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Controlling PM2.5 in Chengdu: Analysis and Recommendations from the China, U.S. and California Experience

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Controlling PM2.5 in Chengdu:
Analysis and Recommendations from the China, U.S. and California Experience

by

Weijia Li

Abstract

Chengdu, China, is experiencing rapid economic growth and urbanization at a cost of serious air pollution problems. China has developed a series of policies to reduce PM2.5 emissions and to reform energy structure. However, problems exist which may prevent effectively implementation of the PM2.5 policies, include poor PM2.5 monitoring, isolated environmental management, lack of health improvement target, unclear consequence of non-compliance, and unequally distributed PM2.5 management.

This research reviews U.S. PM2.5 emission control technologies related to coal-fired boilers and iron and steel manufacturing industries, which represent major emission sources of Chengdu. Chengdu's choice of PM2.5 control technology should always consider its local characteristics. By learning the U.S. and California PM2.5 control experiences, their effective policy features are identified, include clear consequence of failure to compliance, strong states and local authorities, comprehensive monitoring and reporting system, health-based standards, and regional air quality management district. U.S. practice also shows innovative policy tools, such as technology standards, use of economic incentives, and cap and trade programs. These U.S. and California policy mechanisms can help to address problems and challenges existing in Chengdu and China's PM2.5 management.

Based on the analysis of the China, U.S. and California policies related to PM2.5, I make the following recommendation: develop integrated policy framework and giving stronger authority to environmental protection agencies; consider health effects as a qualification of the PM2.5 standards; establish comprehensive and accurate PM2.5 monitoring and reporting system; specify clear consequences for non-compliance and strengthening enforcement; divide provinces and big areas into regional air quality management districts by considering local characteristics; use technology-based emission standards to reflect emission limitation and performance; use economic incentives to drive emission reduction; and enhance public disclosure of information.

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1. Introduction

Over the past several decades, China has experienced rapid economic growth and extensive urbanization. Along with that are serious pollution resulting from energy, industrial, transportation sectors. Chinese government is facing challenges of maintaining economic development without compromising environmental quality. Severe haze weather that shrouds eastern and southwestern China arouses public panic to the villain—PM2.5. Chengdu is one of those PM2.5 polluted cities but few researches targeting at Chengdu's PM2.5 controlling are available. U.S. has more than 60 years of air quality management experience. Its comprehensive environmental legal framework and advanced control technology are worth learning. This paper reviews emission control technologies related to coal-fired boilers and iron and steel manufacturing and major national to regional government strategies regarding PM2.5 reduction in the U.S. The paper then discusses what Chengdu and China can learn from them, and evaluates feasibilities of control methods and regulations in the context of China and Chengdu. This report will conclude with recommendations for PM2.5 reduction program designs that could be implemented in Chengdu in support of a PM2.5 reduction target.

1.1. Definition of PM2.5

Particulate matter (PM) is mixture of extremely small solids and liquid droplets that are comprised of a number of components including pollen, dust, sulfates, nitrates, acid aerosols, ammonium, element carbon, carbon compounds and metals (EPA, 2009). Fine particulate matter (PM2.5) refers to PM with an aerodynamic diameter of less than 2.5 micrometers (μm). Chemical composition of PM depends on emission sources, locations, and weathers. PM2.5 can occur naturally from sources including volcanoes, dust storms and forest fires. However human activities significantly increase presence of PM2.5, which cause environmental and human health problems. Anthropogenic sources of PM2.5 include fuel combustion, on-road dust, biomass burning, coal-fired power plants, road and construction fugitive dust and residential wood combustion (Karmel & FitzGibbon, 2002). These anthropogenic process and activities result in both primary and secondary PM2.5 emissions. Primary, or direct, emissions are emitted directly from combustion and other sources, while secondary emissions are generated in chemical reactions between non-particulates such as sulfur dioxide (SO2), nitrogen oxides (NOx), volatile organic compounds (VOC) and ammonia (NH3). Emissions of these non-particulates are also associated with coal-fired power plants, fuel combustions and vehicles. PM2.5 is a key air pollutant in terms of adverse human health problems and serious environmental effects.

1.2. Health Effects of PM2.5

Extensive research has been focused on health effects of PM2.5 and more monitoring and analysis are underway. The health effects of PM2.5 are predominantly to the cardiovascular and respiratory system. In a comprehensive epidemiological literature review done by EPA in 2009, a substantial body of scientific evidence indicates that a causal relationship exists between short-term and long-term exposure to PM2.5 and cardiovascular effects (such as heart attacks and strokes), and a causal relationship is likely to exists between short-term and long-term exposure to PM2.5 and respiratory effects (such as lung disease and asthma).

1.3. PM2.5 Air Pollution in China

Over the past several decades, China has experienced rapid economic growth and extensive urbanization. Along with that are pollution challenges from energy, industrial, transportation and other sectors. One of sign of the pollution is an increase in low-visibility days, or hazy weather in eastern and southwestern cities in China (Che et al, 2008). In most recent years, the severe winter haze that shrouded eastern China aroused strong repercussions among Chinese government, citizens, domestic and international media (Turk, 2013; Wong, 2013, Tang & Hoshiko, 2013). On January 12, 2013, the U.S. Consulate at Beijing announced a PM2.5 reading of 755 microgram per cubic ($\mu g/m^3$) based on monitoring equipment of the consulate. The toxicity in the air was so high that was beyond upper end of "hazardous" level defined by EPA's 2012 Air Quality Index (AQI)—the level of 24-hour PM2.5 standard is set from 0 to 500 µg/m3. PM2.5 spike days appear frequently in recent years.

China's government has taken actions to address environmental problems by elevating environmental protection priorities to the highest level of policy. In 2012, China first ever sets PM2.5 concentration standards in national law. Also in 2012, the government issued "12th Five-Year Plan on Air Pollution Prevention and Control in Key Regions", which is the first time that China set ambient air concentration targets (MEP, 2013). The plan requires 3 key regions and 10 city clusters total including 117 cities to reduce ambient concentration of SO_2 and PM10 by 10%, NO_2 by 7%, and PM2.5 by 5% from 2011 to 2015. The government has also made steps to enhance regulatory and enforcement tools aimed at air pollution, for example operating permits, total emission control, higher fines and greater transparency. However, the government admits that it is very difficult to achieve the targets since emissions are difficult to slow down in a short period of time and clean air quality will require a major reconstruction in energy consumption.

1.4. Chengdu: Geography, Economy, and Air Quality

Chengdu, located west of the Sichuan Basin, is the capital city of Sichuan province (See Figure 1). It is one of the few inland megacities in the world. It has a population of approximate 14 million, ranked fourth most populous city in mainland China (Chengdu Bureau of Statistics, 2011). Chengdu is one of the most important economic, transportation and communication centers in western China. Fertile soil conditions and rich natural resources makes Chengdu a national agriculture base. Chengdu also holds an important position in the industry of China. Major industries comprise metallurgy, construction material, food, medicine, metal products, automobile, petrochemical, and electronic information.

However, due to topography surrounding Chengdu, along with reasons including huge amount of coal consumption, emissions from biomass burning, and increasing number of vehicles, Chengdu is suffering serious air pollution. A PM2.5 sampling done from 2009 to 2010 showed that the annual average PM2.5 concentration was $165 \mu g/m^3$, suggesting serious air pollution in the city (Tao et al, 2014). Five major sources of PM2.5 in Chengdu comprise secondary inorganic aerosols, coal combustion, biomass burning, iron and steel industries, and soil dust (Tao el al, 2014). PM2.5 sources in Chengdu are presumably dominated by local sources surrounding the Chengdu plain resulting from basin topography, which makes it unique comparing with those found in Beijing and Shanghai, where cross-boundary transport play a major role in contributing PM2.5.

Figure 1. Map of Chengdu, China

Picture from: http://chengdu.usembassy-china.org.cn/about_the_consulate.html

1.5. Research Overview

In spite of much scientific research conducted by academic institutions, and national and local regulatory strategies implemented by the government, air pollution in Chengdu is slow to improve. Therefore, innovative PM2.5 control methods and strategies employing the experience and strategies of other countries are worth investigating and practicing. This research reviews emission control technologies related to coal-fired boilers and iron and steel industries and major national to regional government strategies regarding PM2.5 reduction in the U.S. The research then analyses what Chengdu and China can learn, and concludes with recommendations for PM2.5 reduction program designs that could be implemented in Chengdu in support of a PM2.5 reduction target.

2. PM2.5 Air Pollution and Prevention Methods in China and Chengdu

Serious PM2.5 has significantly affects Chinese daily lives. Sources of PM2.5 varies in different locations, but common characteristics are found across the country. Coal burning, industrial emission, biomass burning and vehicle emissions are major PM2.5 sources in China. A large portion of PM2.5 from coal use indicates that an effective PM2.5 control will require a reformation of energy consumption. PM2.5 problem has been elevated to the highest level of policy. In 2012, China first ever sets PM2.5 concentration standards in the national law. Also in 2012, the government issued “12th Five-Year Plan” which is the first time that China sets ambient air concentration targets. National and local action plans have also published. However, several problems exist and needs to be addressed in implementation of PM2.5 control: most cities have short history of PM2.5 monitoring and different PM2.5 monitoring stations provides inconsistence of data; local environmental protection bureau has limited authorities in supervision and enforcement and local government tends to think short-term interests; PM2.5 reduction target sets in a conservative way which does not reflect the real compliance ability and the health improvement target ; failure of compliance and punishment is not clearly defined and not strictly implemented by local government.

2.1. PM2.5 Crisis in China and Chengdu

In recent years, heavy PM2.5 pollution has become a major environmental concern and a cause of social unrest in China. The growing concerns result from an increasing realization of negative health effects from fine particles and the significant impact of air pollution on people’s daily lives. The young and elderly were warned to stay indoors, schools were closed, and flights were suspended. A sharp reduction of visibility and growing haze weather in urban areas are one of the most evident signs of PM pollution (Che et al. 2009; Cheng et al. 2013).

PM2.5 is blamed for 8,571 premature deaths and 1 billion dollars of economic loss in Beijing, Shanghai, Guangzhou, and Xi’an—four of the largest cities in China, according to Greenpeace 2012 estimation. Heaviest pollution concentrates in Beijing-Tianjin-Hebei region and Yangtze Delta region. According to Greenpeace 2013 PM2.5 pollution rankings of major 74 Chinese cities, nearly 92% of these cities fail to reach the China's National Ambient Air Quality Standards (NAAQS)—annual average PM2.5 level below 35µm/m^3. 32 of these cities have an annual PM2.5 concentration two or more times larger than the standards. Of the top ten cities with highest annual PM2.5 concentration, seven of them are located in Hebei Province, which surrounds Beijing and produces one quarter of China's steel (Sheenhan et al. 2014). Chengdu ranks 15th of these cities, with an annual average PM2.5 of 86.3µg/m^3 and average maximum daily PM2.5 of 374 µg/m^3 (Greenpeace, 2014).

Table 1. 2013 Top 15 PM2.5 Polluted Cities in China

City	Province	Annual average PM2.5 level (µg/m^3)	Average of the maximum daily PM2.5 level (µg/m^3)
Xingtai	Hebei	155.2	688
Shijiazhuang	Hebei	148.5	676
Baoding	Hebei	127.9	675
Handan	Hebei	127.8	662
Hengshui	Hebei	120.6	712
Tangshan	Hebei	114.2	497
Jinan	Shandong	114.0	490
Langfang	Hebei	113.8	772
Xi'an	Shaanxi	104.2	598
Zhengzhou	Henan	102.4	422
Tianjin	Tianjin	95.6	394
Cangzhou	Hebei	93.6	380
Beijing	Beijing	90.1	646
Wuhan	Hubei	88.7	339

Chengdu	Sichuan	86.3	374

Source: Greenpeace, 2014

2.2. Sources of PM2.5 in China and Chengdu

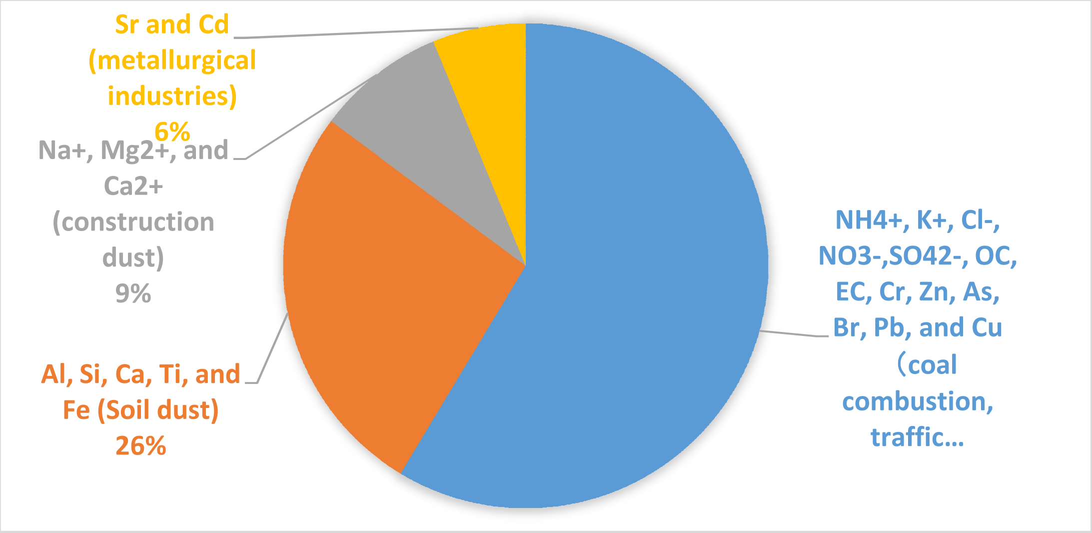
For pollution control measures, having an inventory that quantitatively shows sources of emissions, for example source apportionment, is crucial. However, a national level PM2.5 inventory has not been published officially. Most research projects are focused on PM2.5 emissions in a single location or area. Local studies are conducted because primary sources vary in different locations, and because secondary PM2.5 emissions are strongly influenced by local meteorology as well as sources of pre-cursor emissions. Beijing, Yangtze River Delta, and Pearl River Delta have become the hot spots where most source apportionments are conducted (such as Dai et al. 2013; Song et al. 2006; Xu et al. 2012; Zhang et al. 2013; Zhao et al. 2013; to name a few). Although chemical composition of emission vary in different locations, common characteristics are found across literature. Primary emissions including coal combustions, industrial pollution, biomass burning, and vehicle emissions and secondary emissions of SO_2 and NO_x are dominant PM2.5 sources in China.

