Emission trends and mitigation options for air pollutants in East Asia

S. X. Wang[1,2], B. Zhao[1], S. Y. Cai[1], Z. Klimont[3], C. P. Nielsen[4], T. Morikawa[5], J. H. Woo[6], Y. Kim[6], X. Fu[1], J. Y. Xu[1], J. M. Hao[1,2], K. B. He[1,2]

[1] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China

[2] State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China

[3] International Institute for Applied System Analysis, Laxenburg, Austria

[4] Harvard China Project, School of Engineering and Applied Sciences, Harvard University, 29 Oxford St, Cambridge, MA 02138, USA

[5] Japan Automobile Research Institute, Tsukuba, Japan

[6] Department of Advanced Technology Fusion, Konkuk University, Seoul, South Korea

Correspondence to: S. X. Wang (shxwang@ tsinghua.edu.cn)

Abstract.

Emissions of air pollutants in East Asia play an important role in the regional and global atmospheric environment. In this study we evaluated the recent emission trends of sulfur dioxide (SO_2), nitrogen oxides (NO_X), particulate matter (PM), and non-methane volatile organic compounds (NMVOC) in East Asia, and projected their future emissions up to 2030 with six emission scenarios. The results will provide future emission projections for the modeling community of the model inter-comparison program for Asia (MICS-Asia). During 2005-2010, the emissions of SO_2 and $PM_{2.5}$ in East Asia decreased by 15% and 12%, respectively, mainly attributable to the large-scale deployment of flue gas desulfurization (FGD) at China's power plants, and the promotion of highly efficient PM removal technologies in China's power plants and cement industry. During this period, the emissions of NO_X and NMVOC increased by 25% and 15%, driven by rapid increase in the emissions from China due to inadequate control strategies. In contrast, the NO_X and NMVOC emissions in East Asia except China decreased by

13-17%, mainly due to the implementation of stringent vehicle emission standards in Japan and South Korea. Under current regulations and current levels of implementation, NO_X, SO_2, and NMVOC emissions in East Asia are projected to increase by about one quarter over 2010 levels by 2030, while $PM_{2.5}$ emissions are expected to decrease by 7%. Assuming enforcement of new energy-saving policies, emissions of NO_X, SO_2, $PM_{2.5}$ and NMVOC in East Asia are expected to decrease by 28%, 36%, 28%, and 15%, respectively, compared with the baseline case. The implementation of "progressive" end-of-pipe control measures would lead to another one-third reduction of the baseline emissions of NO_X, and about one-quarter reduction of SO_2, $PM_{2.5}$, and NMVOC. Assuming the full application of technically feasible energy-saving policies and end-of-pipe control technologies, the emissions of NO_X, SO_2, and $PM_{2.5}$ in East Asia would account for only about one quarter, and NMVOC for one third, of the levels of the baseline projection. Compared with previous projections, this study projects larger reductions in NO_X and SO_2 emissions by considering aggressive governmental plans and standards scheduled to be implemented in the next decade, and quantifies the significant effects of detailed progressive control measures on NMVOC emissions up to 2030.

1 Introduction

Air pollutant emissions in East Asia contribute a large share of the global emissions. Cofala et al. (2012) reported that East Asia contributes about 36%, 29%, and 36% to global emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_X), and particulate matter less than or equal to 2.5 μm ($PM_{2.5}$), respectively, much more than those of the United States (U.S.) and Europe. Moreover, both emission calculations and satellite observations indicate that NO_X emissions in China have experienced rapid increase during 1995-2010, with annual average growth rates ranging between 5.5%-7% (Zhao et al., 2013c; Zhang et al., 2007; Zhang et al., 2012a). As a result, emissions in East Asia have greatly degraded regional air quality and visibility (Wang and Hao, 2012; Zhang et al., 2012c) and damaged human health (WB and SEPA, 2007). They also affect air quality and climate forcing beyond the region through the outflow that travels across Pacific (Liu et al., 2003). In light of this situation, the control of emissions in East Asia is very important for the improvement of regional and global atmospheric environment.

With the objectives of air quality improvement and mitigation of climate change, the countries of East Asia, e.g., China, Japan, and South Korea, have taken substantial measures to improve energy efficiency and reduce emissions of air pollutants. These measures have often been stringent and have been rapidly enhanced. During 2006-2010, China set a target to reduce energy use per unit of Gross Domestic Product (GDP) and national SO_2 emissions by 20% and 10%, respectively (The State Council of the People's Republic of China, 2006). During 2011–2015, China plans additional 16%, 10%, and 8% reductions for energy use per unit GDP, NO_X emissions, and SO_2 emissions, respectively (The State Council of the People's Republic of China, 2011). Japan has taken measures to meet its commitments under the Kyoto Protocol, which require that annual CO_2 emissions during 2008-2012 should be 6% lower than those of 1990 (IEA, 2008). The vehicle emission standards in China, Japan, and South Korea have also been updated repeatedly in the past decade. A number of studies have investigated the recent emission trends in East Asia (or a specific country therein) and the effects of typical control policies. For example, reductions in China's SO_2 emissions since 2005 both by observations from satellites (Li et al., 2010), and by bottom-up emission estimations (Lu et al., 2010; Lu et al., 2011; Klimont et al., 2013). Some studies also estimated the trends of the emissions of NO_X (Zhang et al., 2012a; Lin et al., 2010b; Zhao et al., 2013c) and particulate matter (PM) (Lin et al., 2010a; Lu et al., 2011). Kurokawa et al. (2013), Zhao et al. (2013d), and Zhao et al. (2013a) estimated the recent emission trends of multiple air pollutants. Future emissions were also predicted by previous studies (Streets and Waldhoff, 2000; Klimont et al., 2001; Cofala et al., 2007; Ohara et al., 2007; Klimont et al., 2009; Xing et al., 2011; Cofala et al., 2012; Zhao et al., 2013c). However, most of these projections were based on emissions for 2005 or earlier and did not consider more recent, sometimes dramatic, changes. The latest projections include Cofala et al. (2012) and Zhao et al. (2013c). Cofala et al. (2012) projected global emissions of SO_2, NO_X, and $PM_{2.5}$ for four energy scenarios developed by IEA (2012a), but did not envisage further end-of-pipe mitigation measures in the future. Zhao et al. (2013c) developed six NO_X emission scenarios up to 2030 based on a 2010 emission inventory, and quantified the effects of various control policies, but did not analyze other air pollutants.

Although there have been a number of studies of recent and future emission trends in East Asia, they are inadequate for development of broadly effective air quality and climate mitigation policies. First, future control measures must be developed while taking full account of the latest policies, and a comprehensive and up-to-date review for the entire region is currently lacking in the literature. As described above, the base years of most projections were 2005 or earlier, and therefore they underestimated China's economic growth over the last decade, especially from 2006 to 2010. These early projections also did not anticipate new emission control policies announced in 2011 under China's 12th Five Year Plan (for the period of 2011-2015; The State Council of the People's Republic of China, 2011), nor a number of emission standards released after 2010, both of which may fundamentally alter the future emission pathways. The most recent projections (Cofala et al., 2012; Zhao et al., 2013c) considered only a specific pollutant or a specific set of control measures, providing only partial insight into the future trends of all major air pollutants. Second, the attainment of stringent ambient air quality standards (e.g., China's standard of 35 μg m^{-3} for the annual average $PM_{2.5}$ concentration, released in 2012) requires simultaneous reductions of multiple pollutants including SO_2, NO_X, $PM_{2.5}$, and non-methane volatile organic compounds (NMVOC) (Wang and Hao, 2012). Therefore it is essential to consider a full range of relevant pollutants and scenarios at different stringency levels from the business-as-usual case to the maximum feasible reduction case, so that cost-effective emission controls can balance measures over all pollutants and control levels. Third, most studies focused on either end-of-pipe or energy-saving measures; their roles in integrated policies that simultaneously tackle multiple pollutants and climate forcers have been insufficiently studied. Considering the above, a comprehensive projection of emissions of multiple pollutants that incorporates the latest available base-year data, control measures scheduled for implementation, and other potential energy-saving and end-of-pipe measures at different stringency levels will contribute to both air pollution research and future decision making.

