), but may be as high as 2.3 million per year for women and young children in India alone (Smith, 2000). These health effect estimates may seem high, but even the 2.3 million figure is not surprising given that the average ambient particle levels in solid fuel-burning households in India often exceed 2,000 μg/m^3 PM_{10} (Smith, 2000; Anderson et al., 2004), or 100 times and 40 times,

---

[12] While the literature confirms the carcinogenicity of black carbon, no single component of PM is known to be primarily responsible for health effects, nor has any component been eliminated from consideration. Thus, the relative severity of the health effects of black carbon versus other PM components is an open question (Personal communication, Ben Gibson, International Energy Agency, December 24, 2009).

respectively, of the WHO annual mean and 24-hour mean guidelines (WHO, 2006). Indoor smoke from solid fuel combustion is the second-leading environmental risk factor contributing to the total burden of disease in India, and the third-largest risk factor overall (Smith et al., 2005). Indoor air pollution is a major contributor to child mortality in India. Mishra et al. (2005) found that acute respiratory infections, the leading cause of childhood mortality in India, were almost twice as likely in households in India that used only biomass for cooking and heating as in households using cleaner fuels.

In China as in India, household exposure levels are greatest in the residential sector due to poor ventilation in most kitchens (Streets et al., 2001), leading to large-scale health impacts. According to the most recent global analyses of the health effects of major risk factors (Cohen et al. 2004; Smith et al. 2004; Zhang and Smith, 2007), solid fuels used in Chinese households cause approximately 420,000 premature deaths annually, on the same scale as premature deaths from particulate matter-related outdoor air pollution, estimated to be approximately 300,000 in Chinese cities with populations of more than 100,000 alone. Household use of solid fuels is thus estimated to be the single largest environmental risk factor in China and ranks sixth among all risk factors examined for ill-health (Smith et al., 2005).

The morbidity impacts of indoor air pollution from solid fuels are a primary health concern as well. For example, in a comprehensive review and meta-analysis of the literature, Dherani et al. (2008) found that combustion of unprocessed solid fuels in households almost doubled the risk of pneumonia in young children.

Black carbon emissions from older and often badly maintained vehicle engines, industries and other sources lead to outdoor ambient particulate matter concentrations in many cities in poor countries that far exceed those in wealthier countries (Molina and Molina, 2004).

Although open biomass burning in many areas further adds significantly to ambient concentrations of inhalable particulate matter, the primary source of particulate matter emissions in most urban areas is fuel combustion (Anderson et al., 2004). An estimated two-thirds, or 487,000, of the approximately 800,000 worldwide annual excess deaths from outdoor air pollution occur in Asia (Cohen et al., 2005), with the majority of these occurring in China (Cohen et al. 2004; Smith et al. 2004; Zhang and Smith, 2007). In an unrelated study, Zhang et al. (2008) estimated that outdoor air pollution in the 111 largest Chinese cities (including most large and medium-sized cities) caused over 281,000 deaths in 2004 and resulted in a total cost of all related health effects of over $29 billion.[13]

Ramanathan et al. (2005) report that first rough estimates of the magnitude of the health costs of just the predicted excess mortality from ABC-related $PM_{2.5}$ increases indicate the potential for very significant health costs associated with ABCs in both China and India, which could amount to 3.6 and 2.2 per cent of the countries' GDPs, respectively, even when using mid-range mortality cost estimates. Even though these estimates should be interpreted with caution, they do show the level of magnitude of the costs associated with fuel combustion and biomass-related air pollution health impacts.

Of course, not all inhalable particulate matter consists of black carbon. Indeed, $PM_{2.5}$ concentrations and associated health effects are expected to increase by 2030, even though black carbon emissions are expected to fall over the commonly-analyzed range of future scenarios (Carmichael et al., 2009), indicating that the health effects from non-black carbon particulate matter will become relatively stronger. Nevertheless, black carbon accounts for a substantial share of inhalable particulate matter and thus of the associated health effects.[14] Its contribution to these effects is further increased by its small size (much of it being PM_1; Li et al., 2009) and toxicity (Knaapen et al., 2004; Koelmans et al., 2006).

---

[13] These numbers and associated costs are underestimates for the country as a whole since they exclude many smaller and medium-sized cities. For example, Saikawa et al. (2009) estimate Chinese deaths from energy-related PM emissions (sulfur dioxide, BC and OC) in China as a whole at 470,000 in 2000.

[14] For example, black carbon accounted for an average of 8.3 percent of $PM_{2.5}$ in Xi'an, China in 2003-2005 (Cao et al., 2009).

3.6 THE GENDER DIMENSION OF HEALTH IMPACTS FROM BLACK CARBON SOURCES

In many developing countries, women bear primary responsibility for cooking (Smith el al., 2005). In many rural areas, women - and young children, especially girls - also are responsible for fuel collection, an activity that frequently requires substantial time inputs (Energy Sector Management Assistance Programme, 2004; Smith et al., 2004) and exposes them to health risks from violence, disease and injury (Smith et al., 2005; Wickramasinghe, 2003).

As a consequence of the larger amount of time spent indoors, women and young children are the ones most exposed to indoor air pollution (Smith et al., 2004; Naeher et al., 2006) and thus are the primary beneficiaries of cleaner household fuels or improved stoves (Smith et al., 2005).

Health impacts attributed to exposure to indoor air pollution from biomass burning include increased prevalence of acute lower respiratory infections (in children), chronic obstructive pulmonary disease, reduced lung function, asthma in school-age children, tuberculosis, and interstitial lung disease, heart disease, stillbirth, cataracts and other visual impairments, pre-term delivery, and low birth weight, among others (Smith et al., 2004; Smith, 2000). In addition, a number of health effects have been attributed to outdoor air pollution at much lower levels, and thus likely also are caused by the much higher concentrations of those same pollutants found indoors (Smith et al., 2004). Indoor air pollution from the burning of coal has been found to affect many of the same health endpoints, and in addition has been associated with lung cancer (Smith et al., 2004).

Smith's (2000) conservative best estimate is that in India in the late 1990s, exposure to indoor air pollution from biomass burning caused a total of 400,000-550,000 premature deaths per year in women and children under five years of age, and a total of 12-17 million of DALY and 11-15 million years of life lost in those populations.[15] However, the burden from solid household fuel combustion in India may have been as high as 2.3 million premature deaths annually in women and children under five years of age (Smith, 2000). These estimates suggest that women and young children, who accounted for 44 percent of India's population at the time of the study, bore a disproportionate share - about two-thirds - of the disease burden (Smith, 2000).

---

[15] Smith's analysis included all solid household fuels. However, coal accounts for only a small share of the solid fuel used in Indian households (Smith, 2000). Therefore, the vast majority of the health impacts reported in his study are caused by biomass fuels.

SECTION 4

BLACK CARBON ABATEMENT OPTIONS

Reductions in black carbon emissions offer a significant short-term option for reducing excess radiative forcing and thus global warming, with some estimates suggesting that elimination of all current black carbon sources would reduce excess temperature forcing by about 15 percent (Kandlikar et al., 2009). Although complete elimination of human-made black carbon emissions is unlikely, the abatement potential over the next 50 years adds up to another global climate "stabilization wedge" (Grieshop et al., 2009), complementing the CO_2 wedges identified by Pacala and Socolow (2004).

While black carbon has many sources, a handful of source types - residential and industrial solid-fuel combustion, open biomass burning and many vehicle super-emitters - dominate emissions globally as well as in Asia (Bond and Sun, 2005) and thus are potential key targets for control. However, efforts to reduce black carbon concentrations should be targeted in particular on sources that emit aerosols with a high absorptivity and relatively low reflectance (Quinn et al., 2008), that is, sources with a high black carbon/organic carbon emission ratio (Aunan et al., 2009). These emissions are dominated by diesel and industrial coal combustion and unimproved residential stoves burning coal and biomass fuels. Reductions in emissions from these sources are the most desirable ones from a climate perspective as such reductions increase the net cooling effects of the remaining aerosol mix by increasing the latter's scattering-to-absorbing ratio (Carmichael et al., 2009). The challenge in achieving such differential reductions in aerosol emissions consists in the often high correlation between emissions of black and organic carbon (Carmichael et al., 2009). Thus, changing the overall black/organic carbon ratio will require changes in combustion technology, emissions control technology, or fuel (ibid.).

The main sectors in Asia to be targeted by black carbon control efforts are households, industry, and transport (Figure 4). Opportunities for black carbon control in South and East Asia are large, especially in China, where the reduction potential is greater because of the predominance of poorly-controlled, coal-fired industrial facilities (Streets, 2007). Top targets for reducing black carbon emissions are the East Asia household sector and the East Asia industrial sector, through emission control and fuel substitution, while the East Asian household sector is the top target (in Asia) for maximizing the black carbon/organic carbon ratio of reductions (Streets, 2007). Historic experience with large-scale household-level interventions in Asia demonstrates that realizing these potentially substantial black carbon reduction opportunities in the residential sector will only be possible if interventions take into account the requirements and preferences of consumers (Bond, 2007a).

Proven control technologies for the key black carbon sources are available. In the case of households, these include cleaner fuels and improved cook stoves that burn fuel more efficiently and result in fewer products of incomplete combustion (PICs). In the transport sector, the main control options include diesel particle filters, especially in densely populated areas, cleaner fuels (CNG or LPG), especially for high-mileage cars like taxis, long-distance trucks and buses, a change in the modal split towards electricity- or clean fuel powered mass-transit, more stringent emission standards, and in-use vehicle emission inspection and maintenance programs. Finally, black carbon emissions in industry can be reduced through improved emission control, process switching and cleaner fuels (electricity, LPG).

Concerted deployment of these measures can make a short-term impact on black carbon emissions as demonstrated by the Chinese Government during the Beijing Olympics, where the banning of cars from use on certain days, the closing of some industries, the halting of construction, and the use of improved transportation fuels are estimated to have reduced black carbon emissions by ~40 percent and sulfate emissions by ~15 percent (Carmichael et al., 2009).[16]

It should be noted that micro-level (process) improvements in emissions in themselves may be insufficient to achieve overall reductions in black carbon emissions. For example, projections indicate that even in scenarios that reduce energy-related biomass combustion (e.g., IPCC scenarios A1B, A2, B1 and B2), increased energy consumption and reliance on coal at the macro level would still lead to increased $PM_{2.5}$ levels (Carmichael et al., 2009).

The following sections discuss the control measures for the individual sectors in more detail.

4.1 RESIDENTIAL SECTOR

Control of black carbon emissions from the residential sector in Asia forms a key component in any black carbon control strategy, because of the size of the residential sector's radiative forcing and its extension over much of the northern hemisphere (Shindell et al., 2008), and because of the magnitude and cost-effectiveness of their abatement potential. As Levy II et al. (2008:2) note, "[r]eductions of short-lived pollutants from the domestic fuel burning sector in Asia, whose climate impacts in this study are dominated by black carbon (soot), appear to offer the greatest potential for substantial, simultaneous improvement in local air quality and reduction of global warming."

China's and India's household sectors in particular represent prime targets for reductions in carbonaceous aerosols because, due to the current importance of coal and woody biomass use in the case of China and of solid biomass (wood and cow dung) and diesel in the case of India, reductions would have a high BC/OC ratio (Streets, 2007; Li et al., 2009) and thus would lead to comparatively large reductions in net forcing.[17] An across-the-board 30 percent reduction of Asian domestic (household) emissions from fuel burning is estimated to result in an about 20 percent reduction in surface particulate pollution, dominated by reductions in black carbon (Shindell et al., 2008).[18] As a result, the introduction of cleaner fuels and combustion technologies for cook stoves, both of which are feasible, in addition to climate benefits can yield dramatic improvements in health (Smith and Haigler, 2008). The type of clean fuel used is of little relevance, with the replacement of solid biomass combustion with clean fuels in Asia's household sector projected to lead to essentially identical carbonaceous aerosol emission reductions in the range-spanning IPCC scenarios A1B, A2, B1 and B2, irrespective of whether the biomass is wood or agricultural waste and whether the clean fuel is biogas, liquid petroleum gas (LPG) or electricity (Streets, 2007).[19]

Because improved stove efficiencies and cleaner fuel types may alter emission factors and ratios among species, detailed information on stove technologies and fuel properties is needed to assess the net impact on radiative forcing of control options for household black carbon emissions (Aunan et al., 2009; Edwards et al., 2007). For example, switching from biomass to coal by households

---

[16] It should be reiterated however that to assess the full impacts of control strategies on global warming as opposed to simply local surface air pollution, secondary aerosols (SOAs and nitrates) need to be included in the analysis (see Aunan et al., 2009).

[17] Reductions in black carbon emissions from China's residential sector have an average BC/OC ratio of 0.31 for the respective IPCC scenarios, compared to 0.27 for Asia as a whole (Streets, 2007).

[18] These reductions would result in reductions of 4.4-11.6 percent for tropospheric BC loads and of 2049 pptv in annual mean local black carbon surface concentration) (Shindell et al., 2008).

[19] The BC/OC ratio for these reductions is 0.27 for the relevant IPCC scenarios (Streets, 2007).

would increase the positive forcing from black carbon and ozone (O3), but this would likely be balanced by negative forcing from increased sulfate emissions. Increasing deployment of sulfate-reducing technologies in turn would increase the forcing that would result from a switch to coal compared to biomass, because then a net positive increase in forcing from such a switch would result (Aunan et al., 2009). On the other hand, switching from biomass to clean fuels or technologies (e.g., LPG or advanced-combustion renewable biomass technologies) would have beneficial (negative) forcing impacts (Aunan et al., 2009).[20]

Black carbon emissions in the residential sector can be reduced through fuel switching or the use of improved (more efficient) stoves. Since the focus on black carbon is relatively recent, most studies in the literature report emission factors in terms of total suspended particulates (TSP), particulate matter or products of incomplete combustion (PIC), all of which include other species in addition to black carbon. Table 4 shows estimates of black carbon emission factors per kilogram of conventional (solid) fuel used in both unimproved and improved stoves from some of the few studies that did measure these factors.

Table 4. Black carbon emission factors for solid fuels used in different stove types

Stove type	Fuel	BC emissions g/kg fuel	BC-OC ratio	Field (F) or Lab (L)	Source
Unimproved stoves	Crop waste	0.4±0.3		F	Li et al. (2009)
	Wood	1.5±0.7	0.95-2.51	F	Li et al. (2009)
	Wood	0.7	n/a		Bond and Sun (2005)
	Coal	8	n/a		Bond and Sun (2005)
	Wood	0.88	0.6	L	MacCarty et al. (2008)
Improved stoves					
Rocket	Wood	1.16	2.1	L	MacCarty et al. (2008)
Karve (gasifier)	Wood	0.28	0.35	L	MacCarty et al. (2008)
Fan	Wood	0.06	0.41	L	MacCarty et al. (2008)
Charcoal	Charcoal	0.2	0.14	L	MacCarty et al. (2008)

Data in the table show that switching from unimproved to improved stoves can substantially reduce black carbon emissions. It also shows that black carbon emissions from wood are generally higher than those from crop residues (Smith, 2006). However, Edwards et al. (2004) found that the ranking of stoves in terms of climate-relevant emissions varied depending on the particular mix of traditional fuels used (brushwood, wood, or crop residues). Most emissions shown in Table 4 were obtained under laboratory conditions. However, actual particulate emissions under field conditions generally exceed those obtained in laboratory tests (Sinton et al., 2004; Roden et al., 2009; Bond and Hopke, 2009). In some cases, these differences are several-fold (Roden et al., 2009), with field emission factors highly dependent on the care and skill of the operator and the resulting combustion. Evidence from field research also suggests that installation of chimneys is a necessary requirement for achieving BC emission reductions in improved stoves (Roden et al., 2009; Bond, 2010).

---

[20] Uncertainties remain about BC/OC ratios in Asia's household emissions. Although most studies estimate a positive forcing from Asian solid fuel household aerosol (BC, OC and sulfate) emissions (e.g, Koch et al., 2007b), some report a small or perhaps even negative forcing for overall household emissions from solid fuel burning (Aunan et al., 2009; Schulz et al., 2006), with only household coal use causing a clearly positive forcing. Aunan et al.'s (2009) findings of a negative global annual-mean radiative forcing results from a relatively large positive forcing from BC and tropospheric ozone but an even larger negative forcing from scattering aerosols and shortened lifetime of methane resulting from NO_x emissions. However, Li et al. (2009) report substantially higher BC/OC ratios in field studies of biomass combustion in China than those commonly used in forcing modeling, the use of which, as Aunan et al. (2009) note, would make their estimates of net radiative forcing from BC and OC from Asian household biomass emissions positive instead of negative.

From a climate change mitigation perspective, it is important that stove and fuel interventions consider the climate impacts of all emissions from household combustion in order to identify the most effective control options. Several studies have demonstrated that doing so may change the ranking of control options. Specifically, if products of incomplete combustion, or PICs (CH_4, CO, NO_x and total non-methane hydrocarbons) are included in the analysis, kerosene, LPG, compressed gas (CG) and natural gas - even if used in traditional stoves - are by far cleaner than biomass fuels and coal (Edwards et al., 2004).[21] Smith et al. (2000) show that if all climate-relevant emissions are included, LPG and Kerosene are superior to all biomass-stove combinations (improved and unimproved), even under renewable harvesting of biomass, due to their much lower PIC emissions. For example, Smith (2006) reports that for Indian households, emissions of particulate matter and other climate-relevant compounds were found to be between 20 and over 100 times higher for biomass fuels than for LPG per meal cooked, with emissions from kerosene only between 1.3 and 4.2 times those from LPG. Thus, the switch from traditional solid to clean fossil fuels in Asia's household sector is one important black carbon control strategy.