Chengdu's PM2.5 source analysis is mainly based on two studies conducted by Tao et al. (2013 & 2014). Figure 2 and 3 provides source analysis of two studies. Both studies indicate that coal combustion, biomass burning, and soil and construction dust are primary PM2.5 sources, although they have contradictory statements contribution of vehicle exhaust. The 2013 study considers vehicle exhaust as one of the major PM2.5 emission sources in Chengdu (although stationary sources are more important than vehicle emission), while the 2014 study does not. The possible cause of this difference may be that two analysis uses different classifications of PM2.5 sources. The 2013 study emphasizes on chemical composition analysis while the 2014 study provides more accurate source apportionment. The 2013 study lays out all chemical species in PM2.5 samples and groups those with high loadings (NH_4^+, K^+, Cl^-, NO_3^-,SO_4^{2-}, OC, EC, Cr, Zn, As, Br, Pb, and Cu) as major sources of PM2.5. Because these chemical species are indicators of coal combustion, traffic exhaust, and biomass burning, the analysis infers that they most important sources of PM2.5 in Chengdu. The 2014 analysis categorizes PM2.5 sources into six main sources—secondary inorganic aerosols, coal combustion, biomass burning, the iron and steel industry, Molybdenum-related industries (the analysis identifies a specific Molybdenum source but call further investigation of which specific industry it belongs to), and soil dust. Traffic emissions might be incorporated into other emission sources since secondary emission of PM2.5 result from oxidation of precursor gases (SO_2 and NOx) emitted from vehicle emissions. Lack of data and inconsistence of data make the source apportionment inaccurate and call for more monitoring and analysis.

In Tao's 2014 study, PM2.5 in Chengdu shows distinct seasonal variation which is high in spring and autumn due to burning of straw and other crop residue, and high in winter as enhanced secondary inorganic aerosols formation under favorable temperature (see Figure 4). Waste crops produced in harvest seasons are habitually burned outdoors. Biomass fuels are often used for cooking in rural areas in China.

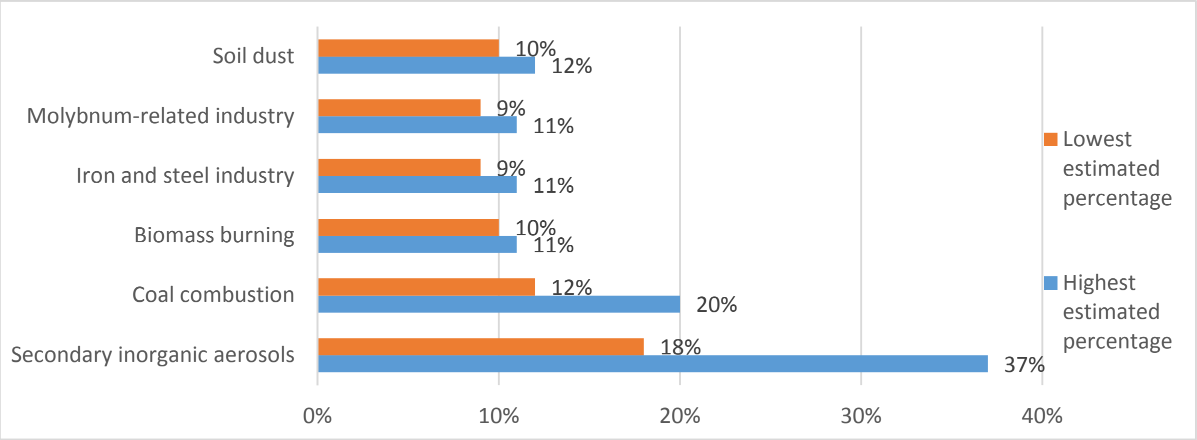
In China, PM research is not evenly distributed. Most research projects are located in cites and areas that have greatest economic power and highest GDP. Much fewer analysis of Chengdu's PM2.5 are found than those of Beijing and eastern cities. A national PM2.5 source apportionment in China has not been developed. Besides, researches that conducts source apportionment use different models and methods to identify and quantify PM2.5 characteristics, which makes it hard to summarize and compare among those researches. An effective PM2.5 control cross the country need massive local analysis conducted using the same methodology to compile a national picture of PM2.5 source apportionment. Na^+, Mg^{2+}, Ca^{2+}

Figure 2. Chemical composition of Chengdu's PM2.5



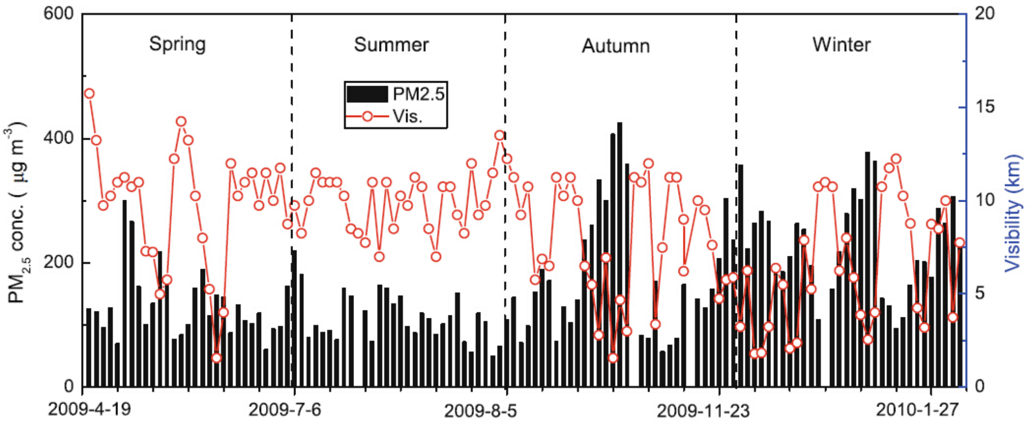
Source: Tao et al. 2013

Figure 3. PM2.5 emission sources in Chengdu



Source: Tao et al. 2014

Figure 4. Seasonal variations of PM2.5 concentrations and atmospheric visibility



Source: Tao et al. 2014

2.3. Energy consumption in China and Chengdu

Heavy PM2.5 pollution in China indicates economic growth that are mainly dependent on fossil fuels (Figure 5. Energy Consumption in China, 1978-2012). To make an improvement in air quality, a transformation of energy system is necessary. China has developed radical policy in cutback of coal consumption and promotion of renewable energy (details in Chapter 3.). But the question remains that whether the shift to natural gas and renewables is able to meet increasing energy demand (Sheehan et al. 2014).

Coal, as the leading energy source in China, does not only contribute to PM but also other air pollution sources, especially CO2. China's CO2 emission has far surpassed U.S. to be the largest CO2 emitter in the world (Sheehan et al. 2014). In China, use of poor quality of coal and lack of clean coal technology even worsen the air pollution (Hu & Jiang, 2013). CO2 is an important greenhouse gas causing climate change. Harvard scientists said it is possible that climate change can downgrade any government's efforts in air pollution and even worsen air pollution in China (Tatlow, 2014). The hypothesis is, as the earth warms, Siberian High that influences China weakens, and there is less wind to blow away the smog and less rainfall to clear the air. The potential influence of climate change make it necessary to incorporate PM and climate change policies.

In Chengdu, coal and natural gas are the primary energy sources (See Table 2). In 2013, natural gas has surpassed coal in quantities to be the largest energy source, thanks to abundant resource available in the Sichuan Province. Mr. Yang, researcher at Chengdu Environmental Protection Bureau, said in the interview that hydro power also play an important role in the city, but data of hydro power is available at this point. Figure 6 shows energy consumption of the Sichuan Province. Chengdu is the major energy consumer in the province where most industries and buildings are located in. In the province, coal represent about 62 percent of energy consumption.

Figure 5. Total Energy Consumption in China, 1978-2012

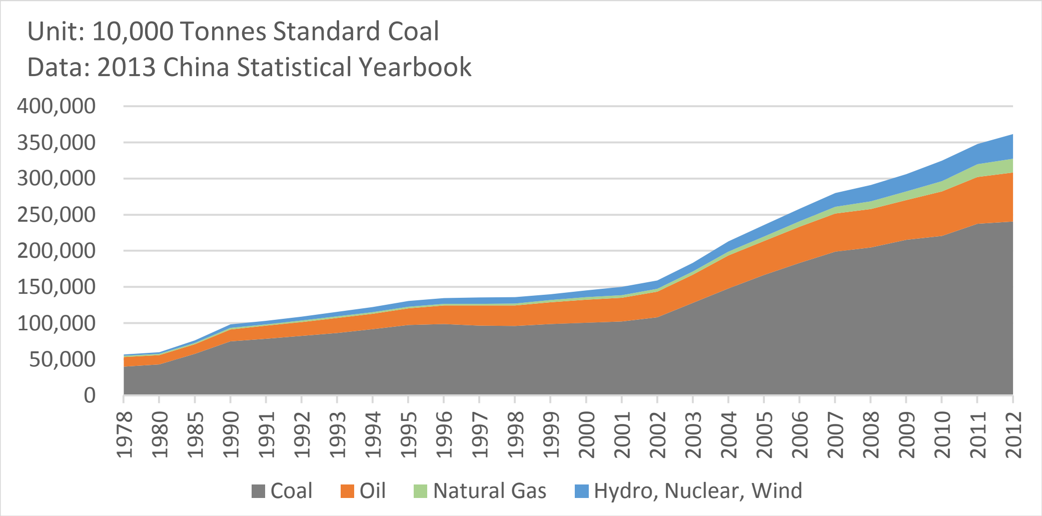
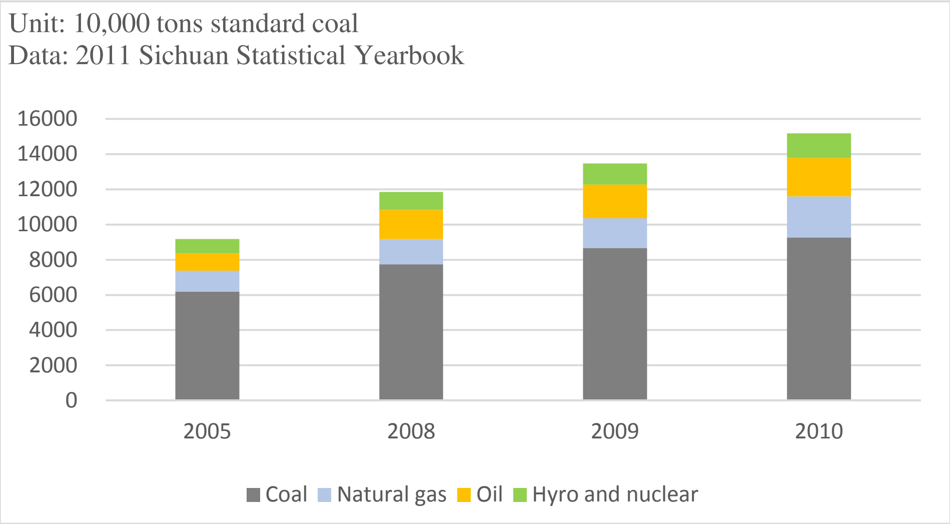


Table 2. Energy consumption by fuel in Chengdu, 2010-2013

Fuel type	**2010**	**2011**	**2012**	**2013**
Coal **(10,000 tonnes standard coal)**	676.40	809.39	681.27	584.25
Natural gas **(10,000 tonnes standard coal)**	540.50	554.61	602.09	662.34
Oil **(10,000 tonnes standard coal)**	229.35	245.06	286.95	292.80

Source: Chengdu EPB, 2014

Figure 6. Total Energy Consumption in Sichuan Province, 2005-2010



Note: Data of 2006 and 2007 is not available.

2.4. China's PM2.5 Policy

Ministry of Environmental Protection (MEP) is in the highest administrative unit of the Chinese government that is responsible for sketching national environmental strategies, laws, and regulations. MEP is authorized by the State Council to implement and enforce environmental laws, to guide local government on monitoring of pollution, to coordinate and participate in investigation and handling of emergencies and extremely large accidents, and to publish national environmental reports and information. Under the MEP are local government agencies constituted by provincial, prefecture (referred as city in this paper) and county environmental protection bureau, from high to low level. Each level of bureau make its own environmental regulations and plans besides complying with those from higher level of bureau.

Environmental management functions are distributed in multiple government departments, not only in the environmental protection bureau. Chengdu Environmental Protection Bureau (EPB) is mainly responsible for monitoring and regulating industrial emissions (P. Yang, Personal Communication, October 15, 2014). Other government departments are responsible for other pollution sources, depending on the source of pollution. For example, construction site dust is in the charge of the Chengdu Commission of Housing and Urban-Rural Development; on-road dust is in the charge of the Chengdu Bureau of City Administration and Law Enforcement; dust from land to be built is in the charge of the Chengdu Bureau of Land and Resources. Punishment and enforcement in a specific company or factory is usually implemented by the county bureau. The municipal bureau will participate in more important and serious pollution incidents, while the provincial bureau will participate in extra serious incidents. But extent of authority is blurred, which sometimes causes overlapping and clash.

Realizing the adverse environmental and health effects of PM2.5, multiple programs have been launched to prevent and control PM2.5 and its precursors, and more new programs are proposed and piloted. However, it may take years and require continuous investment to see improvement in air quality since pollution is so severe in China and fast economic growth has come at the cost of environmental degradation. Periodical revision of these programs are necessary since emission control technologies keep updating and legal framework changes. The following section introduces three major PM2.5 regulations in China—National Ambient Air Quality Standards (2012), The Twelfth Five-Year Plan on Air Pollution Prevention and Control in Key Regions (2012), and The Air Pollution Prevention and Control Action Plan (2013).

2.4.1. China's NAAQS

On February 2012, the State Council passed the new version of NAAQS (MEP, 2012). The standards was first published in 1982 and the last revision was in 2000. 1982 standard prescribed SO_2, CO, NO_x and total suspended particulates. PM10 standard was set in the 1996 and monitoring of PM10 started in some cities. The 2012 standard prescribes the first-ever limits for PM2.5—annual average concentration is 35 $\mu g/m^3$ and 24-hour average concentration is 75 $\mu g/m^3$.

PM2.5 monitoring in most Chinese cities are developed after new NAAQS (Liu et al, 2013). It means long-term track of PM2.5 in most cities are not available. It is difficult for a city or a county to make an implementation plan without a large-scale of monitoring data. Based on existing data and the fact of frequent occurring spikes of heavy PM2.5 pollution, meeting NAAQS places challenges on many Chinese cities. Many of them are far exceeding the standards.

