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Air quality management in China: Issues, challenges, and options

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Abstract

This article analyzed the control progress and current status of air quality, identified the major air pollution issues and challenges in future, proposed the long-term air pollution control targets, and suggested the options for better air quality in China. With the continuing growth of economy in the next 10–15 years, China will face a more severe situation of energy consumption, electricity generation and vehicle population leading to increase in multiple pollutant emissions. Controlling regional air pollution especially fine particles and ozone, as well as lowering carbon emissions from fossil fuel consumption will be a big challenge for the country. To protect public health and the eco-system, the ambient air quality in all Chinese cities shall attain the national ambient air quality standards (NAAQS) and ambient air quality guideline values set by the World Health Organization (WHO). To achieve the air quality targets, the emissions of SO_2, NO_x, PM_{10}, and volatile organic compounds (VOC) should decrease by 60%, 40%, 50%, and 40%, respectively, on the basis of that in 2005. A comprehensive control policy focusing on multiple pollutants and emission sources at both the local and regional levels was proposed to mitigate the regional air pollution issue in China. The options include development of clean energy resources, promotion of clean and efficient coal use, enhancement of vehicle pollution control, implementation of synchronous control of multiple pollutants including SO_2, NO_x, VOC, and PM emissions, joint prevention and control of regional air pollution, and application of climate friendly air pollution control measures.

Key words: regional air pollution; particulate matter; ozone; control strategy; China

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Introduction

China has experienced dramatic economic growth over the past three decades, accompanied by an annual growth rate of energy consumption as high as 10%. China has become the world's second largest energy consumer after United States, with an annual energy consumption of 2.275 billion tons of oil equivalent (toe) in 2010. Energy consumption, especially fossil fuel consumption, is the main source of anthropogenic air pollution emissions in Chinese cities. The urban air quality of China has been seriously polluted with high concentrations of sulfur dioxide (SO_2) and total suspended particle (TSP) for many years mainly due to its coal-dominated energy structure. With rapid urbanization and development of transport infrastructure, vehicle exhaust pollution has also aggravated in China. Regional air pollution complex, coal-combustion pollution, vehicle exhaust, and pollution caused by multiple other pollutants were experienced in cities and regional city clusters of China. More than three-quarters of the urban population are exposed to air quality that does not meet the national ambient air quality standards of China (Shao et al., 2006). In recent years, intensive efforts have been made to reduce air pollution in China. The number of days reported as attaining the daily Chinese National Ambient Air Quality Standard (NAAQS) for cities, called 'Blue Sky' days, has increased gradually. In this study, we review the current status, achievements, challenges and options of the air pollution control in China.

1 Control progress and current status of air quality in China

1.1 Sulfur dioxide (SO_2)

The SO_2 emission in China has changed dramatically since 2000. During the Chinese 10th Five-Year Plan period (2001–2005), the State Environmental Protection Administration (SEPA) targeted to reduce the national SO_2 emission level in 2000, i.e., 20 million tons (Mt)/year, by 10% by the year 2005 (i.e., to 18.0 Mt/year). However, due to the massive increase in fossil-fuel consumption, the lag of the introduction of desulfurization equipment, and the low efficiency of the installed desulfurization devices, the national SO_2 emission in 2005 increased to 25.5 Mt/year, 27% higher than that in 2000 (SEPA, 2006). The 11th Five-Year Plan set targets to reduce the national energy consumption per unit GDP output and SO_2 emissions of 20% and 10%, respectively, measured in 2010 against 2005 levels. To achieve the targets, several regulations have been enforced in the power sector: all new thermal power units as well as most existing ones must have flue

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gas desulfurization (FGD) systems installed, and small units with low energy efficiency should be gradually shut down. By the year 2010, over 81% of coal-fired power plants, up to 560 gigawatts (GW) have installed FGD. The amount of coal washing has increased from 0.70 billion tons in 2005 to 1.65 billion tons in 2010, resulting in a coal washing ratio increase from 33.28% in 2005 to 50.8% in 2010. The control measures have had significant effect, i.e., national SO_2 emissions decreased 14.29% from 2005 to 2010 (MEP, 2011), in contrast with substantial increases every year during the prior five years, as shown in Fig. 1. Consequently, the annually average ambient SO_2 concentrations in 113 key cities decreased from 57 to 42 μg/m^3. The large reduction in sulfur dioxide emissions from Chinese power plants were also observed by satellite monitoring instruments such as Ozone Monitoring Instrument (OMI) (Li et al., 2010).

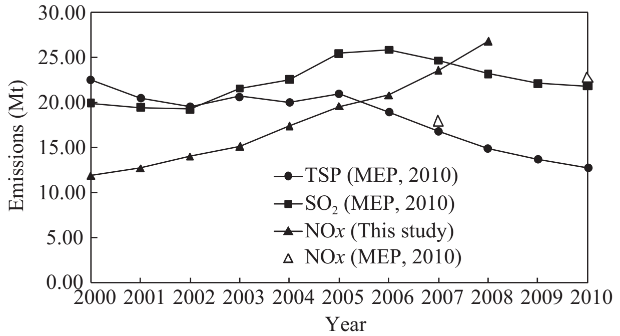

Fig. 1 Emission of SO_2, NOx and TSP in China, 2000–2010. TSP: total suspended particle.

1.2 Nitrogen oxide (NOx)

Current NOx emission control in China only involves power plants and on-road vehicles. By 2005, only about 46% of power plants had installed low NOx burners (LNB). Due to the lag of NOx emission control legislations, NOx emissions have been increasing dramatically during the past decade in China (Fig. 1). Intensive studies were conducted on NOx emissions in China (Streets et al., 2003; Wang et al., 2004, 2007; Zhang et al., 2007, 2009a, 2009b; Zhao et al., 2008; Zhao and Wang, 2009) in response to their fast growth. China's first nationwide pollution census reported that the NOx emission was 17.98 Mt in 2007 (MEP et al., 2010). Based on the census, MEP estimated that the NOx emission was over 22 Mt in 2010, exceeding that of United States and Europe. However, both previous studies and this study report a much higher NOx emission, i.e., 26.83 Mt/year in 2008, with an increase of 126% compared to that in 2000. The growth of NOx emissions is mainly from the constructions of new power plants and the rapid increase of vehicle population. During 2000–2010, the installed capacity of thermal power plants and the vehicle population increased 195% and 300%. Over the same period, NOx emissions from power plants and transport increased over 100% and 200%, respectively.