However, despite the increasing displacement of solid fuels by cleaner fuels in urban areas, solid fuel use is expected to remain high in many parts of Asia, especially in poor households (Smith, 2006), for reasons of cost and unreliable supply in rural areas (Zhang and Smith, 2007). Thus, interventions to make solid fuels less polluting will form an important component of any black carbon control strategy (Zhang and Smith, 2007).

These fuel interventions comprise three options: the replacement of raw coal in household use with less polluting briquettes; the switch from direct combustion of biomass and coal to use of biogas and coal gas; and the switch from solid biomass to solar cookers.[22] Studies show that bituminous coal causes much higher black carbon emissions than anthracite coal or coal briquettes (Streets et al., 2001). Replacing raw coal with processed coal dramatically reduces the global warming commitment (Edwards et al., 2004) and thus is an important option for reducing particulate matter emissions from homes in Chinese cities and towns (Streets et al., 2001). Different kinds of formulated coals also reduce toxic emissions and thus have human health benefits, though overall performance is difficult to gauge due to the variety of formulations and measurements (Zhang and Smith, 2007).

A significant reduction in emissions from residential biomass combustion can be achieved through the use of gasifier and other clean stoves (Ramanathan and Balakrishnan, 2007), which achieve high combustion efficiency and thus lower PIC emissions through designs that promote secondary combustion (Zhang and Smith, 2007).[23] Biogas stoves have slightly higher particulate matter emissions compared to LPG and kerosene, but biogas has an even lower overall global warming commitment than either of the two fossil fuels due to its much lower PIC emissions (Smith et al., 2000; Smith, 2006). To reliably achieve low emissions under field conditions, however, such stoves require more uniform fuels – for example, biomass pellets - that could be provided through, for example, the development of small local biomass-processing enterprises (Zhang and Smith (2007). China and India in particular

---

[21] Edwards et al. (2004) also report very low climate-relevant emissions from fuel wood used in brick ovens. However, their analysis does not include black carbon emissions, which are high from wood combustion. Including black carbon in the analysis thus would result in much higher climate-relevant emissions from wood compared to kerosene, LPG, CG and natural gas.

[22] MacCarty et al. (2008) show that the sustainability, or lack thereof, of biomass fuel harvests has a major impact on their climate impacts. They find that while under sustainable harvesting (where CO_2 emissions are considered neutral) some improved stoves with rocket-type combustion or fan assistance can reduce overall climate warming impact from PICs by as much as 50-95 percent, in non-sustainable situations, improved combustion methods were shown to potentially reduce warming by only 40-60 percent. Thus, stove interventions have smaller abatement potential for non-renewably-harvested biomass fuels than for renewably-harvested biofuels, and increasing the share of biofuels derived from sustainable sources reduces the fuels' climate impacts. It is important to note, however, that even renewably harvested biomass has a climate impact, due to the warming impacts from PICs (Smith et al., 2000). In any case, the sustainability of biomass fuels has no effect on black carbon emissions and thus does not constitute an option for controlling the latter.

[23] Replacing biomass cooking with black carbon-free cookers (solar and bio and natural gas) in South and East Asia would lead to dramatic reductions of black carbon heating of 70-80 percent over South Asia and 20-40 percent over East Asia (Ramanathan and Carmichael, 2008). Similar reductions can be achieved with kerosene and LPG (Smith, 2006).

have a large potential energy source in the form of crop residues (after accounting for fertilizer, fodder and industrial feedstock uses), equivalent to around one quarter of the country's coal use in all sectors combined (Zhang and Smith, 2007). In China, this fuel source is increasing due to the shift to modern fuels in wealthier regions, which creates an excess of crop residues that are commonly burned in the field, leading to widespread ambient pollution in some seasons. Village-scale gasifiers, still small in number, can make more efficient and cleaner use of these residues by distributing the gas to individual households (Zhang and Smith, 2007; Smith et al., 2000; Ramanathan and Balakrishnan, 2007). Multi-family biogas plants are already more common, with over three million having been built in India alone (Ramanathan and Balakrishnan, 2007). Replacing solid biomass cookers with biogas, natural gas or solar cookers is expected to yield dramatic reductions in BC heating, of 70-80 percent in South Asia and 20-40 percent in East Asia (Ramanathan and Carmichael, 2008). Improved solid biomass fuels (e.g., pellets) can achieve important reductions as well and are one of the interventions with reliably demonstrated adoption (Bond, 2010).

Importantly, the more widespread adoption across Asia of cleaner household fuels and improved stoves would disproportionately benefit women and thus could make an important contribution to reducing the existing gender imbalance in the health burden (mortality and morbidity) from indoor air pollution.

4.2 TRANSPORT SECTOR

With the transport sector being the third-largest source of energy-related black carbon emissions in Asia as a whole and projected to become the second-largest source, control of transport-based black carbon emissions form an essential part in any comprehensive black carbon control strategy.[24]

Within the transport sector, on-road diesel combustion accounts for the majority of black carbon emissions, due to diesel's much higher emission factors compared to gasoline (Streets et al., 2001) and its dominance as a transport fuel in Asia (Timilsina and Shrestha, 2009).[25] Combustion from off-road uses (shipping, trains, construction and resource extraction) accounts for a smaller but substantial part of diesel-related black carbon emissions (see Table 1 and Figure A3).

Control of transport-related black carbon emissions comprises four approaches:[26] (1) Fuel conversion, that is, the replacement of existing fuels with cleaner ones like LPG or compressed natural gas (CNG); (2) post-combustion (emission) control in diesel vehicles through diesel particulate filters (DPFs), both for new vehicles and for existing vehicles (retrofits);[27] (3) the replacement of outdated vehicles with newer ones that comply with more stringent emission standards; and (4) the reduction of high emission rates from poorly-maintained vehicles through the

---

[24] A 30 percent reduction in developing Asia surface transportation emissions would result in an estimated 2.2 percent reduction in tropospheric black carbon loadings and a reduction by 436 pptv (parts per trillion by volume) in annual mean black carbon local surface concentration (Shindell et al., 2008), or approximately a quarter of the effects a 30 percent across-the-board reduction in residential black carbon emissions would have.

[25] PM emissions from diesel vehicles are primarily (generally 50-80 percent) black carbon (Bond et al., 2004). A recent study in Bangkok (Subramanian et al., 2009) found that carbonaceous composition of diesel vehicle emissions was relatively consistent across vehicle size classes, with particulate elemental carbon at 40 ± 8 percent and organic carbon at 17 ± 1 percent of PM.

[26] Reducing the often still high sulfur (S) content of fuels is an important air pollution control strategy in Asia as such reductions reduce S-related PM emissions and produce large health benefits (Asian Development Bank, 2008). However, fuel S reduction is not a black carbon control measure per se and thus is not listed among the control measures here, as it affects black carbon emissions only indirectly, to the extent that S reduction is a necessary condition for application of black carbon control technologies such as DPFs.

[27] A diesel particulate matter filter (DPF) is a ceramic device that collects the particulate matter in the exhaust stream. The collected particles are then burned off (oxidized) in order to prevent the filter from clogging. This regeneration process converts the collected particulate matter to ash, which contains less harmful components. The ash is periodically removed (vacuumed) from the filter, usually at intervals of 100,000 miles. In passive filters, the oxidation is driven by the high temperature of the exhaust that heats the ceramic structure, or is achieved with the help of fuel-borne catalysts or by coating of the filter substrate with metal, both of which lower the exhaust temperature required for oxidation of the collected particles. In active systems, the exhaust gas is heated to the required temperature externally through specially installed fuel burners, electrical heaters or some other method.

implementation of mandatory and well-enforced inspection and maintenance programs. In addition to these short-term approaches, a shift of the modal split towards mass transit, and the shift towards renewable transport fuels are important black carbon and GHG control strategies (International Council on Clean Transportation, 2010).

Conversion of urban heavy-duty diesel vehicles to natural gas already is widely applied in many Asian cities. For example, all public transport vehicles in New Delhi have been converted following regulation in 2001 (Reynolds and Kandlikar, 2008), and there were nearly 4,000 CNG-powered buses operating in Beijing in 2007, accounting for 20 percent of the city's bus fleet (UNEP, 2007). In 2007, India had an estimated total of almost 1.4 million natural gas-powered vehicles, with another 1.3 million operating in Pakistan (GNV Magazine, 2007). In developing Asia, LPG still accounts for a minimal share of transportation fuel, although its use has been growing in Thailand and China (Timilsina and Shrestha, 2009).

Diesel particulate filters (particulate traps) remove upwards of 90 percent of black carbon from exhaust (Walsh, 2009) and thus can be a very effective control technology. However, they require low to ultra low-sulfur diesel (ULSD) with at most 50 parts per million (ppm) sulfur, and ideally only 10-15 ppm (ADB, 2008). Currently, only a few metropolitan areas in developing Asia meet the 50 ppm requirement, although Thailand and Malaysia are expected to implement a 50 ppm standard nationwide in 2010 and 2012, respectively (see Appendix Figure A1). Given the modest increase in Asian diesel fuel production costs that desulfurization from existing levels would entail (0.5-0.8 cents per liter for reduction to 50 ppm, with an additional 0.6 cents per liter for reduction to 10 ppm) (ADB, 2008), and given the large ancillary (from a black carbon control perspective) health benefits it would produce, desulfurization to levels that allow the widespread deployment of DPFs is essential. DPFs are standard on most modern (2007 or newer) diesel vehicles produced for developed country markets.[28] However, due to the slow fleet turnover, retrofitting older vehicles will allow penetration of DPFs into the existing vehicle fleet. For cost reasons, retrofitting DPFs in many cases will likely initially be limited to urban heavy-duty diesel vehicles (Kandlikar et al., 2009), and use on older vehicles may require additional technology (Bond and Sun, 2005).

Adoption of stringent vehicle engine and fuel standards (Schneider, 2009) and their vigorous support by governments (ADB, 2008) also will reduce black carbon emissions. However, new engine standards will take time to penetrate the fleet due to long life of vehicles in developing countries (ADB, 2008). The effective implementation of in-use (inspection and maintenance) programs also can substantially reduce particulate matter and black carbon emissions, especially by reducing the number of "super emitting" vehicles that have excessive emissions due to poor maintenance and account for a disproportionally large share of emissions in a given area (Kandlikar et al., 2009; Schneider, 2009; Subramanian et al., 2009). International experience, including in Asia, amply demonstrates that setting up an effective inspection and maintenance program is not a trivial task, with success (reduction in criteria pollutant emissions) being dependent on a number of key design aspects of the system as well as the continued and vigorous support by senior government officials and the public (Hausker, 2004). However, experience also shows that I/M systems can be designed so that they are revenue neutral and do not put an overly large burden on vehicle operators or the government (Hausker, 2004).

---

[28] Jacobson (2007) notes that because diesels, even with particle traps, have higher soot emissions than gasoline engines, expansion of diesel's share, often advocated because of diesel engines' higher inherent efficiency, will increase black carbon emissions and thus global warming. Even a diesel with 30 percent better mileage than the comparable gasoline car and emitting PM at 0.01 g/mi (0.006 g/km) (US Tier 2, bins 2-6 emission standard) would warm the climate for about 10 years relative to gasoline and all 2006 and earlier diesel vehicles available in the US warm the climate relative to the best gasoline cars (Jacobson, 2007). Therefore, policies that promote increasing the share of diesels in Asia's vehicle fleet should be examined carefully to avoid negative climate outcomes. Nevertheless, Jacobson's analysis is for private cars. For buses and trucks, gasoline engines generally are not offered due to diesel's torque and mileage advantages. In addition, the large existing stock of outdated diesel vehicles will only slowly turn over. Thus, in Asia, DPFs form an effective component in a black carbon control strategy.

4.3 INDUSTRIAL SECTOR

Although stringent new emission standards for Chinese coal-fired cement and new power plants have dramatically reduced particulate matter emissions from these sources in China in recent years (Zhang et al., 2009), the industrial sector of developing East Asia as a whole remains a top target for controlling black carbon emission (Streets, 2007; Ramanathan and Carmichael, 2008), particularly very polluting rural industries that use coal as the main fuel source (Cao et al., 2006).[29] Improving the efficiency and pollution control of old power plants in India with few soot controls also represents an important black carbon abatement opportunity (Carl, 2009). In addition to old power plants and uncontrolled coal-fired industrial boilers, diesel-powered back-up generators (Carl, 2009), coke ovens and unimproved kilns (mainly for brick-making) are important sources of black carbon emissions (Baum, 2009; Schneider, 2009).[30] Fuel switching to low-emission electricity from well-controlled power plants or clean renewable (solar electricity) or fossil fuel sources (kerosene) are the main options for smaller operations, as the highly effective black carbon removal devices employed in power plants are too expensive. However, reducing the reliance on diesel-powered back-up generators will be difficult in countries like India that suffer from unreliable and poor-quality power from electricity grids (Natarajan and Tharakan, 2008; Carl, 2009). For kilns, black carbon abatement options exist mainly in the form of replacement of kilns with improved technology (Baum, 2009).

---

[29] A 30 percent overall reduction in developing Asia industry/power sector emissions is estimated to lead to a 0.4-1.0 percent reduction in tropospheric BC burden and a reduction by 280 pptv (parts per trillion by volume) in annual mean BC local surface concentration (Shindell et al., 2008). However, due to the difference in radiative forcing in lower and high latitudes from Asian aerosol emissions, reductions in industrial and power sector emissions induce a substantial negative radiative forcing (reduced warming) in the Arctic, but in some models are estimated to yield positive forcing at lower latitudes (Shindell et al., 2008).

[30] In India, diesel generators may account for as much as 17 percent of total generation (Natarajan and Tharakan, 2008).

SECTION 5

ECONOMIC ANALYSIS OF BLACK CARBON ABATEMENT OPTIONS

All of the black carbon abatement options presented in the previous section can yield reductions in black carbon emissions. However, in a given context, they are likely to differ in terms of their associated cost per unit emission reduced. In addition, the various control measures also will tend to vary in terms of the co-benefits they produce, most importantly, reductions in negative health effects, due to differences in exposure characteristics associated with emissions from particular sources.

Economic analysis can help guide the selection of abatement measures. Cost-effectiveness analysis can identify the control measure or bundle of measures that produce(s) the largest emission reduction for a given budget or, alternatively, that produce(s) a given reduction at the lowest cost. However, ideally, the size of the benefits in the form of avoided health damages (from direct exposure to particulate matter pollution and from climate impacts of black carbon), reduced environmental impacts (crop yields, water availability, habitat loss) and reduced fuel costs – all of which represent co-benefits from a climate perspective – that result from implementing particular black carbon control measures should be taken into account when evaluating the relative performance of alternative control measures. This can be done with the help of benefit-cost analysis, which ranks the various control measures on the basis of their net benefits (total benefits minus total costs) or benefit-cost ratios.[31] Benefit-cost analysis is the superior analysis tool whenever alternative control options differ in the size of the benefits they produce. However, it is also more demanding because of the additional information requirements it imposes. In cases where the required benefit information shows large gaps or is highly uncertain, cost-effectiveness may be the more suitable evaluation tool.

Benefit-cost and cost-effectiveness analysis are not only useful for comparing the economic attractiveness of particular black carbon control measures. They also allow comparisons of the economic performance of black carbon control measures vis-à-vis that of abatement measures directed at other global warming contributors (e.g., CO_2, methane, NO_x) or public health risks.[32]

In the following, we present a summary of the findings reported in the very few studies that estimate the cost-effectiveness or benefit-cost ratio of the principal black carbon abatement options identified in the literature. Due to the small number of studies, and because of the disparity across local contexts in a number of the variables that influence the economic performance of the various abatement measures, the representativeness of the reported estimates of conditions across Asia in some cases is uncertain. Nevertheless, most studies reported on here present ranges of cost-effectiveness or benefit-cost ratios that do incorporate ranges in the values of several key parameters. The findings presented in the following

---

[31] Net benefits are the preferred metric because unlike benefit-cost ratios, the net benefits of an intervention are unaffected by whether the cost savings from an intervention are counted as benefits or as cost reductions.

[32] The comparison of the economic performance of black carbon control measures with that of other global warming substances is complicated by the fact that the length of warming impacts varies among different substances. Such comparisons therefore must explicitly state the time frame used in the analysis. For example, a 20-year time frame more than triples the global-warming-specific cost-effectiveness of black carbon control measures, due to the fact that the GWP_{20} of black carbon is three-times higher than its GWP_{100} (Bond and Sun, 2005).

thus may offer some degree of representativeness of the economic performance of these abatement options across the region.

5.1 RESIDENTIAL SECTOR

Studies suggest that improving household stoves or switching to cleaner fuels are efficient means of protecting public health (Mehta and Shahpar, 2004) and reducing GHG emissions (Smith and Haigler, 2008). They also appear to be highly cost-effective means of controlling black carbon emissions (Bond and Sun, 2005). Achieving this cost-effectiveness will require careful design and implementation of cook stove interventions.