It should be noted that the new NAAQS group residential, commercial, industrial and rural areas in a same category. It means all these areas obey the same air quality standards. It's obvious that these areas have different air quality, even close to each other, which might be influenced by topography, distance to the emission source, and climatic characteristics. For example, downwind and surrounding area of a coal power plant might have higher concentration of PM2.5 than that in upwind area. In addition, there are seasonal variation of

PM2.5 (Tao et al. 2013). Overall, NAAQS is a general and broad air quality requirement widely applied in China.

2.4.2. “Twelfth Five-Year Plan”

China’s Five-Year Plan is a centralized plan for economic development that sets direction and targets. In December 2012, MEP issued its “Twelfth Five-year Plan” on Air Pollution Prevention and Control in Key Regions (referred to “the Plan”, MEP, 2012). The Plan is valid from 2011 to 2015. It is the first time the environmental problems are elevated to the priority of government tasks. The Plan covers 3 key regions (Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta) and 10 city clusters constituted by 19 provinces and 117 cities. Chengdu is included in the Plan as a city cluster with Chongqing. These areas contribute about 70% of China’s GDP and more than half of coal consumption, although covering only 14% of country’s land area. The Plan sets both air quality concentration targets and pollution reduction targets (Table 2 & Table 3).

The key idea of the Plan is to reform China’s energy consumption by increasing energy efficiency and switching from coal to clean energy: banning new coal power plants and new high-pollution projects including iron & steel, coking, and building material; placing more stringent regulations and controls on existing industry; accelerating elimination of obsolete production capacity; developing and improving more infrastructure of natural gas and renewable energy. Other guidelines related to PM2.5 include strengthening fugitive dust management and supervision of straw burning, for example, requiring dust control plan, forbidding open construction field, developing straw utilization plan, increasing fire point monitoring, etc. Beyond that, PM2.5 levels can be lowered by guidelines targeting precursors (SO_2 and NO_2) of fine particulates.

The Plan emphasizes importance of developing monitoring systems and improving information disclosure. However, there is only one more year until the end of the Plan and monitoring systems has not been set up across the country. Lack of data still places a major obstacle on local government to make an effective strategy and test effectiveness of previous strategies. Local environmental bureaus, universities, institutions, NGOs and U.S. Embassy have their own monitoring stations, respectively. All the data should be integrated into a map of China's PM2.5. Big cities like Beijing and Shanghai utilize most academic resources and learn information and foreign experience faster than other cities. Cities should always communicate and share their information.

Table 3. Ambient Air Quality Concentration Targets for Key Regions and Cities, 2011-2015.

SO2	NO2	PM10	PM2.5	PM2.5 (in three key regions)
10%	7%	10%	5%	6%

Source: MEP, 2014

Table 4. Emission Reduction Targets for Key Regions and Cities, 2011-2015.

Total emission reduction targets	SO2	NOx	Industrial PM
National targets by 2015	8%	10%	No target
Targets in key regions by 2015	12%	13%	10%

Source: MEP, 2014

2.4.3. Air Pollution Prevention and Control Action Plan

Under the request of The Twelfth Five-Year Plan, the State Council published the Air Pollution Prevention and Control Action Plan (referred to "the Action Plan") in 2013. The Action Plan is in accordance of The Twelfth Five-Year Plan's goal of emission reduction, except that it applies across the country (the Twelfth Five-Year Plan on Air Pollution Control applies to specific regions and cities in China). By 2017, PM_{10} concentration in urban areas are required to decrease by 10% at 2012 level. The Action Plan does not specify national reduction target for $PM_{2.5}$.

Similar to the Twelfth Five-Year Plan, the Action Plan emphasizes emission reduction and energy restructuring. To be specific, for example, coal-fired boilers with size below 10 tons of steam per hour will be phased out in urban area and new plants with size smaller than 20 tons per hour will be forbidden by 2017. Coal cap programs will be strengthened by prohibit burning of poor quality coal and usage of high polluting fuel. New incentives of emission reduction are introduced: publishing cities with best and worst air quality monthly; regarding implementation of PM as part of the performance evaluation indicators for government leaders.

The targets of the Action Plan are conservative, given that the PM2.5 concentration target for Beijing—60 µm/m^3 is still almost twice higher than the China's NAAQS and that PM targets for the rest of cities are unclear. In addition, the Action Plan requires to reduce coal usage to 65% of total energy consumption by 2017, despite the fact that coal consumption account for 66.6% of that in 2012.

Combined with situation in Chengdu, Chengdu EPB released Chengdu's Air Pollution Control and Prevention Action Plan of 2014 to 2017. By 2017, there will be evident air quality improvement and reduction of heavy pollution periods. PM2.5 concentration will reduce 20% at 2013 level. Based on Greenpeace's 2013 Chengdu annual PM2.5 record (86.3 µm/m^3), Chengdu is hoping to lower PM2.5 concentration to 69.4 µg/m^3. Comparing with NAAQS (35 µg/m^3), and it's still high enough. Chengdu's Action Plan also sets specific PM2.5 concentration targets for each counties and districts. But again, the target is unclear, as they require percentage reductions in PM2.5 concentration compared with a base year. However, the annual average PM2.5 concentration in all of these counties and districts has not been disclosed by the government, and may not even exist because PM2.5 had not been monitored until 2012 when PM2.5 was first included in NAAQS. Daily Air Quality Notice on the official website of Chengdu EPB is supposed to release daily PM2.5 concentration. But instead, the Notice shows a number named Air Quality Index telling a broad level of pollution—good, moderate, hazardous, extra hazardous, while the criteria to determine the pollution level is not well defined there.

Under the request of National Action Plan, Chengdu's Plan identifies key companies and factories that required strengthened monitoring and inspection. Responsibilities of related government departments are defined. Chengdu will also establish warning and emergency response plan. A 24-hour and 72-hour air pollution forecast warning system will be established.

In 2013, Beijing has already released emergency measures named Beijing Heavy Air Pollution Contingency Plan. Beijing's Plan establishes warning system comprising of blue, yellow, orange and red alerts while the red is the most hazardous air pollution. The emergency measures include closure of schools, factory operation suspended, bans on cars entering the city. However, the alerts won't be activated until three days of PM2.5 exceeding 300 $\mu m/m^3$.

2.5. Co-benefits of PM2.5 Policy

PM2.5 prevention and control methods aim to improve air quality and safeguard public health in China. The key strategy among PM2.5 control measures is energy reform by shifting coal to renewable energy. Coal burning not only creates PM2.5 and its precursors, but is also the major source of CO2 in China. In an UNEP's report on the benefits of climate and air quality, regional implementation of carbon and ozone reduction can result a worldwide reduction of temperature, about 2.4 million fewer premature deaths, and about 52 million tonnes of crop losses avoided (2011). Clean Air Alliance of China (CAAC) suggests that coal cap programs in the Action Plan can significantly improve air quality and reduce green-house gas emissions. It is estimated that by 2017, nine key provinces representing the most coal intensive areas in China will reduce 426 million tons of coal use, and 605 million tons of carbon. But CO2 emission co-reduction effects varies from different coal substitution approaches: backward capacity elimination and replacement of renewable energy bring the strongest co-benefits, while using natural gas to replace coal will add cost of gas transferring (CAAC, 2014).

2.6. Analysis of design and implementation of PM2.5 policies

China's government has sought to address air pollution challenge by prescribing PM2.5 standards, setting PM2.5 emission reduction targets and employing more powerful regulations. But it is important to recognize problems existed that may prevent implementation of these targets and regulations. This research identifies following problems that need to be addressed in the future PM2.5 emission management:

- **Poor PM2.5 monitoring and reporting**

PM2.5 monitoring system has not been introduced in most cities across the country before the new NAAQS first defined PM2.5 limits (Liu et al. 2013). National and local PM2.5 prevention plan set their pollution reduction plan. But without a sound PM2.5 monitoring system, it's hard to evaluate consequences of the measures and to make plan for the future. PM2.5 monitoring data from different sources (e.g. EPB, U.S. Embassy, universities, NGOs) are often inconsistent, such inconsistence can lead to considerable deviation in real PM2.5 estimation. Lack of data and inconsistence of data can also allow cities to use "little tricks", for example making up PM2.5 progress, because there is not enough data to evaluate performance of measures. In addition, researches that conducts source analysis based on existing monitoring data use different models and methods to identify and quantify PM2.5 characteristics, which makes it hard to summarize and compare among those results.

- **Isolated environmental management**

Supervision of PM2.5 emission involves in several government departments other than EPB. In Chengdu, EPB is only responsible for PM2.5 emission from industrial operation. Energy departments only focus on energy issues and assume environmental protection bureau will take care of the environmental problems. But environmental agencies are not given sufficient authority to engage in the energy policy. The extent of authority is blurred, which causes overlap, clash, or even blank space in duty. Environmental agencies should have stronger authority on environmental supervision and enforcement and strengthened coordination. Most other departments still place economic growth as priority because that is the source of their income. The Twelfth Five-Year Plan does not only set targets on air quality improvement but also set targets on economic growth. Besides, local government works on local environmental issues only, making it hard to solve regional pollution problems (CAAC, 2011).

- **Lack of long-term target of health improvement**

Most targets and plans are short-term, based on four- or five-year time period. Action

Plan will push reduction of PM2.5 emission cross the country. But in most serious polluted Chinese cities, achieving targets does not mean air quality is satisfying. For example, if Chengdu is able to reduce 20% of PM2.5 concentration at 2013 level by 2017, its annual average PM2.5 concentration will be 69.4 μm/m^3, doubling national 35 μm/m^3 limit. Besides, PM2.5 is regulated concerning its adverse health effects. But in China, PM2.5 reduction targets are conservative which take into account economic cost and do not completely reflect health requirements. Making progress in achieving the targets aren't sufficient to meet health improvement goal.

- **Unclear consequence of failure to achieve targets**

National and local PM2.5 plans do not clearly defines the consequences of failure to achieve targets. This lack of consequences might cause government officials and companies to take a passive attitude towards PM2.5 control. MEP and EPBs should be given stronger authority to enforce against failure to meet standards and targets, including influence over government officials' evaluations, regional project approval limitations and other tools (NRDC et al. 2009).

- **Unequally distributed PM2.5 emission management**

In Chinese cities that have highest GDP and most academic power such as Beijing, Shanghai and Guangzhou, massive researches about PM2.5 control have been conducted and the more stringent policies have been placed on industries and transportation. But in Chengdu, limited researches on local PM2.5 control are found. What's more, due to extremely air pollution in these first-tier cities, they are transferring plants and factories to second-tier cities like Chengdu. Air pollutions are also transferred. Governments pursuing economic development sees immediate interests at cost of environmental degradation.

3. PM2.5 Control Technology of Major Sources：U.S. Experience

PM2.5 control technology is widely used in industry processes. In Chengdu, coal burning （mainly coal-fired boilers) and iron and steel manufacturing are major industrial PM2.5 emission sources. This chapter reviews U.S. technical options of controlling PM2.5 from coal-fired boilers and iron and steel manufacturing. The technologies reviewed do not include all available technologies since technology keeps upgrading and advancing. It also should be noted that coal-fired boilers and iron and steel industry do not represent all PM2.5 sources of Chengdu, although they do account for a large portion of total emission. Chengdu's choice of PM2.5 control should always take into consideration of local characteristics.

3.1. Boiler technology

A boiler is a closed vessel in which fuel is combusted to generate steam (STAPPA & ALAPCO, 2006). Steam is used to provide heating and produce electricity. Particulate matter is produced during coal combustion process. In China and Chengdu, coal-fired boilers are dominate boiler type and are contributing large quantity of PM2.5 and its precursor gases.

The following section reviews three technical options of controlling PM2.5 from boilers: fuel switching; coal washing; and using combustion and post-combustion control technologies. Switching to a cleaner-burning fuel can reduce PM2.5, SO_2 and NO_x emissions before combustion. Coal washing can remove impurities (such as sulfur) and to increase coal's heating value (STAPPA & ALAPCO, 2006). Control technology can be used to reduce emission during and after combustion.

3.1.1. Fuel switching

Fuel switching can be an effective strategy of PM2.5 control. For instance, use of lower-sulfur coal to displace higher-sulfur coal can reduce more than 70 percent of SO_2 emissions per unit (STAPPA & ALAPCO, 2006). However, a boiler may not be applicable to all kinds of fuels and boiler performance may be affected. Fuel switching may require significant investment on modification and retrofitting of existing boilers and plants. Availability of substitution may place an additional cost of fuel. Therefore, the feasibility of fuel switching is case-by-case, take into consideration of characteristics of the boiler and cost of substitutions.

Emission reduction effectiveness of different substitutions varies. Table 1 provides EPA estimates of potential PM2.5 emission reductions for switching from bituminous coal or subbituminous coal to oil and gas.

Cost of fuel switching depends on cost of modification of the existing facility and purchasing substitute fuel (EPA, 1998). Retrofitting and modification of the combustion process are unique to each type of boiler. But generally, switching from coal to coal is less costly than switching from coal to natural gas or oil. Switching to a fuel that is much more expensive than the fuel which is currently use can also increase cost drastically.

Table 5. Potential PM2.5 Emission Reductions with Fuel Switching

Estimated PM2.5 Reductions with Replacement Fuel (percent of reduction)					
Sector	Original Fuel	Switch to Subbituminous	Switch to Residual Oil[1]	Switch to Natural Gas	Switch to Distillate Oil[2]
Industrial[3]	Bituminous Coal[5]	21.4	7.4	93.1	99.1
	Subbituminous Coal[6]	--	--	91.2	98.9
Utility[4]	Bituminous Coal	21.4	14.8	97.5	--
	Subbituminous Coal	--	--	96.8	--

Source: EPA, 1998

1. Assuming ash content of 0.03% by weight and sulfur content of 2.5% by weight.
2. Assuming ash content of less than 0.01% by weight and sulfur content of 0.22% by weight; typically not used in utility boilers.
3. Based on emission from dry bottom boilers.
4. Utilities tend to operate more efficiency than industrial units and have longer resulting PM2.5 emissions.
5. Assuming ash content of 8.6% by weight.
6. Assuming ash content of 5.2 by weight.

3.1.2. Coal washing

Coal washing is a process of removing ash and sulfur from coal by crushing the coal and separating the different components in a liquid (STAPPA & ALAPCO, 2006). Coal particles are lighter and will float on the top of the liquid for collection, while impurities are heavier and will sink to the bottom for removal. Amount of ash and sulfur that can be removed depends on type of coal and the washing process used. However, disposal of waste water produced in coal washing place a major undertaking. Coal washing can also increase heating value, or the amount of heat released, of the fuel, thus reducing PM2.5 produced per unit of energy.

