Chapter 9

Mitigation Approaches for Stationary Sources

9.1 Summary of Key Messages

- There has been a dramatic decline in BC emissions from industry in developed countries over the last century. Stationary sources in the United States now account for only 8% of the U.S. BC inventory; sources include industrial, commercial, and institutional (ICI) boilers; power plants; industrial processes such as cement manufacturing; and stationary diesel engines.

- Internationally, emissions from stationary sources account for about 20% of the global inventory, with highest emissions in China, the former USSR, India, and central/South America. Main sources are brick kilns, coke ovens (largely from iron/steel production), and industrial boilers.

- Available control technologies and strategies include direct $PM_{2.5}$ reduction technologies such as fabric filters (baghouses), electrostatic precipitators (ESPs), and diesel particulate filters (DPFs). Once installed, these strategies range in cost-effectiveness from as little as \$48/ton $PM_{2.5}$ to \$685/ton $PM_{2.5}$ (2010\$) or more, depending on the source category. However, they also may involve tens of millions in initial capital costs. Additional source testing data is needed to clarify the efficiency of these controls for removing BC specifically.

- Internationally, emissions from a number of source categories may grow as countries industrialize. Reducing emissions from smaller, inefficient facilities may require phasing out or replacing the entire unit, while larger facilities can apply many of the existing PM filter technologies already in commercial use. However, both of these options may be associated with substantial cost and implementation difficulties.

9.2 Introduction

Emissions of BC from stationary sources[1] generally represent a smaller portion of current global inventories than mobile sources and other source categories. As mentioned in Chapter 4, this is due in large part to a significant decline in industrial BC emissions from developed countries over the past century. These reductions have been achieved through improved combustion, shifts in fuel use, and application of control technologies to limit direct PM emissions. Although some uncertainty remains regarding the exact efficiency of these control techniques for reducing the BC fraction of $PM_{2.5}$ emissions, that uncertainty does not change the conclusion that emissions of BC from U.S. stationary sources are relatively modest in comparison to other key sectors of the national inventory. In contrast, stationary sources represent a larger fraction of international inventories, and in some regions these sources are key contributors to overall direct $PM_{2.5}$ emissions which adversely affect public health and the environment. Thus, continued mitigation of stationary source BC emissions domestically and internationally will lead to improved public health and will also provide climate co-benefits.

There are a number of relatively well-developed control technologies that have successfully been applied to reduce direct $PM_{2.5}$ (including BC) from stationary sources. This section discusses PM control technologies and strategies that are applicable to BC mitigation from domestic and international stationary sources. Where possible, it provides information about the applicability, performance, and costs of these approaches. Since these control technologies are well-established, much of this information is drawn from EPA and other control technology guidance documents developed for PM mitigation purposes.

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[1] The term "stationary sources" as used in this chapter refers to large and small industrial or combustion operations. It does not include residential fuel combustion for heating or cooking.

9.3 Emissions from Key Stationary Source Categories

The combustion of fossil fuels such as coal or oil is often the primary source of BC emissions at an industrial facility. In the United States and other developed countries, stationary source emissions of BC have been reduced substantially from historic levels. As discussed in Chapter 4, current emissions from stationary sources (including both "industrial sources" and "fossil fuel combustion" categories in the U.S. inventory) account for roughly 8% of the U.S. BC inventory (see Table 4-2). These emissions come from industrial, commercial, and institutional (ICI) boilers; power plants; and other types of industrial sources, such as cement manufacturing or stationary diesel engines used for many purposes including irrigation or oil and gas extraction.

Stationary sources account for a slightly higher percentage (20%) of total worldwide BC emissions, and more than 30% of BC emissions from contained combustion (i.e., sources other than open biomass burning) (see Table 4-6 and Bond et al., 2004). In certain developing world regions, such as China and India, stationary sources represent a very significant percentage of the BC inventory. The regions with the highest percentage of "contained" BC emitted from industry and power generation are China, the former USSR, India, and central/South America (Zhang et al., 2007). Key source categories include brick kilns, coke production/iron and steel production, and industrial boilers. As discussed in Chapter 7, however, BC emissions from industrial sources are expected to decline worldwide under most scenarios. This decline is anticipated to occur in developing countries as well as developed countries.