Analyzing the costs and benefits for major world regions of clean fuel (LPG) and improved stove interventions that would reduce by 50 percent the population without access to clean fuels or improved stoves over ten years, Hutton et al. (2006) find that cost reductions from improved stoves exceed intervention costs in East and Southeast Asia. For clean fuel, intervention cost reductions also exceed intervention costs in urban areas in low-mortality Southeast Asia (WHO region SEAR-B), and generate positive benefit-cost ratios in the rest of Southeast Asia, including very high benefit-cost ratios (21 to 27) in East Asia.[33]

In the case of wood stoves, available estimates suggest that the cost-effectiveness of measures like switching to cleaner stoves or fuels varies considerably, ranging from \$0.3-11.0 /tCO_2eq. over a 20-year timeframe to \$1-34/tCO_2eq. over a 100-year timeframe (Bond and Sun, 2005).[34] For coal cook stoves, cleaner stoves or fuel switching have a cost-effectiveness range of \$0.1-2.0/tCO_2eq. (20-year timeframe) to \$0.2-6.0/tCO_2eq. (100-yr time frame) (Bond and Sun, 2005), making stove and fuel interventions very competitive global warming abatement options.

Kandlikar et al. (2009) estimate that replacing traditional stoves in India with improved biomass-gasifier stoves would have an overall average global warming abatement (GHG plus aerosols) cost-effectiveness of around \$4/ton CO_2eq., based on an assumed 50 percent effectiveness of the program. The average cost-effectiveness of only the particulate matter abatement achieved by the measure is lower at an estimated \$6/tCO_2eq., but still is high compared to most other abatement options available.[35, 36] Replacing household coal use in China with LPG stoves has an estimated average cost-effectiveness of \$45/ton CO_2eq. for particulate matter, but a combined (GHG plus particles) cost-effectiveness of \$10/ton CO_2eq. (Kandlikar et al., 2009), the latter making it highly competitive with many of the frequently-considered main GHG abatement options. Both of these interventions have positive and, depending on the assumptions about their associated avoided climate change damages, potentially very high benefit-cost ratios (3-15 for replacing coal stoves with LPG in China; 9-54 for biogasifier stoves in India).

5.2 TRANSPORT SECTOR

Accounting for the cooling effect from reduced OC and SO2 emissions that are co-controlled by black carbon abatement measures, and for the change in fuel efficiency, cost and GHG emissions, Kandlikar et al. (2009) estimate the cost-effectiveness of converting urban heavy-duty diesel vehicles to natural gas fuel (CNG) at on average \$100/ton CO_2eq. The cost-effectiveness of conversion to CNG is relatively low due to increased methane emissions and reduced fuel efficiency of CNG compared to diesel.

---

[33] Hutton et al.'s (2006) analysis includes health benefits as well as climate benefits from reductions in CO_2 and methane emissions, but does not include benefits from reductions in black carbon, thus underestimating the climate benefits associated with the interventions.

[34] Due to the relatively short lifetime of black carbon-related warming impacts compared to those of CO_2, longer time frames of analysis reduce climate impacts and thus the cost-effectiveness of abatement measures.

[35] One biogas unit can serve four families comfortably and costs about \$1000. Family-size (2-4 m^3 gas per day) biogas plants have been disseminated and popularized in India, China and many other countries (Bhat et al., 2001), with over 3 million biogas plants built in India alone (Ramanathan and Balakrishnan, 2007).

[36] Globally, the marginal cost-effectiveness of most CO_2 abatement measures with substantial impacts is negative for many efficiency-improvement measures, and ranges from \$10 to over \$50 per tCO_2eq. for most other measures (Vattenfall, 2007). See Figure A2.

Retrofitting urban heavy-duty diesel vehicles with after-treatment devices (particulate traps) is estimated to have an average cost-effectiveness of \$115/ton CO_2eq., where improved emissions again are partly offset by reduced fuel efficiency (Kandlikar et al., 2009). Installation of DPF in all diesel vehicles in Thailand, combined with a switch to low sulfur diesel, is expected to result in a 90 percent reduction in direct particulate matter emissions from diesels, at an estimated cost-effectiveness of \$29-46/tCO_2eq. (20-year time frame) or \$116-185/tCO_2eq. (100-year time frame) (Mejia, 2009).[37] Installation of DPF on "pre-regulation trucks" is estimated to have a cost-effectiveness of \$11-23/tCO_2eq (20-yr timeframe) or \$36-71/tCO_2eq (100-yr time frame), while the cost-effectiveness of equipping current light vehicles with DPF is estimated at \$8-16 and \$25-50/tCO_2eq over 20- and 100-year timeframes, respectively (Bond and Sun, 2005). Taking into account health benefits and low and high estimates of potential climate benefits, Kandlikar et al. (2009) estimate that the benefit-cost ratio of converting heavy-duty diesel vehicles to CNG ranges from 0.06-2.6. For DPF retrofits, they estimate ratios of 0.07-1.1. It should be noted that the lower-end benefit-cost ratios are based on benefit estimates for reductions in climate change that probably are too low.[38] Use of perhaps more reasonable climate benefit estimates would bring the lower end of the benefit-cost ranges to one (1) or just below, indicating that the costs and benefits of these measures would approximately balance at that lower bound.

The cost-effectiveness of repairing "super-emitting" vehicles, which cause excessive emissions due to poor maintenance, is estimated at \$15/tCO_2eq. assuming that an inspection and maintenance program would identify half of the super-emitters and that repairs would reduce the emissions of these vehicles by 50 percent (Kandlikar et al., 2009). The cost-effectiveness of repairing super-emitting light vehicles is estimated at \$10-40/tCO_2eq. (20-yr time frame) to \$30-130/tCO_2eq. (100-yr time frame) (Bond and Sun, 2005). However, emissions reduction impacts and costs vary widely among super-emitters (McCormick et al., 2003). Hence, at the individual source-level, the cost-effectiveness of black carbon reduction can range from high to poor. However, in many developing countries with poorly maintained vehicle fleets, emission reductions may be larger and costs lower, resulting in higher cost-effectiveness than in developed countries. Kandlikar et al. (2009) estimate the benefit-cost ratio of repairing super-emitters at 0.4-17.3. As in the case of DPF retrofits and CNG conversion of heavy-duty vehicles, the low-end benefit-cost ratio for repairs of super-emitters is based on very conservative climate change benefit estimates. Using higher climate benefit estimates lifts this ratio from less than one to more than five (Kandlikar et al., 2009), indicating that each dollar spent on this measure is estimated, on average, to yield over five dollars in benefits.

A well-designed and successful I/M program can reduce emissions cost-effectively (Hausker, 2004). However, whether it will do so in a given context depends on a number of factors, including the current fleet composition, the speed of fleet turnover, the severity of the air pollution problem (Hausker, 2004), as well as the costs and impacts of alternative control approaches both within and outside of the transport sector. Crucially, the cost-effectiveness of an I/M program critically depends on its effectiveness in controlling criteria pollutant emissions: a system that results in very poor emission control can be extremely cost-ineffective (i.e., having very high costs per unit of emission[s] avoided). The success of I/M systems in Asia has been mixed, and thus the cost-effectiveness of Asian I/M programs is expected to vary widely, and in many cases is unknown (Hausker, 2004). In Thailand, implementation of an I&M program for diesel vehicles is estimated to be the most cost-effective measure for reducing transport sector emissions from diesel fuels, with \$17-\$27/ tCO_2eq (20-

---

[37] Based on an estimated cost-effectiveness of \$21.6 t PM/million \$US (Mejia, 2009), adjusted for the black carbon content of diesel PM (50-80 percent; Bond et al., 2004) and the 20- and 100-yr GWPs of black carbon of 2000 and 500, respectively (Hansen et al., 2007).

[38] Kandlikar et al.'s (2009) low benefit-cost estimates use avoided climate change cost estimates from Nordhaus (2007), while their high benefit-cost ratios use benefit estimates from Stern (2007). As Weitzman (2007, 2009) points out, Nordhaus may underestimate climate change costs (and thus benefits from avoided climate change) due to his treatment of low probability-extreme damage events.

yr timeframe) to \$67-\$107/tCO_2eq (100-yr timeframe), and the measure with the second-largest overall pollution reduction after introduction of DPFs (Mejia, 2009; Joint UNDP/World Bank Energy Sector Management Assistance Programme, 2008).[39]

The lower benefit-cost ratio of vehicle fleet interventions compared to household stove or fuel interventions is due in part to the lower exposure associated with outdoor particulate matter pollution (Kandlikar et al., 2009). Although the health benefits of controlling particulate matter pollution from diesel vehicles in developing Asia are very large in absolute terms, they are far smaller (by two to three orders of magnitude) than those from stove or household fuel interventions.

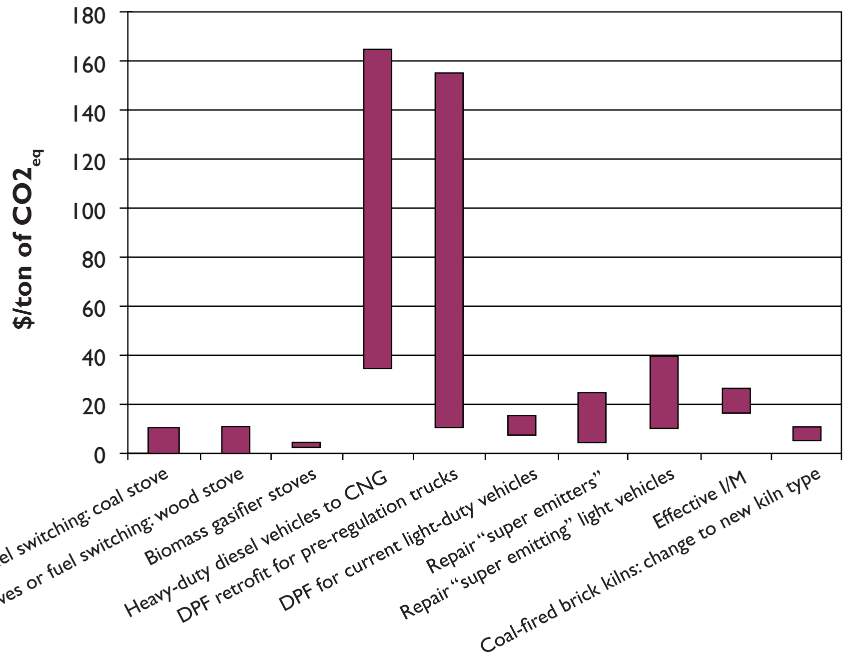
5.3 INDUSTRIAL SECTOR

Available estimates for industrial black carbon control options in Asia are extremely limited. In many cases, this is due both to uncertainty about the emission rates of many source types and to lack of data on the local cost of available control options. Bond and Sun (2005) estimate that the cost-effectiveness of controlling emissions from an important black carbon source, namely, low-tech, coal-fired brick kilns, by switching to a new kiln type is \$5.5-\$11/tCO_2eq. This estimate is very uncertain, due to the large uncertainty in emission factors (ibid.). However, even the upper end of this range is competitive with many of the commonly-considered main GHG abatement options.

Keeping in mind that the foregoing analysis in some cases is based on sparse and spatially limited data that may not represent region-wide averages, the literature does support a few broad conclusions. First, clean fuel and stove interventions in the household sector generally appear to be the most cost-effective black carbon control options in developing Asia, followed by the control of particulate matter emissions from super-emitting vehicles (**Figure 7**).

It should be noted that only about half of the cost-effectiveness estimates in Figure 7 account for not only

Figure 7: Estimated cost-effectiveness (20-year time frame) of key black carbon abatement measures for contained combustion sources in Asia



Sources: Based on data in Bond and Sun (2005), Kandlikar et al. (2009), and Mejia (2009).

---

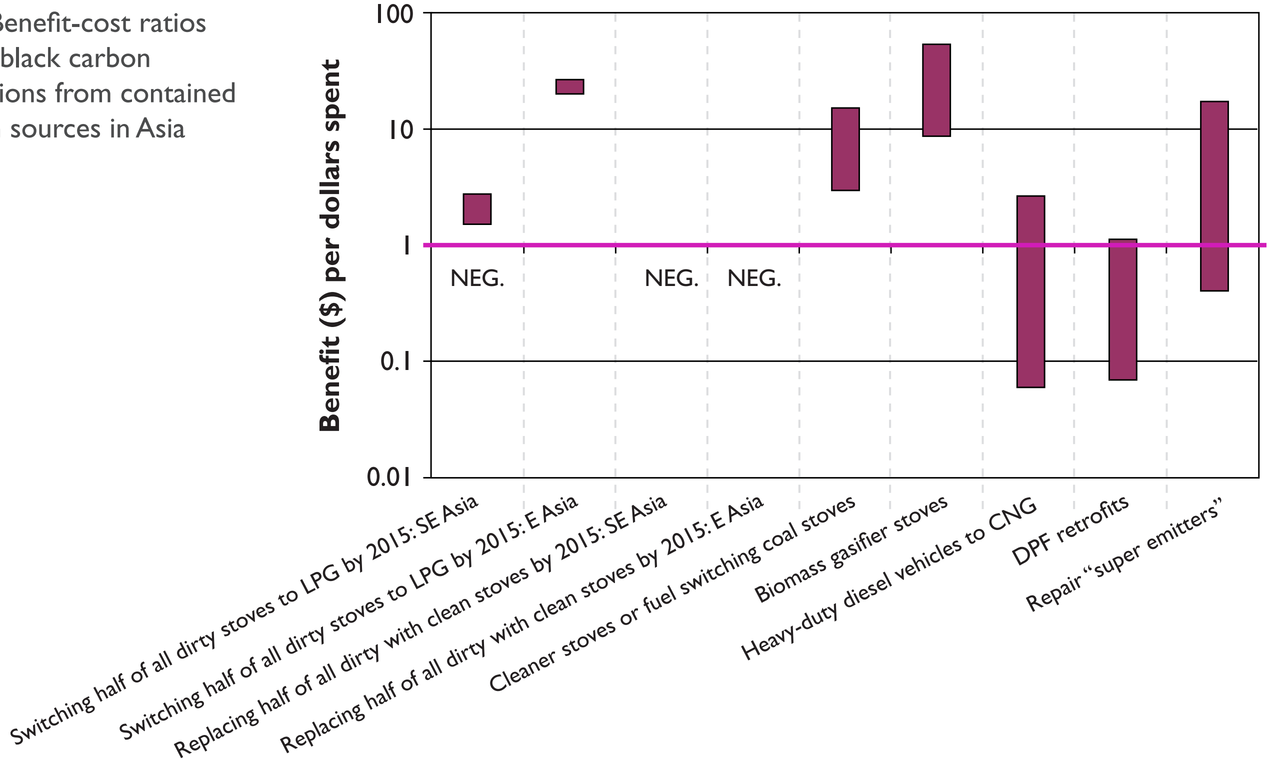
[39] Based on an estimated cost-effectiveness of \$37.3 t PM/million \$US (Mejia, 2009), adjusted for the black carbon content of diesel PM (50-80 percent; Bond et al., 2004) and the 20- and 100-yr GWPs of black carbon of 2000 and 500, respectively (Hansen et al., 2007).

reductions in black carbon emissions but also for the co-produced changes in GHG emissions that result from the interventions. In addition, the estimates do not account for the accompanying reductions in light-scattering (i.e., cooling) aerosols like sulfur dioxide, organic carbon and organic matter that will result from black carbon control measures. The climate impact of the latter effect is still uncertain and may vary in strength and even sign with the location of emissions. However, such reductions in light-scattering aerosols are expected on balance to partly offset the cooling produced by reductions in black carbon emissions, which in turn would reduce the cost-effectiveness of the interventions somewhat.

By comparison, switching to transportation fuels with lower black carbon emissions, while certainly effective in reducing emission, is unlikely to be a cost-effective first step in black carbon control efforts. The relative economic performance of DPFs depends on the vehicle type (age, annual distance traveled, emissions per mile). Thus, DPFs in some cases may be a suitable candidate for inclusion in early-stage black carbon control strategies, while in others they should be added into the mix only if reductions from more cost-effective measures are insufficient. Importantly, vehicle-targeted control measures will be more important to achieving overall emission reduction goals in urban than in rural areas.

The results of the benefit-cost analysis of the analyzed control options based on Kandlikar et al. (2009) and Hutton et al. (2006) support these findings. **Figure 8** shows that all well-designed household fuel and stove interventions have large benefit-cost ratios, indicating that they generate benefits that are a multiple of the cost of the intervention. Furthermore, some of these stove interventions lead to costs reductions and thus negative benefit-cost ratios (indicated by "NEG." in the figure), because they result in lower fuel, labor or maintenance costs than current, traditional technologies. This indicates that even in the absence of any benefits, these measures

Figure 8: Benefit-cost ratios of selected black carbon control options from contained combustion sources in Asia



Sources: Based on data in Hutton et al. (2006) and Kandlikar et al. (2009).

should be adopted on private financial grounds.[40] Moreover, none of the benefit-cost ratios of the four stove and fuel interventions on the left of the figure include any climate benefits. Thus, their actual benefit-cost ratios and net benefits are higher still than is suggested in Figure 8.