3.1.3. Combustion and Post-Combustion Control technology

Boiler control technologies can be divided into two basic categories: combustion controls and post-combustion controls (STAPPA & ALAPCO, 2006). Combustion controls are process of reducing formation of NOx during combustion. The most common technologies used on coal-fired boilers are low-NOx burners (LNBs) and over fire air (OFA), used alone or in combination. Post-combustion controls are capturing or converting emissions before releasing to the air. The most common technologies used in coal boilers include selective catalytic reduction (SCR) for NOx control, flue gas desulfurization (FGD) or scrubbers for SO_2 control, and fabric filters and electrostatic precipitators (ESPs) for PM control. Industrial and commercial boilers and boilers used for electric generating units (EGU) use similar control technologies. Appendix 1 and 3 provides list of control technologies for industrial, commercial, and EGU boilers.

LNBs reduce NOx either produced at high-temperature combustion (thermal NOx) or bounded to the fuel (fuel NOx). Flame temperature are lowered when using LNBs to prevent formation of NOx. LNBs are installed on more than 75 percent of U.S. coal-fired boilers. Use of LNBs on coal-fired boilers is estimated to reduce about 50 percent of NOx with a cost-effectiveness of \$400-\$3000 per ton of NOx removed (STAPPA & ALAPCO, 2006).

OFA, or staged combustion, reduce NOx formation by lowering the combustion temperature in the boiler too but using different approach. OFA transfers a portion of the combustion air from the burners to the region above the burner. It is usually paired with LNBs. OFA alone can reduce NOx emission from coal boilers to 30 percent. But if combined with LNBs, NOx can be reduced up to 65 percent. The cost-effectiveness of LNBs and OFA on a coal-fired boiler is estimated to be \$500-\$4000 per ton of NOx removed.

SCR is a widely applied post-combustion NOx control technology of boilers which uses a reducing agent and a catalyst. EPA estimates that SCR applied to a coal-fired boiler can reduce NOx emission of 80 to 95 percent. But SCR has high capital cost and operation cost which will affect its cost-effectiveness. Cost-effectiveness of a 350 MMBtu industrial coal boiler is about \$2000-\$3000.

FGD or scrubbers are used in SO2 post-combustion control. FGD use lime or limestone as sorbent to remove SO2 from the exhaust gases of a boiler. In the U.S. most FGD scrubbers are wet system and some of them are sprayed dry. FGD can reduce 50 to 98 percent of SO2.

Fabric filters can effectively capture up to 99.9 percent of total particulate emissions and 99.8 percent of PM2.5 in coal boilers. Fabric filters are baghouse or a flat envelope that trap particulates before they exit the stack. There are several types of fabric filters (such as mechanical shaker cleaned and pulse jet cleaned) using same dust collection methods but different cleaning mechanisms. Cost-effectiveness of fabric filters also varies from less a hundred dollars to hundreds of dollars.

ESPs collect particulates by imposing electrical charge to the particles, attracting them to the opposite charged plate or tube, and removing them. The effectiveness of an ESP varies due to different electrical resistivity of the particles. In general, ESPs can reduce up to 98% of PM2.5 with a cost of \$40-500 per ton of emission removed.

3.2. Iron and steel manufacturing

Iron and steel industry grows rapidly in China and is one of the primary economic drivers. China ranks as the first iron and steel producer in the world who contributed more than 40 percent of world’s production in 2010 (Tao et al. 2014). In Chengdu, steel mills spread all over the city including the largest iron and steel factory of Sichuan province named Chengdu Steel Plant located in the northern city.

There are two types of steel factories: integrated mills and minimills (STAPPA & ALAPCO, 2006). Integrated mills makes new steel from iron ore whereas minimills melt and refine scrap steel. Steel manufacturing starts with coke making (RIT, 2006). Coal is heated at high temperature in the absence of oxygen to produce coke in coke ovens. Coke, iron ore and limestone are then heated in a blast furnace to produce molten iron. The molten iron combined with ferrous scrap are charged to the basic oxygen furnace (BOF). Oxygen is injected into BOF to remove carbon and produce steel. The steel is cast into various shapes for final processing.

Coke production and primary iron and steel production account for the major emission contribution ($PM_{2.5}$, SO_2 and NO_x) in iron and steel manufacturing. The following section introduce emission control techniques of each these process.

3.2.1. Coke production

There are a number of emissions sources from coke ovens, including leaks from doors, lids and offtakes, coke pushing into the quench car, quenching, and combustion stack (STAPPA & ALAPCO, 2006). Emission control opportunities associated with each emission points and steps include using improved capture and control technology, improved work practice, and reducing the amount of coke in the production of steel.

Emissions from poorly sealed doors, charge lids and offtake caps can be sealed with water and a water and refractory mixture called luting. Emissions from lid leaks have almost prevented in the U.S. thanks to diligence work practice including door cleaning and rebuilding, and use of luting (RTI, 2006). Emissions occur at coke pushing during the transfer of coke from the oven to the quench car. In the U.S. almost all plants have capture and control system for pushing because it’s a large PM source. If incomplete coking occurs, named “green pushing”, heavy emission will overwhelm the pushing capture system. Limiting use of green pushing can reduce emissions. PM emission can occur when the finished coke is soaked with water, called quenching. Baffles are used to intercept particulates and water droplets carried in the quench vapor updraft. Periodic cleaning of the baffles can help to remove mist adheres. Water quality can also influence quenching emissions as pollutants in the water are vaporized. Switching from water quenching to dry quenching can limit emissions although require major construction and investment (STAPPA

& ALAPCO, 2006). Emission can also occur in combustion stack through gas leaks. This emission can be controlled by good combustion practices, inspection and maintenance of oven walls.

Another approach to control emissions is to limit use of coke. Coal can be substituted by pulverized coal and other fossil fuels, although pulverized coal may degrade the final steel product (STAPPA & ALAPCO, 2006). There are technologies to produce steel without coke, such as Direct Reduced Iron process. Corex process using untreated raw coal in place of coke can avoid using coke in direct smelting.

3.2.2. Iron making

A blast furnace is a tall steel vessel used for smelting to convert iron ore into more pure and uniform iron. In the blast furnace, iron ore together with coke and limestone are charged into the top of the furnace allowing hot air heating from the bottom. Molten iron and slag are produced and then removed, or cast, from the furnace. In this process, PM is produced at several emission points: raw material handling, casting operation, the stove stack, and transporting (RIT, 2006).

Raw material handling including storage, sizing, mixing, screening and transport can release dust or generate PM emissions when expose to the atmosphere. Suppression techniques are used to control emission from this process. Flue gas from the blast furnace is used to preheat the blast air. PM must be removed from flue gas before burning. A settling chamber or dry cyclone can remove about 60% of the PM. Wet scrubber can remove 90 percent of remaining PM (STAPPA & ALAPCO, 2006).

Cast operation produce PM when molten iron and slag contact with air in the blast furnace and is the major PM emission source during iron making. Some plants using natural gas consumes oxygen to prevent the formation of metal oxides. Some plants covers iron and slag runners to minimize air space between the runners and covers. Capturing emission to a baghouse is also an effective control methods. About half of U.S. blast furnaces control casting emissions with covered runners and by evacuating emission to a baghouse through capture hoods.

Wet-collection system including dust catchers, venture scrubbers and precipitators are used to control emissions from the blast furnace top.

No control technologies are used in the stove stack, though it represents a small portion of PM emissions. The gas leaving the blast furnace is comprised of CO, nitrogen and PM. The gas is cleaned in venture scrubbers and is burned in the blast furnace stoves. PM is proced when it burns. Control technology of stove is not economical because PM concentration is very low.

3.2.3. Steelmaking

The BOF is a large, open-mouthed vessel in which molten iron and scrap are converted into molten steel. Operations in the BOF including charging (placing molten iron and scrap into the furnace), oxygen blow (injecting oxygen to refine the iron), turndown (obtaining sample by tilting the vessel), reblow (introducing additional oxygen if necessary), tapping (pouring the molten steel into a ladle) and deslagging (removing slag) ((RIT, 2006). Among these processes, charging, oxygen blow and tapping produce most of the PM emissions.

Primary emissions in BOF are produced in oxygen blow and are usually controlled by either high-energy venturi scrubbers or electrostatic precipitators (ESPs). There are two types of capture and control system adding to the ESP or a scrubber—open hood that allows full combustion and closed hood that processed closed suppressed combustion. In the U.S. open hood BOF is much more common than the closed one (STAPPA & ALAPCO, 2006).

Charging and tapping emit secondary emissions or fugitive emissions comprised by mainly metal oxides. Control technologies targeting at secondary emission include furnace enclosure, local hoods, and full or partial building evacuation. Baghouses and wet scrubbers are typically used for PM removing in the U.S.

3.3. Recommendations for Chengdu

Applying control technology is essential for the PM2.5 emission reduction methods.

Control technology is very effective, for example, the fabric filter can capture up to 99.9 percent of total particulate emissions and 99.8 percent of PM2.5 in coal boilers, according to U.S. experience. In Chengdu, information on PM2.5 control technologies applied to specific plants and factories is not available. But it is assumed that the control technologies are not widely applied in Chengdu's industry due to the fact that a great portion of PM2.5 emission comes from the industry. China's Air Pollution Prevention and Control Action Plan requires the phase out of the small sized coal-fired boiler and backward facilities. But dependence on coal-fired boilers still poses a major air pollution challenge. Also, the industries lack incentives to retrofit existing facilities and to use control technology. Corresponding policies and regulations should be established to enforce compliance by the industry. This research lists PM2.5 control technologies that U.S. industries have used, and focuses only on technologies for coal-fired boilers and iron and steel industry. Technologies applied to other industry type and recently invented wait to be investigated. Based on review of U.S. PM2.5 control technologies and local characteristics of Chengdu, I make following recommendations to strengthen Chengdu's PM2.5 emission control technologies:

- **Establish technology inventory.** Require each factory and plant to disclose information on type of facility and technology. This will not only help to find the most cost-effective technology case-by-case but also help to develop the local emission inventory.
- **Calculate and compare cost of different technologies.** U.S. and Chengdu have different costs and difficulties of using emission control technologies. Some technologies may not be available in Chengdu and China. Sichuan Basin is rich in natural gas, but switching boilers from coal to natural gas requires significant investment in modification and retrofitting of existing system and consideration of costs of substitute fuels.
- **Strengthen government authority in enforcement and punishment.** On the one hand, strengthen authority of Chengdu's EPB and counties' EPB to gather information from emitters about emission data and control technologies, to enforce application of emission control technologies, and to punish incompliance. On the other hand, increase penalties on government agencies on covering up company pollution behavior and false reporting.

- **Increase technology cooperation.** Increase technology research cooperation between research institutions and universities, and increase business partnership between emission control equipment companies and emitters. Chengdu can take advantages of a technology market which will attract investment and promote technological progress.

4. U.S. PM2.5 Policy

U.S. has more than 60 years of air pollution management history. The Air Pollution Control Act of 1995 was the first federal law to address air pollution. This Act "provided funds for federal research in air pollution" (EPA, 2013). The Clean Air Act (CAA) of 1963 was the first federal legislation designed to control air pollution nationwide. CAA was amended in 1963, 1970, 1977 and 1990. The enactment of 1970 CAA resulted in formation of Environmental Agency (EPA) and development of three influential regulatory programs regarding find particulate matter—the National Ambient Air Quality Standards (NAAQS), State Implementation Plans (SIPs), and New Source Performance Standards (NSPS). U.S. EPA is a federal government agency who formulates regulations and enforce those regulations. There are EPA regional offices and state offices which are responsible for implementing programs within their states. The 1990 CAA Amendments provides the base of current legal authority for federal programs related to air pollution.

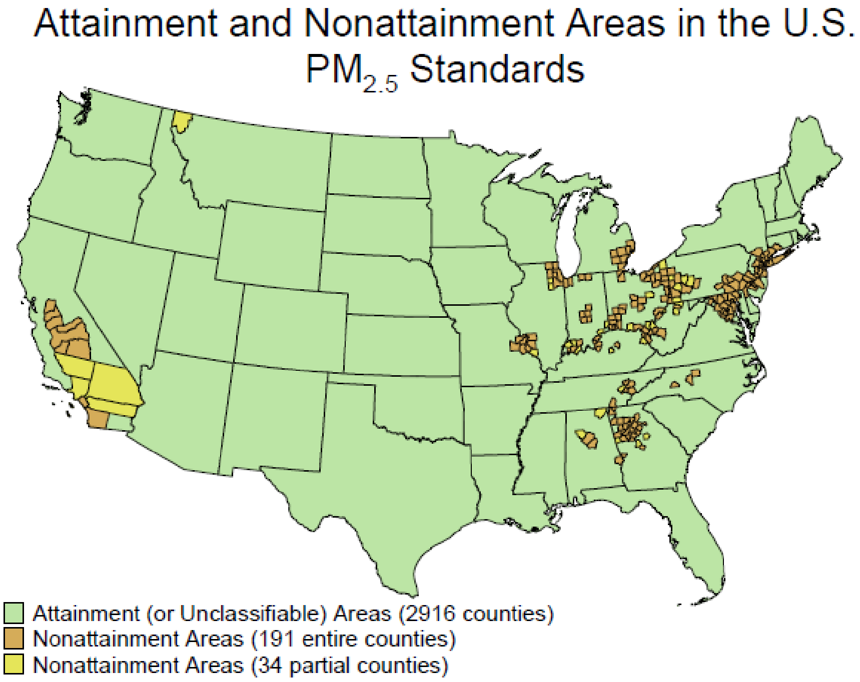
A comprehensive legal framework regarding air pollution including PM2.5 lead to compliance and implementation of the standards and target and play a critical role in the success of air pollution reduction in the U.S. (NRDC et al. 2013). This chapter will deeply review major U.S. national level regulations related to PM2.5 and discuss lessons learned to PM2.5 pollution management of China.

4.1. Clean Air Act and Amendments

CAA provides major framework for pollution control in the U.S. It requires EPA to develope NAAQS based on adverse human health, and requires states to establish state implementation plans (SIP) to achieve the standards (EPA, 2013). Three categories of pollutants are concerned in CAA. They are "major source" ("stationary source or group of stationary sources that emit or have the potential to emit 10 tons per year or more of a hazardous air pollutant or 25 tons per year or more of a combination of hazardous air pollutant", such as power plants and refineries), "mobile source" (moving source such as cars and trucks), and "area source" (any stationary source other than major source, such as fugitive dust and residential wood stove). To guarantee effective control over these pollutants, a series of technique-based criteria for pollutant treatments and regulatory programs are embodied in the CAA, which are the essence that China can extract from the Act.