This study aims to evaluate the emission trends and mitigation options for multiple air pollutants in East Asia. The results will provide future emission projections for the modeling community of the model inter-comparison program for Asia (MICS-Asia), which aims to have a common understanding of the model performance and uncertainties in Asia.

In Sect. 2, we review major control policies in East Asia over the last decade and evaluate their impact on air pollutant emissions during 2005-2010. Compared with previous studies of emission trends, we are particularly devoted to presenting a comprehensive review of the recent mitigation measures in this region, and illuminating the driving forces underlying the emission trends. In Sect. 3, we project future emissions of SO_2, NO_X, NMVOC, and PM up to 2030 for six emission scenarios (see Table 1), considering both energy-saving and end-of-pipe measures. In Sect. 4, we compare our results with other emission estimates as well as observations. In this study, the domain of East Asia consists of seven countries/regions, i.e., mainland China (People's Republic of China except Hong Kong, Macao, and Taiwan), Japan, South Korea, North Korea, Mongolia, Hong Kong & Macao, and Taiwan. In the following text, China is short for mainland China. We focus on Japan, South Korea, and especially China, the key energy consumers in the region that dominate the emissions of air pollutants. Japan and Korea have relatively long histories of air pollution policies, while China has been enhancing its emission regulations in the last decade at an acclerating rate, has very ambitious future goals, and contributes the largest share of regional emissions. Therefore, developments in China are given special attention.

2 Recent control measures and emission trends

Recent control measures not only serve as the major driving forces of recent emission trends, but also lay the foundation for the development of future control policies. Control measures contributing to reductions of air pollutant emissions include energy-saving measures, e.g., energy efficiency improvements, co-generation of heat and power, fuel substitution, and end-of-pipe control measures such as installations of dust collectors and flue gas desulfurization systems. A careful mix of measures to simultaneously address energy conservation, air pollution control and climate change mitigation is considerably cheaper than tackling each issue separately (Wang and Hao, 2012). In this section we review both recent energy-saving and end-of-pipe measures in East Asia, and then quantify their effects on recent emission changes.

2.1 Energy-saving measures

Japan, South Korea, and China have released a number of policies addressing energy conservation and climate change mitigation. Under the Kyoto Protocol, Japan committed to reduction of its greenhouse gas (GHG) emissions by 6% during 2008-2012 from the base year of 1990. In the "New National Energy Strategy" formulated in May 2006, the Japanese government set a long-term target to improve energy intensity of GDP by an additional 30% by 2030 (IEA, 2008). The government of South Korea has made a commitment to reduce its GHG emissions by

30% compared to its business-as-usual projection by 2020 (IEA, 2012b). The Chinese government has set a target to reduce CO_2 emissions per unit GDP by 40%-45% in 2020 compared with 2005 levels (Wang and Hao, 2012). Total energy consumption in East Asia increased by 31% during 2005-2010. China experienced the fastest increase, 43%, driven by its rapid GDP growth rate, while Japan's energy consumption decreased during these five years due to a lower GDP growth rate and stringent energy-saving policies. The growth rate of South Korean energy consumption was intermediate between those of China and Japan, at 19%.

2.1.1 Power plants

The energy consumption of China's power sector increased sharply by 35% during 2005-2010, due to the rapid increase in the demand for electricity (NBS, 2007, 2011a), while those of Japan and South Korea remained relatively stable (http://www.iea.org/statistics/).

Up to 75% of China's power generation is coal-fired (Zhao et al., 2013c). In contrast, the installed capacity in Japan is highly diversified, with coal, oil, natural gas, nuclear, and hydro contributing about 27%, 8%, 27%, 26%, and 8% of total electricity generation in 2010, respectively (http://www.iea.org/statistics/). In South Korea, fossil fuels accounted for 69% of the total electricity generated, followed by nuclear at 30%, in 2010 (http://www.iea.org/statistics/). While nuclear power has played central roles in Japan's and South Korea's low-carbon strategies, its share of Japanese power generation dropped dramatically to less than 10% in 2011 due to the Fukushima accident in March of that year (http://www.iea.org/statistics/), making the future of nuclear power in Japan quite uncertain. In South Korea, by contrast, nuclear power generation is expected to keep increasing in the next decade, with five reactors under construction and six more announced (IEA, 2012b). Given China's coal-intensive power generation mix, its government has been promoting the development of cleaner electricity through subsidy policies. By 2010, its capacities of hydro, natural gas-fired, wind, and solar power generation had increased dramatically to 213 GW, 27 GW, 31 GW, and 0.24 GW, respectively, or 1.82, 2.25, 23.8, and 3.43 times those of 2005 (China Electric Power Yearbook Committee, 2006, 2011).

China has also undertaken major efforts to improve the efficiency of coal-fired power generation. Its government forced the closure of 77 GW of small and inefficient coal-fired units during 2006-2010 (NDRC, 2011), with an additional 20 GW of small units scheduled for early retirement during 2011-2015 (The State Council of the People's Republic of China, 2012). At the same time, the capacities of most new units built after 2005 have been ≥ 300 MW, driving their capacity share from 50% in 2005 to 73% in 2010 (The State Council of the People's Republic of China, 2012). The share of advanced supercritical and ultra-supercritical units, moreover, rose to over 13% (Li et al., 2012). As a result of these changes, the coal consumption per unit electricity supplied by thermal power plants decreased from 370 gce/kWh to 333 gce/kWh during the same period (The State Council of the People's Republic of China, 2012).

2.1.2 Industrial sector

During 2005-2010, the energy consumption of China's industrial sector increased dramatically, at an annual average rate of 9.0% (cf. 7.4% for total energy consumption), due largely to the rapid increase of energy-intensive products, e.g., cement and steel (NBS, 2007, 2011a). However, driven by a target to reduce energy intensity per unit GDP by 20% from 2005 to 2010, China mandated widespread replacement of outmoded production technologies with more energy-efficient ones. For example, the share of cement produced by precalciner kilns increased from 45% in 2005 to about 80% in 2010. During the same period, the proportion of large units (⩾4000 t/d) of all precalciner kilns increased from 33% to 60% (Zhao et al., 2013c; Zhao et al., 2013d). The share of coke produced in machinery coking ovens (versus indigenous ovens) increased from 82% in 2005 to 87% in 2010 (NBS, 2007, 2011; Huo et al., 2012); the share of blast furnaces larger than 1000 m^3 increased from 48% to 61% over the same time period (The State Council of the People's Republic of China, 2012). In effect, the average energy intensity of cement and crude steel production decreased by 29% and 12%, respectively, from 2005 to 2010 (The State Council of the People's Republic of China, 2012).

While China's industrial sector has grown swiftly but only recently undertaken aggressive energy efficiency improvements, Japan's industrial sector has played a central role in national energy conservation for several decades (IEA, 2008). Major policies have included compulsory submission of energy-saving plans for large energy consumers, frequent on-site inspections, and subsidies to assist small companies to introduce energy-efficient equipment (IEA, 2008; Energy Conservation Center of Japan, 2011). These measures decreased the average energy consumption per ton of production of cement and crude steel by 6.3% and 5.6%, respectively, from 2000 to

2010 (Wang, 2010). Japan's industrial energy use as a proportion of total energy use has declined from 26% in 2000 to 18% in 2010 (IEA, 2002, 2012c), and the share of coal and petroleum products of total energy consumption has decreased from 64% to 56% during 2000-2010 (IEA, 2002, 2012c).