In the United States, direct emissions of PM and BC from stationary sources have been reduced significantly due to improved combustion efficiencies in industrial operations and implementation of federal and state clean air regulations over the past several decades. This declining emissions trend is expected to continue as further reductions will be needed to meet revised air quality standards and mitigate adverse effects on public health and the environment. EPA's modeled emissions inventory projections indicate that direct PM emissions from stationary sources are expected to decline by about 20% between 2005 and 2020. For example, sources in nonattainment areas will be required to implement emissions reduction strategies to help areas attain the 1997, 2006, and any future revisions to the $PM_{2.5}$ NAAQS. Certain facilities will also be required to comply with revisions to maximum achievable control technology (MACT) and new source performance standards (NSPS) for specific source categories. These standards will lead to control of some sources that currently do not have any PM controls; they will also lead to improved levels of control for certain sources that already have PM controls. Older power generation sources may be retired as well. However, in an overall sense, near-term BC emissions reductions from domestic stationary sources are expected to be modest when compared to expected reductions in other sectors, such as the mobile source category.

In general, stationary sources burning coal dominate the U.S. BC emissions inventory for stationary sources. However, many of these sources have high combustion efficiencies and have already applied substantial emissions controls. For example, nearly all large coal-fired EGUs have electrostatic precipitators (ESPs) or fabric filters for PM control. Estimates by the U.S. Department of Energy indicate that 76% of fossil-fuel steam-electric generating units in the United States (1,194 of 1,568) have some form of PM control—and those that do not are likely to be fueled by natural gas (USEIA, 2010). More than 80% of these sources operate ESPs, while about 14% have fabric filters. These control technologies are described further, below.

ICI boilers are a wide-ranging category of combustion units that collectively can burn a wide variety of combustible fuels, including coal, oil, natural gas, and biomass. There are thousands of ICI boilers across the country, varying in size from a few million Btu/hr for small commercial or industrial units to over 10 million Btu/hr for large boilers. Their operations range from intermittent to near-steady state. Most large units are covered under new regulations issued in April 2011 that include stringent standards for PM, mercury, and certain hazardous air pollutants, although EPA is currently reconsidering these standards.[2] Under the proposed reconsideration of this rule issued in December 2011, EPA has projected that the new emissions limits applicable to major source boilers and process heaters would reduce $PM_{2.5}$ emissions from these sources by 41,200 tons by 2014.

Stationary engines burning diesel fuels also account for substantial BC emissions. These engines are similar to mobile diesel engines and typically use the same fuels, but they can also operate using natural gas or heavier fuel oil grades than mobile diesel engines. They are used to perform a range of different tasks, such as pumping water or oil

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[2] The April 2011 final rule is available at *http://www.epa.gov/airquality/combustion/actions.html#feb11*. EPA issued a proposed reconsideration of this rule on December 2, 2011 (see *http://www.epa.gov/airquality/combustion/actions.html*), and expects to issue a revised final rule in 2012.

through pipelines, operating equipment in remote locations, or providing backup power generation.

Many other categories of industrial sources emit relatively low amounts of BC. In the current U.S. inventory, the "natural gas combustion" sector appears to have substantial BC emissions, but this is likely due to severe constraints on the data used to generate these estimates.[3] Given current knowledge of the utility and major source boiler inventory and the mechanisms of BC formation, EPA does not believe that there are significant BC emissions from natural gas combustion sources with good combustion practices. It is recommended that additional source testing and research be conducted to improve current emission factors associated with natural gas combustion. It is also recommended that additional source testing and research be conducted on the related category of oil and gas flaring (see additional discussion in section 9.7.4 below).

Another category of note is use of biomass for power and steam generation. While wood-fired boilers are currently a fairly small part of the U.S. inventory, there is the possibility that more stationary sources may increase their use of biomass as a fuel source with the intention of reducing their carbon footprint. To the extent that sustainable biomass becomes a more common source of fuel, BC emissions could rise in absolute terms if not effectively controlled. Fortunately, effective technologies are already available on the market that can control emissions from these sources, as described below.

9.4 Available Control Technologies for Stationary Sources

This section provides an overview of the main technologies for reducing $PM_{2.5}$ emissions from stationary sources. Several post-combustion PM control technologies have been in operation for many years and have been demonstrated to be quite effective in reducing $PM_{2.5}$. These technologies are also considered to be relatively effective at controlling BC because BC is a filterable component of $PM_{2.5}$. Many studies to date have assumed that $PM_{2.5}$ control technologies will reduce similar fractions of $PM_{2.5}$ and BC mass. However, it has also been recognized that reduction efficiency declines to some extent as particle size decreases (and BC particles are commonly smaller than 1 micrometer in diameter). For this reason, it is recommended that additional source testing and research be conducted on stationary sources to better understand control efficiencies for BC and to develop improved emission factors for specific source categories.