4.1.1. "Attainment" and "nonattainment"

After establishing NAAQS, CAA requires EPA to determine whether an area does or does not meet the standards and treat them differently (EPA 2013). To do this, EPA divide the country in to "air quality management area" (AQMA) based on urban geographical boundaries. AQMA can cross state boundaries to develop interstate cooperation. "Attainment areas" are AQMAs that meet air quality standard whereas "nonattainment areas" are those do not meet the standards (Figure 3. Attainment and Nonattainment areas in the U.S.: PM2.5 Standards). There are also "unclassifiable areas" where there are not sufficient data for designation, and they are generally treated the same as attainment areas.



Source: EPA, 2013

Figure 7. Attainment and Nonattainment areas in the U.S.: PM2.5 Standards.

4.1.2. RACM/RACT/LAER

For nonattainment area, CAA specified general mandates and more specific requirements are applied to PM because is attainment had proven to be extra difficult (EPA, 2013). Areas are required to complete a comprehensive emission inventory, emission projections, and computerized air quality model for air quality prediction and compliance schedules. An area has 3, 5, or more years to achieve the standard depending on the severity of pollution and availability of control. For PM2.5, there are two levels of nonattainment—moderate and serious. Moderate nonattainment areas can reach attainment in five years, while serious nonattainment areas require more than five year of actions. The area are required to present "Reasonable Further Progress" (RFP) to demonstrate emission reduction achievement before the deadline and capabilities to attain the standards in the time giving.

Besides, nonattainment area must take specific measures including "Reasonable

Available Control Measures" (RACM), which include "Reasonable Available Control Technology" (RACT). RACT is the lowest emission limitation that an emitter can meet by using reasonably available techniques considering technological and economic feasibility.

In addition, nonattainment areas are required to do "New Source Review" (NSR) to prevent new major sources from further degrading. NSR requires new stationary sources to set the most stringent emission limitation using best control methods regardless cost—named "Lowest Achievable Emission Rate" (LAER). NSR also requires "emission offsets" for new sources. It means emissions increase from a new source must be offset by reducing emissions from existing sources and providing a net air quality benefit. It provides incentives to retrofit existing facilities for companies who want to prose new one.

4.1.3. BACT

For attainment area, there should be a Prevention of Significant Deterioration (PSD) program aiming at preventing emission concentration from increasing above the standards. Before construction of a new stationary source, the emitter must obtain a PSD permit from the states or local agencies. To obtain a PSD permit, emitters should prove they have applied Best Available Control Technology (BACT). BACT sets emission limitation based on the "maximum degree of control that can be achieved" considering cost and other factor (EPA, 2014). BACT can be control equipment, pollutant treatment or operational standard. PSD also requires an air quality analysis to prove that new emission will result in violation of air quality standards and allowable increment.

EPA does not set actual limits on RACT, LAER or BACT. EPA only provides guidelines called "Control Technique Guidelines" (CTGs) to assist states in determine what approach is for a specific pollutants. Areas have freedom in choosing RACT considering cost of compliance (STAPPA & ALAPCO, 2006).

4.1.4. NSPS

In addition to NSR for nonattainment areas and PSD for attainment areas, all areas comply with “New Source Performance Standards” (NSPS) which limit amount of emission allowed from new and modified stationary sources. NSPS reflects level of pollution based on best achievable control methods considering cost and other factors.

4.1.5. Effective Policy Features

- **Integrated technology standards**

The CAA requires general technology standards applicable for all areas in the country and specific standards for designated areas. These standards are reviewed and revised periodically. This integrated system constituted by standards, limitations and permits presents industry with choices of available options of air pollution control. Violation of any of the standards makes a company subject to enforcement. It places pressure on companies who want to propose new emission sources. Companies save time and money from investigating best achievable control methods because this process has been done by the EPA and states.

- **Specific requirements at national level**

CAA provides federal legislation and regulation and specifies requirements for attainment and nonattainment areas, leaving less flexibility to the states. It avoids states and local areas to slack off in establishing their own rules. It pushes nonattainment areas to make progress toward attainment areas, while attainment areas must remain on the alert from degrading to nonattainment areas.

4.2. U.S. NAAQS

The U.S. NAAQS are a driver of all air pollution control programs in the U.S. All those programs are established and enforced as compliance to the NAAQS. U.S. NAAQS set two types of standards: “primary standard” to protect public health and “secondary standard’ to protect the public from adverse environmental effects (EPA, 2013). Primary standard is discussed here.

4.2.1. Revision of U.S. NAAQS and amendments

U.S. NAAQS is regularly reviewed and revised when new scientific evidences are sufficient to update existing standards. A series of evolution of NAAQS has happened (Table 3. History of PM Standards in U.S. NAAQS). The first NAAQS of 1971 promulgated total suspended particulate (TSP)—particulates less or equal to 45 microns in diameter (Bryan Cave LLP, 2002). PM10 standards were promulgated in 1987. PM2.5 was first promulgated in 1997. Revisions or adoption of NAAQS requires a long administrative process and substantial scientific evidences about the pollutants (NRDC et al. 2009).

The recent NAAQS were revised in 2012. As part of the new standard review, EPA reviewed hundreds of new studies released after last review in 2006, including more than 300 new epidemiological studies. Many of those studies found adverse health effects even in areas that meet previous PM2.5 standards (EPA, 2013). As a result, EPA lowered the annual PM2.5 standard is lowered from 15 $\mu m/m^3$ to 12 $\mu m/m^3$. This means an area will achieve the standard if the annual average PM2.5 concentration over three years equals or less than 12 $\mu m/m^3$. PM2.5 monitoring data is collected by using a spatial average approach that "reflects average community-oriented area-wide exposure level" (Bryan Cave LLP, 2002). This approach allow monitoring stations that exceed the standard to be offset by nearby monitoring stations who are able to stay below the standard.

Table 6. History of PM Standards in U.S. NAAQS

Year of Implementation	**Indicator**	**24 hr Average ($\mu g/m^3$)**	**Calculation**	**Annual Average ($\mu g/m^3$)**	**Calculation**
1971	TSP	260	Not to be exceeded more than once per year	75	Annual average
1987	PM10	150	Not to be exceeded more than once per year on average over three years	50	Annual mean, average over three years

1997	PM10	150	Same as 1987	50	Annual mean, average over three years
1997	PM2.5	65	98th percentile, averaged over three years	15	Annual mean, average over three years
2006	PM10	150	Same as 1987 NAAQS	None[a.]	Annual average was vacated
2006	PM2.5	35	Same as 1997 NAAQS	15	Same as 1997 NAAQS
2012	PM10	150	Same as 1987 NAAQS	None	Annual average was vacated in 2006
2012	PM2.5	35	Same as 2006 NAAQS	12	Annual mean averaged over three years

Source: EPA, 2013

a. Annual PM10 was revoked by EPA in 2006.

4.2.2. Effective policy features

- **Health-based standards**

U.S. NAAQS is a public-health and environmental-health based standard applied to the whole country. NAAQS are set to protect the public health “with an adequate margin of safety” (EPA, 2013). Economic cost is not considered in the attaining of NAAQS (NRDC et al. 2009). Although industry had struggled but failed to require EPA to revise the Standard as a consideration of cost of establishing NAAQS since 1970. Pollutants are listed because they “may reasonably be anticipated to endanger public health or welfare” (“welfare” is defined as “effects on the natural and built environment, visibility, or economic values that depend on the quality of the air”). The health-based standards drive scientific research on adverse effects of PM2.5. It increases public acceptance and participation because public are informed what has been and will be done to make air healthier to breathe.

- **Clear consequences for failure to meet NAAQS**

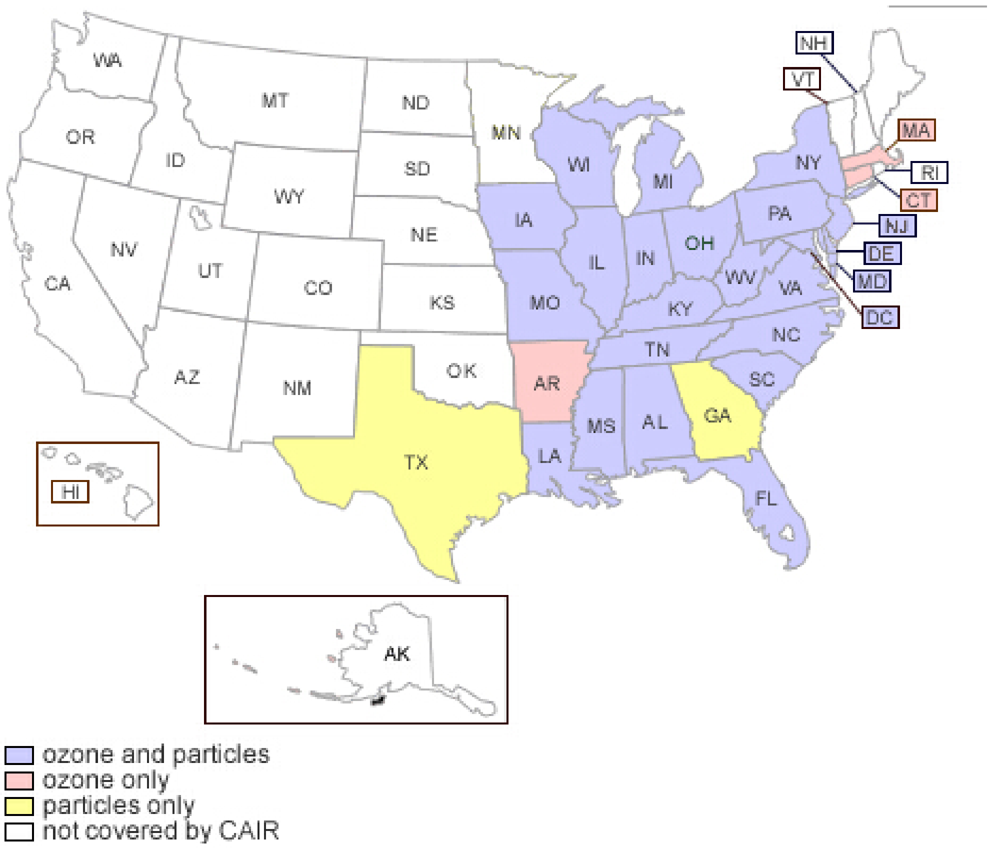
The states and localities suffer sanctions for failure to meet NAAQS (NRDC et al. 2009). They are required to adopt additional limitations on emission and traffic. Continued failures result in sanctions, for example limitations in highway funding and more stringent requirements on new factories which may affect local economy. Such a tool extends authority of EPA and drive better implementation at the local level.

5. Regional PM2.5 policy

5.1. Clean Air Interstate Rule

In the U.S, some states that have successfully controlled emissions within their states still cannot meet air quality standards because of the presence of out-of-state pollutants carried by wind. To better address such out-of-state emissions, EPA established the “Clean Air Interstate Rule” (CAIR). CAIR regulates SO_2 and NO_x, which contributes to the formation of PM and ground-level ozone. CAIR focuses on large sources of SO_2 and NO_x (mainly power plants) in eastern half of the country (Figure 8). It uses a “cap and trade” approach to control target pollutant drifting from one state to another. CAIR sets emission reduction targets for each participating state and states must achieve the targets by using either interstate cap and trade system or using measures of the state’s choosing.

Figure 8. States covered by CAIR



Source: EPA, 2014

5.1.1. Cap and Trade

EPA provides emission "allowance" for SO_2 and NO_x to each states to achieve the overall cap emission (EPA, 2014). The participating states distribute allowance to sources (individual power plants). Power plants can choose from saving allowances from installing pollution control equipment or switching fuels and selling allowances, or directly buying allowances from other plants who have excess allowances (Shen et al, 2014). In case of noncompliance, individual source will be mandated to implement emission reductions and meet stringent emission monitoring and reporting requirements.

5.1.2. Effective policy features

- **Economic incentives**

Cap and trade programs create flexibility of allowance which on the one hand require individual emitter to achieve emission reduction target and on the other hand create economic incentives for power plants to look for cost-effective emission control techniques. Industries also have incentives to invest new techniques to lower the compliance cost.

- **Regional air quality management**

Regions are geographically closer to each other which will improve scientific knowledge and understanding of local air quality problems (NRDC et al. 2009). Regions can be places to launch pilot programs for testing effectiveness of new programs. Regions can respond and adjust rules faster than national laws. Reduction target made in regional rules are more location-specific than national target based on local policy, economic condition and air quality condition. In addition, it provides an opportunities for states to cooperate and communicate to better improve air quality for all the states.

6. State PM2.5 policy: California

6.1. State Implementation Plan

CAA requires states to establish State Implementation Plan (SIP) containing policies, regulations and methods that a state implement and enforce to achieve its pollution reduction goal within its jurisdiction. SIP helps to develop long-term planning and cooperation for a states to establish regionally consistent approaches to improve air quality (NRDC, 2009).

In California, SIP is prepared and proposed by California Environmental Protection Agency named Air Resources Board (ARB). Current statewide PM2.5 control strategies—PM2.5 State Strategy are based on 2007 SIP. Revisions of the State Strategy had been made in 2009 and 2011 according to progress report which reflects adjustments of rules, advanced techniques, and RFP. California's SIP focus on PM2.5 attainment for the two nonattainment AQMAs of South Coast and the San Joaquin Valley. SIP includes both adopted SIP measures and proposed new measures.

6.1.1. Emission inventory

California SIP relies on region specific emission inventories because large difference exists in PM2.5 concentrations between attainment and nonattainment areas (ARB, 2007). Emission inventory provides data necessary to develop emission reduction modeling and is used to track progress of implementation of the plan. AQMAs in California maintains their local emission inventory constituted by four major emission categories: stationary sources (industrial facilities), area-wide sources (small individual sources, such as residential fireplaces, and distributed source, such as consumer products and dust from unpaved roads), on-road mobile sources (on-road cars, trucks, buses, etc.), and off-road mobile sources (boats, off-road recreational vehicles, aircraft, trains, ships, industrial and construction equipment, farm equipment, and other equipment).

6.1.2. Target setting

Setting emission reduction target requires to use air quality modeling. SIP uses a weight of evidence analysis to develop the model (ARB, 2007). It means the modeling consider entire information at hand to provide a more comprehensive information and a better understanding of the overall problem. The modeling includes consideration of monitored emission and meteorological data and evaluation of other air quality indicators, and additional air quality modeling. The modeling helps areas to set short-term and long-term emission reduction target forecast future emissions.

6.1.3. PM2.5 control measures

Emission inventory helps to look for most effective PM2.5 control measures by providing source apportionment of pollution sources. For example, monitoring data of South Coast area shows diesel and gasoline vehicle exhaust, wood burning and cooking, and fugitive dust are major contributors of PM2.5, which results main emphasis of the PM2.5 control strategy focusing on these problems.