Industrial energy consumption in South Korea increased steadily in recent years, in part because its energy intensity (energy consumption per unit GDP) did not notably improve from the 1990s to 2006 (IEA, 2006). In 2008, South Korea set new targets for national energy intensity in its "Strategy for Green Growth": from 0.328 toe/US$1000 in 2007 to 0.290 toe/US$1000 in 2013, and 0.233 toe/US$1000 in 2020. Enforcement of these policies is expected to occur mainly through "voluntary agreements" between the government and large companies (IEA, 2006, 2012b; UNEP, 2010).

2.1.3 Residential sector

Residential energy consumption in China and South Korea increased steadily during 2005-2010, driven by increases in total building area (NBS, 2007, 2008a, b, 2009, 2011a, b; http://www.iea.org/statistics/). During the same period, Japan's residential energy consumption decreased slightly, attributed to the stable demand for building space and aggressive energy-saving policies (IEA, 2008; http://www.iea.org/statistics/).

By the end of 2006, 96% of China's new buildings complied with the energy-saving design standard released in 1996 (THUBERC, 2009); this was succeeded by a more stringent standard in 2010 (The State Council of the People's Republic of China, 2012). The energy efficiency standards in Japan's building codes, first released in 1980 and strengthened in 1992 and 1999, have all been voluntary. As of 2005, 30% of new houses and 85% of new buildings larger than 2000 m^2 complied with the voluntary standards (IEA, 2008). In Korea, energy efficiency codes for buildings had long been relatively weak until a strong, performance-based design code applicable to large commercial buildings was issued in 2011 (IEA, 2006, 2012b).

Japan is a world leader in the energy efficiency of residential and commercial appliances. The "Top Runner program," which set energy-efficiency targets for appliances based on the most energy-efficient products on the market, has been successfully enforced. For example, the efficiency of air conditioners and refrigerators increased by 68% (over 1997-2004) and 55%

(1998-2004), respectively, both exceeding the targets of 66% and 31% (IEA, 2008; Energy Conservation Center of Japan, 2011). Similar programs have recently been promoted in South Korea and China (UNEP, 2010).

China has been promoting clean energy in the residential sector. Direct combustion of biomass in rural areas has been gradually replaced with commercial fuels in the last decade, and its share in rural cooking decreased from 38% in 2005 to 31% in 2010. The production of biogas for residential use and ownership of solar water heaters both doubled during 2005-2010 due to subsidy policies.

2.1.4 Transportation sector

During 2005-2010, the energy consumption of China's transportation sector grew at an annual average rate of 10%, attributed to explosive growth of the vehicle population (NBS, 2007, 2011a). In contrast, the transportation energy consumption in South Korea was stable and that of Japan declined (http://www.iea.org/statistics/).

The reduction in Japan's vehicle energy consumption is largely due to its fuel-efficiency standards, which are among the most aggressive in the world. For passenger vehicles, there was a consistent improvement in the average fuel economy from 13.5 km/L in 2000 to 17.8 km/L in 2009 (Energy Conservation Center of Japan, 2011). Japan was also the first country in the world to implement fuel efficiency standards for heavy-duty (freight) vehicles, which decreased from 851 kcal/t-km in 2000 to 722 kcal/t-km in 2008 (Institute of Energy Economics of Japan, 2010). China has also implemented fuel-efficiency standards for light-duty vehicles since 2004, leading to an increase in the efficiency of new gasoline passenger cars from 11.0 km/L in 2005 to 13.5 km/L in 2010 (Zhao et al., 2013c). An updated standard (14.3 km/L by 2015) for passenger cars was issued in 2011. In 2006, the South Korean government introduced its first mandatory fuel-economy standards, requiring car manufacturers to meet average fuel economy standards of 12.4 km/L for vehicles with engines of less than 1500 cubic centimeters (IEA, 2006). In July 2009, a new fuel-economy standard of 17 km/L was announced (IEA, 2012b).

China has also launched several initiatives to promote electric vehicles, and their population reached 12,000 by 2010 (Yang, 2012). The most recent development plan for new-energy vehicles (issued in 2012) aimed to increase the population of electric vehicles to 0.5 million and 5 million in 2015 and 2020, respectively, through a series of subsidy policies.

2.2 End-of-pipe control measures

2.2.1 Power plants

Due to their relatively large scales of energy use and emissions, power plants are usually subject to the most stringent control measures of all sectors. The penetrations of major control technologies in the power sectors of China, Japan, and South Korea are summarized in Table 2.

In 2006, China set a target to reduce national SO_2 emissions by 10% by 2010 over 2005 levels (Wang and Hao, 2012). By 2010, over 83% of coal-fired power plants (about 88% of pulverized coal combustion plants, representing 560 GW) had installed flue gas desulfurization (FGD) (MEP, 2011). The recently released 12th Five-Year Plan aims at another 8% reduction in total SO_2 emissions by 2015, which would require nearly all coal-fired power plants to be equipped with high-efficiency FGD facilities (i.e., with at least 95% removal efficiency).

Low-NO_X combustion technology (mainly Low-NO_X Burners, LNB) was the major NO_X control technology in China's coal-fired power plants by 2010. The penetration of flue gas denitrification (Selective Catalytic Reduction, SCR, and/or Selective Non-Catalytic Reduction, SNCR) was only 1.1% in 2005 and 12.8% in 2010 (MEP, 2011). In the 12th Five-Year Plan, the Chinese government aims to reduce national NO_X emissions by 10% from 2010 to 2015, and the key measure to meet this target is large-scale deployment of SCR/SNCR facilities. The NO_X emission control policies are described in more detail in our previous paper (Zhao et al., 2013c).

The emission control of primary particulate matter in China's power sector has achieved noticeable progress in the last decade. Since 2003, all new and rebuilt units have had to attain the in-stack concentration standard for PM of 50 mg/m^3 (GB13223-2003). As a result, over 92% of pulverized coal units had installed electrostatic precipitators (ESP) by 2005. In addition, fabric filters (FF) have been put into commercial use in recent years, and their penetration increased to 7% by 2010 (Zhao et al., 2013a). Furthermore, the rapid deployment of wet-FGD also helped to reduce PM emissions due to its ancillary benefit on PM removal (Zhao et al., 2010). In 2011, China's Ministry of Environmental Protection (MEP) announced a revised in-stack concentration standard for PM of 20 mg/m^3 for environmentally sensitive regions and 30 mg/m^3 for other regions.

In Japan, application of best-available technologies to control SO_2, NO_X, and PM is required for most power generation units across the country. The penetrations of wet-FGD, LNB+SCR and high-efficiency dedusters (HEDs, e.g., FF, and electrostatic-fabric integrated precipitator) are all over 90%, having increased slightly during 2005-2010 (Klimont et al., 2009).

In South Korea, FGD systems have been installed at most power generation units; the penetration increased slightly, from 95% to 97%, during 2005-2010. For NO_X, SCR has been the dominant control technology, with its share increasing from 56% in 2005 to 68% in 2010. About one third of coal-fired power generation units had been equipped with HED systems by 2010, and the rest was equipped with ESP equipment (NIER, 2010; NIER 2013; Clean Air Policy Supporting System, CAPSS, http://airemiss.nier.go.kr/).

2.2.2 Industrial sector

The penetrations of control technologies for industrial boilers and industrial processes are presented in Table 3, Table 4 and Table S1.