The two most effective control technologies for $PM_{2.5}$ (and therefore for BC) are fabric filters (sometimes called baghouses) and ESPs. Although there are other technologies used to reduce emissions of PM (such as cyclones and Venturi scrubbers), they are often designed to control larger particles (PM_{10} and larger), and therefore are considered to be less effective in terms of BC mitigation. EPA provides a thorough overview of the principles of operation, design variations, applicability, performance, and associated costs of fabric filters and ESPs in the 2002 EPA Air Pollution Control Cost Manual (see U.S. EPA, 2002b).

9.4.1 Fabric Filters

A fabric filter unit consists of one or more isolated compartments containing rows of fabric bags in the form of round, flat, or shaped tubes, or pleated cartridges. Particle-laden gas passes up (usually) along the surface of the bags then radially through the fabric. Particles are retained on the upstream face of the bags, and the cleaned gas stream is vented to the atmosphere. The filter is operated cyclically, alternating between relatively long periods of filtering and short periods of cleaning. During cleaning, dust that has accumulated on the bags is removed from the fabric surface and deposited in a hopper for subsequent disposal. Fabric filters are not recommended for boilers burning oil because particles from oil combustion are sticky and tend to clog the filter.

A properly designed and well run baghouse will generally have extremely high particle collection efficiencies (i.e., greater than 99.9%). Baghouses are particularly effective for collecting fine particles from power generation and a range of industrial facilities. For example, tests of bag houses on two utility boilers (Broadway and Cass, 1975; Cass and Broadway, 1976) showed efficiencies of 99.8 % for particles 10 µm in diameter and larger and 99.6% to 99.9% for particles 2.5 µm in diameter and smaller. Studies have shown that collection efficiencies greater than 99% can be achieved for particles less than 1 µm in diameter (NESCAUM, 2005; Buonicore and W.T. Davis (eds.), 1992). A recent report for the U.S. Forest Service on the applicability of different PM emissions control technologies to small wood-fired boilers found that mechanical collectors, such as multicyclones, were only modestly effective in reducing PM emissions, with an average of about

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[3] The current AP-42 emissions factor for BC from natural gas combustion is considered to be highly questionable. Bond et al. (2006b) indicated significantly lower emissions factors for industrial natural gas combustion than that published in AP-42. Bond reported an emission factor of 0.004±0.004 g PM per kg fuel, two orders of magnitude lower than the 0.21 g/kg found in AP-42.

15% control efficiency. In the Forest Service study, fabric filters achieved 74% reduction of $PM_{2.5}$, even with some of the uncontrolled flue gas circumventing the baghouse (Hinckley and Doshi, 2010).

9.4.2 Electrostatic Precipitators

An ESP is a particle control device that uses an electrical charge to move the particles out of the flowing gas stream and onto collector plates. Appropriately designed ESPs are effective at removing particles from sources operating at high temperatures and having large volumes of gas. They operate on many types of facilities that emit PM and BC. ESPs typically achieve greater than 99% PM removal efficiency (depending upon the design parameters of the specific unit), although the removal efficiency is generally lower for submicrometer size particles such as BC. Smaller particles are more easily carried by the gas stream, and therefore the ESP collection efficiency for very fine particles like BC is typically lower than the efficiency for removing larger particles (i.e. greater than 1 micrometer in diameter). In general, fabric filters are more effective than ESPs at removing BC.

To address the lower ESP collection efficiency on submicrometer particles, a hybrid PM collection system can be employed. Some designs place the baghouse downstream of an existing ESP to improve overall collection efficiency. Others integrate the ESP and baghouse components. This type of system can achieve 99.99% control of all particle sizes from 0.01 to 50 micrometers (Zhu, 2003).

Sources such as biomass combustors that also generate significant levels of condensable PM may benefit from wet ESP designs, in which the collector surfaces are washed with water (either continuously or intermittently) to clean the particles from the collectors. Tubular ESPs are most commonly used for operations where the PM is either wet or sticky (U.S. EPA, 2002b, Chapter 1). Typical applications include sulfuric acid plants, coke oven by-product gas cleaning (tar removal), and recently in iron and steel sinter plants. Because wood combustion systems in particular can produce PM that is sticky, tubular ESPs may be appropriate for use in small systems for reduction of PM and BC.