Measures with lower benefit-cost ratios are still economically beneficial until the point at which their benefits just offset their costs – indicated by the purple line in Figure 8. The figure shows that switch to CNG and deployment of DPFs may or may not be economically beneficial, as the reported cost-effectiveness of these measures ranges from less than 1 to above one. Thus, their performance will depend on the particular context. The large range in the benefit-cost ratios of these measures is due to the uncertainty as to the climate benefits their black carbon emission reductions generate (Kandlikar et al., 2009). Note the log scale in Figure 8, which visually reduces the difference in benefit-cost ratios among the measures.[41]

As already mentioned, the cost-effectiveness in Asia of many of the black carbon control options appears to exceed or be competitive with many of the main conventionally-proposed global warming abatement measures. This result may be due either to the fact that black carbon control in general is among the most cost-effective near-term global warming control options, or to the fact that the latter is particularly attractive in Asia. Supporting the latter hypothesis, Rypdal et al. (2009), in their analysis of the costs and global impacts of black carbon abatement strategies (excluding fuel switching) for contained combustion sources, conclude that prioritizing emission reductions in Asia represents the most cost-effective global abatement strategy for black carbon, with this result being due to Asia's large share of total emissions, its lower abatement costs compared to Europe and North America, and the large health co-benefits from reduced PM_{10} emissions.

---

[40] Generally, the reasons these measures are not currently deployed despite their lower costs include a lack of institutional support, unfamiliarity, or uncertainty on the part of potential buyers.

[41] This scale allows the inclusion of all the measures in a single graph.

SECTION 6

TECHNOLOGY CONSIDERATIONS, INSTITUTIONAL CAPACITY NEEDS, PERSISTENT BARRIERS, EXAMPLES OF INNOVATIONS AND ONGOING INITIATIVES

All of the black carbon-controlling interventions described in the previous sections, though technically clearly feasible, will require sufficient institutional capacity (technical and administrative) for careful program design and implementation. They also require continued and high-level political support to overcome political and institutional opposition to their implementation. Finally, and perhaps most important of all, the new technologies need to address the requirements and preferences of consumers to achieve widespread adoption (Bond, 2007a). Experience with poorly effective stove interventions and vehicle I/M programs in some countries in Asia illustrates the importance of meeting these non-technical conditions for program success.

In many cases, improved household stove and cleaner fuels will tend to be adopted voluntarily for health and convenience reasons if they are affordable and reliable (Jacobson, 2007). In contrast, measures that reduce black carbon emissions from the transport sector and industrial sources may require regulatory approaches (ibid.), since adoption of these measures primarily entails costs for owners while benefiting others.

Furthermore, effective black carbon control strategies will involve the targeting of sources that satisfy subsistence needs. In some cases, targeted sectors will be dominated by poor households and informal activities with sources that are dispersed and often intractable, placing special demands on sensitive program design (Bond and Sun, 2005).

International experience with stove and fuel interventions and vehicle I/M programs indicates several key requirements for success. Both stove interventions and vehicle inspection and maintenance programs require strong technical and administrative capacity, sound program design and sustained national-level attention and high-level government support (Kandlikar et al., 2009).

China's successful National Improved Stove Program (NISP; 1983-1996) in particular offers lessons that can benefit future efforts. Its success in introducing improved biomass stoves (which reached an estimated 65 percent of all rural households) is widely attributed to strong administrative, technical, and outreach competence and resources situated at the local level, motivated by sustained national-level attention (Sinton et al., 2004; Smith et al., 1993). The program:

(1) kept bureaucratic complexity and number of involved actors small, focusing on the center (the program authority) and the periphery (the local bureaucracy);

(2) featured independent (regular, systematic and consistent) monitoring and evaluation of program, which, based on international experience, is a necessary condition for a successful intervention program (Smith et al., 2007);

(3) had little direct government contribution, letting users pay the full cost of the materials and labor, with government assistance limited to training, administration and promotion;

(4) had minimal money flow through bureaucracy (limiting turf battles, inefficiencies and graft;

(5) had a strategy for commercialization of the cook stoves;

(6) adjusted stove design to local conditions in the field; and

(7) made stoves as convenient for households to use as possible.

Despite its remarkable overall success, the NISP has not been as effective in improving coal stoves as it has been for biomass stoves. A survey in 2002 found that most coal stoves (>70 percent), even those using improved fuel (briquettes), lacked flues and thus could not be considered improved. It also found that large roles for government oversight of quality control and support of R&D remained inadequately fulfilled (Sinton et al., 2004). This underlines the fact that to achieve deep market penetration, all intervention technologies, from simply adding a chimney to the more complex modernized bioenergy program, can be viable only with coordinated support from the government and the commercial sector (Zhang and Smith, 2007). Importantly, education alone is not effective in reducing emissions from stoves; it needs to be complemented with stove interventions (Zhou et al., 2006), a prime reason being that financial constraints often prevent implementation of new knowledge on cleaner stoves and stove operation (Jin et al., 2006; Zhang and Smith, 2007). Widespread and continued adoption also requires support for the development of a reliable supply and service infrastructure that reduces uncertainty and adoption costs (Bond, 2007a).

An important barrier to the more widespread adoption of cleaner fuels is that wood and crop residues are often perceived as "free" for households - even though in many places women and children may spend considerable time and endure considerable hardship in collecting these supplies (Hutton et al., 2006) - whereas marketed cleaner fuels (LPG, kerosene, briquettes, and especially natural gas and electricity) must be purchased and are still only affordable only to a small minority of consumers in many poor countries (Bond, 2007a). This presents a difficult problem for clean fuel programs, as policies to reduce solid biomass use inevitably will tend to create disproportionate hardship for the poorest sector of the population. Alleviating these impacts will require well-designed assistance programs that manage to generate sufficient incentives for fuel switching on the part of poor households while minimizing associated negative impact on household budgets. In some cases, new technologies like (multiple) household-scale biogas plants may be able to resolve this dilemma by achieving black carbon reductions without fuel switching while also reducing biomass inputs.

An innovative project that employs some of the lessons learned from earlier international experiences is currently underway in India. Project Surya (Ramanathan and Balakrishnan, 2007), launched in March 2009, aims to reduce indoor air pollution and climate forcing from solid fuel combustion by promoting black-carbon free cooking using renewable sources on improved stoves (solar cookers and biogas plants and burners). After completion of the ongoing pilot phase that involves approximately 6,500 homes, phase I of the project, scheduled for 2010-12, will expand the project to two rural areas of 15,000 households each at a cost of $4 million per area.[42] The project includes an air pollution measurement component that engages the local community and will help document changes in air quality and associated health effects resulting from fuel and stove switching, and explicitly takes into account community preferences and needs. The eventual goal is to make Project Surya a subcontinent-wide initiative. The Partnership for Clean Indoor Air (PCIA) (Moss, 2009) is another innovative cook stove effort. The partnership features stove testing, networking, tools, the PCIA website, and quarterly bulletins and supports capacity building for monitoring, stove design and enterprise development. From 2003 – 2008, PCIA partners increased their results by

---

[42] For more detail, see *http://www-ramanathan.ucsd.edu/ProjectSurya.html*

nearly 300 percent, collectively helping 2.4 million homes adopt cleaner cooking/heating practices, and reducing harmful exposures for more than 18 million people (Moss, 2010). A next phase (2014-2030) is envisioned to scale up the existing initiative substantially, with a global campaign to reduce smoke from cook stoves that aims to reach about half of the 3 billion people affected by poor indoor air quality from cooking, at an estimated cost of several hundred million dollars.

Many countries in Asia continue their own household energy intervention projects, and several large corporations or foundations have started their own projects or are collaborating with national efforts. These efforts include the Indian Ministry of New and Renewable Energy's National Biomass Cookstove Initiative announced by the Indian government in December 2009 (Adler, 2010);[43] the Shell Foundation and Envirofit's clean cook stoves initiative (Rai and McDonald, 2009), part of the Shell Foundation's Breathing Space Program; Philips and the Appropriate Rural Technology Institute's Chulha project (Beck, 2009); Grameen Shakti's Improved Cookstove program (Chandra Barua, 2009); and bio-energy Modernization Demonstration Projects in China designed to develop combined heat, electricity, and cooking fuel production (trigeneration) from corn stalks (Zhang and Smith, 2007; Whitfield, 2009). Large-scale improved cookstove programs face considerable challenges in that they must generate user motivation, be affordable, and achieve behavioral change, in addition to requiring a commercial support infrastructure (Slaski and Thurber, 2009). Most past efforts have neglected one or more of these requirements and as a result more often than not have had limited success.

Implementing an effective I/M program for vehicles is a challenging task because it requires large behavioral change, but it can be done in a revenue-neutral way that limits the burden on vehicle operators or the government (Hausker, 2004). A number of Asian countries already have I/M programs in place, but many of these do not yet fulfill several of the essential best practice design standards (Mejia, 2009). Key obstacles to an effective I/M system include inadequately trained personnel, inadequate test equipment, lacking or inadequate oversight of inspection centers, and fraud and corruption, resulting in low compliance rates and poor enforcement (ibid.; Mejia, 2009). However, international experience, including in developing countries, shows that these obstacles can be overcome through committed leadership, the right institutional design and the right incentives. Several key "essential" best design practices have been identified for I/M systems that dramatically increase the likelihood of success of these systems (Hausker, 2004; Mejia, 2009). These include:

- having emission tests performed in private test-only facilities, which themselves are subject to strong oversight by government authorities or private third-party providers to provide quality assurance;
- implementing I/M programs in a phased approach that targets the heaviest polluters first and begins with reasonably stringent standards that are tightened over time, thus allowing learning, adaptation and capacity building and ensuring sufficient public support for the program;
- making I/M compliance a requirement for being able to operate a vehicle, which in turn is enforced through an effective periodic registration system;
- making the I/M program self-financing through inspection fees that at a minimum cover the operating costs of the system;
- making sure that all actors in the I/M system have the capacity (infrastructure and training) to effectively carry out their tasks, including the private repair shops that carry out the maintenance work; and
- ensuring public support by clearly communicating the objectives of the I/M system.

These essential best practices are accompanied by a second, much larger suite of "ordinary" best practices that

---

[43] The goal of the National Biomass Cookstove Initiative is to sell 150 million stoves in 10 years (Adler, 2010). An analysis of a hypothetical program in India similar to the Initiative is estimated to yield health benefits in the form of 2.07 million total avoided premature deaths corresponding to a reduction of 55.5 million DALY, and climate benefits from a reduction in 0.5 million tons of black carbon over the ten years, in addition to reductions in GHGs (Wilkinson et al., 2009).

enhance program effectiveness (Hausker, 2004).

Several diesel retrofit projects have been carried out in Asia with involvement of the US Environmental Protection Agency (EPA), including in Pune (India), Bangkok and Beijing, with the EPA providing modest funding, technical expertise and support to local partners, as well as help with program design, and access to information and vendors (Walsh, 2009). Such technical assistance projects are crucial for technology and capacity transfer, and speed up adoption of advanced technologies. For example, following the pilot project, over 6,000 vehicles were retrofitted in Beijing (Walsh, 2009). However, the truly widespread deployment of diesel particulate filters across Asia currently still is hampered by fuel sulfur contents that in many countries are too high for DPFs (see Appendix Figure A1). The Partnership for Clean Fuels and Vehicles (PCFV), hosted by the United Nations Environment Programme (UNEP), is assisting developing countries in Asia (and worldwide) in the development of low sulfur strategies as part of its promotion of clean fuels and vehicles (PCFV, 2007).

Furthermore, the demands of DPFs in terms of the support infrastructure needed for the maintenance and effective operation of the filters requires careful program design. For example, the pilot installations in Beijing have been hampered by a still too-high fuel sulfur content, poor maintenance, and inadequate filter regeneration.[44] There is a clear and important role for bi-lateral assistance in helping Asian countries draw on the wealth of experience gained in developed countries with comprehensive DPF retrofit programs for heavy-duty vehicles, DPF mandates for new diesel vehicles and the introduction of ultra low-sulfur diesel fuel. Specific actions include the financing of the provision of technical assistance on DPF deployment programs and fuel desulfurization to Asian countries on the part of the US Environmental Protection Agency and state agencies (e.g., the California Air Resources Board) and private sector experts and the assistance with the transfer of ULSD technology.

6.1 METHODOLOGIES FOR MEASURING BLACK CARBON EMISSIONS FROM SOURCES REPRESENTING KEY ABATEMENT OPPORTUNITIES

In order to estimate the actual abatement achieved through the implementation of particular control options for black carbon, black carbon emissions from sources representing key abatement opportunities must be measurable. This section provides a brief overview of the feasibility and technical requirements of conducting black carbon emissions measurements for the key abatement options identified in the preceding sections.

6.1.1 Residential sector: Use of improved cooking and heating stoves or cleaner-burning fuels

There is no one, universally accepted standard or methodology for measuring black carbon emissions from stoves (Baldinger, 2010). A variety of standardized tests have been developed for the measurement of particle emissions from residential stoves. For example, the US Environmental Protection Agency (EPA) has developed estimation methods for performance tests that all residential stoves sold in the US must undergo to obtain certification (Weant, 1989; Eastern Research Group, 1996).[45] Most developed countries have similar mandatory certification requirements for residential stoves, with in some cases substantial differences among particulate matter measurement standards (OMNI, no date).

Due to their complexity, such laboratory methods in general are not conducive to field application. This is an important concern since actual emissions under common operating conditions in the field commonly vary considerably from those obtained in laboratory settings (e.g., Roden et al., 2009; Johnson et al., 2010). Thus, reliable estimates of actual particulate matter emission of residential stoves under everyday use conditions should

---

[44] Personal communication, Dr. Pradeep Tharakan, DCOP, ECO-Asia Clean Energy Program, Bangkok, Thailand. November 20, 2009.

[45] For example, for woodstoves, the sampling methods - EPA Methods 28 and 5G or 5H - are described in detail in Houck et al. (1986). Method 28 contains stove operating procedures to be used during testing, while Method 5G and Method 5H contain the criteria for sampling the emissions in the flue gas.

be based on direct measurements in the field (Bond et al., 2004).[46]

To measure emissions from stoves under field conditions, several in-home sampling techniques have been developed. These include the well-established Automated Wood stove Emissions Sampler (AWES) and field samplers such as that developed by the Virginia Polytechnic Institute and State University (VPI) (McCrillis and Jaasma, 1993; Eastern Research Group, 1996).[47] The AWES, VPI and EPA methods-based estimates are interconvertible using estimated relationships between the measurements generated by these methodologies (McGillis and Jaasma, 1993; Eastern Research Group, 1996). A more recently developed particle monitor, called the University of California Berkeley (UCB) particle monitor, appears to be a validated, robust, inexpensive ($600 including user manual and software CD; Berkeley Air Monitoring Group, 2010) and easy to use light-scattering particle monitor that allows the reliable measurement of $PM_{2.5}$ in field settings (Chowdhury et al., 2007; Edwards et al., 2006). This monitor was designed specifically to aid in epidemiological studies of indoor air pollution and to facilitate the evaluation of interventions such as improved fuels and stoves for reduction of indoor air pollution levels in developing countries. The UCB particle monitor has been validated in a series of field studies and its measurements compare well with the gravimetric sampling method, the "gold standard" for particulate matter measurements (Chowdhury et al., 2006). It is also much cheaper than commercially available light scattering devices (~$4,000) and does not have the high initial set-up cost or labor intensity of gravimetric pump filters (ibid.).

None of these particulate matter measurement techniques are designed to yield estimates specifically of the black carbon fraction of the emitted particles. Rather, their purpose is to generate reliable estimates of total particle emissions or of emissions of certain size classes. Determining the black carbon fraction requires additional analyses of the collected particulate matter emission samples.

Several other field-based methods for generating particulate matter emission estimates from residential stoves have been developed. For example, Zhang et al. (2000) conducted stove tests in India and China applying sampling design that had been employed in a series of previous field studies. Their sampling configuration included (from upstream to downstream of the sampling train) a stainless-steel probe, a filter holder, a pump, a clean Tedlar bag, and, in some cases, a hood over the flue inside which emissions samples were taken. Total suspended particulate (TSP) matter was collected using heat-treated quartz fiber filters. TSP concentrations were determined gravimetrically using the particle mass collected on the filters and the sampling volumes. One filter for each fuel/stove combination was analyzed for carbon content of TSP using a thermal-optical carbon analysis technique. For quality control purposes, the researchers conducted trial runs prior to their three planned tests. These runs served to standardize the burn cycle and minimize variability due to differences in stove operator behavior.[48] Determining the black carbon content in the emitted TSP will require additional analysis not performed in this study.

MacCarty et al. (2008) used a laboratory emission

---

[46] Johnson et al. (2010) propose a new approach to stove performance testing for improved cook stoves that uses simple and low-cost measurement methods and allows recreating representative emissions profiles in a laboratory setting. The authors suggest performance criteria that can be used as benchmarks for laboratory testing of improved stoves in the absence of site-specific information. However, those approaches would still require confirmation by field testing during daily cooking activities

[47] AWES is an intermittent, pump-driven particulate sampler that collects particulate and condensable organics on a filter and organic adsorbent resin. A sensor in the sample line measures oxygen concentration (McCrillis and Jaasma, 1993). The VPI system extracts samples from the exhaust stream using an evacuated cylinder as motive force, with particulates and organics collected in a condenser and dual filter. The sampler operates continuously whenever the stack temperature exceeds the set point. Average stack gas concentrations are measured from the evacuated cylinder at the end of the sampling period. Both the AWES and VPI samplers are designed to operate unattended (McCrillis and Jaasma, 1993).