In China, SO_2 and NO_X control technologies have been rarely installed in the industry sector. In recent years, FGD units to control SO_2 have been installed at a small number of coal-fired boilers and sintering plants in selected regions. The application of NO_X-control technologies is described in more detail in our previous paper (Zhao et al., 2013c). In contrast with SO_2 and NO_X, China has been controlling PM emissions from industrial sources since late 1980s; the emission standards for industrial sources, however, were updated only gradually until 2010 (see details in Lei et al., 2011). The 11th Five-Year Plan promoted high-efficiency FF in some high-emission industries. Most industrial boilers were historically equipped with wet scrubbers (WET) and cyclone dust collectors (CYC), while penetration of high-efficiency FF began recently (Lei et al., 2011; Zhao et al., 2013a). Blast furnaces in China are usually equipped with washing towers and double venturi scrubbers, which have approximately the same removal efficiency as the combination of ESP and WET. ESP and FF had gradually become the major control technologies applied at cement plants, sintering plants, and basic oxygen furnaces by 2010, while large numbers of electric arc furnaces and coking ovens were still equipped with WET (Lei et al., 2011; Zhao et al., 2013a).

The only control measures for NMVOC emissions in China's industry sector are associated with fossil-fuel exploitation and distribution. Emission standards for gasoline distribution released in 2007 require: (1) installation of vapor-recovery systems and modified loading techniques (Stage IA control) for loading and unloading operations; (2) improvement in the service station tank (Stage IB control) and installation of a vapor-balancing system between a vehicle and service station tank (Stage II control); (3) installation of internal floating covers (IFC) or secondary seals for newly-built or retrofitted storage tanks. These standards were scheduled to be implemented in relatively large cities of "key regions" (areas defined by the government as environmentally sensitive, including the Greater Beijing region, the Yangtze River Delta, and the Pearl River Delta) from 2008-2010 onwards, and in relatively large cities in other provinces from 2012-2015 onwards. We estimated that vapor-recycling systems had been installed at about 15% of all gasoline storage and distribution operations by 2010 (see Table 4 for details).

In Japan, industrial emissions are limited strictly by the Air Pollution Control Act. The thresholds have changed only very slightly since 1995, but are still among the most stringent in the world (Ministry of the Environment of Japan, 2013). Under such strict regulations, the vast majority of blast furnaces, basic oxygen furnaces, electric arc furnaces, and cement kilns are controlled with HEDs. The PM control portfolio for industrial boilers, sintering plants, glass production plants, and coke ovens is typically a mix of ESPs and HEDs. Effective SO_2 removal technologies (70-80% removal efficiency) are applied in various industries, including sintering, cement production, coke ovens, sulfuric acid production, and a number of lesser production processes (Gains-Asia model of the International Institute for Applied System Analysis, IIASA, http://gains.iiasa.ac.at/models/). The average efficiency of such removal equipment increased gradually as old facilities were retired. The dominant controls for NO_X emissions as of 2010 were low-NO_X combustion technologies; flue gas denitrification has not been widespread due to relatively high cost.

Emission standards for industrial sources in South Korea are generally less stringent than those of Japan but more stringent than those of China (Ministry of Environment of South Korea, 2013). In contrast with Japan, the PM control portfolio for cement kilns is an equal mix of ESPs and HEDs; ESPs still dominate PM removal for industrial boilers and sintering machines, and HEDs are not widely applied. FGD systems were widely applied at some high-emitting sources such as industrial boilers and sintering plants by 2010, with penetrations of 85% and 100%, respectively (NIER, 2013; NIER 2010). Similar to Japan, the dominant control measures for NO_X emissions were low-NO_X combustion technologies by 2010.

2.2.3 Residential sector

There are only limited regulations in the three countries addressing residential sources. In Japan, about half of residential and commercial boilers are equipped with HEDs, driven by stringent regulations of local government. In South Korea and China, dominant control technologies are CYC and WET (Table 3).

Compared with boilers, emissions from small stoves are more difficult to control. In Japan, small incinerators dwindled rapidly in the last decade due to a 2000 regulation designed to mitigate dioxin pollution (Ministry of the Environment of Japan, 2013; Wakamatsu et al., 2013). A previous study found briquette stoves have lower emission factors for SO_2 and PM (Lei et al., 2011). We estimate briquette use accounted for 6-7% of total residential coal consumption in China during 2005-2010 (NBS, 2007, 2008a, b, 2009, 2011a, b). Emissions from small stoves can be further reduced by switching to new technologies, e.g., those using catalyst or non-catalyst inserts and/or primary and secondary air deflectors. These types of improved stoves have been spreading gradually in Japan and Korea (see Table 3).

2.2.4 Transportation sector

China has issued a series of emission standards for new vehicles and engines based on the European Union (EU) "Euro" Standards since 2000; the implementation years and penetrations of major emission standards are shown in Figure 1 and Table 5. At the national level, Euro I, II, and III standards began to be put into effect in 2000, 2004, and 2007, respectively. The Euro IV standard for light-duty vehicles was implemented in 2011. The Euro IV standard for heavy-duty diesel vehicles was originally planned for implementation in 2010, but was postponed until July 2013 by the MEP due largely to an insufficient supply of low-sulfur fuel (Wu et al., 2012). Megacities including Beijing and Shanghai are subject to greater pressure for regulating vehicle emissions, and are therefore 2-3 years ahead of the national regulation. Recently, the Beijing

Environmental Protection Bureau announced enforcement of Euro V in 2012 and Euro VI in 2016. Aside from regulations for new vehicles, emission reductions are also achieved with control of in-use vehicle emissions and improvement of fuel quality (Wang and Hao, 2012).

Japan's emission standards for new vehicles have been among the most stringent in the world. Since the introduction of the first regulation in 1981, the standards have been repeatedly strengthened. For light-duty vehicles, the prevailing emission standard for NO_X and NMVOC during 2005-2010 (under the "New Long-term Regulation") was comparable to that in U.S. (Tier II), and more stringent than that of the EU (Euro IV) before Euro V took effect in the second half of 2009. A more recent "Post New Long-term Regulation" released in 2009 added a limit for PM comparable to U.S. Tier II, while maintaining the prior limits for other pollutants. For heavy-duty vehicles, Japan's NO_X emission regulations before 2005 had been stricter than those of Europe and the U.S. (Japan Automobile Manufacturers Association, 2011). During 2005-2010, Japan's prevailing standard was comparable to Euro V (issued in 2008), and between the 2004 and 2007 standards of the U.S. Since the early 2010s, European, U.S. and Japanese regulatory standards for NO_X and PM emissions for diesel vehicles have been roughly similar (Ministry of the Environment of Japan, 2013; Delphi Company, 2013a, b).

South Korea has gradually intensified its vehicle emission standards to the level of advanced countries. In December of 2003, Korea issued new vehicle emission standards corresponding to the level of Ultra-Low Emission Vehicles (ULEV) for gasoline vehicles and the levels of Euro IV for diesel vehicles, taking effect in 2007. Since January 2013, South Korea has adopted California's Non-methane Organic Gases (NMOG) Fleet Average System (FAS) for gasoline-fueled vehicles, which has been in place in California since 2009 (http://transportpolicy.net/). For diesel vehicles, Euro V was introduced starting from September 2009, and Euro VI standard will be in place by 2014 (Ministry of Environment of South Korea, 2013; Delphi Company, 2013a, b). The penetrations of vehicle emission standards in Japan and South Korea are given in Table 5.

2.2.5 Solvent use

The Chinese government has released standards to limit the solvent content of some products, including wood paint, interior wall paint, adhesives for shoe production, decorative adhesives, and printing inks. Driven by these standards, the solvent content of some products declined, and the penetration of low-solvent products increased during 2005-2010. Table 6 and Table S2 show the penetrations of major control measures for solvent use; Table S3 shows the changes in the emission factors of typical sources (especially regulated ones) during 2005-2010. Despite the existing standards, most emissions from solvent use remain uncontrolled in China.