A relatively new technology known as an agglomerator can also be used in conjunction with a control device (such as an ESP) in utility or industrial applications. This technology is installed in the high velocity ductwork leading to the control device. It pre-treats the dust particles prior to entering the device, agglomerating small and large particles together, thereby making it easier for the control device to collect the larger particles. It has been shown to improve the ESP collection efficiency of very fine particles (less than 1 micrometer in size) by 75-90% (Truce and Wilkison, 2008).[4] There are a number of commercial installations of the Indigo Agglomerator technology in place; most installations are upstream of an ESP, but this technology has also been successfully operated in conjunction with a fabric filter or wet scrubber.

Wet particulate scrubbers are generally not appropriate for control of BC. Collection efficiencies for wet scrubbers vary with the particle size distribution of the waste gas stream. In general, collection efficiency for submicrometer particles is much lower than for ESPs or fabric filter systems. Submicrometer particle collection efficiencies for wet scrubbers typically are on the order of 50% or less, although cyclonic wet scrubbers may be able to remove as much as 75% of submicrometer particle mass (U.S. EPA, 2002b).

9.4.3 Diesel Particulate Filters and Oxidation Catalysts

There are more than a million stationary diesel engines in use today and together these sources have substantial emissions of PM and NO_x. For most diesel engines, BC is a significant component of untreated exhaust; these emissions can be reduced through DPF technology.

DPFs were originally developed for mobile engine applications (see Chapter 8). They include variations such as diesel particle traps and catalytic and noncatalytic soot oxidation systems. These units typically involve mechanical filtering of soot particles and a mechanism for oxidation of the soot to CO_2. This second step is sometimes referred to as regeneration, and eliminates the need for collecting and disposing of the captured particles. Catalysts are used to enhance the oxidation process. Depending upon the design and operation of the DPFs, removal efficiencies of between 40% and 99% can be achieved (van Setten et al., 2001).

To ensure optimal performance of DPFs and to avoid poisoning of the catalyst, the diesel engine should burn fuel with low sulfur content. DPFs have been identified by the California Air Resources Board (CARB) as a verified technology for stationary engines serving prime and emergency standby generators and pumps.[5] In some situations, such as where loads are not transient and exhaust

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[4] See also *http://www.indigotechnologies.com.au/agg_overview.php*.

[5] A summary of CARB-verified diesel emission control strategies is located at *http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm*.

temperatures are high enough, non-catalytic DPFs can be used with fuels having a higher sulfur content.

EPA issued new source performance standards in July 2006 (71 FR 39153) for new compression ignition (CI) stationary internal combustion engines. These standards implemented new restrictions on emissions of PM, NO_x, VOC, and CO as well as new limits on the level of sulfur permitted in diesel fuel. In June 2011, EPA further strengthened these standards, establishing stringent new performance standards for stationary CI engines with a displacement of 10 to 30 liters per cylinder (76 FR 37954), consistent with recent revisions to standards for similar mobile source marine engines.[6]

9.5 Cost-Effectiveness of PM Control Technologies

The cost-effectiveness of an emissions control device for a stationary source is often expressed in terms of dollars per ton of pollutant reduced. Factored into this amount are capital costs (amortized over several years) for design and installation of the control equipment, and annual costs for operating and maintaining the equipment. Because many emission standards for stationary sources to date have included emission limits for total filterable PM (as opposed to $PM_{2.5}$ or BC), many of the cost-effectiveness values found in published reports are expressed in terms of the cost per ton of reducing total PM. It has been noted earlier that we assume that BC emissions will be reduced with the operation of a fabric filter or ESP on a stationary source. However, it is acknowledged that actual control efficiencies for capturing submicrometer BC particles are uncertain, and they are likely to be somewhat lower than the assumed control efficiencies for total PM or $PM_{2.5}$. For this reason, additional research and source testing is needed to develop improved measurement techniques and development of robust emission factors for specific source categories.

The effectiveness of a given control technology used for a specific source category will depend not only upon the performance of the particular technology, but also upon the level of control that is already in place. For instance, most large coal combustion sources, such as EGUs, are likely to be well controlled to comply with prior PM emission standards. In contrast, smaller and older coal combustion units that have not been subject to similar emission standards may in some cases be able to reduce PM emissions for a lower dollar cost per ton because installation of the same technology will remove a greater mass of PM (including $PM_{2.5}$ and BC) compared to a well-controlled EGU. Therefore, some sources that have been completely exempt from PM control because of their age, small size, or limited operation (such as certain distillate oil or coal combustion systems) may present favorable mitigation opportunities. Thus, a reasonable and cost-effective mitigation strategy requires detailed knowledge of the sources and their emissions, on both a per-source basis and across the full population of those sources.