[48] For detailed description of sampling techniques and equipment, see Zhang et al. (2000).

collection hood to collect particles produced by combustion in residential cook stoves, and portable emissions sampling equipment to analyze the samples.[49] However, this study recognizes that their laboratory-based approach to measuring particulate matter emissions can be used to generate reliable field data at low cost and with minimal "expert" involvement if a portable emission hood - available from Aprovecho Research Center - is fitted with a filter and bag sampling system. MacCarty et al. (2008) report that for EC/OC particle analysis, which is required in order to determine the amount of black carbon in the collected particulate matter, real-time measurements with a particle soot absorption photometer do not seem to be necessary. Rather, an inexpensive filter system can suffice, reducing the cost and technical know-how required to conduct measurements. Nevertheless, the EC/OC particle analysis of the particulate matter samples does require a high-tech laboratory (ibid.).

Roden et al. (2009) examined the particulate matter emissions of traditional and improved cook stoves under field conditions using the same battery-powered ARACHNE (Ambulatory Real-time Analyzer for Climate and Health-related Noxious Emissions) sampling system developed by the University of Illinois Urbana-Champaign used by MacCarty et al. (2008). This system was designed specifically to allow actual in-use emissions measurements from cook stoves in remote locations. It uses a nephelometer and a particle soot absorption photometer (PSAP) to measure real-time scattering and absorption by particles, respectively. Scattering is a proxy for particle emissions, while high absorption relative to scattering is an indicator of elemental (black) carbon emissions. The ARACHNE system thus allows the estimation of black carbon emissions from cook stoves under field conditions.

The above studies do not present an exhaustive overview of all the sampling methods that have been developed for measuring particulate matter or black carbon emissions from cook stoves. Nevertheless, they show that well-established laboratory and field systems exist for measuring these emissions.

6.1.2 Transport sector: Diesel particulate filters, switch to cleaner transport fuels (cng or lpg), and more stringent emission standards combined with in-use vehicle emission inspection and maintenance programs

All of these vehicle emission-targeted measures result in reduced exhaust emissions of particles in general and of black carbon in particular. These reductions can be quantified through tests of representative vehicles. Particulate matter emission tests for vehicles are well-established and already are a standard component of virtually all existing mandatory I/M programs for diesel vehicles, at least in developed countries. These tests, using the appropriate equipment, can also reliably measure the very low particulate matter emissions from DPF-equipped vehicles (Bergmann et al., 2009). Filter-based measurements of carbonaceous composition, particulate light absorption, and water uptake of particles can be added to standard particulate matter emission tests in order to identify the carbonaceous composition of particulate matter emissions and thus their black carbon content (e.g., Subramanian et al., 2009).

In addition to these emission measurements at vehicle inspection centers, black carbon emissions can also be measured under field conditions through roadside or on-road tests using mobile laboratories with commercially available micro-soot sensors (e.g., Ban-Weiss et al., 2009; Schneider et al., 2008). In one application in Mexico city (Jiang et al., 2005), a field campaign totaling 75 hours of on-road emissions sampling by a mobile emission lab was sufficient to generate fleet-average emission factor estimates of black carbon (among other pollutants).

---

[49] The equipment included a nephelometer to measure particle scattering, a particle soot absorption photometer (PSAP) to measure particle absorption in real time and a pump-and-filter system to collect and later analyze mass and elemental carbon/organic carbon ratios using a Sunset Laboratories carbon analyzer, both of which form part of the University of Illinois Urbana-Champaign's ARACHNE (Ambulatory Real-time Analyzer for Climate and Health-related Noxious Emissions) battery-operated sampling system (Roden and Bond, 2006).

6.1.3 Industrial sector: Switch to cleaner fuels (e.g., electricity or lpg), process switching (use of improved boiler designs), or use of particulate filters

Many industrial processes show less variability in operating conditions than residential stoves. Thus, the impacts of the black carbon control options identified for the industrial sector can be more reliably estimated on the basis of particulate matter emission factors combined with black carbon speciation factors, if those estimated factors reasonably accurately describe the particular source in question. Unlike in most developing countries, there are many process types in developing countries for which few if any black carbon emission factors have been measured. Thus, there is a need for more research aimed at deriving such factors for the relevant sources.

Well-established standards exist for measuring combustion-related particulate matter emission factors for industrial sources. For example, the US EPA's Compilation of Air Pollution Emission Factors (AP-42) contains detailed information on the quantity and size class distribution of particulate matter emissions for all major industrial source types.[50]

In addition to emission-factor based estimates, particulate matter emission estimates can also be derived through the use of real-time, continuous particle monitors. This is a more expensive approach to generating emission estimates, but it can generate more reliable estimates, especially in the case of sources for which no reliable emission factors exist. Continuous particulate matter monitoring is usually achieved through the use of integrating nephelometers, which measure the visual quality of local ambient air by measuring the scattering of light due to particles in continuous air samples. Integrating nephelometers are simple to install, operate, and calibrate and have been applied in a wide range of operational and research monitoring programs. They have a rugged design, are small, consume little energy, are sensitive and self-calibrating and can make precise and accurate measurements with few requirements for operator maintenance. However, they are sensitive to particle size distribution and characteristics and do not measure mass. Thus, they must be calibrated against a reference such as the US EPA's Federal Reference Method (Eiseman, 1998).

However, whether particulate matter measurements are based on emission factors or continuous emission sampling, they still need to be adjusted for the black carbon/particulate matter emission ratio of the respective source to yield estimates of black carbon emissions. These ratios have been measured for a variety of sources (for example, see Bond et al., 2004).

However, black carbon emissions can also be determined directly. For example, Bond et al. (1999; 1998) measured the absorption efficiency of emissions from a low-technology coal burning plant. The higher the absorption coefficient, the higher black carbon content of the emissions. The absorption coefficient was estimated using an absorption photometer (model PSAP, calibrated to 550 nm), with simultaneous samples collected on Nuclepore filters (polycarbonate membranes) that were analyzed for absorption by light transmission measurements with a 4-wavelength soot-photometer. Calibration factors were applied to both measurements to adjust for absorption by suspended particles.

This brief overview demonstrates that readily-available, well-established technologies and approaches exist for the generation of reasonably reliable estimates of black carbon emissions from the sources identified as key abatement targets in Asia. Nevertheless, application of most of these methods requires highly-skilled and knowledgeable test personnel, and the sampling protocols should be designed with the help of experts in the field.

---

[50] US EPA. AP 42, Fifth Edition. Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. *http://www.epa.gov/ttn/chief/ap42/index.html*

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the evidence reported in the published literature on the main sources of black carbon emissions in Asia and the impacts of black carbon on global and regional climate, food, water and public health. It also has reviewed the available black carbon emission control options, the limited number of available assessments of the cost-effectiveness and benefit-cost ratios of these control measures, the technological and institutional considerations associated with the implementation of these measures, and several promising ongoing control efforts.

Based on these reviews, this report reaches the following conclusions:

1) Black carbon is the second or third largest contributor to global warming, and has important negative impacts on regional climate, food and water supplies, and human health

Black carbon in soot is the dominant anthropogenic absorber of incident solar radiation in the atmosphere and contributes to the warming of the atmosphere at the global level. Black carbon also warms the atmosphere by absorbing thermal infrared radiation from the ground and within clouds. Furthermore, because it directly heats surfaces on which it is deposited and changes surface albedo, black carbon is a major contributor to the accelerated melting of Arctic sea and land ice, glaciers and seasonal snow covers. Because of these multiple warming pathways, one kilogram of black carbon is estimated to heat the atmosphere on average 500-680 times as much as one kilogram of CO_2 over a 100-year timeframe, and 1500-2200 times over a 20-year timeframe. Recent studies identify black carbon as the second- or third-largest contributor to current anthropogenic global warming, surpassed only by carbon dioxide and possibly methane.

Black carbon emissions also are a major contributor to several large regional hazes or ABCs. One of these, the South Asian ABC covers most of the Arabian Sea, the Bay of Bengal, the Northern Indian Ocean and the South Asian region from at least November through May, and according to some estimates is fuelled by as much as 75 percent by biomass burning and fossil fuel combustion. The South Asian ABC has important regional climate impacts in Asia, with recent research suggesting that its regional radiative impacts at the surface and within the atmosphere exceed those of anthropogenic greenhouse gases by an order of magnitude. These regional climate perturbations negatively impact food production in India and China. The South Asian ABC also accelerates the melting of the Hindu Kush-Himalayan-Tibetan glaciers, with projected severe consequences for the freshwater supply for much of Southern and Eastern Asia. Furthermore, Asian black carbon emissions have long-range snow and ice impacts, contributing substantially to the accelerated melting of Arctic sea ice and glaciers.

In addition to these climate impacts, black carbon emissions from unimproved residential cook- and heating stoves burning coal or solid biomass (wood and dried animal residues) produce indoor air pollution levels in millions of homes that lead to a variety of severe chronic and acute health impacts. In addition, black carbon emissions from industrial and transport sources are a major contributor to outdoor particulate matter pollution levels that in large regions in Asia exceed World Health Organization particulate matter guidelines several-fold. As a result of these indoor and outdoor air quality impacts, black carbon and its co-emitted pollutants are the third-leading contributor to the burden of disease in South Asia and the fifth-leading cause of mortality in Asia as a whole.

2) The principal black carbon emission sources in Asia contributing to global net climate forcing are biomass and coal burning in household cooking and heating stoves, industrial burning of coal and petroleum products, and diesel-powered engines in the transport sector.

Residential solid biomass (wood, dung) and coal burning in cook- and heating stoves, burning of coal and petroleum products in the industrial sector, and diesel fuel use in the transport sector are the leading sources of global climate forcing black carbon emissions in developing Asia. On the other hand, open biomass burning, which also is responsible for large quantities of black carbon emissions, generally (though not unanimously) is estimated to have a neutral or negative global climate forcing impact, due to the large quantities of co-emitted organic matter that produce a climate cooling effect. Nevertheless, open biomass burning in Asia does have important negative regional climate impacts - via deposition on snow and ice surfaces and associated warming and melting - and health impacts. Within Asia, available estimates indicate that China is the dominant emitter of black carbon from contained combustion, accounting for 61 percent of all Asian black carbon emissions in 2006, followed by India (12 percent) and Indonesia (6 percent).

3) The most immediate opportunities (in terms of technological or economic viability) for reducing black carbon emissions in Asia and for mitigating the impact of those emissions are the switching to cleaner fuels and stoves in the household sector; the widespread adoption of low-sulfur diesel fuel together with the use of diesel particulate filters, the repair of high-emitting vehicles, the implementation of in-use inspections and stricter emission standards, and fuel switching of heavy-duty and high-mileage vehicles in urban areas in the transport sector; and the modernization of traditional and inefficient combustion technology employed by industrial sources. Major obstacles for the effective implementation of these abatement measures vary by sector, but generally include a lack of high-level and long-term commitment to the control measures, a lack of support infrastructure for the abatement technologies, deployment programs that do not pay sufficient attention to the preferences of the target population or lack effective and continued monitoring and enforcement mechanisms, and the lack of sufficient funding for the training and compensation of qualified personnel.

Proven and in many cases readily-available control technologies exist that could substantially reduce emissions from key black carbon sources in Asia. In the case of households, these include cleaner fuels like biogas, natural gas, LPG or kerosene or direct solar power, and improved cook stoves that burn fuel more efficiently and result in fewer emissions of black carbon and other climate-relevant pollutants. In the transport sector, the main control options include diesel particle filters (DPFs), especially in densely populated areas, though their widespread deployment currently still is inhibited by the lack of availability of sufficiently low-sulfur diesel fuel outside of major metropolitan areas in Asia; cleaner fuels (CNG or LPG), especially for high-mileage vehicles like taxis, long-distance trucks and buses; a change in the modal split towards electricity or clean fuel powered mass-transit; and more stringent emission standards and in-use vehicle emission inspection and maintenance programs. Finally, industrial black carbon emissions can be reduced through improved emission control, process switching and cleaner fuels (electricity, LPG). Changes in aerosol emissions from the household sector in developing Asia are thought to offer the largest potential leverage on near-term climate forcing via short-lived species emissions.

Based on a review of the existing literature on black carbon control options in developing Asia, this report identifies a clear cost-effectiveness hierarchy among the major control measures. At the top of this hierarchy sit household fuel and stove interventions, which consistently achieve the highest reduction in black carbon emissions per unit cost. This finding holds true for all stove and fuel interventions examined here. Moreover, these interventions are cost-effective not only for black carbon control, but also for global warming abatement more broadly. That is, they are cost-effective compared to most large-scale greenhouse gas abatement options presently considered. Importantly, residential stove and fuel interventions also yield the highest net benefits per unit intervention cost if health benefits are included in the analysis – as they should be from an economic efficiency perspective – due to the much higher indoor exposure to fine particulates. Existing analyses suggest that in many cases, these measures actually will reduce costs for households. Finally, stove and fuel interventions can achieve the largest total reduction in black carbon emissions of all the main control options analyzed in the literature because Asia's household sector is the dominant source of the region's black carbon emissions from contained combustion.

Several past large-scale fuel and stove interventions have resulted in the identification of key characteristics of intervention programs that determine the success and effectiveness of such efforts. Many of those efforts have had mixed results at best, because they failed to address one or more of the key challenges facing cookstove programs: motivating users to adopt the improved stoves; being affordable; requiring changes in user behavior; and having a reliable distribution network for parts and supplies. There are a number of ambitious ongoing initiatives in Asia that build on this experience and may yield both cost-effective and large reductions in black carbon emissions as well as massive public health benefits, especially among the poorer sectors of the population. These initiatives, including Grameen Shakti's Improved Cooking Stoves project (Bangladesh), Project Surya (India), PCIA (Asia-wide), the Shell Foundation and Envirofit's clean cook stoves initiative (India), and Philips and ARTI's Chulha project (India) present promising opportunities for bilateral and multilateral cooperation and funding assistance yielding win-win outcomes (Smith et al., 2000) that could substantially expand the reach of these initiatives and the speed of their roll-out.

The next level in the cost-effectiveness ranking of black carbon abatement measures is occupied by a suite of control options directed at the transport sector. These comprise the equipping of new diesel vehicles with diesel particulate filters (DPFs) and DPF retrofits for existing heavy-duty vehicles, the repair of super-emitting vehicles, and the implementation of in-use inspection and maintenance (I/M) systems. The literature identifies cost-effectiveness ranges for each of these control options that in many cases are overlapping, indicating that the local context will determine which of these options are the most cost-effective in a particular situation. Nevertheless, equipping new diesels with DPFs and repairing super-emitters will generally tend to have lower costs per unit black carbon reduction (Figure 7). The limited information on the benefit-cost performance of these measures also indicates that repairing super emitting vehicles will generally yield net economic benefits. It should be noted that the effectiveness of both DPFs and repairing of super-emitters, though not conditional on effective I/M programs, will benefit from such programs, as regular, mandatory and effective vehicle inspections will help ensure the deployment and adequate maintenance of DPFs as well as identify high-emitting vehicles. Thus, these measures should be considered for joint implementation. At a minimum, based on a recognition of the substantial institutional capacity required for establishing and maintaining an effective I/M program, such a program should be implemented at some later stage following the implementation of other emission control measures for the transport sector.

Bi- and multilateral assistance can play important roles in Asian efforts to control black carbon emissions, as demonstrated by past and ongoing efforts, with provision of technical assistance perhaps playing a primary role in this sector. This is particularly true for designing, implementing and evaluating I/M programs. Donors should consider funding the creation of a model tender, the guidelines on conducting the bidding process, the selection of contractors, more rigorous program evaluations along with the data collection efforts that would support them, exploration of "one-stop" government facilities for emission and safety inspections as well as vehicle registration, the development of I/M test procedures and standards for particulate matter that take advantage of particulate matter meters which have become available only very recently (Hausker, 2004). They should also assist policymakers in making sure they have sufficient capacity to carry out their own roles, particularly through engaging independent experts to access needed technical knowledge (ibid.).

Deployment of DPFs requires ready availability of ultra-low sulfur diesel (ULSD) fuel. Except for a few metropolitan areas, ULSD currently is not available in developing Asia. Thailand will introduce ULSD in 2010, India is considering its introduction in metropolitan areas in the same year, and Malaysia is considering introduction nationwide in 2012 (Appendix Figure A1). Reducing the sulfur content of fuels provides substantial and cost-effective particulate matter reductions and associated health benefits in its own right, in addition to enabling the deployment of DPFs. Thus, there is a critical role for bi- and multilateral assistance in promoting desulfurization both in countries in Asia that are considering the measure as well as in the majority of other countries that currently are not planning to do so in the coming years. Assistance should focus on facilitating technology transfer and provision of technical expertise both in the development of fuel standards and desulfurization technologies and policy measures (Schneider, 2009).

Controlling black carbon emissions from industrial sources will form part of any comprehensive control strategy, given that industrial emissions are estimated to account for almost one quarter of black carbon emissions from contained combustion in Asia (Figure 4). However, estimates of the cost-effectiveness of control measures in this sector are almost completely lacking. Emissions from one important black carbon source, coal-fired brick kilns, are though to be controllable comparatively cost-effectively, but the uncertainty associated with this assessment is large. Thus, there is an important role for bilateral and multilateral assistance in promoting and supporting studies of the impact and cost-effectiveness of black carbon control measures from industrial sources.

Finally, the open burning of biomass in Asia, one of the leading contributors to black carbon emissions, can and should be reduced. Current assessments suggest that black carbon emissions from open biomass burning on balance have a negative impact on global climate forcing due to their low ratio of black to organic carbon compared to emissions from contained combustion. Nevertheless, biomass burning is an important contributor to Asian Atmospheric Brown Clouds, which have important local and regional impacts on climate, water and food supplies, and human health. Reducing the scale of open biomass burning will require addressing the multiple drivers of this practice, including the need for additional agricultural lands to feed growing populations and replace exhausted crop lands. One driver, the burning of agricultural residues, could be addressed directly through one of the black carbon abatement measures discussed in this report, namely, by using the residues as fuel for village-level biogas plants or multi family-level biogas stoves, both of which are cost-effective black carbon control options. In addition, the impact of agricultural burning also can be reduced by shifting the burning to after the spring melt season.