In 2004, Japan's Ministry of Environment set a target to reduce NMVOC emissions by 30% from 2000 levels by 2010 using both regulations (10%) and voluntary efforts (20%), with a focus on emissions from solvent use (Ministry of the Environment of Japan, 2013). The actual reductions are estimated to be higher, but the O_3 and PM concentrations have not declined as expected (Wakamatsu et al., 2013).

South Korea issued concentration limits for stack emissions of NMVOC for coating plants and more recently for gravure printing facilities. For outdoor application of paints, the government reached agreement with producers regarding the development of low solvent products as well as improved application methods to minimize NMVOC emissions (Ministry of Environment of South Korea, 2013).

2.3 Effect of control measures on recent emission trends

The historical emissions of China are estimated using a model structure developed in our previous paper (Zhao et al., 2013c). The emissions from each sector in each province were calculated from data on activities (e.g., energy consumption or industrial production), technology-based uncontrolled emission factors, and penetrations and removal efficiencies of control technologies. The data sources for China are also described in Zhao et al. (2013b).

The historical emissions of Japan are consistent with the JATOP Emission Inventory-Data Base (JEI-DB), developed by the Japan Petroleum Energy Center (JPEC) (JPEC, 2012a, b, c). Special attention was paid to on-road vehicle emissions. The basic estimation method is to multiply the traffic volume (considering the vehicle type mix) and emission factors for vehicle types. JPEC adjusts that value with correction factors to take account of accumulated mileage, temperature, and humidity. It also includes data from original research on start emission factors, evaporation emission factors, the ratio of high-emission vehicles, and vehicle usage profile from a questionnaire-based survey (JPEC, 2012c). The emissions from other sources were calculated using local statistical information and emission factors, similar to the methodology for the estimation of China's emissions (JPEC, 2012a).

The historical emissions of South Korea were calculated by the National Institute of Environmental Research (NIER), and the data sources are described in its research reports and a web-based database (NIER, 2010; NIER 2013; CAPSS, http://airemiss.nier.go.kr/). Note that continuous emissions monitoring systems (CEMSs) were installed at most large point sources starting in 2002, allowing CEMS-based emission estimation for 2007-2010, while earlier years were calculated using emission factors. This methodological change produced emission discontinuities in 2007, leading us to replace pre-2007 emissions from those stacks with values extrapolated from 2007-2010 CEMS-based estimates, taking account of changes of control measures.

The emissions for North Korea, Mongolia, Hong Kong & Macao, and Taiwan are adopted directly from the Gains-Asia model of IIASA (http://gains.iiasa.ac.at/models/).

The national energy consumption and air pollutant emissions are summarized in Table 7 and Table 8, respectively. The sectoral emissions in China are given in Figure 2, and those in Japan and South Korea are shown in Figure 3. The provincial emissions in China are shown in Table S4.

2.3.1 NO_X

The total NO_X emissions in East Asia were 29.7 Mt in 2010 and the growth rate was 25% during 2005-2010. This trend was dominated by the increase in emissions from China, which contributed 82-88% of total NO_X emissions in East Asia.

During this period, NO_X emissions in China increased by 34%, driven by the rapid increase of industry and transportation. The emissions from power plants stopped growing by 2010 due to the application of LNBs and penetration of non-fossil energy sources in the sector. But emissions from industry and transportation continued to grow rapidly due to swiftly expanding industrial energy consumption and vehicle populations.

NO_X emissions from the rest of East Asia decreased by 13% during the five years, mainly attributed to a 21% reduction in emissions from Japan due chiefly to the implementation of tight emission standards for new vehicles. The emissions of South Korea decreased slightly, by 5%, for the same reason.

2.3.2 SO_2

The total SO_2 emissions in East Asia decreased by 15%, from 30.4 Mt in 2005 to 25.9 Mt in 2010, with both China and the rest of East Asia experiencing the same 15% rate of decline and Chinese emissions accounting for as much as 94% of the regional total.

The decline in China's SO_2 emissions is mainly attributable to the widespread deployment of FGD at power plants, even as emissions from China's industrial sector continued to rise during this period; this is consistent with the recent estimates by Zhang et al. (2012b), Lu et al. (2011), Klimont et al. (2013).

SO_2 emissions of Japan decreased by 20%, mainly attributed to the increasing penetration of higher-efficiency desulfurization technologies in the industrial sector, and the replacement of coal and oil with cleaner energy sources. South Korea's SO_2 emissions remained roughly constant, because the reduction of the emissions from power plants (due to the deployment of FGDs) was offset by the increasing emissions from industrial sources.

2.3.3 PM_{10} and $PM_{2.5}$

In 2010, the total PM_{10} and $PM_{2.5}$ emissions in East Asia were 16.8 Mt and 12.5 Mt, respectively, decreasing 15% and 12% from 2005 levels. This trend was also domimated by emission trends in China, as its PM_{10} and $PM_{2.5}$ emissions represent about 94% of those of East Asia.

China's PM_{10} and $PM_{2.5}$ emissions decreased by 15% and 12%, respectively, during the five years. We estimate that emissions of power plants and the cement industry experienced the greatest decrease (43%-47% during 2005-2010), a result of the rapid evolution of end-of-pipe controls (see Table 2 and Table 4). The emissions of industrial boilers and steel industry increased by 14%-32%, while the emissions of other sectors remained relatively stable.

PM_{10} and $PM_{2.5}$ emissions decreased by 7% and 9% in the rest of East Asia. The reduction rate was as large as 19%-28% in Japan, with the transportation sector contributing 70% of this decline. Emissions from South Korea increased somewhat due to the increase in industrial fuel consumption and the relatively stable energy intensity of the industrial sector (see Sect. 2.1.2).

2.3.4 NMVOC

The total NMVOC emissions in East Asia were 25.9 Mt in 2010, reflecting 15% growth over 2005 levels, an integrated effect of a 21% increase in emissions from China (contributing 84-88% of the total emissions) and a 17% reduction in emissions from other countries.

In China, the NMVOC emissions from transportation and residential combustion decreased due to improved vehicle emission standards and the replacement of biomass with cleaner energy sources. However, these reductions were more than offset by the dramatic increase of emissions from industrial processes (+46%) and solvent use (+102%).

Japan's NMVOC emissions decreased by 30%, mainly attributed to the government's efforts to reduce the emissions from solvent use and the implementation of stringent vehicle emission standards. In South Korea, although the enhancement of vehicle emission standards lowered NMVOC emissions from transportation, the emissions from solvent use increased even more rapidly, leading to a 15% increase in total NMVOC emissions.

2.4 Uncertainty analysis

A Monte Carlo uncertainty analysis was performed on the emission inventories of East Asia for 2005-2010, following the methodology described in Bo et al. (2008) and Wei et al. (2008, 2011a). The probability distribution of the activity data and emission factors were determined using the method and data used in Wei et al. (2008, 2011a) as a starting point. We re-evaluated the uncertainties of the emission factors taking account of new field measurements in recent years. Specifically, we assumed that the uncertainties of the activity data and emission factors had lognormal distributions. The uncertainties of activity levels were rated from level I to level V, corresponding to coefficients of variation (CVs, defined as the ratio of the standard deviation to the mean of a probability distribution, indicating the extent of variability in relation to the mean of the population) of ±30%, ±80%, ±100%, ±150%, and ±300%, respectively. For example, the activity levels derived directly from statistics were rated as level I, and those calculated using nonstatistical data and empirical conversion factors were rated as level V. The uncertainties of emission factors were also rated from level I to level V, with the corresponding CVs of ±50%, ±80%, ±150%, ±300%, and ±500%, respectively. The emission factors for the sources with stable emission rates and over 10 local field measurements were rated as level I, while a rating of level

V was assigned when the emission factors for similar sources were applied due to the lack of measurements. With the determined probability distribution of the activity data and emission factors of each source, the Monte Carlo method was used to propagate these uncertainties into an uncertainty for the total inventory. Table S5 shows the calculated uncertainties by sector.