The 2002 EPA Air Pollution Control Cost Manual and several related 2003 control technology fact sheets provide typical cost effectiveness ranges for PM reduction by fabric filters and ESPs. The cost-effectiveness range identified for a fabric filter was $51 to $462 per ton (2010$); for an ESP it was $48 to $685 per ton (2010$).

Table 9-1 presents information on PM control cost ranges as adapted from multiple sources referenced in a 2009 NESCAUM report for ICI boilers (NESCAUM, 2009). Capital costs can vary significantly depending on the source specific characteristics. For some large utility boilers (500 megawatts), a fabric filter can require an investment on the order of $70 to 105 million (2010$) (NESCAUM, 2010). Cost-effectiveness values per ton are commonly higher for oil combustion units than for those burning coal or wood. In general, however, PM control technologies are well-established.[7]

The reduction of BC and $PM_{2.5}$ from industrial categories can provide significant public health benefits, particularly for communities located close to emissions sources. For example, recent regulations on different sizes of ICI boilers in the U.S. were estimated to provide $73,000 - $294,000 in health benefits per ton $PM_{2.5}$ reduced (2010$) (U.S. EPA, 2011a).[8] This suggests that controlling BC

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[6] In addition, the action revises the requirements for engines with displacement at or above 30 liters per cylinder to align more closely with recent standards for similar mobile source marine engines, and for engines in remote portions of Alaska that are not accessible by the Federal Aid Highway System. See *http://www.epa.gov/ttn/atw/nsps/sinsps/fr28jn11.pdf*.

[7] It should also be noted that control of PM and BC results in millions of pounds of particulates being captured and disposed of as solid waste; and in some cases it is discharged as part of wastewater discharges. The problems associated with disposal of coal combustion residues are well recognized, and it will be important to manage such wastes effectively in the future.

[8] For major boilers: $73,000 to $182,000 per ton of directly emitted fine particles (range from Pope to Laden, 3% discount rate, 2014 analysis year, 2010$). For area boilers: $122,000 to $294,000 per ton of directly emitted fine particles (range from Pope to Laden, 3% discount rate, 2014 analysis year, 2010$). See *http://www.epa.gov/ttn/ecas/regdata/RIAs/boilersriafinal110221_psg.pdf*, Tables 7-2 and 7-3.

Table 9-1. PM Control Costs for ICI Boilers. (Source: U.S. EPA, based on data from (NESCAUM, 2009). Costs have been updated to 2010$.)

Fuel Type	Technology	PM Reduction Potential	Size of ICI Boiler (mmBTU/hr)	Capital Costs (Million, 2010$)	Cost Effectiveness ($/ton removed, 2010$)	Reference
Coal	Dry ESP	90–99%	250	$3.5 – 47	$184 – 1,529	MACTEC (2005)
Coal	Fabric Filter	90–99%	250	$2.4 – 27	$498 – 1,183	MACTEC (2005)
Oil	Dry ESP	90–99%	250	$2.4 – 26	$2,739 – 24,715	MACTEC (2005)
Wood	ESP	99.5%	Medium	—	$239 – 344	STAPPA (2006)
Wood	Fabric Filter	99.5%	Medium	—	$173 – 293	STAPPA (2006)

emissions from industrial sources may be highly cost-effective and should remain a part of any overall BC reduction strategy.

9.6 Mitigation Approaches Other than PM Control Technologies

9.6.1 Process Modification/Optimization

As a product of the combustion process, BC can be reduced by approaches other than direct reduction using PM control devices. Process modification and/or optimization can be an effective means of reducing PM emissions. Some general examples of process optimization include reducing the frequency of mass transfer operations, improving operational efficiency, and the proper use of dust collection devices at the point of generation.

Cost values for these approaches are difficult to estimate. Often, steps to improve operational efficiency require only investments in instrumentation or operator training to yield ongoing reductions in fuel consumption and emissions of all pollutants, including BC. Changes in fuel can be more expensive and are incurred over the entire period in which they are used, but are dependent upon fluctuating and often highly localized market conditions. However, for many situations, particularly smaller boilers for which the costs of control technology investment and operation would make up a significant fraction of the system's initial capital and operating cost, conversion to fuels (such as natural gas) that generate lower PM and BC can be less expensive than use of post-combustion control equipment.

One specific example technique to reduce PM emissions for existing boilers is a boiler tune-up. Fuel usage can be reduced by improving the combustion efficiency of the boiler. At best, boilers may be 85% efficient and untuned boilers may have combustion efficiencies of 60% or lower. As combustion efficiency decreases, fuel usage increases to maintain energy output resulting in increased emissions. Lower combustion efficiency also results in formation of PM constituents like BC that are formed from incomplete combustion of the fuel. The objective of good combustion is to release all the energy in the fuel while minimizing losses from combustion imperfections and excess air. A tune-up can make a significant difference in energy consumption and emissions levels.