REFERENCES

Adler, T. 2010. Better burning, better breathing: Improving health with cleaner cook stoves. Environmental Health Perspectives 118:a124-a129. doi:10.1289/ehp.118-a124

Anderson, H.R., R. Atkinson, B. Chen, A. Cohen, D. Greenbaum, A.J. Hedley, W. Huang, J. Pande, C.A. Pope III and K. Smith. 2004. Health effects of outdoor air pollution in developing countries of Asia: A literature review. Special Report 15. Boston, MA: Health Effects Institute. 117 pp.

Asian Development Bank. 2008. A Road Map for Cleaner Fuels and Vehicles in Asia. TA 6144 (REG): Better Air Quality Management in Asia. Final Consultants' Report. November 2008. Asian Development Bank. 139 pp.

Aufhammer, M., V. Ramanathan and J.R. Vincent. 2006. Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India, Proceedings of the National Academy of Sciences 103(52):19668-19672.

Aunan, K., T.K. Berntsen, G. Myhre, K. Rypdal, D.G. Streets, J.-H. Woo and K.R. Smith. 2009. Radiative forcing from household fuel burning in Asia. Atmospheric Environment 43:5674-5681.

Bachmann, J. 2009. Black Carbon: A Science/Policy Primer. Arlington, VA: Pew Center on Global Climate Change. December 2009. 45 pp.

Baldinger, P. 2010. (Energy Advisor, Office of Infrastructure and Engineering, EGAT Bureau, US Agency for International Development). Personal communication. February 17, 2010.

Ban-Weiss, G.A., M.M. Lunden, T.W. Kirchstetter and R.A. Harley. 2009. Measurement of black carbon and particle number emission factors from individual heavy-duty trucks. Environmental Science and Technology 43:1419-1424.

Baron, Robert E., W. David Montgomery and Sugandha D. Tuladhar. 2009. An Analysis of Black Carbon Mitigation as a Response to Climate Change. Report prepared for the Copenhagen Consensus on Climate. Frederiksberg, Denmark: Copenhagen Consensus Center, Copenhagen Business School. 30 pp.

Baum, E. 2009. Industrial and agricultural burning sources of black carbon emissions. Briefing for Senate Staff. March 6, 2009. US Senate Visitor Center.

Beck, E. 2009. Project Chulha Stove. The Design Observer. 9. Dec. 2009. *http://changeobserver.designobserver.com/entry.html?entry=10717* Last accessed 3 March, 2010.

Bergmann, M., U. Kirchner, R. Vogt and T. Benter. 2009. On-road and laboratory investigation of low-level PM emissions of a modern diesel particulate filter equipped diesel passenger car. Atmospheric Environment 43(11):1908-1916.

Berkeley Air Monitoring Group. 2010. Instrument Services: UCB Particle Monitor. *http://www.berkeleyair.com/index.php?option=com_content&task=view&sectionid=22&id=49&Itemid=1* Last accessed March 3, 2010.

Bice, K., A. Eil, B. Habib, P. Heijmans, R. Kopp, J. Nogues, F. Norcross, M. Sweitzer-Hamilton and A. Whitworth. 2009. Black Carbon: A Review and Policy Recommendations. Woodrow Wilson School of Public and International Affairs, Princeton University (Report). 71 pp.

Bond, T.C. 2010. Personal communication, February 18, 2010.

Bond, T.C. 2007a. Testimony for the Hearing on Black Carbon and Climate Change House Committee on Oversight and Government Reform United States House of Representatives. The Honorable Henry A. Waxman, Chair. October 18, 2007.

Bond, T.C. 2007b. Can warming particles enter global climate discussions? Environmental Research Letters 2(4):045030.

Bond, T.C. and P.K. Hopke. 2009. Climate implications of improved stoves. ASEAN-US Next Generation Cook stove Workshop. Bangkok, Thailand. November 19, 2009.

Bond, T.C., E. Bhardwaj, R. Dong, R. Jogani, S. Jung, C. Roden, D.G. Streets and N.M. Trautmann. 2007. Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. Global Biogeochemical Cycles 21, GB2018, doi:10.1029/2006GB002840.

Bond, T. and H. Sun. 2005. Can reducing black carbon emissions counteract global warming? Environmental Science Technology 39:5921-5926.

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo and Z. Klimont. 2004. A technology-based global inventory of black and organic carbon emissions from combustion. Journal of Geophysical Research 109:D14203, doi:10.1029/2003JD003697.

Bond, T.C., M. Bussemer, B. Wehner, S. Keller, R.J. Charlson and J. Heintzenberg. 1999. Light absorption by primary particle emissions from a lignite burning plant. Environmental Science and Technology 33(21):3887-1891.

Bond, T.C., R.J. Charlson and J. Heintzenberg. 1998. Quantifying the emission of light-absorbing particles: Measurements tailored to climate studies. Geophysical Research Letters 25(3):337-340.

Cao, J.-J., C.-S. Zhu, J.C. Chow, J.G. Watson, Y.-M. Han, G.-h. Wang, Z.-x. Shen and A. Zhi-Sheng. 2009. Black carbon relationships with emissions and meteorology in Xi'an, China. Atmospheric Research 94(2):194-202.

Cao, G., X. Zhang and F. Zheng. 2006. Inventory of black carbon and organic carbon emissions from China. Atmospheric Environment 40:6516–6527.

Carl, Jeremy. 2009. Rising from the ashes: India's black carbon opportunity. *http://casi.ssc.upenn.edu/iit/carl*

Carmichael, G.R, B. Adhikary, S. Kulkarni, A. D'Allura, Y. Tang, D. Streets, Q. Zhang, T.C. Bond, V. Ramanathan, A. Jamroensan and P. Marrapu. 2009. Asian Aerosols: Current and year 2030 distributions and implications to human health and regional climate change. Environmental Science & Technology 43(15):5811-5817.

Chameides, W.L., H. Yu, S.C. Liu, M. Bergin, X. Zhou, L. Mearns, G. Wang, C.S. Kiang, R.D. Saylor, C. Luo, Y. Huang, A. Steiner and F. Giorgi. 1999. Case study of the effects of atmospheric aerosols and regional haze on agriculture: An opportunity to enhance crop yields in China through emission controls? Proceedings of the National Academy of Sciences 96(24):13626-13633.

Chandra Barua, D. 2009. Grameen Shakti: Improved cooking stoves for 2.6 billion people. Presented at World Bank Energy Week, April 1-2, 2009. Washington DC. *http://siteresources.worldbank.org/INTENERGY/Resources/335544-1232567547944/5755469-*

1239633250635/Dipal_Barua_Parallel_10.pdf Last accessed March 3, 2010.

Chowdhury, Z., R.D. Edwards, M. Johnson, K. Naumoff Shields, T. Allen, E. Canuz and K.R. Smith. 2007. An inexpensive light-scattering particle monitor: Field validation. Journal of Environmental Monitoring 9:1099-1106.

Chowdhury, Z., E. Castro, J. Higashiyama, R. Edwards and K.R. Smith. 2006. Field validation of the UCB particle monitor. *http://www.vrac.iastate.edu/ethos/files/ethos2006/stove_emissions/Update%20on%20IAP%20Monitoring%20--%20Zohir%20Chowdhury.ppt* Last accessed March 3, 2010.

Chung, S.H. and J.H. Seinfeld. 2002. Global distribution and climate forcing of carbonaceous aerosols. Journal of Geophysical Research 107(D19):AAC14.1-AAC14.33.

Cohen, A.J., H.R. Anderson, B. Ostro, K. Dev Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, A. Pope, I. Romieu, J.M. Samet and K.R. Smith. 2005. The global burden of disease due to outdoor air pollution. Journal of Toxicology and Environmental Health, Part A 68:1-7.

Cohen, A.J., H.R. Anderson, B. Ostro, K. Dev Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, A. Pope, I. Romieu, J.M. Samet and K.R. Smith. 2004. Mortality Impacts of Urban Air Pollution. In Ezzati, M., A.D. Rodgers, A.D. Lopez and C.J.L. Murray (eds). Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors, Vol 2. Geneva: World Health Organization. Pp. 1353-1433.

Dherani, M., D. Pope, M. Mascarenhas, K.R Smith, M. Weber and N. Bruce. 2008. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: A systematic review and meta-analysis. Bulletin of the World Health Organization 86(5):390-398.

Eastern Research Group. 1996. Report on Revisions to 5th Edition AP-42. Section 1.10. Residential Wood Stoves. Prepared for US Environmental Protection Agency. Research Triangle Park, North Carolina.

Edwards, R., Y. Liu, G. He, Z. Yin, J. Sinton, J. Peabody and K.R. Smith. 2007. Household CO and PM measured as part of a review of China's National Improved Stove Program. Indoor Air 17:189-203.

Edwards, R., K.R. Smith, B. Kirby, T. Allen, C.D. Litton and S. Hering. 2006. An inexpensive dual-chamber particle monitor: Laboratory characterization. Journal of the Air & Waste Management Association 56:789-799.

Edwards, R.D., K.R. Smith, J. Zhang and Y. Ma. 2004. Implications of changes in household stoves and fuel use in China. Energy Policy 32(3):395-411.

Eiseman, Elisa. 1998. Monitoring for Fine Particulate Matter. Rand Monograph Report. Washington DC and Santa Monica, CA: Rand. 59 pp.

Energy Sector Management Assistance Programme (ESMAP). 2004. The Impact of Energy on Women's Lives in Rural India. Washington, D.C.: World Bank. 86 pp.

Ezzati, M., S. Vander Hoorn, A.D. Lopez, G. Danaei, A. Rodgers, C.D. Mathers and C.J.L. Murray. 2006. Comparative Quantification of Mortality and Burden of Disease Attributable to Selected Risk Factors. In Lopez, A.D., C.D. Mathers, M. Ezzati, D.T. Jamison and C.J.L. Murray (Eds.) Global Burden of Disease and Risk Factors. New York: Oxford University Press. Pp. 241-268.

Ezzati, M., Alan D. Lopez, Anthony Rodgers, Stephen Vander Hoorn, Christopher J.L. Murray, and the Comparative Risk Assessment Collaborating Group. 2002. Selected major risk factors and global and regional burden of disease. Lancet 360(9343):1347-1360.

Flanner, M.G., C.S. Zender, P.G. Hess, N.M. Mahowald, T.H. Painter, V. Ramanathan and P.J. Rasch. 2009. Springtime warming and reduced snow cover from carbonaceous particles. Atmospheric Chemistry and Physics 9:2481-2497.

Flanner, M.G., C.S. Zender, J.T. Randerson and P.J. Rasch. 2007. Present-day climate forcing and response from black carbon in snow. Journal of Geophysical Research 112:D11202.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland. 2007. Changes in Atmospheric Constituents and in Radiative Forcing. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Pp. 129-234.

GNV Magazine. 2007. *http://www.gnvmagazine.com/ingles/detalle_estadisticas.php?id=4* Last accessed Oct. 27, 2009.

Grieshop, A.P., C.C.O. Reynolds, M. Kandlikar and H. Dowlatabad. 2009. A black-carbon mitigation wedge. Nature Geoscience 2:533-534.

Guazzotti, S.A., D.T. Suess, K.R. Coffee, P.K. Quinn, T.S. Bates, A. Wisthaler, A. Hansel, W.P. Ball, R.R. Dickerson, C. Neusüß, P.J. Crutzen and K.A. Prather. 2003. Characterization of carbonaceous aerosols outflow from India and Arabia: Biomass/biofuel burning and fossil fuel combustion. Journal of Geophysical Research-Atmospheres 108(D15).

Guoliang, C., Z. Xiaoye, W. Yaqiang, C. Huizheng and C. Dong. 2007. Inventory of black carbon emissions from China. Advances in Climate Change Research 3 (Suppl.):75-81.

Gustafsson, Ö., M. Kruså, Z. Zencak, R.J. Sheesley, L. Granat, E. Engström, P.S. Praveen, P.S.P. Rao, C. Leck and H. Rodhe. 2009. Brown clouds over South Asia: Biomass or fossil fuel combustion? Science 323(5913):495-498.

Hadley, O.L., V. Ramanathan, G.R. Carmichael, Y. Tang, G.C. Roberts and G.S. Mauger. 2007. Trans-Pacific transport of black carbon and fine aerosols (D < 2.5µm) into North America. Journal of Geophysical Research 112:D05309. doi:10.1029/2006JD007632.

Hansen, J., M. Sato, P. Kharecha, G. Russell, D.W. Lea and M. Siddall. 2007. Climate change and trace gases Philosophical Transactions of the Royal Society of London A 365:1925–1954.

Hansen, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G.A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N.Y. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R.L. Miller, P. Minnis, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao and S. Zhang. 2005. Efficacy of climate forcings. Journal of Geophysical Research 110:D18104, doi:10.1029/2005JD005776.

Hansen, J. and L. Nazarenko. 2004. Soot climate forcing via snow and ice albedos. Proceedings of the National Academy of Sciences 101(2):423-428.

Hausker, K. 2004. Vehicle Inspection and Maintenance Programs: International Experience and Best Practices. Report prepared for the Office of Energy and Information Technology. US Agency for International Development. Washington, DC: PA Government Services, Inc.

Haywood, J. M. and V. Ramaswamy. 1998. Global sensitivity studies of the direct radiative forcing due to anthropogenic sulfate and black carbon aerosols. Journal of Geophysical Research 103(D6):6043-6058.

Hegg, D.A., S.G. Warren, T.C. Grenfell, S.J. Doherty, T.V. Larson and A.D. Clarke. 2009. Source attribution of black carbon in Arctic snow. Environmental Science and Technology 43:4016-4021.

Houck, J.E., C.A. Simmons, P.G. Burnet and R.G. Merrill. 1986. A system to obtain time integrated woodstove emission samples. Proceedings of the 1986 EPA/APCA Symposium on Measurement of Toxic Air Pollutants. Raleigh, NC, April 1986, EPA-600/9-86-013.

Hutton, G., E. Rehfuess, F. Tedioso and S. Weiss. 2006. Evaluation of the costs and benefits of household energy and health interventions at global and regional levels. Geneva: World Health Organization. 96 pp.

Institute for Governance & Sustainable Development (IGSD) and International Network for Environmental Compliance & Enforcement (INECE). 2009. Reducing Black Carbon May Be Fastest Strategy for Slowing Climate Change. IGSD/INECE Climate Briefing Note. 29 June 2009.

International Council on Clean Transportation. 2010. A policy-relevant summary of black carbon climate science and appropriate emission control strategies. January 2010. 10 pp.

Jacobson, M.Z. 2009. Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. Manuscript under review. 58 pp. *http://www.stanford.edu/group/efmh/jacobson/* Last viewed Feb. 20, 2010.

Jacobson, M.Z. 2007. Testimony for the Hearing on Black Carbon and Global Warming House Committee on Oversight and Government Reform United States House of Representatives The Honorable Henry A. Waxman, Chair. October 18, 2007

Jacobson, M.Z. 2006. Effects of externally-through-internally-mixed soot inclusions within clouds and precipitation on global climate. Journal of Physical Chemistry A 110:6860-6873.

Jacobson, M.Z. 2005. Correction to "Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. Journal of Geophysical Research 110:D14105.

Jacobson, M.Z. 2004a. Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity. Journal of Geophysical Research 109:D21201.

Jacobson, M.Z. 2004b. The short-term cooling but long-term global warming due to biomass burning. Journal of Climate 17:2909-2926.

Jacobson, M.Z. 2002. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. Journal of Geophysical Research 107(D19):4410.

Jacobson, M.Z. 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. Nature 409:695-697.

Jiang, M., L.C. Marr, E.J. Dunlea, S.C. Herndon, J.T. Jayne, C.E. Kolb, W.B. Knighton, T.M. Rogers, M. Zavala, L.T. Molina and M.J. Molina. 2005. Vehicle fleet emissions of black carbon, polycyclic aromatic hydrocarbons, and other pollutants measured by a mobile laboratory in Mexico City. Atmospheric Chemistry and Physics 5:3377-3387.

Jin, Y., X. Ma, X. Chen, Y. Cheng, E. Baris and M. Ezzati. 2006. Exposure to indoor air pollution from household energy use in rural China: The interactions of technology, behavior, and knowledge in health risk management. Social Science and Medicine 62:3161-76.

Johnson, M., R. Edwards, V. Berrueta and O. Masera. 2010. New approaches to performance testing of improved cook stoves. Environmental Science and Technology 44(1):368-374.

Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP). 2008. Developing Integrated Emissions Strategies for Existing Land-transport (DIESEL). Bangkok, Thailand. April 2008. 184 pp.

Junker, C. and C. Liousse. 2008. A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860-1997. Atmospheric Chemistry and Physics 8:1195-1207.

Kandlikar, M., C.C.O. Reynolds and A.P. Grieshop. 2009. A Perspective Paper on Black Carbon Mitigation as a Response to Climate Change. Report prepared by for the Copenhagen Consensus on Climate. Frederiksberg, Denmark: Copenhagen Consensus Center, Copenhagen Business School. 20 pp.