During 2005-2010, the average 90% confidence interval of the total NO_X emissions is [-31%, 44%]. The CV is ±25% on average. The uncertainties of emissions vary with emission sectors (see Table S5), attributable to the different magnitudes of uncertainties associated with activity levels and emission factors. Biomass open burning has the largest CV (±177%) because both the activity levels and the emission factors are quite uncertain. The transportation sector has the second highest uncertainty (CV=±66%), as its fuel consumption is calculated from vehicle population, annual average mileage travelled, and fuel economy, rather than from energy statistics.

The average 90% confidence interval and CV of the total SO_2 emissions are [-29%, 45%] and ±28%, respectively, during 2005-2010. Similar to that of NO_X emissions, the SO_2 emissions from biomass open burning have the highest uncertainty (CV=±179%). The uncertainties of the industrial, residential, and transportation sectors are quite close to each other, with CVs in the range of ±48%-±51%.

During 2005-2010, the average 90% confidence interval and CV of the total $PM_{2.5}$ emissions are [-39%, 49%] and ±39%, respectively. Biomass open burning is the sector subject to the highest uncertainty (CV=±216%). The residential sector has the second highest uncertainty due to the relatively few emission factor measurements for coal stoves and biomass stoves, the dominant $PM_{2.5}$ emission sources of this sector.

The average 90% confidence interval and CV of the total NMVOC emissions are [-42%, 67%] and ±42%, respectively. The “other sectors”, which include biomass open burning (contributing over 80% of NMVOC emissions in this category), waste treatment, cooking, and smoking, have the highest uncertainty (CV=±184%). This is followed by solvent use (CV=±78%), for which the activity levels are not directly available from official statistics and emission factor measurements are lacking. The CVs for the industrial, residential, and transportation sectors are all within the range of ±57%-±65%.

It can be seen that NMVOC is the pollutant subject to the highest uncertainty, followed by $PM_{2.5}$. The high uncertainty of NMVOC emissions is mainly attributable to the lack of local measurements for many industrial and solvent use sources. The higher uncertainties of $PM_{2.5}$ emissions compared with NO_X and SO_2 result from the larger uncertainties in the emission factors (e.g., uncertainties in the emission factors of industrial fugitive dust and in the removal efficiencies of dust collectors), and a relatively large share of emissions from small-scale emission sources (e.g., coal stoves and biomass stoves).

3 Future emission scenarios for air pollutants

To quantify the effects of various measures on future air pollutant emissions, in this study we developed emission scenarios for SO_2, NO_X, PM, and NMVOC based on energy-saving policies and end-of-pipe control strategies. The scenarios are developed with the same model structure as that for the estimation of historical emissions developed in our previous paper (Zhao et al., 2013c). The energy service demand is estimated based on driving forces (e.g., GDP and population). The future technology distribution and energy efficiencies are assumed and the energy consumption is calculated accordingly. Both historical and future emissions are derived from energy consumption, emission factors, and assumptions on the penetration of control technologies. For details, see Zhao et al. (2013c).

We developed two energy scenarios, a business-as-usual scenario (BAU) and an alternative policy scenario (PC). The BAU scenario is based on current regulations and implementation status (as of the end of 2010). In the PC scenario, we assume the introduction and strict enforcement of new energy-saving policies, including ones leading to a more energy-conserving lifestyle, structural adjustment, and energy efficiency improvement. Energy-conserving lifestyle is defined by a slower growth of energy service demand that would result from less building area, a smaller vehicle population, and reduced consumption of energy-intensive industrial products, electricity, and heat. Structural adjustment includes promotion of clean and renewable fuels and energy-efficient technologies. Examples include renewable energy sources and CHP for power plants and heat supply, arc furnaces and large precalciner kilns for the industrial sector, biogas stoves and heat pumps for the residential sector, and electric and biofuel vehicles for the transportation sector. Energy efficiency improvement refers to the improvement of the energy efficiencies of individual technologies.

We developed three end-of-pipe control strategies for each energy scenario, including baseline (abbreviated as [0]), progressive [1], and maximum feasible control [2], thereby constituting six emission scenarios (BAU[0], BAU[1], BAU[2], PC[0], PC[1], and PC[2]). The baseline control strategy [0] assumes that all current pollution control regulations (as of the end of 2010) and the current implementation status would be followed during 2011-2030. Control stategy [1] assumes that new pollution control policies would be released and implemented in China, representing a progressive approach towards future environmental policies. For other countries, we assume the same controls as strategy [0]. Control strategy [2] assumes that technically feasible control technologies would be fully applied by 2030, regardless of the economic cost. The definition of the energy scenarios and emission scenarios are summarized in Table 1.

In this paper we focus on the development of energy scenarios and emission scenarios for China. The scenarios for other countries are adapted from those developed by IIASA in a project funded by United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO) (Shindell et al., 2012; UNEP and WMO, 2011). Both the energy consumption and air pollutant emissions were calculated with a 5-year time step, although the parameters and results are presented for selected years only. Detailed assumptions of the energy scenarios and emission scenarios are documented below.

3.1 Development of energy scenarios

For countries other than China, our BAU and PC scenarios are consistent with the energy pathways of the reference and 450-ppm scenarios in Shindell et al. (2012), and UNEP and WMO (2011), which were based on the reference and 450-ppm scenarios presented in the World Energy Outlook 2009 (IEA, 2009), respectively. While the reference scenario is based on current energy and climate-related policies, the 450-ppm scenario explores the global energy consumption if countries take coordinated action to restrict the global temperature increase to 2ºC. The details of energy scenarios are described in Shindell et al. (2012), UNEP and WMO (2011) and IEA (2009).

For China, we have developed two energy scenarios that are consistent with our previous paper (Zhao et al., 2013c). Presented below is a brief description of the assumptions and results of the energy scenarios; see Zhao et al. (2013c) for detailed information. Note that because that paper focused on the emission trends of NO_X, it did not project activity data in terms of fossil fuel distribution (included in the industrial sector for this study) nor the use of solvents. These two projections are incorporated below.

We assume that the annual average GDP growth rate will decrease gradually from 8.0% during 2011-2015 to 5.5% during 2026-2030. The national population is projected to increase from 1.34 billion in 2010 to 1.44 billion in 2020 and 1.47 billion in 2030, and the urbanization rate (proportion of people in urban areas) is assumed to increase from 49.95% in 2010 to 58% and 63% in 2020 and 2030, respectively.

The total electricity production is projected to be 10%-12% lower in the PC scenario than that of the BAU senario. The PC scenario considers aggressive development plans for clean and renewable energy power generation; therefore, the proportion of electricity production from coal-fired power plants is expected to decrease to 57% in 2030 in the PC scenario, contrasted with 73% in the BAU scenario.

We applied an elasticity coefficient method for the estimation of future production of industrial products, the governing equation of which is as follows:

$$Y_{t1} = Y_{t0}\left(\frac{dv_{t1}}{dv_{t0}}\right)^{\delta} \qquad (1)$$

where, $t0$, $t1$ are time periods, e.g., $t0 = 2010$, and $t1 = 2030$; Y is the yield of a specific industrial product; dv is the driving force, namely sectoral value added or population; and δ is the product-specific elasticity coefficient. The values of δ are determined through (1) historical trends during 1995-2010; (2) the experience of developed countries; and (3) projections of industrial associations. Generally speaking, production of most energy-intensive commodities used in construction of infrastructure are expected to increase until 2020, and then to stabilize or even decline after 2020, whereas products associated with household consumption are expected to increase through 2030, although at a declining rate. We projected lower production of industrial products in the PC scenario than those of the BAU scenario because of more energy-conserving lifestyles. The penetrations of less energy-intensive technologies are assumed to be higher in the PC scenario than the BAU scenario.