Observations of tropospheric column densities of NO_2 obtained from satellites such as Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric CartograpHY (SCIAMACHY) also indicate the rapid increase of NOx emissions from east China (Ritcher et al., 2005; Zhang et al., 2007). Satellite even sees the increased emissions from newly built large power plants in north China (Wang et al., 2010a). The increase of NOx emissions also deteriorated the $PM_{2.5}$ pollution in megacities of China. The observations in Beijing find that the nitrate aerosol in $PM_{2.5}$ observations has experienced a solid growth by 20% from 2000 to 2008. In Guangzhou, the $[NO_3^-]/[SO_4^{2-}]$ ratio in $PM_{2.5}$ was as high as 2.1 in 2008, indicating the large contribution of NOx emissions. NOx is also one of the most important precursors of ozone. Regional NOx emissions are strong contributors to surface ozone mixing ratios in the megacities such as Beijing, Shanghai and Guangzhou. NOx control is more effective than anthropogenic VOC control during periods of heavy photochemical pollution (Xing et al., 2011a).

Considering the significant impact of NOx emissions on regional air quality, i.e., ozone formation, nitrate in fine particles and acid deposition, there is urgent needs to control NOx emissions in China.

1.3 Particulate matter (PM)

In China, the control of particulate matter has achieved noticeable progress. A strengthened PM emission standard for power plants was issued in 2003 (GB13223-2003). Since then, all new and rebuilt units have to meet the PM emission Standard with PM concentrations in flue gas less than 50 mg/m^3. As a result, over 92% of pulverized coal units installed electrostatic precipitators (ESP). In addition, fabric filters have been put into commercial use for the units with a capacity of over 600 MW. With the PM control measures implemented, emission factors of $PM_{2.5}$ decreased by 7%–69% from 1990 to 2005 in different industry sectors of China, and emission factors of TSP decreased by 18%–80% as well (Lei et al., 2011). However, the effects of efficient PM control technologies were offset by the dramatic growth of the high PM emitting industries. For example, the production of steel, cement and aluminium has increased by 179%, 79% and 157% during 2000–2005, respectively. As a result, TSP emissions reached peaks of 20.94 Mt in 2005 (Fig. 1).

Measured by the frequency and degree of violations of the China's national ambient air quality standards (NAAQS), PM_{10} is the most significant air pollutant in Chinese cities. The annually average of PM_{10} concentrations in 113 key cities was 82 μg/m^3, which is about 4–6 times that in the developed countries. In Beijing, the annual average level of PM_{10} fluctuated around 114–127 μg/m^3 from 2005 to 2010 (Beijing EPB, 2011). In fact, only one percent of the country's urban population lives in cities with an annual average level of PM_{10} that is below the European Union's air quality standard of 40 μg/m^3 (World Bank, 2007).

So far, there are only few data on $PM_{2.5}$ pollution in China. Limited researches show that the ratio of $PM_{2.5}$ to PM_{10} is as high as 58%–77% in some big cities such as Guangzhou (Wu et al., 2008). $PM_{2.5}$ concentrations in some northern cities reached as high as 80–100 μg/m³, while those in the south were 40–70 μg/m³, 5–6 times and 2–5 times higher, respectively, than the ambient air quality standard in the United States (15 μg/m³, annual average) (Yang et al., 2011). The simulation of Community Multi-scale Air Quality (CMAQ) model, a regional air quality model developed by the United States Environmental Protection Agency (US EPA) indicate that large areas of China are covered with high $PM_{2.5}$ concentrations (Fig. 2), signifying that $PM_{2.5}$ pollution is a severe regional environmental issue in China. At both urban and rural sites of east China, the sum of sulfate, nitrate and ammonia typically constituted high fractions (40%–57%) of $PM_{2.5}$ mass, indicative of more local formation/production and regional transport of the secondary aerosols, thus an intensive characteristic of "complex atmospheric pollution (Yang et al., 2011).

Fine particulates are one of the major factors responsible for regional haze, which is a common phenomenon characterized by large amounts of imperceptible dry dust particles that float in the air uniformly making the visibility lower than 10.0 km. Monitoring data indicated that the annual average visibility in China in 2005 decreased about 7–15 km compared with that in early 1960s. Visibility deteriorated most dramatically in Guangzhou, with the largest negative change of –2.174 km per decade; a gradual decrease in annual mean visibility (–0.831 km per decade) was also seen in Shanghai (Chang et al., 2009). The number of haze days increased in most parts of eastern China from 1961 to 2007 (Shi et al., 2010).

1.4 Acid deposition

Acid deposition is still a serious issue in China. In 2010, 249 out of totally 494 monitored cities suffered from acid rain, accounting for 50.4% (MEP, 2011). During the period of 1995–2010, the areas with precipitation pH lower than 5.0 (also known as acid rain areas) remained stable and covered 30%–40% of the whole country. However, heavily polluted areas with precipitation pH lower than 4.5 increased. In recent years, the precipitations in some northern cities, such as Beijing, Tianjin, Dalian, Dandong, Tumen, Chengde, and Shangluo acquired a pH lower than 5.6. Another important change is that the ratio of the equivalent concentration of SO_4^{2-} to that of NO_3^- in wet precipitation in north, east, and south China decrease from 4–10 in 1990s' to 2–3 in 2009 (Tang et al., 2010). This is mainly because of the emission changes of SO_2 and NO*x*. As seen in Fig. 1, with the increase of NO*x* emissions, the ratio of SO_2 emission to NO*x* emission has decreased from 1.7 in 2000 to less than 1 in 2008.

1.5 Ozone and photochemical smog

As a result of large NO*x* and volatile organic compounds (VOC) emissions, photochemical smog and high ozone concentration have been observed in many Chinese areas such as Beijing, Pearl River Delta, and Yangtze River Delta. For example, very high mixing ratios of O_3 (1 hr O_3 up to 286 ppbV) were also reported in urban plumes of Beijing in June (Wang et al., 2006). Besides, researchers at Tsinghua University measuring the diurnal variations of episodic ground-level ozone found that O_3 concentrations often exceed 120 ppb in summer at Miyun, a rural station of Beijing (Wang et al., 2008). A similar study in the Yangtze River Delta region showed that high ozone concentrations are also often found at sites some distance removed from urbanized or industrial regions (Wang et al., 2005). Zhao et al. (2009) also found that all of East China suffers from high ozone concentrations with a maximum daily 8 hr average of 93 ppbV, which normally occurs in the urban and suburban regions in the United States. Both Aunan et al. (2000) and Wang et al. (2005) warn that ground-level ozone has already caused reductions in some crop yields. Ground-level ozone also causes damage to human health.