Knaapen, A.M., P.J.A. Borm, C. Albrecht and R.P.F. Schins. 2004. Inhaled particles and lung cancer. International Journal of Cancer 109:799-809.

Koch, D., T.C. Bond, D. Streets and N. Unger. 2007a. Linking future aerosol radiative forcing to shifts in source activities. Geophysical Research Letters 34(5):L05821.

Koch, D., T.C. Bond, D. Streets, N. Unger and G.R. Werf. 2007b. Global impacts of aerosols from particular source regions and sectors. Journal of Geophysical Research 112: doi:10.1029/2005JD007024.

Koch, D. and J. Hansen 2005. Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment. Journal of Geophysical Research 110:D04204, doi:10.1029/2004JD005296.

Koelmans, A.A., M.T. Jonker, G. Cornelissen, T.D. Bucheli, P.C. Van Noort and O. Gustafsson. 2006. Black carbon: the reverse of its dark side. Chemosphere 63(3):365-77.

Levy II, H., D.T. Shindell, A. Gilliland, M.D. Schwarzkopf and L.W. Horowitz. 2008. Executive Summary in Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols. H. Levy II, D.T. Shindell, A. Gilliland, M.D. Schwarzkopf and L.W. Horowitz, (eds.). A Report by the US Climate Change Science Program and the Subcommittee on Global Change Research, Washington, D.C.

Li, X., S. Wang, L. Duan, J. Hao and Y. Nie. 2009. Carbonaceous aerosol emissions from household biofuel combustion in China. Environmental Science & Technology 43(15):6076-6081.

MacCarty, N., D. Ogle, D. Still, T. Bond and C. Roden. 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy for Sustainable Development 12(2):56-65.

Mayol-Bracero, O.L., R. Gabriel, M.O. Andreae, T.W. Kirchstetter, T. Novakov, J. Ogren, P. Sheridan and D.G. Streets. 2002. Carbonaceous aerosols over the Indian Ocean during the Indian Ocean Experiment (INDOEX): Chemical characterization, optical properties, and probable sources. Journal of Geophysical Research (Atmospheres) 107 (D19):INX2 29-1.

McConnell, J.R., R. Edwards, G.L. Kok, M.G. Flanner, C.S. Zender, E.S. Saltzman, J.R. Banta, D.R. Pasteris, M.M. Carter and J.D.W. Kahl. 2007. 20th-Century industrial black carbon emissions altered arctic climate forcing. Science 317:1381-1384.

McCormick, R.L., M.S. Grabowski, T.L. Alleman, J.R. Alvarez and K.G. Duleep. 2003. Quantifying the emission benefits of opacity testing and repair of heavy-duty diesel vehicles. Environmental Science & Technology 37(3):630-637.

McCrillis, R.C and D.R. Jaasma. 1993. Woodstove emission measurement methods: Comparison and emission factors update. Environmental Monitoring and Assessment 24:1-12.

Mehta, S. and C. Shahpar. 2004. The health benefits of interventions to reduce indoor air pollution from solid fuel use: A cost-effectiveness analysis. Energy for Sustainable Development 8(3):53-59.

Mejia, A. 2009. I&M in Southeast Asia: Safety through Enforcement and Inspection & Maintenance. Clean Air Initiative for Asian Cities Center. 17 June 2009. 27 pp.

Menon, S., J. Hansen, L. Nazarenko and Y. Luo. 2002. Climate effects of black carbon aerosols in China and India Science 297(5590):2250-2253.

Mishra, V., K.R. Smith and R.D. Retherford. 2005. Effects of cooking smoke and environmental tobacco smoke on acute respiratory infections in young Indian Children. Population and Environment 26(5):375-396.

Molina, M. and L. Molina. 2004. Megacities and atmospheric pollution. Journal of the Air & Waste Management Association 54(6):644-680.

Moss, J. 2010. Personal communication. March 10, 2010.

Moss, J. 2009. Cook stoves, indoor smoke and climate. Presentation given at the Senate Staff Briefing on "Black Carbon 101: Science, Sources, Solutions." 6 March, 2009. US Senate Visitor Center.

Naeher, L.P., M. Brauer, M. Lipsett, J.T. Zelikoff, C.D. Simpson, J.Q. Koenig and K.R. Smith. 2007. Woodsmoke health effects: A review. Inhalation Toxicology 19:67-106.

Naik, V., D.L. Mauzerall, L.W. Horowitz, M.D. Schwarzkopf, V. Ramaswamy and M. Oppenheimer. 2007. On the sensitivity of radiative forcing from biomass burning aerosols and ozone to emission location. Geophysical Research Letters 34: L03818.

Nakicenovic, N. and R. Swart (eds.). 2000. Emission Scenarios. IPCC Special Report. , Cambridge, UK: Cambridge University Press. 570pp.

Natarajan, B. and P. Tharakan. 2008. Financing Energy Efficiency in India. Report prepared for the United States Agency for International Development (USAID). November 2008. Bangkok, Thailand: USAID, Regional Development Mission for Asia. 49 pp.

Nordhaus, W.D. 2007. A review of the Stern Review on the Economics of Climate Change. Journal of Economic Literature 45(3):686-702.

Novakov, T., M.O. Andreae, R. Gabriel, T.W. Kirchstetter, O.L. Mayol-Bracero and V. Ramanathan. 2000. Origin of carbonaceous aerosols over the tropical Indian Ocean: Biomass burning or fossil fuels? Geophysical Research Letters 27(24):4061-4064.

OMNI. No date. Wood-Burning Stove Emissions Testing and US EPA Emissions Certification. *http://www.omni-test.com/documents/emissions.pdf* Last accessed Jan.2, 2010.

Pacala, S. and R. Socolow. 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. Science 305:968-972.

Partnership for Clean Fuels and Vehicles (PCFV). 2007. A report from the Partnership for Clean Fuels and Vehicles (PCFV). Nairobi, Kenya: UNEP PCFV. 5 pp.

Pew Center on Global Climate Change. 2009. What is black carbon? May 2009. 1p. *http://www.pewclimate.org/docUploads/BlackCarbon-1pager.pdf*

Pope, C.A. and D.W. Dockery. 2006. Health effects of fine particulate air pollution: Lines that connect. Journal of the Air and Waste Management Association 54:709-742.

Quinn, P.K., T.S. Bates, E. Baum, N. Doubleday, A.M. Fiore, M. Flanner, A. Fridlind, T.J. Garrett, D. Koch, S. Menon, D. Shindell, A. Stohl and S.G. Warren. 2008. Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies. Atmospheric Chemistry and Physics 8:1723–1735.

Rai, K. and J. McDonald (eds.). 2009. Cookstoves and Markets: Experiences, Successes and Opportunities. GVEP International. December, 2009. 41 pp. *http://iis-db.stanford.edu/pubs/22804/Markets_and_Cookstoves___.pdf* Last accessed March 2, 2010.

Ramanathan, V. 2007. Role of Black Carbon in Global and Regional Climate Changes. Testimonial to the House Committee on Oversight and Government Reform. Hearing on the role of black carbon as a factor in climate change. October 18, 2007 Rayburn House Office Building, Washington DC. *http://www-ramanathan.ucsd.edu/testimonials/BlackCarbonHearing-testimony.pdf*

Ramanathan, V. and Y. Feng. 2009. Air pollution, greenhouse gases and climate change: global and regional perspectives. Atmospheric Environment 43:37-50.

Ramanathan, V. and G. Carmichael. 2008. Global and regional climate changes due to black carbon. Nature Geoscience 1:221-227. doi:10.1038/ngeo156

Ramanathan, V., M. Agrawal, H. Akimoto, M. Aufhammer, S. Devotta, L. Emberson, S.I. Hasnain, M. Iyngararasan, A. Jayaraman, M. Lawrance, T. Nakajima, T. Oki, H. Rodhe, M. Ruchirawat, S.K. Tan, J. Vincent, J.Y. Wang, D. Yang, Y.H. Zhang, H. Autrup, L. Barregard, P. Bonasoni, M. Brauer, B. Brunekreef, G. Carmichael, C.E. Chung, J. Dahe, Y. Feng, S. Fuzzi, T. Gordon, A.K. Gosain, N. Htun, J. Kim, S. Mourato, L. Naeher, P. Navasumrit, B. Ostro, T. Panwar, M.R. Rahman, M.V. Ramana, M. Rupakheti, D. Settachan, A. K. Singh, G. St. Helen, P.V. Tan, P.H. Viet, J. Yinlong, S.C. Yoon, W.-C. Chang, X. Wang, J. Zelikoff and A. Zhu. 2008. Atmospheric Brown Clouds: Regional Assessment

Report with Focus on Asia. Nairobi, Kenya: United Nations Environment Programme. 39 pp.

Ramanathan, V. and K. Balakrishnan. 2007. Reduction of air pollution and global warming by cooking with renewable sources: A controlled and practical experiment in rural India. A white paper. March 5, 2007. 13 pp.

Ramanathan, V., F. Li, M.V. Ramana, P.S. Praveen, D. Kim, C.E. Corrigan and H. Nguyen. 2007a. Atmospheric brown clouds: Hemispherical and regional variations in long-range transport, absorption, and radiative forcing. Journal of Geophysical Research 112:D22S21. doi:10.1029/2006JD008124.

Ramanathan V., M.V. Ramana, G. Roberts, D. Kim, C.E. Corrigan, C.E. Chung and D. Winker. 2007b. Warming trends in Asia amplified by brown cloud solar absorption. Nature 448(2):575-578. doi:10.1038/nature06019.

Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J.T. Kiehl, W.M. Washington, Q. Fu, D.R. Sikka and M. Wild. 2005. Atmospheric brown clouds: Impacts on south Asian climate and hydrological cycle. Proceedings of the National Academy of Sciences 102(15):5326-5333.

Ramanathan, V. and P.J. Crutzen. 2003. New Directions: Atmospheric brown "clouds". Atmospheric Environment 37:4033-4035.

Reynolds, C.C.O. and M. Kandlikar. 2008. Climate impacts of air quality policy: Switching to a natural gas-fueled public transportation system in New Delhi. Environmental Science and Technology 42(16):5860-5865.

Roden, C.A., T.C. Bond, S. Conway, A.B. Osorto Pinel, N. MacCarty and D. Still. 2009. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmospheric Environment 43:1170-1181.

Roden, C.A. and T.C. Bond. 2006. Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. Environmental Science and Technology 40(21):6750-6757.

Rypdal, K., N. Rive, T. Berntsen, Z. Klimont, T. Mideksa, G. Myhre and Ragnhild Skeie. 2009. Costs and global impacts of black carbon abatement strategies. Tellus Series B: Chemical and physical meteorology 61(4):625-641.

Saikawa, E., N. Vaishali, L.W. Horowitz, J. Liu and D.L. Mauzerall. 2009. Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality, premature mortality and radiative forcing. Atmospheric Environment 43(17):2814-2822.

Sato, M., J. Hansen, D. Koch, A. Lacis, R. Ruedy, O. Dubovik, B. Holben, M. Chin and T. Novakov. 2003. Global atmospheric black carbon inferred from AERONET. Proceedings of the National Academy of Sciences 100(11):6319-6324.

Schneider, C. 2009. Policy Options for Reducing Black Carbon: A Near-Term Climate Strategy. Senate Staff Briefing on "Black Carbon 101: Science, Sources, Solutions." 6 March, 2009. US Senate Visitor Center.

Schneider, J., U. Kirchner, S. Borrmann, R. Vogt, and V. Scheer. 2008. In situ measurements of particle number concentration, chemically resolved size distributions and black carbon content of traffic-related emissions on German motorways, rural roads and in city traffic. Atmospheric Environment 42:4257-4268.

Schulz, M., C. Textor, S. Kinne, Y. Balkanski, S. Bauer, T. Berntsen, T. Berglen, O. Boucher, F. Dentener, S. Guibert, I.S.A. Isaksen, T. Iversen, D. Koch, A. Kirkevåg, X. Liu, V. Montanaro, G. Myhre, J.E. Penner, G. Pitari, S. Reddy, Ø. Seland, P. Stier and T. Takemura. 2006. Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. Atmospheric Chemistry and Physics 6(12):5225-5246.

Seinfeld, J. 2008. Black carbon and brown clouds. Nature Geoscience 1:15-16. doi:10.1038/ngeo.2007.62

Shindell, D. and G. Faluvegi. 2009. Climate response to regional radiative forcing during the twentieth century. Nature Geoscience 2:294-300, doi:10.1038/ngeo473.

Shindell, D., J.-F. Lamarque, N. Unger, D. Koch, G. Faluvegi, S. Bauer, M. Ammann, J. Cofala and H. Teich. 2008. Climate forcing and air quality change due to regional emissions reductions by economic sector. Atmospheric Chemistry and Physics Discussions 8:7101-7113.

Sinton, J.E., K.R. Smith, J.W. Peabody, L. Yaping, Z. Xiliang, R. Edwards and G. Quan. 2004. An assessment of programs to promote improved household stoves in China. Energy for Sustainable Development VIII(3):33-52.

Slaski, X. and M.C. Thurber. 2009. Cookstoves and Obstacles to Technology Adoption by the Poor. Stanford University, Program on Energy and Sustainable Development, Working Paper #89.

Smith, K.R. 2006. Health impacts of household fuelwood use in developing countries. Unasylva 224(57):41-44.

Smith, K.R. 2000. National burden of disease in India from indoor air pollution Proceedings of the National Academy of Sciences 97(24):13286-13293.

Smith, K.R. and E. Haigler. 2008. Co-benefits of climate mitigation and health protection in energy systems: Scoping methods. Annual Review of Public Health 29:11-25.

Smith, K.R., K. Dutta, C. Chengappa, P.P.S. Gusain, O. Masera, V., Berrueta, R. Edwards, R. Bailis and K. Naumoff Shields. 2007. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: Conclusions from the Household Energy and Health Project. Energy for Sustainable Development XI(2):5-18.

Smith, K.R., J. Rogers and S.C. Cowlin. 2005. Household Fuels and Ill-Health in Developing Countries: What improvements can be brought by LP Gas? Paris: World LP Gas Association and Intermediate Technology Development Group (Practical Action). 59 pp.

Smith, K.R., S. Mehta and M. Maeusezahl-Feuz. 2004. Indoor Air Pollution from Household Use of Solid Fuels. In Ezzati, M., A.D. Rodgers, A.D. Lopez and C.J.L. Murray (eds). Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors, Vol 2. Geneva: World Health Organization. Pp. 1435-1493.

Smith K.R., R. Uma, V.V.N. Kishore, J. Zhang, V. Joshi and M.A.K. Khalil. 2000. Greenhouse implications of household stoves: An analysis for India. Annual Review of Energy and Environment 25:741-763.

Smith, K.R., S. Gu, K. Huang and D. Qiu. 1993. One hundred million improved cookstoves in China: How was it done? World Development 21(6):941-961.

Stern, N. 2007. The Economics of Climate Change: The Stern Review. Cambridge and New York: Cambridge University Press.

Stone, E.A., G.C. Lough, J. Schauer, P.S. Praveen, C.E. Corrigan and V. Ramanathan. 2007. Understanding the origin of black carbon in the atmospheric brown cloud over the Indian Ocean. Journal of Geophysical Research 112:D22S23, doi:10.1029/2006JD008118.

Streets, D.G. 2007. Dissecting future aerosol emissions: Warming tendencies and mitigation opportunities. Climatic Change 81(3-4):313-330.

Streets, D.G., T.C. Bond, T. Lee and C. Jang. 2004a. On the future of carbonaceous aerosol emissions. Journal of Geophysical Research 109 (D24). doi:10.1029/2004JD004902.

Streets, D.G., T.C. Bond, G.R. Carmichael, S.D. Fernandes, Q. Fu, D. He, Z. Klimont, S.M. Nelson, N.Y. Tsai, M.Q. Wang, J.-H. Woo and K.F. Yarber. 2004b. The MICS-Asia Phase II Emission Inventory. Paper presented at the Sixth Workshop on the Transport of Air Pollutants in Asia (Model Intercomparison Study -- MICS-Asia). International Institute for Applied Systems Analysis, Laxenburg, Austria, February 9-10, 2004. 6 pp.

Streets, D.G., K.F. Yarber, J.-H. Woo and G.R. Carmichael. 2003. Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. Global Biogeochemical Cycles 17(4):10.1-10.20.

Streets, D.G., S. Gupta, S.T. Waldhoff, M.Q. Wang, T.C. Bond and B. Yiyun. 2001. Black carbon emissions in China. Atmospheric Environment 35:4281-4296.

Subramanian, R., E. Winijkul, T.C. Bond, W. Thiansathit, N.T. Kim Oanh, I. Pawarmart and K.G. Duleep. 2009. Climate-relevant properties of diesel particulate emissions: Results from a piggyback study in Bangkok, Thailand. Environmental Science and Technology 43(11):4213-4218.

Szidat, S. 2009. Sources of Asian haze. Science 323(5913):470-471.

Timilsina, G.R. and A. Shrestha. 2009. Why have CO_2 emissions increased in the transport sector in Asia? Underlying factors and policy options. World Bank Policy Research Working Paper 5098. Sep. 2009. 70 pp.

United Nations Environment Programme (UNEP). 2007. Beijing Olympic Games 2008: An Environmental Review. Nairobi: UNEP. 163.pp.