For mobile sources, SIP's strategy focuses on requirements of cleaner engines and fuel (for example low-sulfur fuel) on new vehicles, getting cleaner technology on old vehicles, and replacing older dirtier vehicles and equipment with cleaner ones. Appendix I provides full List of Mobile Source Control Measures. Wood burning reduction strategy is mainly mandatory curtailment of the use of fireplaces and woodstoves on days with high levels of particulate matter. Stationary and area source are following CAA's technology-based standards (such as RACT).

6.1.4. Effective policy features

- **Strong state and local authority**

Strong states and local authority are powerful tool for driving implementation of pollution control strategy (NRDC et al. 2009). Especially for large pollution sources such as transportation and electricity generators, states' EPA can coordinate each city and share experience. Local level environmental agencies are given strong authorities to investigate, oversee, and enforce pollution activities.

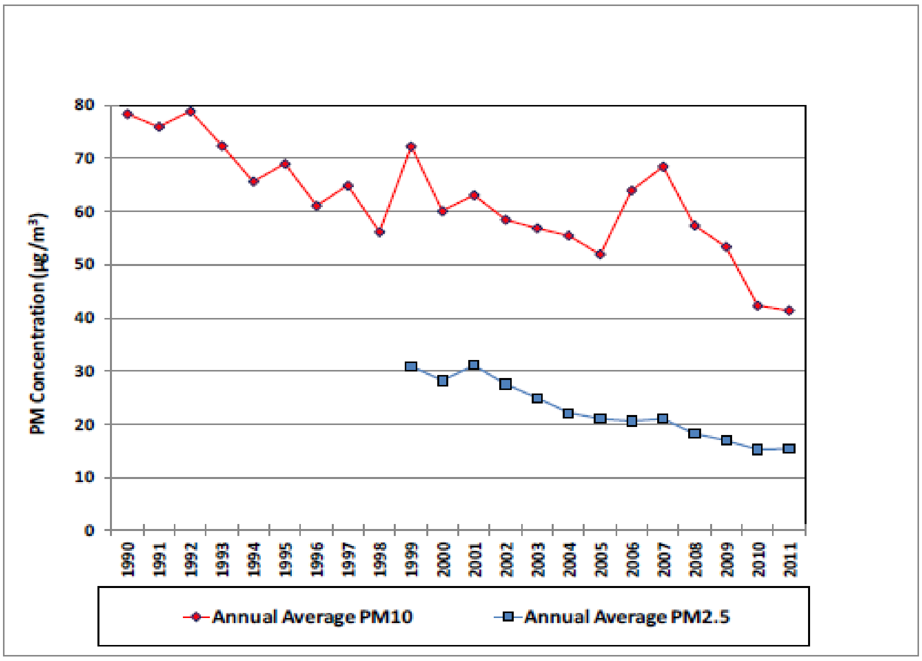
- **Comprehensive monitoring and reporting system**

An accurate emission inventory is essential to an effective attainment strategies. It provides information of source of pollution, the quantities emitted, their geographical distribution, and how control measures will influence future emission levels. Besides, periodical review and reevaluation of SIP make the plan always reflect the updated standards and advanced technology.

6.2. South Coast Air Quality Management Plan

South Coast Air Quality Management District (SCAQMD) is the air pollution control agency containing Orange County, urban area of Los Angeles, Riverside and San Bernardino counties, which are one of the worst air quality regions in the U.S. (2012). SCAQMP is prepared by SCAQMD as a portion of California's SIP applicable within the district boundary. Air pollution control measures conducted by SCAQMD has significantly improved air quality in the district (Figure 4. SCAQMD Annual Average PM10 and PM2.5 Trends). By 2011 (before 2012 SCQMP was released), the district has met both annual (15 μm/m^3) and 24-hour PM2.5 (35 μm/m^3) standards of 2006 NAAQS except one air monitoring station, Mira Loma, in Northwestern Riverside.

Figure 9. SCAQMD Annual Average PM10 and PM2.5 Trends



Source: SCAQMP, 2012

6.2.1. 2007 & 2012 SCAQMP

Successful PM2.5 control in SCAQMD makes it necessary to look back into the historical measures that had been taken and new proposed measures. 2007 SCAQMP includes implemented measures from 2003 SCAQMP and new measures for stationary, area and mobile source (Refer to Appendix IV for full list of 2007 SCAQMP PM2.5 Control Measures). The measures target at a variety of source categories and specific programs: coatings and solvents, combustion sources; fugitive emissions; multiple component sources, best available control measures for fugitive dust sources; compliance flexibility programs; emission growth management, and mobile source programs. 2012 SCAQMP's PM2.5 control measures include stationary source control measures, episodic controls, technology assessments, an indirect source measure and one education measure (Appendix V. 2012 SCAQMP PM2.5 Control Measures). PM2.5 control measures in 2007 and 2012 SCAQMP are mixed with technological requirements and standards, and economic incentives. These control measures can be generalized into several types showing in Table 5.

Table 7. Types of Control Measures in 2007 & 2012 SCAQMP

Source category	**Types of control measures**
Coatings and solvents	● Add-on controls ● Process improvement ● Consumer product certificates
Combustion sources	● Add-on controls ● Market incentives ● Process improvement ● Improved energy efficiency
Fugitive emissions	● Add-on control ● Process improvement ● Stringent limits
Multiple component sources	● Geographic controls ● Process modifications and improvements ● Add-on controls ● Best management practices ● Best Available Control Technology ● Market incentives ● Energy efficiency and conservation
Best available control measures for fugitive dust sources	● Best management practices ● Best Available Control Technology ● Process improvement
Compliance flexibility programs	● Market incentives ● Voluntary participation
Emission growth management	● Emission inventory review ● New sources assessment
Mobile source programs	● Market incentives ● Voluntary participation ● Backward engines and facilities elimination
Indirect Source	● Emission Control Plans ● Contractual Requirements

	● Tariffs, Incentives/Disincentives
Educational Programs	● Increased Awareness ● Technical Assistance

Source: Compiled by author from 2007 and 2012 SCAQMP.

6.2.2. RECLAIM

The Regional Clean Air Incentives Market (RECLAIM) is a pioneering economic incentive program of NOx and SOx developed by SCAQMD. RECLAIM was first adopted in 1993, and until July 1 2012, a total of 276 active facilities were participated (SCAQMD, 2014). The 2012 RECLAIM Report shows that RECLAIM successfully achieved its emission reduction target since total NOx and SOx emissions were both well below total allocations during the compliance year. In addition to benefits of improved air quality and human health, RECLAIM offers a net gain of 2,026 jobs, representing 2% of their total employment in the Compliance Year 2012.

RECLAIM sets facility-specific emission reduction targets and each facility decides for itself the most cost-effective methods to meet the target, including reducing emissions on-site, and/or purchasing RECLAIM Trading Credits (RTCs) from other participating facilities. Compliance savings are created by trading between high and low cost-of-control facilities (SCAQMD, 2002). Thus, the overall compliance cost of all facilities are decreased. What’s more, facilities have the incentive to reduce emissions below the required level as long as their cost of control is cheaper than the price of credits. So facilities have the incentive to invest in innovative and more efficient control methods. Facilities have freedom to choose any technologies rather than being constrained by technology standards.

6.2.3. Effective policy features

- **Air pollution management district.**

Air pollution management districts enhance air pollution control at national level. It promotes monitors and actions at the states and local levels, provides oversight of local government air programs, and facilitate national air pollution programs and policies at the regional level. Air districts are geographically closer to the locations of emitters, which help to improve knowledge of the local air pollution issues. It can effectively improve air pollution reduction because it conflict resolution and information gathering are more easily to be done at smaller geographical areas. Air pollution districts are also appropriate size of area to conduct pilot and experimental programs before launching at the national level.

7. Recommendations for China and Chengdu PM2.5 control

In the analysis of U.S. and California PM2.5 emission control and prevention policies, their strong policy mechanisms were identified, including clear consequence of failure to comply, strong state and local authorities, comprehensive monitoring and reporting system, health-based standards, and a system regional air quality management districts. U.S. practice also shows innovative policy tools, such as technology standards, use of economic incentives, and cap and trade programs. Table 8 illustrates how the U.S. and California policies (analyzed in Chapter 4, 5 and 6) can help to address problems and challenges existing in Chengdu and China's PM2.5 management (identified in Chapter 2). U.S. and California local policies show strong monitoring and reporting requirements which help to establish effectively targets and plans. EPA and local environmental agencies are given powerful authority to enforce technology and performance standards, to set more stringent requirements in nonattainment areas, to require new source review, and to revise standards and plans regularly. U.S. NAAQS are set to protect the public health without consideration of economic cost. All the U.S. and local PM2.5 policies reviewed in this research show clear consequences of non-compliance. States and individual emitters are facing more stringent fines, emission limitations, permits and enforcement for non-compliance.

Table 8. U.S. policies that can help to address problems in Chengdu and China's PM2.5 pollution management

	Problems existing in Chengdu and China PM2.5 pollution management

U.S. Policy Practices that can address these problems	Poor PM2.5 monitoring	Isolated environmental management	Lack of health improvement target	Unclear consequence of non-compliance	Unequally distributed PM2.5 management
Clean Air Act					
Technology (Performance) standards	✔	✔		✔	✔
“Attainment & “nonattainment” designation	✔	✔		✔	
New Source Review	✔			✔	✔
U.S. NAAQS					
Health-based standards	✔		✔		✔
Clean Air Interstate Rule					
Cap and Trade	✔			✔	
Transboundary Air Pollution Management	✔	✔		✔	
State Implementation Plan	✔	✔		✔	✔
SCAQMD					
RECLAIM	✔			✔	
Regional air pollution management district	✔	✔		✔	✔

Based on analysis of U.S. and California practice, I make the following recommendations for PM2.5 reduction designs that could be applied in Chengdu and China to improve air quality:

- **Integrated policy framework and stronger environmental protection authority.** China’s environmental management functions are distributed in multiple government department. Energy departments only focus on energy issues and assume Environmental protection bureaus will take care of the environmental problems. But environmental agencies are not given sufficient authority to engage in energy policy. The extent of authority is blurred, which causes overlap, clash, or gap in duties. Environmental agencies should be given stronger responsibilities and authorities to participate in the environmental problems in various sectors including industry, energy and transportation, to participate in policy-making of other government departments, and to develop cooperation with other departments.

- **Comprehensive PM2.5 monitoring and reporting.** Abundant funding and human resources should be given to environmental agencies in PM2.5 monitoring and reporting. Accurate and timely monitoring is essential to establish targets and plans and to determine compliance of requirements. An emission inventory will help Chengdu to accurately identify emission sources and locate emitters so that PM2.5 emission control regulations can hit the right target.
- **Health-based air quality standards.** China’s NAAQS should consider adverse health effects as a justifiable reason to extend MEP and local EPB authority on PM2.5 control. It is consistent with “human-centered” as a core principle in China’s policy (NRDC et al. 2009). It can drive more scientific research and health-based monitoring programs on effects of PM2.5. More evidence of adverse health effects will empower the public to participate in PM2.5 pollution management and increase pressure on industry to reduce emissions. Health improvement, after all, is the basis and the reason the PM2.5 management.
- **Clear consequences and stronger enforcement.** Establish clear consequences for non-compliance of factories and individual emitters, such as additional fines and temporary shut-down for modification. Environmental agencies should be given stronger enforcement responsibility to investigate, oversee, and punish. Agencies will also be severely punished if they are found to have failed in their environmental responsibilities, such as harboring pollution activities and faking monitoring data.
- **Regional environmental management district.** Complicated topography and large

geographic area makes it necessary to divide China into regional environmental management areas. It would help individual provinces and cities to find the most appropriate methods based their own economic conditions and air quality conditions. Chengdu can look for cooperation opportunity with Chongqing, which is a heavy polluted industrial city close to Chengdu. Although Chengdu is in the Sichuan Basin, which avoids transboundary air pollution at some extent, Chengdu and Chongqing are always related due to history, socio-economic, and academic reasons. An air quality district will help both cities to share experience and technologies to achieve common emission reduction goal.

- **Technology-based emission standards.** The U.S. air pollution control policies use various technology-based emission standards. Chengdu and China should consider development of such standards to drive emission reductions. Technology-based standards can be set to reflect specific emission limits or performance, as allowable emissions per unit of production, such as amount of PM2.5 per ton of cement produced. The standards based on performance allow factories to choose their own emission control methods considering cost and feasibilities because modification and retrofitting existing system are always case-by-case. Simply requiring certain technology to be utilized may prevent technology improvement.
- **Economic incentives.** The U.S. air pollution policy utilizes various economic incentive mechanisms, for example cap and trade in the Clean Air Interstate Rule and RECLAIM in the South Coast Air Quality Management District. PM2.5 is a mixture of various chemical compounds and its emission sources are more localized than many other pollutants. So a trade of PM2.5 is not preferred and is hard to develop. But these two programs are targeting at SO2 and NOx, which are precursors of PM2.5 and can help to reduce secondary PM2.5 emissions. Economic incentives promote flexibility and cost effectiveness in emission reduction. It also encourages emitters to invest in PM2.5 control technologies. But developing an offset market requires funding and human resources to do research and to plan. Chengdu can learn from the pilot CO_2 trading

programs in Chinese cities (Shen et al. 2014). Chengdu can also look for assistance and cooperation with other countries. Development of air pollutant market in Chengdu may help to establish similar markets across the China.

- **Public disclosure of information.** Information of environmental impacts of PM2.5, accurate PM2.5 concentrations, sources of PM2.5, major emitters and emission control technologies should be disclosed to the public. Disclosure of information promotes public participation and enhances public supervision over government and emitters to reduce PM2.5 emissions and concentrations. Disclosure of information also improves the public's understanding of the PM2.5 issue which is an education function. It shows government effort to make the policy process more transparent.

8. Conclusion

Chengdu is experiencing rapid economic growth that has brought about serious air pollution problems from energy, industrial and other sectors. Chengdu has some experience with PM10 emission control but PM2.5 is a relatively new pollution management target. The short history of PM2.5 emission control allows Chengdu to be open to experience from s the U.S. and California.

In recent years, China has developed a series of PM2.5 emission reduction policies. These include the first limits of PM2.5 annual and 24-housr average concentration, setting PM2.5 emission reduction targets, and reformation of China's energy consumption by increasing energy efficiency and switching from coal to clean energy. In Chengdu, the major PM2.5 control strategies include phasing out old and small coal-fired boilers, strengthening monitoring and inspection of key emitters, and moratoriums on factories that use poor quality coal or high polluting fuel. However, Chengdu and China may experience a long period of time to witness air quality improvement. Because air pollution emissions are difficult to slow down in a short period of time and clean air quality will require a major restructuring in energy consumption. Besides that, some problems are identified in this research that may prevent effective implementation of the PM2.5 policies: most cities have short history of PM2.5

monitoring and different PM2.5 monitoring stations provides inconsistence of data; local environmental protection bureau has limited authorities in supervision and enforcement and local government tends to think short-term interests; PM2.5 reduction target sets in a conservative way which does not reflect the real compliance ability and the health improvement target; failure of compliance and punishment is not clearly defined and not strictly implemented by local government.