1.6 Carbon dioxide (CO_2) emissions

As a developing country of responsibility, China attaches great importance to the issue of climate change. The

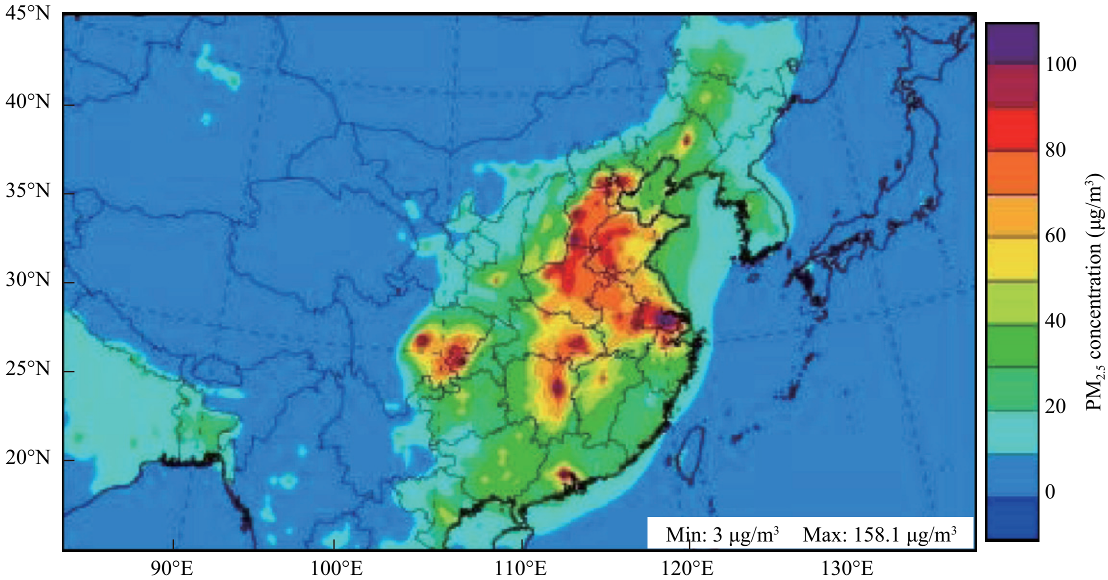

Fig. 2 Annual mean $PM_{2.5}$ concentration in China, 2005.

National Coordination Committee on Climate Change was established, and a series of policies and measures to address climate change has been taken in the overall context of national sustainable development strategy, making positive contributions to the mitigation and adaptation to climate change. However, with the growth of energy consumption, China's CO_2 emissions also increase sharply. Statistics from the International Energy Agency (IEA) indicates that CO_2 emissions from fossil fuel combustion are 7.7 billion tonnes in 2009. China has ranked as the largest CO_2 emitter in the world although its per capita CO_2 emissions (5.82 tons per capita) are only one third of United States (http://www.eia.gov/). On its current trajectory, China will emit 10 billion tonnes of CO_2 in 2015, the same as the United States and European Union combined. More actions shall be taken to lower energy intensity and improve energy efficiency.

2 Challenges, targets and strategies of air pollution control in China

2.1 Air pollution control challenges

China's air pollution control has made positive progress. However, the next 10–15 years is the critical period for China to complete the capital-intensive industrialization and the peak time of China's population. China has set the target as quadrupling GDP per capita by year 2020. It can be predicted that with the continuing growth of economy, China will face a more severe situation of energy consumption, electricity generation and vehicle population leading to increase in pollutant emissions. Compared to 2005, the energy consumption of power plants, industry and transportation in 2020 would increase sharply and coal remains as the dominated source of energy, as shown in Fig. 3 (Xing et al., 2011b). Therefore, China is facing with the task of controlling both air pollution and carbon emissions from fossil fuel consumption including both coal combustion and vehicle emissions.

High $PM_{2.5}$ and O_3 concentrations have resulted in heavy regional air pollution in some populous areas, i.e., the Beijing-Tianjin-Hebei region, Yangtze River Delta and Pearl River Delta. The air pollution in these areas is influenced by both local emissions and long-range transport from outside areas. Emission controls in a single city are hardly effective to solve the problem. Joint prevention and control of regional air pollution must be taken into consideration. A comprehensive control policy focused on multiple source categories at both the local and regional levels is necessary to mitigate the regional air pollution issue in China.

If no further actions taken to control air pollution, the emission of SO_2, NO_x, VOC and NH_3 in 2020 will increase by 17%, 50%, 49% and 18%, respectively, on a basis of 2005. In that case, the surface concentrations of SO_2, NO_2, hourly maximum ozone in summer, $PM_{2.5}$, total sulfur and nitrogen depositions will increase by 28%, 41%, 8%, 8%, 19% and 25%, respectively, over east China (Xing et al., 2011b). To protect human health and ecosystem, it is necessary to set emission limits and air quality targets that are sufficiently ambitious to improve ambient air quality in the coming decades.

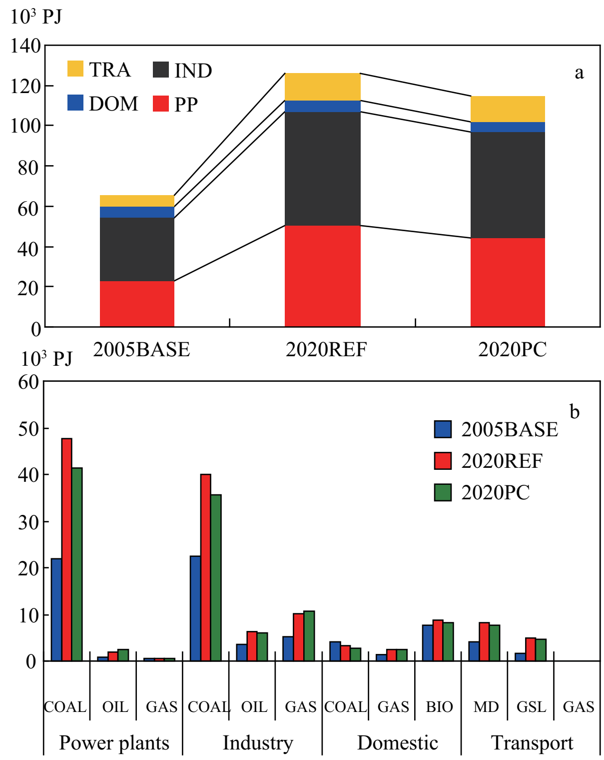

Fig. 3 Energy consumption in 2005 and 2020. (a) energy consumption by sectors in 2005 and 2020; (b) energy consumption by fuel type in 2005 and 2020.