Vattenfall. 2007. The Climate Threat. Can Humanity Rise to the Greatest Challenge of Our Time? Conclusions from Vattenfall's Climate Survey. 31 pp. *http://www.vattenfall.com/www/ccc/ccc/Gemeinsame_Inhalte/DOCUMENT/567263vattenfall/P02.pdf*

Walsh, M. 2009. Diesel Vehicle Emissions of Black Carbon: Important and Solvable. Senate Staff Briefing on "Black Carbon 101: Science, Sources, Solutions." 6 March, 2009.

US Senate Visitor Center.

Weant, G.E. 1989. Emission Factor Documentation For AP-42 Section 1.10: Residential Wood Stoves, EPA-450/4-89-007 Research Triangle Park, NC: US Environmental Protection Agency.

Wehner, B., T.C. Bond, W. Birmili, J Heintzenberg, A. Wiedensohler and R.J. Charlson. 1999. Climate-relevant particulate emission characteristics of a coal-fired heating plant. Environmental Science and Technology 33:935-939.

Weitzman, M.L. 2007. A review of the Stern Review on the economics of climate change. Journal of Economic Literature 45(3):703-724.

Weitzman, M.L. 2009. On modeling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics 91(1):1-19.

Whitfield, Robert. 2009. Black Carbon and Its Relevance for India. Paper II.2. 5 pp. *http://www.climatecommunity.org/documents/PaperII.2BlackCarbon.pdf* Last accessed Sep. 24, 2009.

Wickramasinghe, A. 2003. Gender and health issues in the biomass energy cycle: impediments to sustainable development. Energy for Sustainable Development 7(3):51-61.

Wilkinson, P., K.R Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne and Z. Chalabi. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. The Lancet 374(9705):1917-1929.

World Health Organization. 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005- Summary of risk assessment. WHO/SDE/PHE/OEH/06.02. Geneva: WHO.

Zhang, Q., D.G. Streets, G.R. Carmichael, K. He, H. Huo, A. Kannari, Z. Klimont, I. Park, S. Reddy, J.S. Fu, D. Chen, L. Duan, Y. Lei, L. Wang and Z. Yao. 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmospheric Chemistry and Physics Discussions 9:4081–4139.

Zhang, M., Y. Song, X. Cai and J. Zhou. 2008. Economic assessment of the health effects related to particulate matter pollution in 111 Chinese cities by using economic burden of disease analysis. Journal of Environmental Management 88(4):947-954.

Zhang, J. and K.R. Smith. 2007. Household air pollution from coal and biomass fuels in China: Measurements, health impacts, and interventions. Environmental Health Perspectives 115(6):848-855.

Zhang, J., K.R. Smith, Y. Ma, S. Ye, F. Jiang, W. Qi, P. Liu, M.A.K. Khalil, R.A. Rasmussen and S.A. Thorneloe. 2000. Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors. Atmospheric Environment 34(26):4537-4549.

Zhou, Z., Y. Jin, F. Liu, Y. Cheng, J. Liu, J. Kang, G. He, N. Tang, C. Xun, E. Baris and M. Ezzati. 2006. Community effectiveness of stove and health education interventions for reducing exposure to indoor air pollution from solid fuels in four Chinese provinces. Environmental Research Letters 1:014010. doi:10.1088/1748-9326/1/1/014010.

APPENDIX

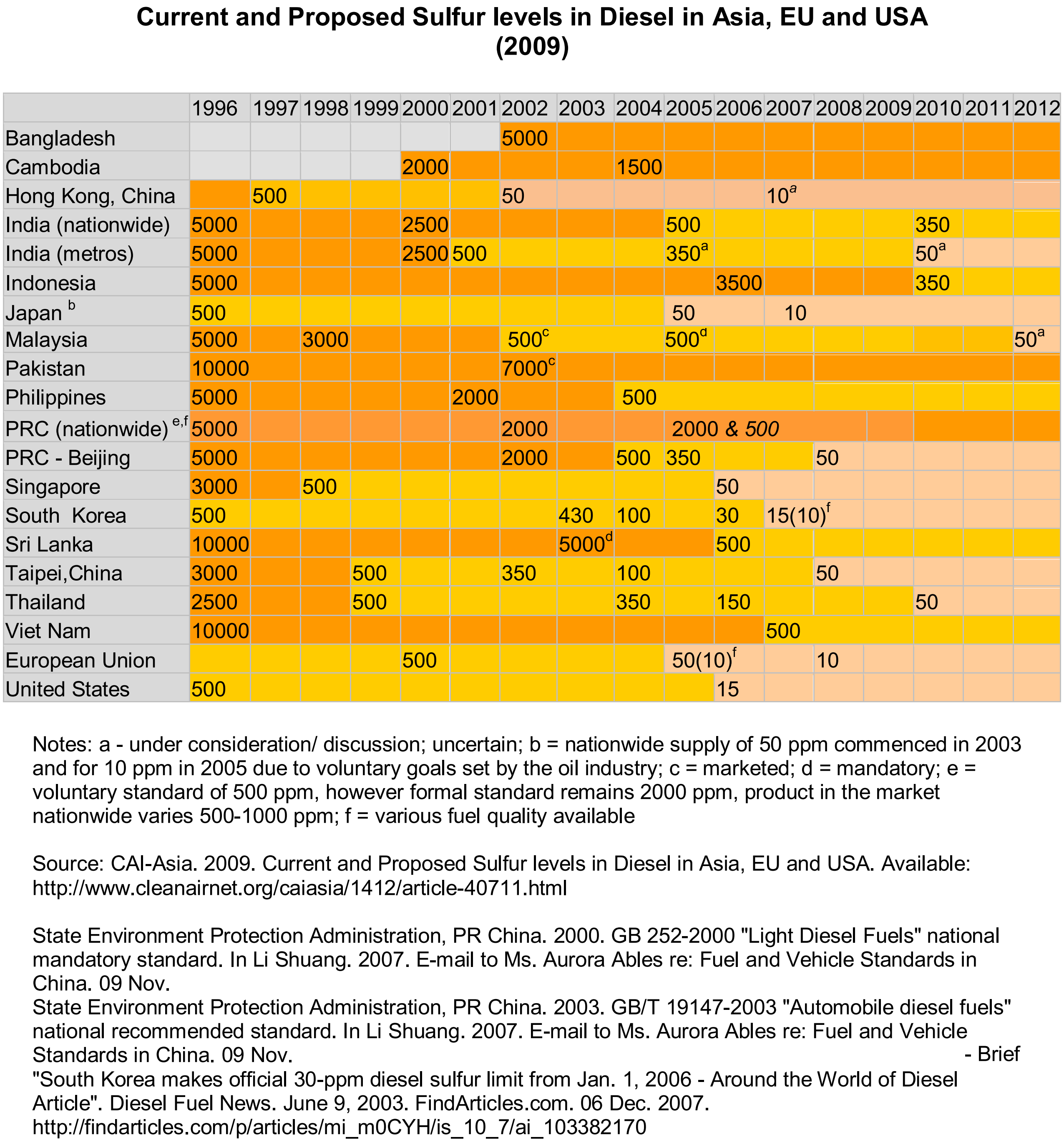
Table A1. Estimated Asian and global black carbon emissions in 1996

	Contained		Combustion type Open		Contained + Open	
	Gg	% of global	Gg	% of global	Gg	% of global
China	1365	30%	124	4%	1489	19%
India	483	10%	92	3%	575	7%
Other Asia	727	16%	275	8%	1002	13%
	2575	56%	491	15%	3066	39%
World	4626		3325		7951	

Notes: Gg = gigagram (1000 metric tons)

Source: Bond et al. (2004)

Figure A1. Current and proposed sulfur levels in diesel in Asia, EU and USA



Current and Proposed Sulfur levels in Diesel in Asia, EU and USA (2009)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Bangladesh							5000										
Cambodia					2000				1500								
Hong Kong, China		500					50					*10*[a]					
India (nationwide)	5000				2500					500					350		
India (metros)	5000				2500	500				350[a]					50[a]		
Indonesia	5000										3500				350		
Japan [b]	500									50		10					
Malaysia	5000		3000				500[c]			500[d]							50[a]
Pakistan	10000						7000[c]										
Philippines	5000					2000			500								
PRC (nationwide) [e,f]	5000						2000			2000 & *500*							
PRC - Beijing	5000						2000		500	350			50				
Singapore	3000		500								50						
South Korea	500							430	100		30	15(10)[f]					
Sri Lanka	10000							5000[d]			500						
Taipei,China	3000			500			350		100				50				
Thailand	2500			500					350		150				50		
Viet Nam	10000											500					
European Union					500					50(10)[f]			10				
United States	500										15						

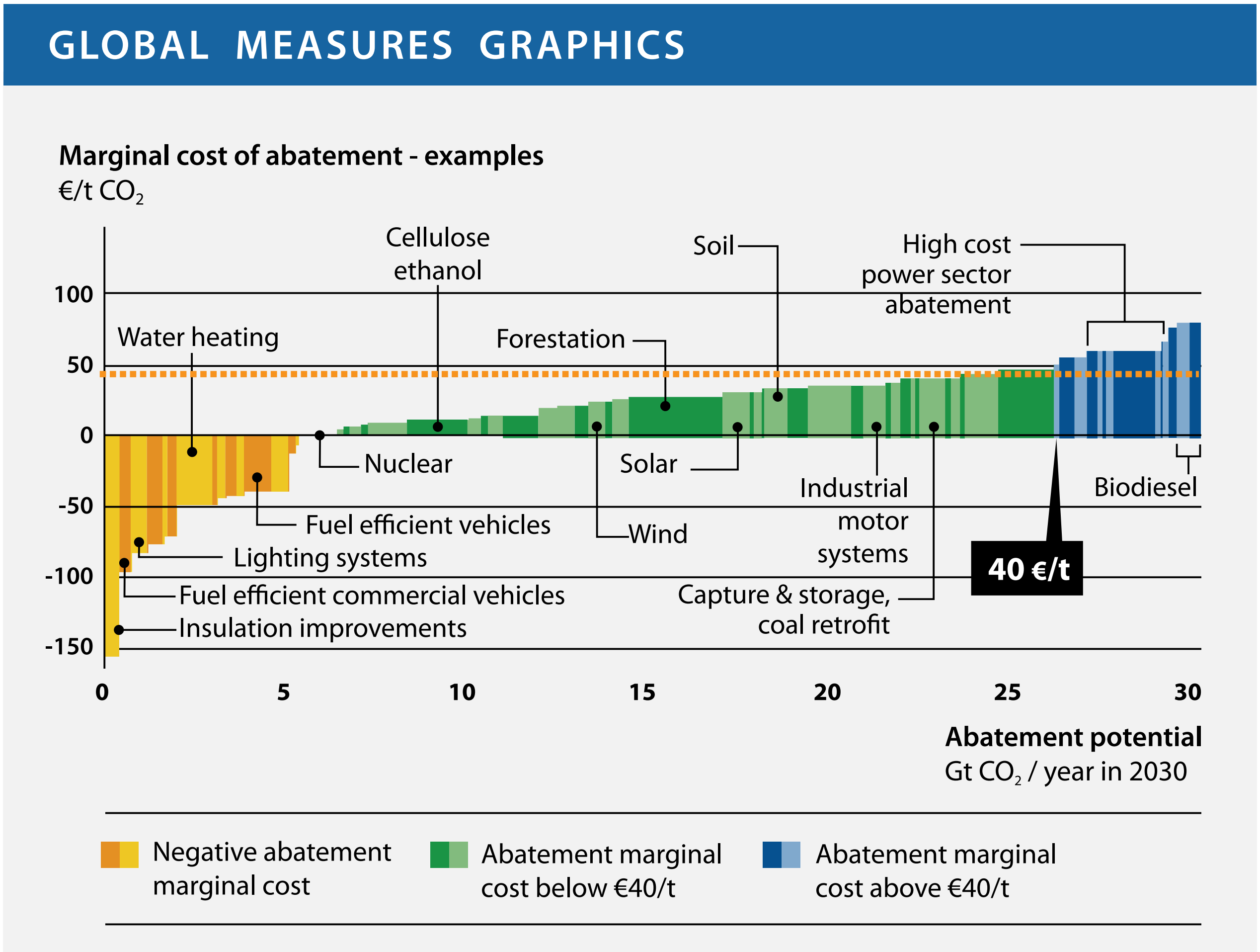
Notes: a - under consideration/ discussion; uncertain; b = nationwide supply of 50 ppm commenced in 2003 and for 10 ppm in 2005 due to voluntary goals set by the oil industry; c = marketed; d = mandatory; e = voluntary standard of 500 ppm, however formal standard remains 2000 ppm, product in the market nationwide varies 500-1000 ppm; f = various fuel quality available

Source: CAI-Asia. 2009. Current and Proposed Sulfur levels in Diesel in Asia, EU and USA. Available: http://www.cleanairnet.org/caiasia/1412/article-40711.html

State Environment Protection Administration, PR China. 2000. GB 252-2000 "Light Diesel Fuels" national mandatory standard. In Li Shuang. 2007. E-mail to Ms. Aurora Ables re: Fuel and Vehicle Standards in China. 09 Nov.
State Environment Protection Administration, PR China. 2003. GB/T 19147-2003 "Automobile diesel fuels" national recommended standard. In Li Shuang. 2007. E-mail to Ms. Aurora Ables re: Fuel and Vehicle Standards in China. 09 Nov. - Brief
"South Korea makes official 30-ppm diesel sulfur limit from Jan. 1, 2006 - Around the World of Diesel Article". Diesel Fuel News. June 9, 2003. FindArticles.com. 06 Dec. 2007. http://findarticles.com/p/articles/mi_m0CYH/is_10_7/ai_103382170

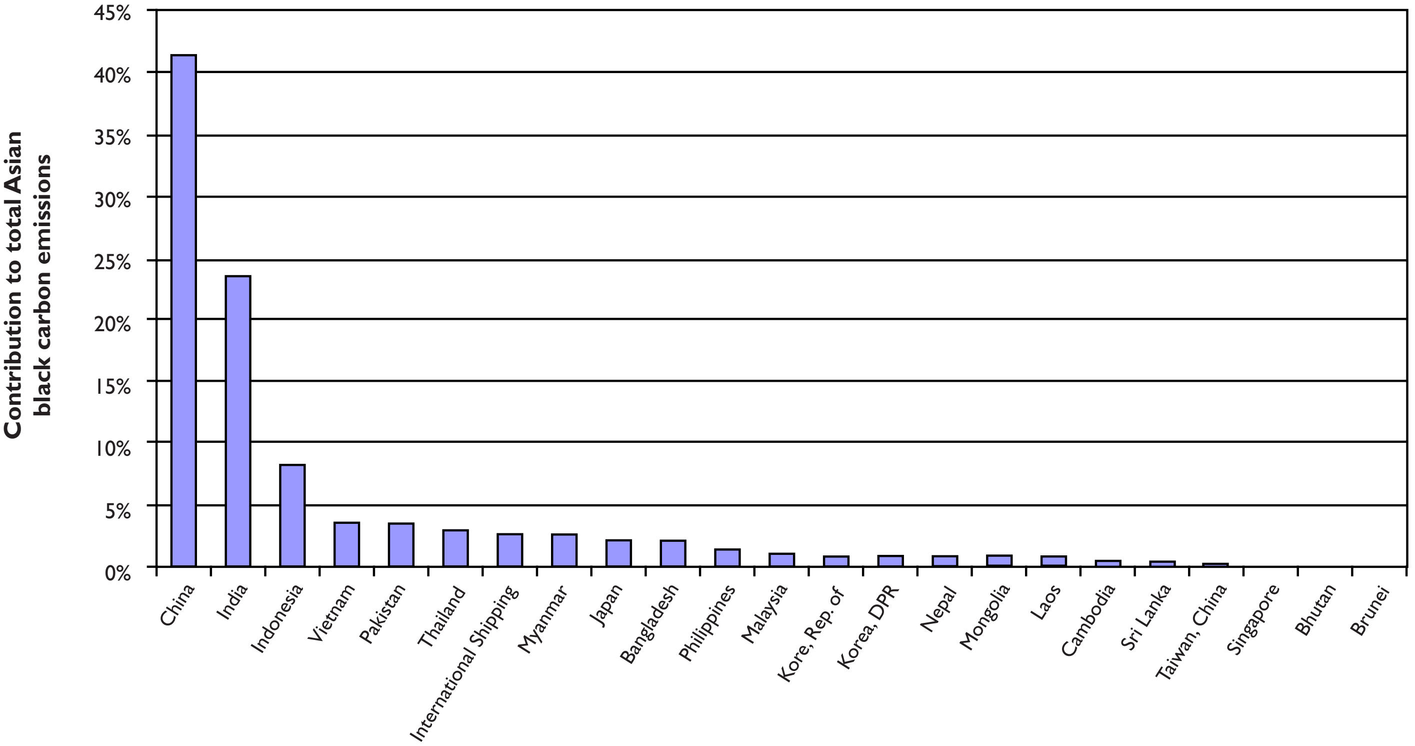
Source: Clean Air Initiative Asia (2009), at *http://www.cleanairnet.org/caiasia/1412/articles-40711_SulfurDiesel.pdf*

Figure A2. Estimated cost-effectiveness of CO_2 abatement measures



Source: Vattenfall (2007)

Figure A3. Contributions of countries and international shipping to total Asian black carbon emissions in 2000



Source: Streets et al. (2004b)

United States Agency for International Development
Regional Development Mission for Asia
Athenee Tower, 25th Floor
63 Wireless Road, Lumpini, Patumwan
Bangkok 10330 Thailand