9.6.2 Fuel Substitution and Source Reduction Approaches for PM

The type of fuel and process has a great impact on PM emissions from combustion. Coal, oil, and natural gas are the most common fuels used. Of these fuels, coal combustion generally results in the highest PM emissions. As noted earlier, increased use of biomass fuels may also lead to higher BC emissions unless suitable control techniques are applied.

Fuel substitution can be an effective means of reducing PM emissions for many industrial fuel combustion processes that generate process heat or electricity. Switching to fuels that generate lower levels of PM and BC per Btu can be a viable alternative. In addition, fuel switching can lead to cleaner and safer unit operation. However, there are several factors to consider when evaluating whether fuel switching would be an appropriate option.

Fuel-switching can often be implemented for a lower capital investment than add-on control technologies. In some situations, the age of a boiler or space constraints may make fuel-switching more cost-effective. It is important to consider, however, that the lower capital cost must be weighed against a change in fuel prices, such as would be incurred by switching from coal to natural gas. The actual cost of converting to a different fuel that reduces BC emissions must account for the cost of installing the necessary fuel feed systems, fuel price differential, and changes in non-fuel maintenance and operational costs. Other considerations include the cost of extraction and associated environmental impacts. Even switching between types of coal can lead to additional capital costs in the event new coal pulverizers or a larger ESP is needed due to differences in coal hardness and fly ash resistivity.

Fuel substitution for the purpose of reducing BC emissions can also reduce emissions of SO_2, NO_x, and CO, depending upon the characteristics of the original and replacement fuels. A common conversion is from coal to natural gas, with coal to distillate oil an appropriate alternative. Switching from distillate oil to natural gas is also a possible approach for reducing BC emissions, but the reductions in BC for such a change will be less than when switching from coal to natural gas. Switching to natural gas from either coal or oil will likely result in significant SO_2 emissions reductions.

When considering fuel switching to reduce BC effects on climate, the impact on CO_2 emissions is obviously a consideration. Conversion from coal to natural gas will reduce CO_2 as well as BC. A further alternative may be to switch to a biomass-based fuel oil. The bulk of liquid biofuels appropriate for use in boilers is in the form of biodiesel, although there have been some evaluations of other biomass-based fuel oils developed specifically for use in boilers (Partanen and Allen, 2005; Adams et al., 2002).

9.7 Mitigation Approaches for Stationary Sources Internationally

As discussed earlier in this section, stationary source emissions of PM are generally considered to be well-controlled in most developed countries due to the operation of common control technologies such as fabric filters and ESPs. The picture is different in developing countries, where a number of specific industrial source categories have been identified as important contributors to BC emissions. The source categories of concern vary by country and region of the world. Mitigation opportunities exist in these countries and regions because known control technologies exist and have been demonstrated to be effective. This section will address the source categories that have been identified in the emissions inventories as being major contributors to BC emissions and for which known control technologies exist. The source categories are brick kilns, coke production/iron and steel production, power generation and industrial boilers, and oil and gas flaring.

9.7.1 Brick Kilns

Brick and masonry production in many developing countries (such as China, India, Bangladesh, Vietnam, Nepal, and Pakistan) has increased in recent decades in response to growing urbanization and increasing demand for construction materials. Currently, brick production is estimated to be growing at a rate of 4% per year.[9]

Conventional brick kilns (such as bull's trench, clamp, and intermittent downdraught kilns) generally are operated by small-scale ventures in rural areas, often with poor conditions for workers (French, 2007; Gupta, 2003). Low-quality coal and firewood are common fuels used in brick-making; in some cases, even waste fuels such as used tires are employed. These kiln designs have inefficient combustion, leading to high emissions of both greenhouse gases and PM (and associated local air pollution health effects). The inefficient operation of these kilns also leads to high fuel costs, and kiln operations have been found to contribute to localized deforestation when cheap firewood is harvested in lieu of purchasing more expensive coal to use as fuel.

The most basic BC mitigation technique is the replacement of inefficient kilns with kilns having improved, energy efficient designs, such as the vertical shaft brick kiln (VSBK), the tunnel kiln, or the hybrid Hoffman kiln (HHK). These kilns generally require less than 50% of the fuel needed for a conventional kiln (UNDP, 2007) and have been estimated to reduce PM emissions proportionally. Bond and Sun estimated that reducing emissions by switching to a more efficient kiln design can be cost-effective, in the range of \$6.5 to \$13 per ton (2010\$) of CO_2-equivalent (based on 20-year GWP) (Bond and Sun, 2005). China has taken steps over the past decade to promote the transition to the more efficient HHK in many areas. In Bangladesh, the United Nations Development Program initiated a \$25 million project in 2010 to implement 15 energy-efficient kiln demonstration projects over the next five years (UNDP, 2010).