2.2 Suggested targets for air pollution control in China

We suggest that the national strategic target of atmospheric environmental protection be set towards the compliance, by 2050, with the national ambient air quality standard for the entire country, and attainment of the World Health Organization (WHO) ambient air quality guideline values (Table 1) for most areas of the country. The air quality targets for years 2020, 2030 and 2050 are listed in Table 2. These targets are proposed as incremental steps in a progressive reduction of air pollution. These targets aim to promote a shift from high air pollutant concentrations, which have acute and serious health consequences, to lower air pollutant concentrations. If these targets are achieved, one could expect significant reductions in risks for acute and chronic health effects from air pollution.

To achieve the targets above, the emissions of multipollutants shall be reduced. The 2005 levels of SO_2, NO_x, PM_{10}, and volatile organic compounds (VOC) should decrease by 60%, 40%, 50%, and 40%, respectively. During 2010–2015, China has set the target to reduce SO_2 and NO_x emissions by 8% and 10%, respectively, on the basis of year 2010.

The establishment of systemic, scientific and dynamic national ambient air quality standards (NAAQS) will significantly contribute to the promotion of human health and the protection of ecological environment. NAAQS provides a clear-cut goal for air quality planners and establish a baseline target for environmental quality that is

Table 1 WHO ambient air quality guideline values*

	$PM_{2.5}$ (μg/m^3)		PM_{10} (μg/m^3)		O_3 (μg/m^3)	NO_2 (μg/m^3)		SO_2 (μg/m^3)	
	Annual mean	24-hr mean	Annual mean	24-hr mean	8-hr mean	Annual mean	Hourly mean	Hourly mean	10-min mean
Interim target-1 (IT-1)	35	75	70	150	160	40	200	125	
Interim target-2 (IT-2)	25	50	50	100				50	
Interim target-3 (IT-3)	15	37.5	30	75					
WHO Guideline	10	25	20	50	100			20	500

* WHO, 2006.

Table 2 Air quality targets in 2020, 2030 and 2050

Year	2020	2030	2050
Urban air quality	Over 95% attainment of the national class II ambient air quality standard; Partially attainment of the Interim target-2 (IT-2) of WHO ambient air quality guideline	Over 80% attainment of the Interim target-3 (IT-3) of WHO ambient air quality guideline	Over 95% attainment of the WHO ambient air quality guideline

not compromised by cost considerations. China's NAAQS were put into effect in October 1996. An amendment to the air quality standards in 2000 actually relaxed the standard for NO_2 to help cities make compliance, and today 100% of cities attain the standard. The standard limits are categorized into three Grades, whereby different functional zones are expected to comply with specific Grade limits. Cities are required to comply with Grade II of the NAAQS. The NAAQS of China is compared with that of United States, Europe, and the international WHO air quality guidelines issued in 2005 (Table 3). We can see that the PM_{10} standards are far above internationally recognized standards (WHO recommended daily limit for PM_{10} exposure is 50 μg/m^3 while China sets 150 μg/m^3, a three-fold difference). Another key point is that the air quality standards of United States, Europe and WHO emphasize limiting the $PM_{2.5}$ concentrations (which cause greater health impact). The international standards also use 8-hr standard for ozone instead of 1-hr average. China lacks an 8-hr standard for ozone as well as any standards for $PM_{2.5}$. China needs a roadmap for ambient air quality standards. A roadmap would help to establish standards for pollutants not covered (specifically $PM_{2.5}$), link ambient air quality standards with emissions standards and catch up with US and EU standards and WHO guidelines, and improve monitoring and reporting of levels against standard. Therefore it is necessary to revise the current NAAQS, especially include the $PM_{2.5}$ concentration limits, substitute the 1-hr ozone standard with 8-hr standard, and delete the specific standard for industrial areas.

2.3 Clean air strategies

2.3.1 Multiple pollutant control strategy

China is facing air pollution issues of both primary and secondary pollutants, i.e., NOx, PM_{10}, $PM_{2.5}$, O_3, as well as the CO_2. Therefore, the traditional, problem-oriented one-issue-at-a-time approach is far from enough in the next decades. What is not in question is that further emission reductions of SO_2, NOx and particles, as well as reductions of VOCs and possibly CO_2, must occur synchronously to address health and environmental impacts of air pollution in China (Fig. 4). There are integrating requirements into a multiple pollutant control strategy, or a climate friendly air pollution control strategy, which calls for the development of a comprehensive emission control plan which considers various atmospheric environmental problems, including

Table 3 Comparison of China's NAAQS with international standards

Pollutant	EU[a]	US[b]	WHO, 2006	China I[c]	China II[c]	China III[c]
SO_2 (μg/m^3)						
24 hour average	125	365	20	50	150	250
Annual average		79		20	60	100
NO_2 (μg/m^3)						
24 hour average				80	120	120
Annual average	40	100	40	40	80	80
PM_{10} (μg/m^3)						
24 hour average	50	150	50	50	150	250
Annual average	40		20	40	100	150
$PM_{2.5}$ (μg/m^3)						
24 hour average		35	25			
Annual average	25	15	10			
O_3 (μg/m^3)						
1 hour average		240		160	200	200
8 hour average	120	160	100			

[a] http://ec.europa.eu/environment/air/quality/standards.htm.
[b] http://epa.gov/air/criteria.html.
[c] http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqhjzlbz/199612/t19961206_67502.htm.