For the residential sector, China's building area per capita in the PC scenario is expected to be 3-4 m^2 lower than that of the BAU scenario in both urban and rural areas. The heating energy demand per unit area is somewhat lower in our PC scenario because of the implementation of new energy-conservation standards in the design of buildings. Replacement of coal and direct biomass burning with clean fuels are assumed in both urban and rural areas, with faster progress in the PC scenario.

The vehicle population per 1000 persons is projected at 380 and 325 in the BAU and PC scenarios, respectively. The PC scenario also assumes aggressive promotion of electric vehicles, and a progressive implementation of new fuel efficiency standards, resulting in 33% and 57% improvement in the fuel economy of new passenger cars and new heavy-duty vehicles by 2030.

The increase of fossil fuels stored and distributed is expected to be consistent with the increase of total fuel consumption in the future. The gasoline or diesel sold at service stations is expected to have the same growth rate as fuel consumption in the transportation sector. Therefore, the activity levels of fossil fuel distribution are derived from the projections of fuel consumption.

The activity data for the solvent use sector are the consumption of products containing solvents. The forecast approach, which is consistent with Wei et al. (2011b), is illustrated as follows:

$$A_{t1} = \sum_j \left(A_{t0,j} \times \frac{Y_{t1,j}}{Y_{t0,j}} \right) \qquad (2)$$

where, $t0$, $t1$ are time periods, e.g., $t0 = 2010$, and $t1 = 2030$; j represents the industries using a specific solvent product; A_{t1} is the consumption of this solvent product in the year $t1$; $A_{t0,j}$ is the consumption of this solvent product in industry j in the year $t0$; $Y_{t0,j}$ and $Y_{t1,j}$ are the yields of the major products (e.g., crude steel for the iron and steel industry) for industry j in the year $t0$ and $t1$, respectively. The yields of industrial products were projected using the elasticity coefficient method as described above.

Table 7 shows current and future energy consumption in East Asia. Total energy consumption in East Asia was 123 EJ in 2005 and 161 EJ in 2010. The energy consumption of China accounts for 69-76% of the total energy amount during 2005-2010, followed by 13-18% for Japan, and about 7% for South Korea. By 2030, the total energy consumption is projected to increase to 243 EJ under the BAU scenario and to 195 EJ under the PC scenario, 51% and 21% higher than that of 2010.

Of all the countries, China is expected to experience the fastest growth rate in energy consumption. By 2030, China's energy consumption is projected to increase by 64% and 27% from the 2010 level in BAU and PC senarios, respectively. Industry fuel consumption is expected to increase notably slower than the total fuel use in both scenarios, resulting from the structural economic adjustment. In contrast, the energy consumption of transportation is projected to increase dramatically by 200% and 101% in the BAU and PC scenarios, respectively, measured in 2030 against the 2010 levels, driven by the swift increase in vehicle population. The growth rate of energy consumption in other sectors is close to that of the total amount. Because of the energy-saving measures, the energy consumption of power plants, industry, residential, and transportation sectors in the PC scenario are 18%, 19%, 27%, and 33% lower than the BAU scenario, respectively. Coal continues to dominate China's energy mix, but the proportion decreases from 68% in 2010 to 60% and 52% in 2030 under the BAU and PC scenarios, respectively. In contrast, the shares of natural gas and "other renewable energy and nuclear energy" are estimated to increase from 3.4% and 7.5% in 2010 to 5.5% and 8.9% in 2030 under the BAU scenario, and 9.3% and 15.8% under the PC scenario, respectively.

By 2030, the energy consumption of East Asia other than China is projected to increase slightly by 12% and 2% over the 2010 level in the BAU and PC scenarios, respectively. Under current policies, Japan's energy consumption is projected to increase very slightly by 2% from 2010 to 2030, because of slow economic growth rate and a trend towards higher energy efficiency resulting from current legislaion. Under implementation of low-carbon policies intended to limit CO_2 concentrations to 450 ppm, Japan's energy consumption would be reduced by 6% by 2030 over the 2010 level. This reduction is mainly attributed to the decline in energy consumption of the transportation sector, resulting from improved fuel economy and reduced mileage travelled. By 2030, South Korea's energy consumption is expected to increase by 26% and 15% over the 2010 level under the two energy scenarios, respectively. Similar to China, there are also evident trends towards clean and renewable energy in Japan and South Korea. For example, from 2010 to 2030, the shares of coal and petroleum products in Japan's energy consumption are expected to decrease from 22% and 40% to 20% and 31% under the BAU scenario, respectively, and to 12% and 29% under the PC scenario. In contrast, the proportion of renewable energy would increase from 16% in 2010 to 23% and 33% in 2030 under the BAU and PC scenarios, respectively.

3.2 Development of emission control scenarios

For the countries other than China, our control strategies [0] and [2] are consistent with the control strategies of the reference scenario and the maximum feasible reduction scenario in UNEP and WMO (2011), respectively. While control strategy [1] assumes that new pollution control policies would be implemented progressively in China, it has the same assumptions as control strategy [0] for the other countries for the following reasons: (1) China accounts for 88%, 94%, 94%, 95%, and 88% of the total NO_X, SO_2, PM_{10}, $PM_{2.5}$, and NMVOC emissions in East Asia in 2010; (2) Japan and South Korea already have stringent environmental policies in the base year, and the progressive control strategy for countries other than China will have negligible effect on the regional outcomes. The major assumptions underlying control strategies [0] and [2] are straightforward: [0] assumes current regulations and implementation status, while [2] assumes full application of best-available technologies in the world. Therefore, in the following text, we will focus on the assumptions for China and omit details for other countries. The penetrations of major control technologies in China, Japan, and South Korea are summarized in Table 2 through Table 5.

3.2.1 Power plants

As documented in Sect. 2.2.1, the recently released 12th Five-Year Plan set specific targets and proposed detailed technological roadmaps for the reduction of SO_2 and NO_X emissions from power plants. The government did not set a total PM emission target, but rather a strict in-stack PM concentration standard in 2011 (30 mg m^{-3} for the entire country except for 20 mg m^{-3} in key regions, as defined in Sect. 2.2.2). Power plants burning coal with low ash content could attain the 30 mg m^{-3} threshold by installing ESP and wet-FGD simultaneously. For units burning coal with high ash content, or when the 20 mg m^{-3} threshold applies, HEDs (including FFs and electrostatic-fabric integrated precipitators) would be the only commercially available control technology.

The BAU[0]/PC[0] scenarios consider only the control policies released before the end of 2010. In other words, NO_X and PM emissions are mainly controlled with LNB and ESP, respectively. The penetration of FGD would increase quite slowly. The BAU[1]/PC[1] scenarios are based on the 12th Five-Year Plan (including the 2011 emission standard for 2011-2015) and the assumption that high-efficiency control technologies will continue to spread gradually after 2015. The penetration of FGD in coal-fired units is assumed to approach 100% by 2015. All newly built thermal power plants will be equipped with low-NO_X combustion technologies and flue gas denitrification (SCR or SNCR) from 2011 onwards. Existing thermal power plants will be upgraded with low-NO_X combustion technologies, and large units (⩾300 MW) will be upgraded with SCR or SNCR during 2011-2015. SCR and SNCR will gradually penetrate to smaller units after 2015. More ambitious measures will be required in the key regions. For PM, HED will spread much more rapidly, with its share in coal-fired units approaching 35% and 50% in 2020 and 2030, respectively. In the BAU[2]/PC[2] scenarios, the best-available technologies (i.e., FGD for SO_2, LNB+SCR for NO_X, and HED for PM) are assumed to be fully applied by 2030. Table 2 gives the national average penetration of control technologies. Note that the penetrations in the key regions are usually larger than those of other regions.