Under a "business as usual" scenario, global BC emissions from brick kilns are expected to decline by about 11% (428 to 381 Gg) over the 2005-2030 time

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[9] See *http://www.resourceefficientbricks.org/background.php*.

period, reflecting a gradual introduction of more efficient kilns. However, the technical mitigation potential for this sector exceeds this projected reduction. Given the rapid rate of urbanization projected for coming decades in many countries, and the high fuel cost and significant health and climate impacts associated with uncontrolled brick kilns, appropriate policy options, technical assistance, and financial incentives could be considered to accelerate the transition to more efficient brick kilns.

9.7.2 Coke Production/Iron and Steel Production

Coke is a key input used in the production of iron and steel. In the coking process, coal is heated to very high temperatures for up to 36 hours in an airless furnace, and volatile carbonaceous gases are driven off. Modern plants minimize emissions by capturing the coke oven gas and using it in a separate chemical recovery process where it is refined into by-products and usually burned for heat production (RTI International, 2008). However, some small-scale plants located in developing regions or countries with economies in transition still do not capture the carbonaceous emissions from coke production. These plants in particular represent potential BC mitigation opportunities.

The global demand for coke and steel has increased significantly in the past two decades and is expected to increase significantly in the future. Bond et al. (2004) developed global emissions estimates for BC from coke production of 380,000 Gg, based on 1996 data (about 8% of estimated global "contained" emissions). It is acknowledged that this estimate was highly uncertain due to the lack of information regarding the number of polluting "beehive" or "indigenous" plants currently in operation globally. In the late 1990s, China was considered to have the largest coke production capacity of any country by far; and it continues to be responsible for more than 60% of global coke production (based on 2008 data) and more than a third of global steel production. Most coke production in China is conducted by state-owned enterprises. However, in 2004 it was estimated that smaller township and village enterprises operating less capital intensive "indigenous" plants were responsible for about 15% of the coke production in China; it is assumed that these smaller but uncontrolled plants are responsible for a majority of BC emissions from the industry (Dukan, 2010; Polenske and McMichael, 2002).

One mitigation option to reduce BC from coke plants is simply to phase out smaller uncontrolled operations. China has initiated policies to phase out certain plants with uncontrolled emissions, but the portion of the industry that has shut down or consolidated, and the extent to which emissions have declined to date, is not well characterized. Other standard mitigation options may be feasible depending on the size of the operation. Emissions generated during the "pushing" of coke from the oven to the quenching operation can be captured by a moveable hood system and then sent to a baghouse for control (with up to 98% PM reduction). Fugitive PM emissions can be minimized during other stages of the coking process with implementation of good combustion practices, frequent maintenance, and proper work practices. The use of a continuous opacity monitor on the combustion stack can help identify ovens that are in need of repair or maintenance (RTI International, 2006). BC emissions associated with larger coking operations could also be reduced via implementation of an energy recycling program to recover waste heat from the very high temperature coking process. The recovered heat would be converted to steam and used to power a generator which in turn would help provide electricity needed for plant operations, reducing the total amount of coal needed run the plant and the associated BC emissions (Polenske and McMichael, 2002).

Coke production and the iron and steel industry are important contributors to BC emissions in other regions as well. Bluestein et al. noted that emissions from uncontrolled blast furnaces in the former Soviet republics may have the potential to contribute to BC levels in the Arctic (Bluestein et al., 2008). However, additional information is needed to improve global inventories of BC from coke production. To the extent that existing sources in China and other coke producing nations are not recapturing exhaust gases, advanced technologies are readily available to reduce emissions significantly.

9.7.3 Power Generation and Industrial Boilers

The worldwide demand for energy is projected to increase substantially over the coming decades. The 2011 *International Energy Outlook* projects global energy demand to increase by 53% between 2008 and 2035. In countries outside the OECD, the increase in demand over this period is estimated to be 85%, while in OECD countries it is estimated to be 18% (USEIA, 2011). With this increased demand for power generation, increasing emissions of PM and BC can be expected unless actions are taken to implement energy conservation programs, to ensure high combustion efficiencies in power plants and industrial boilers, and to implement effective control technologies on new and existing facilities to the maximum extent possible.