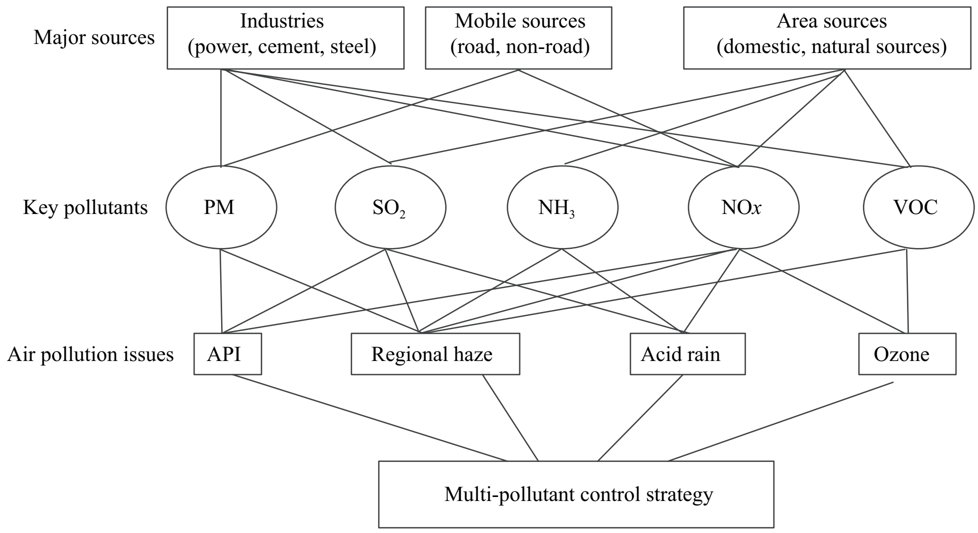

Fig. 4 Schematic illustration of the multiple pollutant control strategy.

acid deposition, ozone, fine particles, and greenhouse gases. In the immediate term, this strategy targets to start with the control of SO_2, NOx, VOC, ammonia (NH_3), and fine particles, with consideration of their co-benefits on global pollutants such as CO_2, and establish corresponding multi-pollutant control regulations and management systems.

2.3.2 Pollution prevention strategy

China's air pollution control in last two decades has emphasized the end-of-pipe control. A typical example is the installation of air pollution devices including ESP, FGD and SCR in power plants. While end-of-pipe abatement is necessary, huge cost savings can be obtained if energy efficiency and renewable energy, as well as mass transit are encouraged, which have been proved in many developed countries. The "best" way to reduce emissions of air pollutants is to change the economic structure and optimize the process or technology, so as less air pollutants are produced. Interventions to reduce fossil fuel consumption and reduce many air pollutants are in one stroke. Economic regulation and pricing of pollution costs is an important avenue for reducing fossil fuel consumption.

2.3.3 Regional air pollution control strategy

Regional air pollution in city clusters has been one of the most challenging issues in pollution control of China. The impact of regional air pollution on human health, quality of life and the environment is an environmental problem likely to remain of great concern in the coming years. Effective decision-making support in regional air quality management based on reliable regional-scale modeling is urgently needed but the lack of an integrated, accurate emission database may be the biggest hurdle at present. There are also needs to establish regional air quality monitoring networks, develop regional air quality modeling and forecast systems, and set up regulations, systems and emergency response mechanisms on photochemical smog and heavy particulate pollution.

3 Future options for a better air quality

3.1 Development of clean energy resources

China's energy consumption heavily relies on coal, which is a major cause of air pollution in China. According to data collected in the 2000–2010 national survey by the China's Ministry of Land and Resources, the country's proven reserves of coal total 187 billion tones. For China, that is about 62 years' worth of coal – at 2009 rates of consumption (roughly 3 billion tones a year). This simple 'lifetime' calculation can generate a false sense of security over the actual state of reserves (Heinberg and Fridley, 2010). A 2009 report from China's Energy Research Institute forecast that coal demand would rise by 700 million to 1 billion tones by 2020, reducing the reserves lifetime to about 33 years. If coal demand grows in step with projected Chinese economic growth, the reserves lifetime would drop to just 19 years (2050 China Energy and CO_2 Emissions Research Team, 2009). Therefore, there is urgent need to limit the total energy consumption and develop clean energy, not only for air pollution control but also for energy security.

First, limits on energy consumption will be essential in all sectors of society. Energy efficiency is defined as the ratio of Gross Domestic Product (GDP) to energy consumption. In 2008, China's energy efficiency was 1291 dollars per metric ton of oil equivalent (toe), 40% of the world average, 25% of that of the United States or 12% of that of Japan, as shown in Table 4 (International Energy Agency, 2010). During 2005–2010, the GDP of China increased 11.2% annually while energy consumption increased 6.6% annually. The elasticity of energy consumption was about 0.6 during 2005–2010. In the next decade, if the elasticity of energy consumption is the same as that in the last five years and the GDP increase at an annual rate of 8%, the national total energy consumption will be over 5.2 billion tons of coal equivalent (tce) in

Table 4 Comparison of energy indicators in China and other countries, 2008*

Country	Population (million)	GDP (billion US$ in 2000)	Energy consumption (million toe)	Energy efficiency (US$/toe)
China	1333.00	2844.00	2203.00	1290.96
United States	304.53	11742.29	2340.45	5017.11
Japan	127.69	5166.27	507.55	10178.84
OECD	1190.00	30504.00	5629.00	5419.08
World	6688.00	40482.00	12369.00	3272.86

* International Energy Agency, 2010.

2020. High priority should therefore be given to energy conservation. China has improved its energy efficiency by 20% during 2005–2010, with an annual growth rate of 4%. If the energy efficiency can be improved by 4% annually from 2010 to 2020, the energy efficiency in 2020 will be 1.4 times of that in 2010. In 2010, the GDP of China was 39,798 billion CNY and the energy consumption was 3.25 billion tce. Assuming the GDP will grow by 8% each year in the next decade, the GDP will be 2.15 times of that in 2010, that is, 85566 billion CNY. In that case, the national total energy consumption of China will be 5.0 billion tce and the energy consumption per capita will be about 3 tce.

Adjusting energy structure and speeding up the development of solar energy, wind energy, nuclear power, hydropower and other clean energies, will significantly reduce emissions of air pollutants. China has a five-year plan for renewable green energy to account for 15% of its energy mix on top of a 20% reduction in greenhouse gas emissions by 2020. It is also planned that coal will account less than 50% of total energy consumption by 2030. China has identified wind power as a key growth component of the country's economy. At the end of 2010, China's wind power accounted for 41.8 GW of electricity generating capacity. With its large land mass and long coastline, China has exceptional wind resources. Researchers from Harvard and Tsinghua University have found that China could meet all of their electricity demands from wind power through 2030 (McElroy et al., 2009). Solar power is another option of clean energy. The country's current solar capacity is 860,000 kW and aims for a 20 GW solar power capacity by 2020. The supply and consumption of natural gas also grows rapidly. Among fossil fuels, natural gas consumption has been growing faster than coal. In 2010, the natural gas consumption in China increased to 107.2 billion m^3, 4.34 times of that in 2000. By 2020, the natural gas consumption will be over 300 billion m^3. Correspondingly, the percentage of coal power will decrease by 4%–5% every five years, as shown in Fig. 5.

