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BLACK CARBON EMISSIONS IN ASIA:

Sources, Impacts and Abatement Opportunities

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.

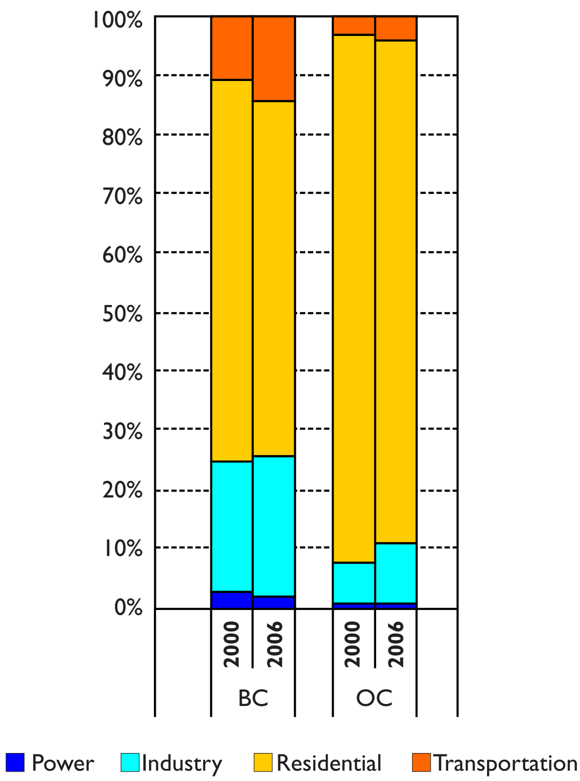
As well as these climate impacts, black carbon emissions from unimproved residential cook stoves and heating stoves that burn coal or solid biomass (i.e., wood and dried animal residues) produce indoor air pollution levels in millions of homes that lead to a variety of severe chronic and acute health 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.

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



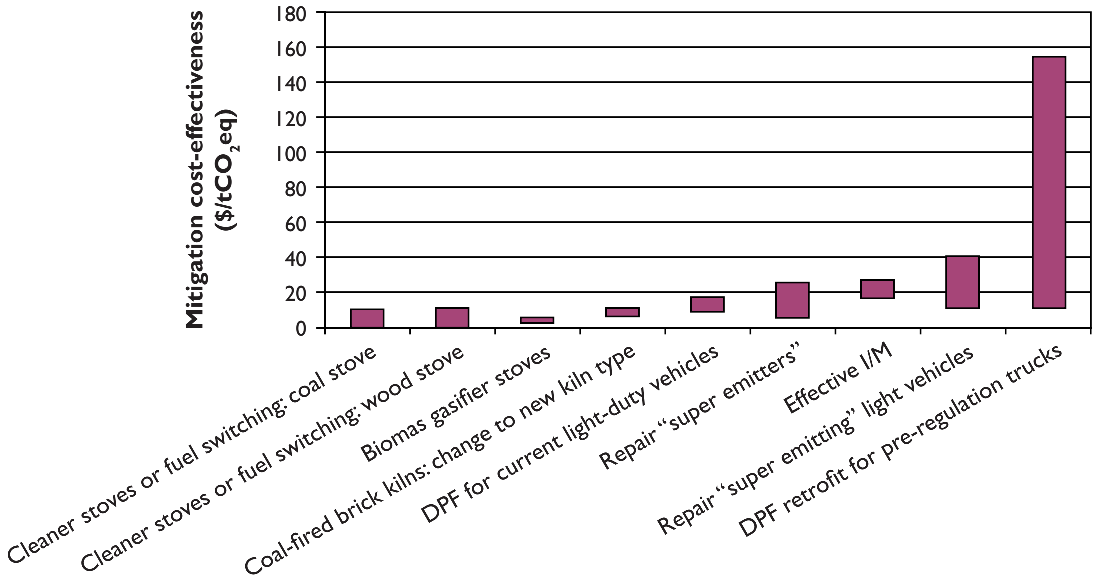
Note: BC = black carbon; OC = organic carbon
Source: Zhang et al. (2009)

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 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-

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).

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 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.

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