In this research, Chengdu’s PM2.5 source apportionment is based on researches conducted by the same authors. Chengdu’s energy profile is inaccurate and is inferred from the energy profile of Sichuan Province. Technology distribution of Chengdu’s industries has not been found at this point. Limited data prevents the full consideration of Chengdu’s characteristics of PM2.5 emissions and energy consumption. Thus there is a future need for accurate monitoring and information disclosure so that recommendations can be better adjusted to local conditions. Besides, this research only presents PM2.5 control technologies of coal-fired boilers and iron and steel industry. Technologies applied to other industry type and recently invented wait to be investigated.

This research examined PM2.5 control technologies that U.S. industries have used, in particular, controls for coal-fired boilers and iron and steel industry. The following recommendations are made to strengthen Chengdu’s PM2.5 emission control using technologies:

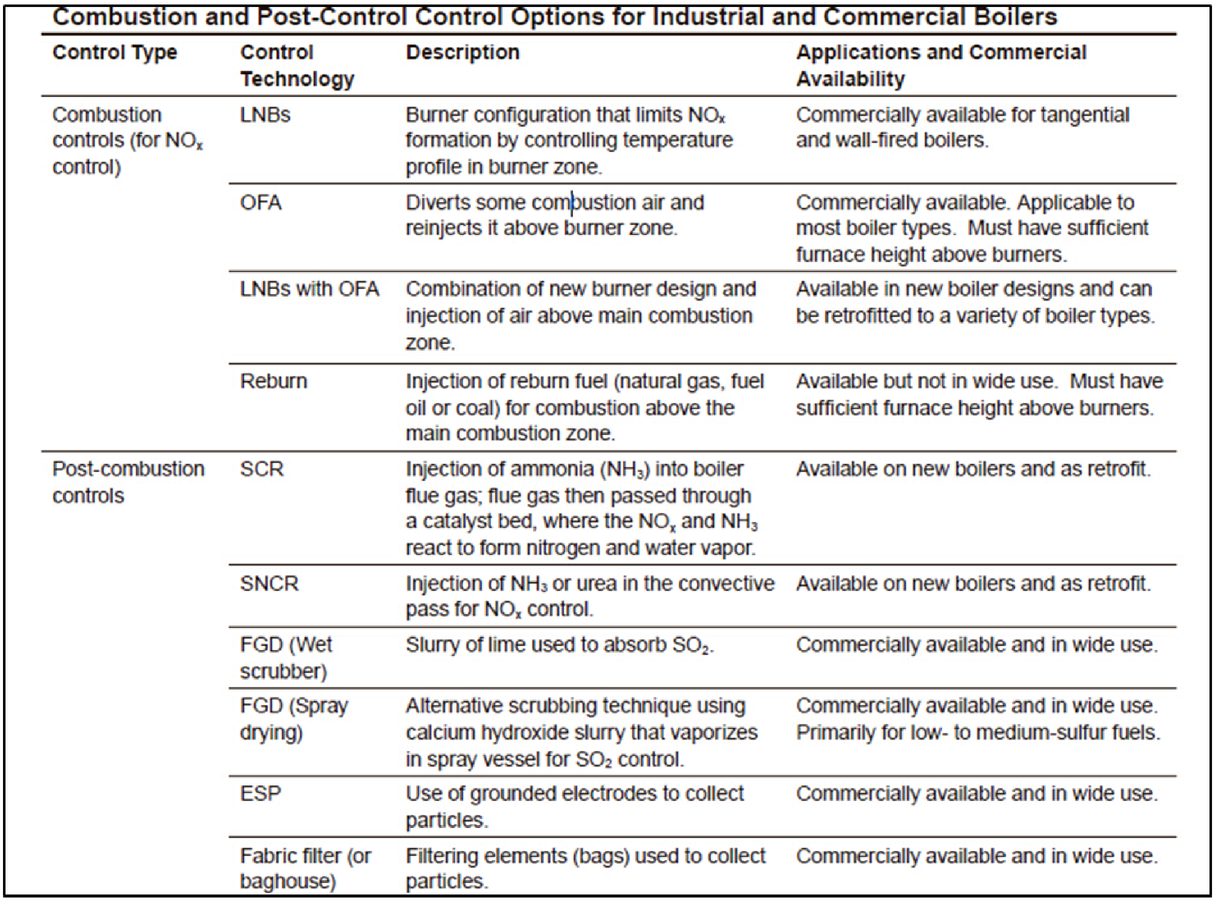
- Require factories and plants to disclose technology information.
- Calculate and compare cost of different technologies to find the most cost-effective strategies.
- Give stronger government authority in enforcement and punishment on emitters and increasing penalties on government agencies on cheating and false reporting.
- Increase technology cooperation with research institutions and business partners on emission control equipment and technologies.

From analysis of the U.S. and California PM2.5 control experiences, their effective policy features are identified and can help to address problems and challenges existing in Chengdu and China's PM2.5 management. The U.S. and California policies show strong monitoring and reporting requirements which help to effectively establish targets and plans. EPA and local environmental agencies are giving powerful authorities to enforce technology and performance standards, to set more stringent requirements in nonattainment areas, to require new source review, and to revise standards and plans regularly. U.S. NAAQS are set to protect the public health without consideration of economic cost and increases public acceptance and participations in PM2.5 pollution management. All U.S. and local PM2.5 policies reviewed in this research show clear consequences of non-compliance. States and individual emitters are facing more stringent fines, emission limitations, permits and enforcement for non-compliance. In addition, pollutant trading markets are developed to promote flexibility and cost effectiveness in emission reduction implementation.

Based on lessons learned from the U.S. and California PM2.5 emission control experience, this research provides a series of recommendations for Chengdu and China's PM2.5 emission management. These recommendations include:

- Develop integrated policy framework and giving stronger authority to environmental protection agencies to participate in the environmental issues in various sectors including energy, transportation and industry.
- Consider health effects as a qualification of the PM2.5 standards and use adverse health effects as a justifiable reason to extend authorities of the government agencies.
- Establish comprehensive and accurate PM2.5 monitoring and reporting system.
- Specify clear consequences for non-compliance and strengthening enforcement.
- Divide provinces and big areas into regional air quality management districts by considering local characteristics.
- Use technology-based emission standards to reflect emission limitation and performance.
- Use economic incentives such as cap and trade to drive emission reduction.
- Enhance public disclosure of information.

Appendix 1. Combustion and Post-Combustion Control Options for Industrial and Commercial Boilers

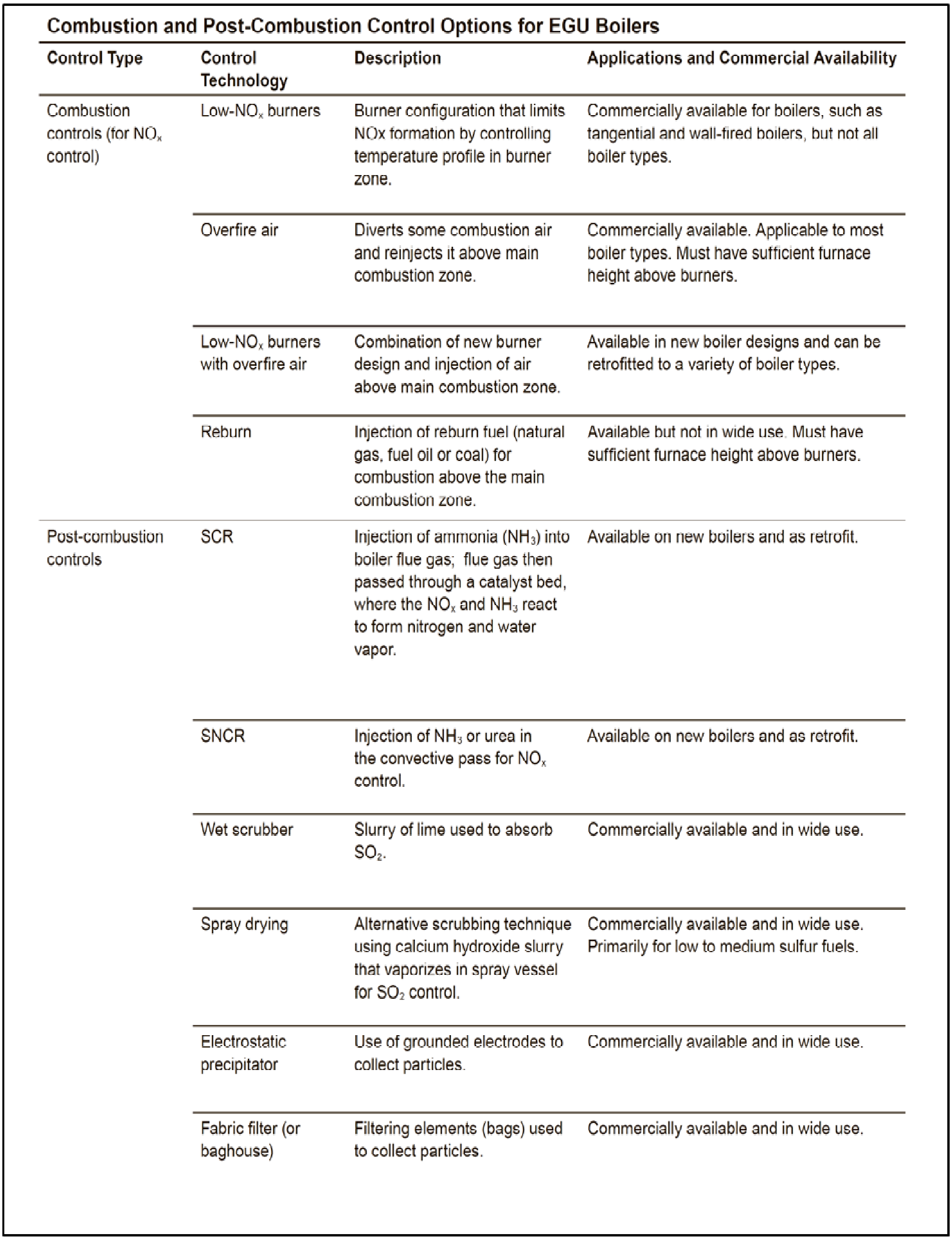


Combustion and Post-Control Control Options for Industrial and Commercial Boilers

Control Type	Control Technology	Description	Applications and Commercial Availability
Combustion controls (for NO_x control)	LNBs	Burner configuration that limits NO_x formation by controlling temperature profile in burner zone.	Commercially available for tangential and wall-fired boilers.
	OFA	Diverts some combustion air and reinjects it above burner zone.	Commercially available. Applicable to most boiler types. Must have sufficient furnace height above burners.
	LNBs with OFA	Combination of new burner design and injection of air above main combustion zone.	Available in new boiler designs and can be retrofitted to a variety of boiler types.
	Reburn	Injection of reburn fuel (natural gas, fuel oil or coal) for combustion above the main combustion zone.	Available but not in wide use. Must have sufficient furnace height above burners.
Post-combustion controls	SCR	Injection of ammonia (NH_3) into boiler flue gas; flue gas then passed through a catalyst bed, where the NO_x and NH_3 react to form nitrogen and water vapor.	Available on new boilers and as retrofit.
	SNCR	Injection of NH_3 or urea in the convective pass for NO_x control.	Available on new boilers and as retrofit.
	FGD (Wet scrubber)	Slurry of lime used to absorb SO_2.	Commercially available and in wide use.
	FGD (Spray drying)	Alternative scrubbing technique using calcium hydroxide slurry that vaporizes in spray vessel for SO_2 control.	Commercially available and in wide use. Primarily for low- to medium-sulfur fuels.
	ESP	Use of grounded electrodes to collect particles.	Commercially available and in wide use.
	Fabric filter (or baghouse)	Filtering elements (bags) used to collect particles.	Commercially available and in wide use.