3.2 Clean and efficient coal use

Coal accounts for 70% of China's primary sources of energy. The direct burning of coal has significant impacts on air quality. Thus, the promotion of clean coal technologies is one of the most important measures to improve air quality. Coal washing is a relative cheap way to cut back pollution and that the government might need to implement relevant policies to encourage it. Integrated Gasification Combined Cycle is another clean coal option. Also known as carbon capture and storage, clean coal is one proposal for reducing greenhouse gas emissions while growing energy supplies.

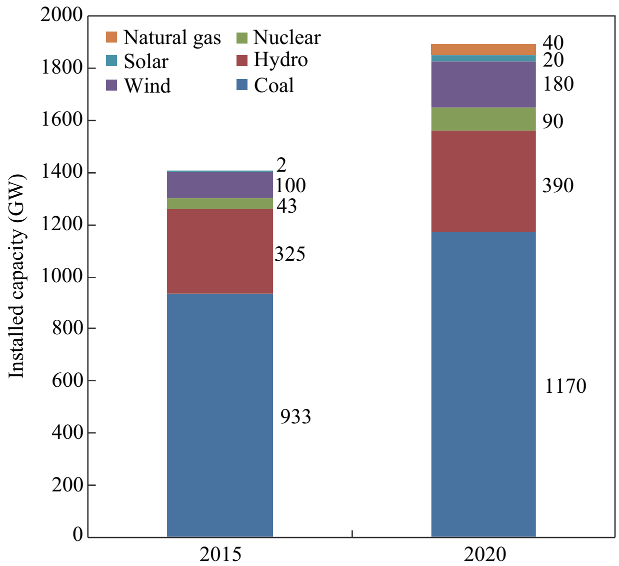

Fig. 5 Projection of installed power capacity in China, 2015–2020.

Another key point is the total coal consumption should be limited in heavily polluted regions such as Beijing and surrounding areas, Yangtze River Delta, and Pearl River Delta. These three regions, accounting for less than 6% of national area, consume 40% of coal, produce 50% of iron and steel, and own 30% of vehicles. Such intensive coal combustion emits a large amount of air pollutants and results in the regional air pollution complex. Studies have unveiled the air pollution issues caused by fossil fuel burning, especially coal combustion, as fine particles, ozone, acid deposition, and regional haze. However, there might be other issues not monitored by current studies, including heavy metals such as mercury and other hazardous air pollutants. The limit on the total amount of coal consumption is one of the preconditions to solve the air pollution problem in these areas. In 2010, the coal consumption in Beijing was 27 Mt. The government plans to cap the total coal consumption in 2015 under 20 Mt. Yangtze River Delta sets a target to control the total coal consumption less than 470 Mt in 2015, with 58, 250, 160 Mt for Shanghai, Jiangsu and Zhejiang provinces, respectively. It is possible to meet the target through transmission of electricity instead of coal, coupled with the improvement of energy use structure, control of the development of coal-fired power plants and iron and steel plants, and the promotion of clean energy supply.

End-of-pipe control of pollutants from coal combustion is also very important considering there are huge numbers of coal-fired boilers in China. China has been putting a lot of efforts to reduce the emissions from power plants and significant progress has been made. Currently the Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2003) is being revised to strengthen the NO_x and particle controls. However, the control in non-power industries such as industrial boilers and kilns shall be emphasized in future.

3.3 Enhancement of vehicle emission control

With the rapid economic development and urbanization, the vehicle population in China has been increasing quickly in recent years. In 2009, China's auto sales hit 13.64 million units, overtaking the United States as the world's top car market. By the end of 2010, the vehicle population in China exceeded 200 million, of which 90.86 million were civil motor vehicles, 19.3% higher than that in 2009. The number of private cars was 65.39 million, 25.3% higher than that in 2009. In 2009, the national vehicle emissions of CO, hydrocarbon (HC), NO_x and particles were 40.19, 4.82, 5.83, and 0.59 million tons, respectively. NO_x and HC emissions from motor vehicles accounted for over 25% of national total emissions. In megacities such as Beijing, Shanghai and Guangzhou, vehicle emissions have been one of the major sources of air pollution. In Beijing, the total vehicle population reached 4.87 million by the end of 2010. Researchers have identified mobile sources as one of the most important contributors to Beijing's air pollution. Westerdahl et al. (2009) found road traffic to be a major cause of ultrafine particles in Beijing. For the summer ozone problem, on-road vehicles are the leading contributors as the leading sources of ozone precursors, VOCs and NO_x (Wang et al., 2010b). Many studies have confirmed that air pollution in Chinese megacities has shifted from being dominated by coal burning to a mix of coal burning and vehicle emissions.

Therefore, enhancement of vehicle pollution control in megacities is an important measure to improve air quality in China. Urban development and economic growth will bring constant increase of urban transport demand over a long period of time. Due to a lag in urban transport planning and public transport facility construction, the private car has played an important role in the urban transportation growth. An urban transportation crisis could not be solved by the mere constant expansion of transport lands and roads. It is necessary to enhance the vehicle pollution control through development of public transport, emission control on new vehicles, emission control on in-use vehicles, fuel quality improvements, alternative-fuel and advanced vehicles (Wu et al., 2011), which make a long-term sustainable transportation in urban areas possible.

The establishment of the "green transportation" system and the implementation of the strategy of public transportation priority are a must to achieve sustainable development of urban transportation. Shanghai has been practicing vehicle population control policy through a license auction system, which significantly contributes in controlling the growth of private cars in the city. However, it must be noted that the implementation of vehicle population control at a large scale may have significant impacts on the automobile industry. Efforts to establish a good public transportation system and to guide the public in choosing more efficient public transportation and in switching from private vehicle to public transport, especially in the urban areas, will help reduce both motor vehicle travel mileage and pollution emissions.