Internationally, many sources of power generation (especially smaller power plants, industrial boilers, and stationary diesel engines) continue to operate without effective controls on PM and represent current opportunities for mitigation. In 2001, it was estimated that 20% of the power plants in China were operating without effective PM controls yet were responsible for 62% of the total $PM_{2.5}$ emissions from power plants. In addition, many industrial boilers in China are known to operate only wet scrubbers and cyclones, which are effective in capturing larger particles but have low fine-particle removal efficiencies (Zhang et al., 2007). In regions of the world where electricity from the grid is unreliable or not available, there is a substantial reliance on stationary diesel generators for power. For example, it is estimated that diesel generators in India account for as much as 17% of total power generation (USAID, 2010a). Diesel generators are also widely used in the Arctic region and contribute to BC deposition locally (Quinn et al., 2008). Since well-established control technologies are available to control emissions from these power generation sources effectively, additional emissions reductions can be achieved. However, further investigation is needed to determine the cost-effectiveness of control options in specific locations.

9.7.4 Oil and Gas Flaring

Natural gas is a byproduct of the oil extraction process and it is often treated as a waste gas and disposed of rather than captured for economic use. When not captured, it is either directly vented to the atmosphere or it is burned through a process called flaring. The combustion process during flaring can be inefficient and characterized by a distinct dark-colored, sooty plume. Oil and gas flaring and venting leads to significant emissions of greenhouse gases (especially methane) and a variety of other air pollutants, including BC, hydrocarbons and toxic air pollutants. Flaring can lead to significant health impacts on nearby communities. BC emissions from flaring are of particular concern if they can impact areas of snow and ice in the Arctic region.

Global estimates of pollutant emissions from flaring and venting are still quite uncertain. It has been estimated that globally the natural gas wasted due to flaring is about 5% of the total annual natural gas consumption. In 2002, the World Bank started the Global Gas Flaring Reduction initiative. Many countries are now self-reporting flaring and venting data. NOAA has also developed methodologies to estimate flaring activity through the use of satellite remote sensing data. Based on this information, the countries with the highest estimated levels of flaring are Nigeria, Russia, Iran, Iraq, and Angola (Buzcu-Guven et al., 2010). More work is needed to improve estimates of BC emissions from flaring. Mitigation of venting and flaring activities will be on ongoing challenge for the future. Reducing BC (and methane) emissions from flaring and venting activities would require expanded efforts to make use of the natural gas for power generation on site or to capture the gas so that it can be distributed and marketed. There are clear economic incentives for this. EPA is working with a number of governmental and private partners to address these issues through the Global Methane Initiative.

9.8 Technical and Research Needs

Emissions of BC from industrial sources, both domestic and international, currently represent a modest percentage of total BC emissions. In some regions, such as Asia, industrial emissions are more significant (almost a quarter of “contained” emissions) (USAID, 2010a). It is expected that over the next two decades, global emissions from the industrial category will become a greater percentage of “contained” global BC emissions as reductions occur in other sectors. The reduction of BC and $PM_{2.5}$ from industrial categories can be very cost-effective when considering the substantial health benefits they provide to local populations, in addition to broader climate benefits. For these reasons, controlling BC emissions from industrial sources should remain a part of any overall BC reduction strategy.

While this is the case, the emission factors and emissions inventories for key sectors are recognized by many experts to be uncertain, and there is a need to improve $PM_{2.5}$ and BC emission factors for industrial sectors. In some cases, only a few source tests may provide the basis for many emission factors. It is difficult to measure BC emissions that remain after control devices have treated the exhaust emissions because it is difficult to measure emission rates directly at the sources. BC emissions are extremely difficult to measure under real-world and field conditions. Our prior experience with PM control clearly indicates that some ultra-fine particles (BC and OC) are being captured in control devices for larger particles, but reduction efficiencies of control devices are generally considered to be lower for sub-micrometer BC particles than for total PM. To what extent is not well documented (Streets et al., 2001).

To help develop improved PM and BC emission factors, global inventories, and future year projections, additional source test information needs to be collected and evaluated for priority categories, both in the United States and abroad. This research would quantify the emissions of BC that pass through existing control devices into the ambient air, establish improved emission factors for different source categories, and assess the engineering modifications that can be made to these control techniques to enhance their BC capture capability. This could be facilitated by additional funding for technical and research programs, and greater collaboration between EPA, state governments, industry groups, academic institutions, and governments from other countries. Bilateral and multilateral assistance programs can also play an important role in evaluating the cost-effectiveness of BC control measures in priority world regions.