Source: STAPPA & ALAPCO, 2006

Appendix 2. Combustion and Post-Combustion Control Options for EGU Boilers

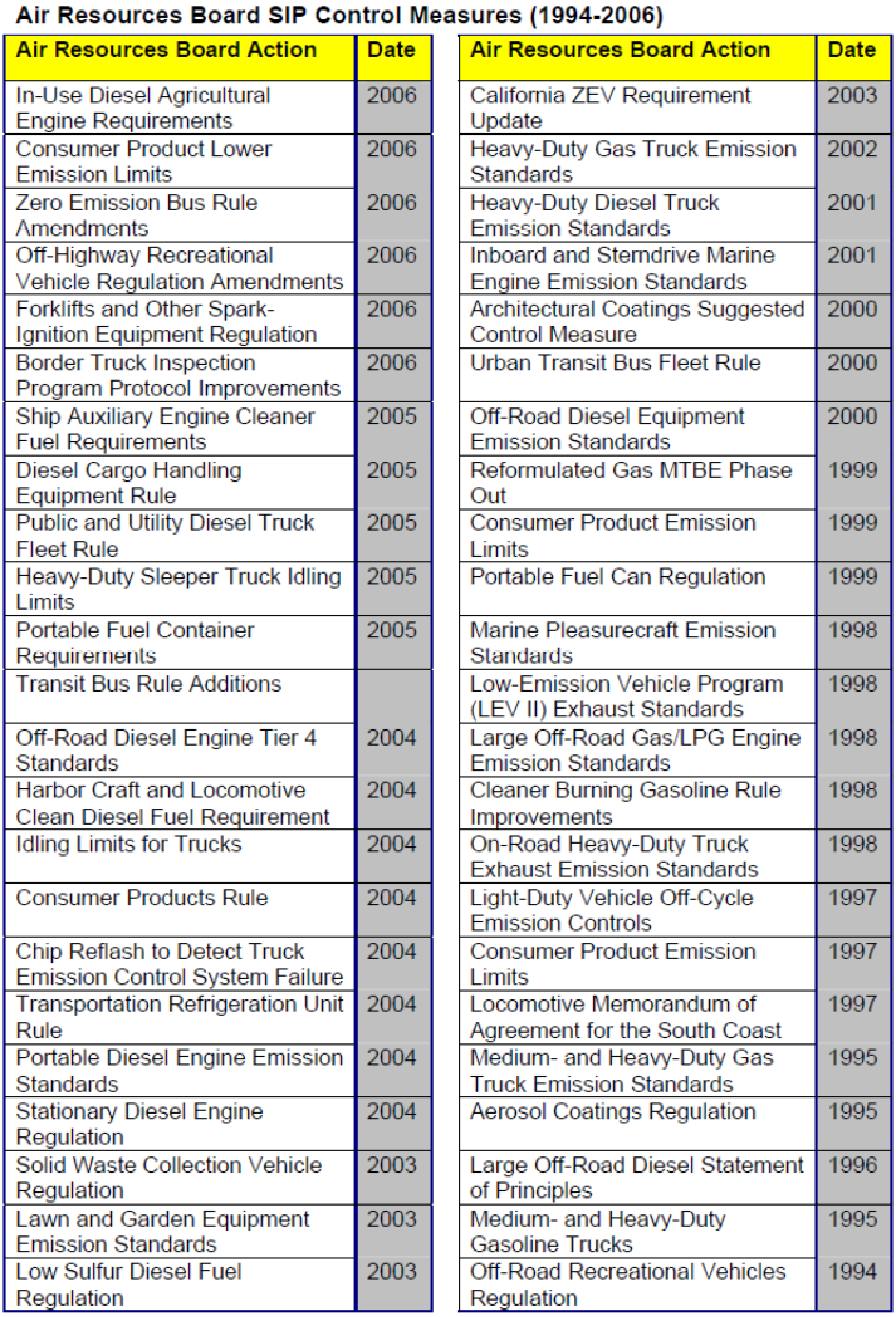


Combustion and Post-Combustion Control Options for EGU Boilers

Control Type	Control Technology	Description	Applications and Commercial Availability
Combustion controls (for NO_x control)	Low-NO_x burners	Burner configuration that limits NOx formation by controlling temperature profile in burner zone.	Commercially available for boilers, such as tangential and wall-fired boilers, but not all boiler types.
	Overfire air	Diverts some combustion air and reinjects it above main combustion zone.	Commercially available. Applicable to most boiler types. Must have sufficient furnace height above burners.
	Low-NO_x burners with overfire air	Combination of new burner design and injection of air above main combustion zone.	Available in new boiler designs and can be retrofitted to a variety of boiler types.
	Reburn	Injection of reburn fuel (natural gas, fuel oil or coal) for combustion above the main combustion zone.	Available but not in wide use. Must have sufficient furnace height above burners.
Post-combustion controls	SCR	Injection of ammonia (NH_3) into boiler flue gas; flue gas then passed through a catalyst bed, where the NO_x and NH_3 react to form nitrogen and water vapor.	Available on new boilers and as retrofit.
	SNCR	Injection of NH_3 or urea in the convective pass for NO_x control.	Available on new boilers and as retrofit.
	Wet scrubber	Slurry of lime used to absorb SO_2.	Commercially available and in wide use.
	Spray drying	Alternative scrubbing technique using calcium hydroxide slurry that vaporizes in spray vessel for SO_2 control.	Commercially available and in wide use. Primarily for low to medium sulfur fuels.
	Electrostatic precipitator	Use of grounded electrodes to collect particles.	Commercially available and in wide use.
	Fabric filter (or baghouse)	Filtering elements (bags) used to collect particles.	Commercially available and in wide use.

Source: STAPPA & ALAPCO, 2006

Appendix 3. 2007 SIP Control Measures



Air Resources Board SIP Control Measures (1994-2006)

Air Resources Board Action	Date
In-Use Diesel Agricultural Engine Requirements	2006
Consumer Product Lower Emission Limits	2006
Zero Emission Bus Rule Amendments	2006
Off-Highway Recreational Vehicle Regulation Amendments	2006
Forklifts and Other Spark-Ignition Equipment Regulation	2006
Border Truck Inspection Program Protocol Improvements	2006
Ship Auxiliary Engine Cleaner Fuel Requirements	2005
Diesel Cargo Handling Equipment Rule	2005
Public and Utility Diesel Truck Fleet Rule	2005
Heavy-Duty Sleeper Truck Idling Limits	2005
Portable Fuel Container Requirements	2005
Transit Bus Rule Additions	
Off-Road Diesel Engine Tier 4 Standards	2004
Harbor Craft and Locomotive Clean Diesel Fuel Requirement	2004
Idling Limits for Trucks	2004
Consumer Products Rule	2004
Chip Reflash to Detect Truck Emission Control System Failure	2004
Transportation Refrigeration Unit Rule	2004
Portable Diesel Engine Emission Standards	2004
Stationary Diesel Engine Regulation	2004
Solid Waste Collection Vehicle Regulation	2003
Lawn and Garden Equipment Emission Standards	2003
Low Sulfur Diesel Fuel Regulation	2003

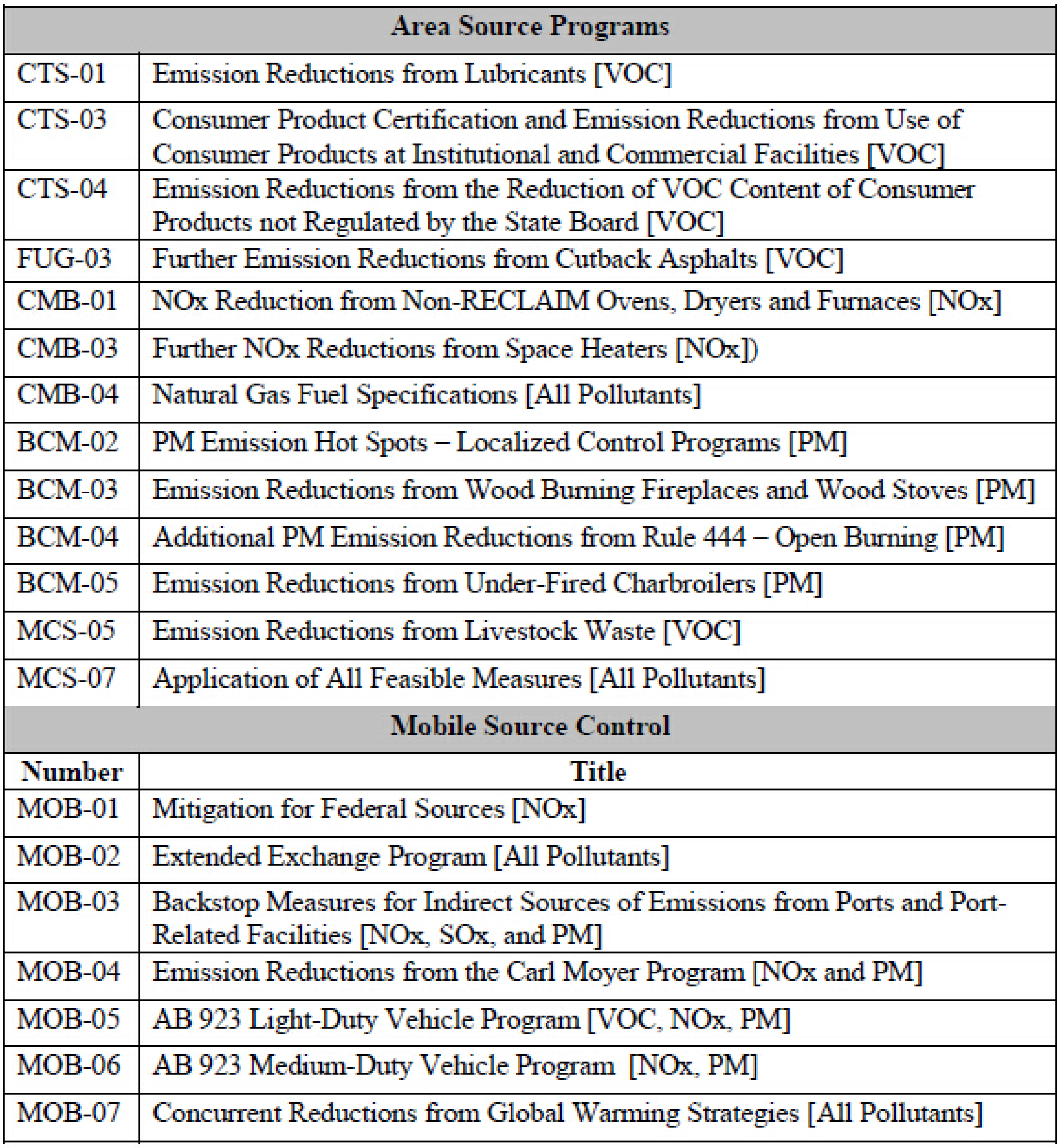
Air Resources Board Action	Date
California ZEV Requirement Update	2003
Heavy-Duty Gas Truck Emission Standards	2002
Heavy-Duty Diesel Truck Emission Standards	2001
Inboard and Sterndrive Marine Engine Emission Standards	2001
Architectural Coatings Suggested Control Measure	2000
Urban Transit Bus Fleet Rule	2000
Off-Road Diesel Equipment Emission Standards	2000
Reformulated Gas MTBE Phase Out	1999
Consumer Product Emission Limits	1999
Portable Fuel Can Regulation	1999
Marine Pleasurecraft Emission Standards	1998
Low-Emission Vehicle Program (LEV II) Exhaust Standards	1998
Large Off-Road Gas/LPG Engine Emission Standards	1998
Cleaner Burning Gasoline Rule Improvements	1998
On-Road Heavy-Duty Truck Exhaust Emission Standards	1998
Light-Duty Vehicle Off-Cycle Emission Controls	1997
Consumer Product Emission Limits	1997
Locomotive Memorandum of Agreement for the South Coast	1997
Medium- and Heavy-Duty Gas Truck Emission Standards	1995
Aerosol Coatings Regulation	1995
Large Off-Road Diesel Statement of Principles	1996
Medium- and Heavy-Duty Gasoline Trucks	1995
Off-Road Recreational Vehicles Regulation	1994

Source: 2007 California SIP

Appendix 4. 2007 SCAQMP PM2.5 Control Measures

Facility Modernization	
Number	**Title**
MCS-01	Facility Modernization [NOx, VOC, and PM2.5]
Energy Efficiency/Conservation	
Number	**Title**
MCS-02	Urban Heat Island [All Pollutants]
MCS-03	Energy Efficiency and Conservation [All Pollutants]

Good Management Practices	
Number	**Title**
FUG-01	Improved Leak Detection and Repair [VOC]
FUG-02	Emission Reductions from Gasoline Transfer and Dispensing Facilities [VOC]
FUG-04	Further Emission Reductions from Pipeline and Storage Tank Degassing [VOC]
BCM-01	PM Control Devices (Baghouses, Wet Scrubbers, Electrostatic Precipitators, and Other Devices) [PM]
MCS-04	Emissions Reduction from Green Waste Composting [VOC and PM]
MCS-06	Improved Start-up, Shut-down & Turnaround Procedures [All Pollutants]
Market Incentives/Compliance Flexibility	
Number	**Title**
CTS-02	Clean Coatings Certification Program [VOC]
CMB-02	Further SOx Reduction for RECLAIM [SOx]
MCS-08	Clean Air Act Emission Fees for Major Stationary Sources [VOC and NOx]
FLX-01	Economic Incentive Programs [All Pollutants]
FLX-02	Petroleum Refinery Pilot Program [VOC and PM2.5]
Emission Growth Management	
Number	**Title**
EGM-01	Emission Reductions from New or Redevelopment Projects [NOx, VOC and PM2.5]
EGM-02	Emission Budget and Mitigation for General Conformity Projects [All Pollutants]
EGM-03	Emissions Mitigation at Federally Permitted Projects [All Pollutants]



Area Source Programs	
CTS-01	Emission Reductions from Lubricants [VOC]
CTS-03	Consumer Product Certification and Emission Reductions from Use of Consumer Products at Institutional and Commercial Facilities [VOC]
CTS-04	Emission Reductions from the Reduction of VOC Content of Consumer Products not Regulated by the State Board [VOC]
FUG-03	Further Emission Reductions from Cutback Asphalts [VOC]
CMB-01	NOx Reduction from Non-RECLAIM Ovens, Dryers and Furnaces [NOx]
CMB-03	Further NOx Reductions from Space Heaters [NOx])
CMB-04	Natural Gas Fuel Specifications [All Pollutants]
BCM-02	PM Emission Hot Spots – Localized Control Programs [PM]
BCM-03	Emission Reductions from Wood Burning Fireplaces and Wood Stoves [PM]
BCM-04	Additional PM Emission Reductions from Rule 444 – Open Burning [PM]
BCM-05	Emission Reductions from Under-Fired Charbroilers [PM]
MCS-05	Emission Reductions from Livestock Waste [VOC]
MCS-07	Application of All Feasible Measures [All Pollutants]
Mobile Source Control	
Number	**Title**
MOB-01	Mitigation for Federal Sources [NOx]
MOB-02	Extended Exchange Program [All Pollutants]
MOB-03	Backstop Measures for Indirect Sources of Emissions from Ports and Port-Related Facilities [NOx, SOx, and PM]
MOB-04	Emission Reductions from the Carl Moyer Program [NOx and PM]
MOB-05	AB 923 Light-Duty Vehicle Program [VOC, NOx, PM]
MOB-06	AB 923 Medium-Duty Vehicle Program [NOx, PM]
MOB-07	Concurrent Reductions from Global Warming Strategies [All Pollutants]

Source: 2007 SCAQMP

Note: Each control measure is identifies by a control measure number such as “MCS-01” which represents the abbreviation for a source category or specific programs: CTS—Coatings and Solvents; CMB—Combustion Sources; FUG—Fugitive Emissions; MCS—Multiple Component Sources; BCM—Best Available Control Measures for Fugitive Dust Sources; FLX—Compliance Flexibility Programs; EGM—Emission Growth Management; MOB—Mobile Source Programs.

Appendix 5. 2012 SCAQMP PM2.5 Control Measures

Number	Title
CMB-01	Further NOx Reductions from RECLAIM [NOx] –*Phase I (Contingency)*
BCM-01	Further Reductions from Residential Wood Burning Devices [PM2.5]
BCM-02	Further Reductions from Open Burning [PM2.5]
BCM-03 (formerly BCM-05)	Emission Reductions from Under-Fired Charbroilers [PM2.5]
BCM-04	Further Ammonia Reductions from Livestock Waste [NH3]
IND -01 (formerly MOB-03)	Backstop Measures for Indirect Sources of Emissions from Ports and Port Related Facilities [NOx, SOx, PM2.5]
EDU-01 (formerly MCS-02, MCS-03)	Further Criteria Pollutant Reductions from Education, Outreach and Incentives [All Pollutants]
MCS-01 (formerly MCS-07)	Application of All Feasible Measures Assessment [All Pollutants]

Number code: Combustion Sources (CMB), PM Sources (BCM), Indirect Sources (IND), Educational Programs (EDU) and Multiple Component Sources (MCS).

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