Implementation of more stringent emission standards is the most cost-effective way to control emissions from new vehicles. China has issued emission standards for new vehicles and engines based on European Union Standards. As the capital city of China, Beijing began to introduce Euro I emission standards in 1999, Euro II standards in 2003, and Euro III in 2005. At national level, phase 1, 2 and 3 standards (similar to Euro 1, 2 and 3, respectively) began to be put into effect in 2000, 2004, and 2007 sequentially (MEP, 2010). Megacities including Beijing and Shanghai are subject to greater pressure for regulating vehicle emissions and have enforced phase 4 emission standard for new vehicles (similar to Euro 4) in 2008 and 2009, respectively. The emission factors of CO, HC, and NO_x from phase 3 vehicles, compared with that of phase 1 vehicles, are decreased 44%, 70% and 70%, respectively. The more stringent emission regulations for new vehicles have been the most important control measures to decrease fleet-average emission factors in China. Studies indicate that due to the implementation of phase 1–4 emission standards since 1995, the fleet-average emission factors of CO, HC, NO_x and PM_{10} for light-duty gasoline cars were annually decreased by 12.5%, 10.0%, 5.8% and 13.0%, respectively (Wu et al., 2011). However, the emission standards for new vehicles in China are still 7 years behind those in developed countries. Therefore, more stringent emission standards for new vehicles shall be implemented in future. Recently, Beijing EPB began promoting regulations for new emission standards, i.e., Euro 5 in 2012 and Euro 6 in 2016.

Although the emission regulations to control new vehicles discussed above are directly toward reducing emissions from in-use vehicles ultimately, the pollution control of in-use vehicles has to be enhanced through the retrofit or retirement of high-emission vehicles and the improvement of the vehicle emissions inspection and maintenance (I/M) system. In China, the old vehicles before phase 1 standard which account for only 17.1% of national total vehicles contribute to over 50% of air pollutant emissions. On the contrast, the phase 3 vehicles accounting for 25.4% of national total vehicles contribute to less than 6% of air pollutant emissions. We can see that the effectiveness of retrofit or retirement of these high-emission vehicles. The I/M program was another effective means for reducing emissions of in-use vehicles. Beijing started preliminary I/M programs with two speed idle tests in 1995, and the complete I/M programs have been enforced since 1999. According to the accomplished study by Tsinghua University, the CO and HC emission from in-use vehicles has been significantly reduced by I/M programs in Beijing.

A close relationship between fuel quality and vehicle emissions has been confirmed by several studies (Hao et al., 2006; ICCT, 2006). Major indicators of gasoline quality include octane, Reid vapor pressure (RVP), lead content, sulfur content, and shares of olefins, aromatics, and oxygenate. For diesel fuel, the sulfur content, cetane number, and shares of aromatics and additives are important indicators. Sulfur content in the fuel is expected to decrease in conjunction with the enhancement of vehicle emission standards (Table 5). There is a necessity to develop fuel quality standards in accordance with the emission standards for new vehicles to gradually decrease the sulfur content and improve fuel quality.

Finally, it is also vital to promote compressed natural gas (CNG), liquefied natural gas (LNG), and other clean alternative fuel vehicles in the public transportation system before 2010, as well as to encourage the use of commercialized clean energy vehicles like the hybrid electric vehicles before 2015 through preferential policies such as the grant of tax subsidies and the gradual development of biodiesel and other clean alternative fuels, and to increase the proportion of clean alternative fuels after 2020. China has conducted several initiatives to promote electric vehicles.

3.4 Synchronous control of multiple pollutants

Emission control of SO_2 has been the focus of air pollution control in China and achieved big progress. However, in order to effectively control acid deposition and other regional environmental problems, further actions shall be taken. During 2011–2015, China is going to further control SO_2 emissions by 8% on the basis of that in 2010. Efforts to achieve the 8% reduction in SO_2 emissions will focus on further installation of FGD equipment, improving overall coal power plant performance and raising the desulfurization rate to 95%. Although 81% of Chinese power plants have installed FGD, the removal efficiencies and operation time of FGD are not satisfied. The small plant closure program will also be extended to shut an additional 50 GW of polluting coal units. The current SO_2 emission level of Chinese power plants is 2.9 g/kWh, which is expected to decrease to 1.5 g/kWh by the end of 2015 through the improvement of FGD operations and phase-out of small thermal power units with high emissions. However, with half of coal consumed outside the power sector, by industrial and small and medium sized users, greater efforts will be needed to regulate emissions from these sources. Industry processes including cement plants, lime plants, coking plants and sinter plants are important SO_2 sources as well. For cement plants, the units with out-of-date technology such as rotary kilns and vertical kiln will be shut down. By 2020, the percentage of advanced pre-calcining kilns will increase to 91% in the cement industry, which decreases the SO_2 emission factor by 53% compared to that in 2005. The lime plants using early kilns will decrease from 70% in 2005 to 13% in 2020, while those using modern kilns will increase from 30% in 2005 to 87% in 2020. All the indigenous coke plants will also be closed before 2020. For sinter plants, more effort will be made to improve the control technology and that emission factor will be decreased by 30% in 2020 compared to that in 2005.

During 2011–2015, China is going to further control NO*x* emissions by 10% on the basis of that in 2010, which is a big challenge. To meet the target, the quantity control of automobiles in China's populous metropolises, and a cap on the discharge of NO*x* in power and cement industries shall be considered. Vehicle emission control was discussed in the above session. NO*x* emissions from thermal power plants, which account for 36% of the national total emissions and comprise a major source of NO*x* emissions in China, should be strictly controlled at national level. NO*x* pollution control of thermal power plants should focus on the following endeavors: (i) amendment of NO*x* emission standards; (ii) retirement of high-emission units; and (iii) application of NO*x* emission control technologies. Major flue gas de-NO*x* technologies

Table 5 Changes of sulfur content in gasoline and diesel in China and its megacities (unit: mg/kg)

<table>
<tr><td colspan="12">Gasoline</td></tr>
<tr><td>Year</td><td>1999</td><td>2000</td><td>2001</td><td>2002</td><td>2003</td><td>2004</td><td>2005</td><td>2006</td><td>2007</td><td>2008</td><td>2009</td></tr>
<tr><td>China</td><td>1500</td><td colspan="3">1000</td><td colspan="3">800</td><td colspan="4">500</td></tr>
<tr><td>Beijing</td><td>1500</td><td>1000</td><td colspan="3">800</td><td>500</td><td colspan="3">150</td><td colspan="2">50</td></tr>
<tr><td>Shanghai</td><td>1500</td><td>1000</td><td colspan="4">800</td><td colspan="4">500</td><td>50</td></tr>
<tr><td>Guangzhou</td><td>1500</td><td>1000</td><td colspan="4">800</td><td>500</td><td colspan="4">150</td></tr>
<tr><td colspan="12">Diesel</td></tr>
<tr><td>Year</td><td>1999</td><td>2000</td><td>2001</td><td>2002</td><td>2003</td><td>2004</td><td>2005</td><td>2006</td><td>2007</td><td>2008</td><td>2009</td></tr>
<tr><td>China</td><td colspan="3">2000/5000/10000</td><td colspan="8">2000</td></tr>
<tr><td>Beijing</td><td colspan="3">2000/5000/10000</td><td colspan="2">2000</td><td>500</td><td colspan="3">350</td><td colspan="2">50</td></tr>
<tr><td>Shanghai</td><td colspan="3">2000/5000/10000</td><td colspan="7">2000</td><td>50</td></tr>
<tr><td>Guangzhou</td><td colspan="3">2000/5000/10000</td><td colspan="4">2000</td><td colspan="4">350</td></tr>
</table>

including Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), and SNCR-SCR systems will be applied in power plants. In 2020, the application ratio of SCR will increase to over 55% in 2020 according to the emission standards under revision. For important regions, ozone shall be included in the air quality evaluation system. NO*x* emission control plan shall be developed according to the regional ozone and $PM_{2.5}$ targets. Additional measures will be considered during high ozone episodes. At local level, NO*x* emissions shall meet both the limits in emission standards and regional/national requirements.

As shown in Fig. 1, China has made certain achievements on particle emission control. However, there is still a long way to go since the PM_{10} and $PM_{2.5}$ concentrations are still very high. Primary particulate emissions contribute over 50% averagely to the high ambient particulate concentrations in Chinese cities. Therefore the particle emissions shall be further strengthened. Cement plants and iron and steel plants are important sources of particulate pollution in China. The particulate emission control of these sectors shall include phasing out old production processes with high energy consumption and serious pollution implication, recycling waste heat of dry kilns as low-temperature exhaust heat generation, installing CEMS to monitor the whole process of production, improving the management of current cement and steel plants, installing high efficiency dust removal facilities, and reducing fugitive dust emissions. Another important measure is to emphasize ecological construction and forestation, speed up the virescence in urban areas, and gradually eliminate the bare land in cities.

Control of VOC emissions has not been initiated in China. Immediate efforts shall be made to develop VOC emission control laws and regulations, compile and issue a list of VOCs to be controlled, and establish ambient VOC standards, source emission limit standards, and solvent product standards of VOC contents. Moreover, VOC emissions from use of industrial organic solvents should comply with the national emission standards. Waste gas from industrial process should be recycled. To prevent VOC emissions from industrial solvent use, the following steps should be taken: (i) store the organic solvents in sealed containers; (ii) minimize the toxic and hazardous gas emissions in the transportation of organic solvents; (iii) encourage and promote the use of low-volatile solvent; and (iv) prohibit VOC emissions from spraying, sand blasting, glass steel production, and vehicle friction chips in the open air and residential area. Oil/gas stations, oil storage tanks and oil tank trucks should use sealing technologies to control VOC emissions and achieve the national emission standards.

3.5 Joint prevention and control of regional air pollution

Regional air pollution has caught high attentions in China. On May 11, 2010, the General Office of the State Council of China issued the Guiding Opinions on Pushing Forward the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality (hereinafter referred to as "Guiding Opinions"). The Guiding Opinions aimed to establish a joint prevention and control system for atmospheric pollution, formulate a system of regulations, standards and policies for regional atmospheric environmental management, significantly reduce the total amount of emissions from the main atmospheric pollutants, ensure that all key enterprises meet the emissions standards, and ensure that all cities in key regions maintain air quality at or better than the Grade II National Ambient Air Quality Standard, greatly reduce the acid rain, haze and photochemical smog pollution and improve regional air quality by 2015. The key regions for beginning the implementation of regional air pollution joint prevention and control are the Beijing-Tianjin-Hebei Region, the Yangtze River Delta Region and the Pearl River Delta Region. In Central Liaoning, the Shandong peninsula, Wuhan and its surrounding area, the Changsha, Zhuzhou and Xiangtan region, the Chengdu and Chongqing region, and the western coast of the Taiwan Strait governments should actively promote regional air pollution joint prevention and control. The

Fig. 6 Three key regions and six city clusters identified for regional air pollution control.

three key regions and six city-clusters (Fig. 6) are the population and economic centers of the country, in aggregate representing 64% of national GDP, 43% of total energy use, and 39% of the population. The key pollutants in joint prevention and control of air pollution include SO_2, NO_x, PM and VOC. The key industries include thermal power plants, iron and steel, non-ferrous metals, petrochemicals, cement and chemicals, those key enterprises that heavily affect regional air quality. The key problems to be addressed are the acid rain, haze, photochemical smog, etc. In order to solve the important issues of regional air pollution, it is necessary to establish the mechanisms of unified planning, unified monitoring, unified supervision, unified evaluation and unified coordination for the joint prevention and control of regional atmospheric pollution. To provide a technology platform for urbanization in the future, study of technologies and methodologies on regional air quality monitoring, emission inventory, air quality forecasting and alarming, and regional air pollution control system should be undertaken.

3.6 Promotion of climate friendly air pollution control measures

Climate change is a big challenge to China. To achieve a given target in ambient air quality, China can dramatically save costs by adopting a smart mix of measures to reduce air pollution and greenhouse gas emissions. In many cases emissions of air pollutants and greenhouse gases are emitted from the same sources. Thus, controls directed at air pollutants frequently affect greenhouse gas emissions, and vice versa. Strategies to reduce greenhouse gas emissions can dramatically lower air pollution control costs. It has been demonstrated that the climate-friendly measures, e.g., energy efficiency improvements, co-generation of heat and power, fuel substitution, integrated coal gasification combined cycle (IGCC) plants, result in lower emissions of SO_2, NO_x and $PM_{2.5}$ at no additional costs. It was estimated that each percent of CO_2 reduction would typically reduce health impacts from PM air pollution by 1% (Amman et al., 2008). A smart mix of measures to simultaneously cut air pollution and greenhouse gas emissions will help combat climate change and air pollution more cheaply than tackling either issue separately.

In the near-term, the climate-friendly air pollution control strategy shall focus on the synergic control of black carbon and CO_2 with conventional air pollutants and in addition, strengthen the construction of abilities in combating climate change including greenhouse gases concentration monitoring, emissions inventory, cost-benefit analysis and synergic control policy making. Further studies are needed to evaluate the co-benefits and develop a strategy of air pollution management and climate change mitigation.

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