3.2.2 Industrial sector

The latest national emission standard for industrial boilers was released in 2001 (GB13271-2001), although several provinces including Beijing and Guangdong have recently issued local standards. As the BAU[0]/PC[0] scenarios are based only on current regulations, i.e., nearly no measures implemented to control SO_2 and NO_X emissions, and WET remains dominant control technology for PM emissions. The BAU[1]/PC[1] scenarios are based on the 12th Five-Year Plan during 2011-2015; progressive control measures would be enforced after 2015 as an extension of the 12th Five-Year Plan. For SO_2, FGDs are assumed to be widely deployed, penetrating 20%, 40%, and 80% of the total capacity by 2015, 2020, and 2030, respectively. For NO_X, LNB will be required at newly built industrial boilers, and existing boilers in the key regions will begin to be retrofitted with LNB during 2011-2015. The vast majority of existing boilers are expected to be equipped with LNB by 2020. For PM, ESP and HED will be gradually deployed to replace the less-efficient WET. In the BAU[2]/PC[2] scenarios, the most efficient removal technologies, including FGD, LNB+SCR, and HED, will be fully applied.

The emissions from industry processes (i.e., other than boilers) were mainly regulated by the "Emission Standard for Industrial Kilns and Furnaces" before 2010. Standards for specific industries were only issued for cement plants (GB4915-2004) and coking ovens (GB16171-1996). However, new emission standards for a variety of industries were rapidly issued during 2010-2012, which may significantly alter their future emission pathways.

A series of new emission standards for the iron and steel industry were released in 2012, including the standards for sintering, iron production, steel production, steel rolling, and other processes. Sintering is the main source of SO_2 and NO_X emissions in the iron and steel industry, and also an important source of PM emissions. Installation of wet-FGDs is required in order to attain the SO_2 concentration standard, and the 12th Five-Year Plan also requires large-scale deployment of FGD. The threshold for NO_X concentration can be attained without additional control technologies, but the 12th Five-Year Plan requires newly built sintering facilities to be equipped with SCR or SNCR. Most sintering plants can meet the PM threshold with simultaneous installation of FGD and ESP, but HED is required for those in key regions and those with poor raw material quality. The BAU[0]/PC[0] scenarios assume only the continuation of the control regulations as of 2010. The BAU[1]/PC[1] scenarios are developed on the basis of the 2012 standard and the 12th Five-Year Plan. FGD would be installed at most sintering facilities and SCR or SNCR at newly built ones during 2011-2015; the penetrations would increase gradually afterwards. While ESP remains the dominant PM-removal technology, HED is assumed to be deployed gradually. FGD, SCR, and HED would be fully applied in the BAU[2]/PC[2] scenarios. Blast furnaces (for pig iron production) in China are usually equipped with washing towers and double venturi scrubbers, which currently remain the best-available technologies. The 2012 emission standard for steel production (with basic oxygen furnaces and electric arc furnaces being the major technologies) implies that low-efficient WET should be phased out, and HED needs to be installed for newly built facilities. While the BAU[0]/PC[0] scenarios assume the emission standard before 2010, the BAU[1]/PC[1] scenarios assume the retirement of WET and gradual promotion of HED, according to the 2012 emission standard. The BAU[2]/PC[2] scenarios assume full utilization of HED.

Current emission standards for the cement industry were released in 2004. The SO_2 and NO_X standards can be met without additional control measures, and the PM standard can be met with both ESP and HED. Therefore, we assume the control technology mix of 2010 would remain the same as in the BAU[0]/PC[0] scenarios. In 2012, MEP published a draft new emission standard for public comment. As cement clinker can absorb most SO_2 produced due to its basic chemistry, even the strengthened SO_2 limit may be attained under favorable technical conditions. The attainment of the NO_X limit requires upgrading with low-NO_X combustion technology for existing kilns (or installation of SNCR as an alternative), and simultaneous utilization of low-NO_X combustion technology and SNCR/SCR for new kilns. The BAU[1]/PC[1] scenarios are based on the 2012 draft standard and the 12^{th} Five-Year Plan. Newly built precalciner kilns (mostly ⩾ 4000 t/d) are required to be equipped with SCR/SNCR, and existing precalciner kilns should be retrofitted with low-NO_X combustion technology during 2011-2015. SCR/SNCR is assumed to continue to spread gradually after 2015. HED would be deployed gradually to meet the strengthened PM threshold for new kilns. The BAU[2]/PC[2] scenarios assume full application of desulfurization facilities, LNB+SCR, and HED.

As for coke ovens, we assume no control measures for SO_2 and NO_X emissions, and continuous application of WET for PM emissions in the BAU[0]/PC[0] scenarios. In the BAU[1]/PC[1] scenarios, we assume the installation of FGD in the coal-charging process or coke oven gas exhaust for newly built plants (contributing about 50% and 30% of emissions, respectively) to meet the requirement of a new standard issued in 2012 (GB16171-2012). In addtion, new plants are assumed to be equipped with HED, also required by the new standard. The BAU[2]/PC[2] scenarios assume full application of the best desulfurization, denitrification, and PM removal facilities available.

As for glass production, the BAU[0]/PC[0] scenarios assume no control measures for SO_2 and NO_X emissions, and the current mix of PM removal technologies. The BAU[1]/PC[1] scenarios are designed according to the new emission standard released in 2011, though enforced leniently because of difficulty in implementation. FGD, as well as end-of-pipe NO_X control technologies (typically oxy-fuel combustion technology, OXFL, or SCR), would be applied gradually at both existing and new plants. Outdated PM removal technologies, e.g. WET, would be phased out. For the brick industry, emissions from about 30% of plants remain uncontrolled in 2010. A draft new emission standard in 2009 calls for a PM removal efficiency of over 60% at existing plants, and over 80% at new plants. In the BAU[1]/PC[1] scenarios, PM emissions from brick plants are assumed to be controlled according to the standard, though enforced leniently due to inspection difficulty.

To attain the new emission standard for the nitric acid industry (GB26131-2010), the dual-pressure process would be equipped with absorption technologies (ABSP) or SCR, while other processes need to adopt both ABSP and SCR. The BAU[0]/PC[0], BAU[1]/PC[1] and BAU[2]/PC[2] scenarios assume the technology mix of 2010, lenient enforcement of the new standard, and stringent enforcement of the new standard, respectively.

In the BAU[0]/PC[0] scenarios, we assume the emission standards for gasoline distribution (GB20950, GB20951, and GB20952) would continue to be enforced in the future. In the BAU[1]/PC[1] scenarios, the enforcement of Stage IA, Stage IB, and Stage II controls would be extended to all of China, and IFC would be applied for both newly built and existing storage tanks. In addition, similar control technologies would be applied for crude oil distribution. As a result, the application rate of IFC, Stage IA, and Stage IB+Stage II control measures in gasoline storage and distribution would approach 75% and 100% by 2020 and 2030, respectively. The application rate in crude oil distribution would be 25% and 50% by 2020 and 2030, respectively (see Table 4). For the BAU[2]/PC[2] scenarios, these control measures would be fully applied by 2030.

For other industries with NMVOC emissions, nearly no control measures are assumed for the BAU[0]/PC[0] scenarios. In the BAU[1]/PC[1] scenarios, we assume that new NMVOC emission standards (similar to or slightly less stringent than the EU Directives 1999/13/EC and 2004/42/EC, depending on specific industry) will be released and implemented in key regions as of 2015, and in other provinces as of 2020. Afterwards, the emission standards will become more stringent gradually (see Table 4). In terms of technologies, we assume application of basic management techniques (e.g., leakage detection and repair for refineries and improved solvent management in paint production) where they are applicable. End-of-pipe controls (condensation, adsorption, absorption, and incineration) are adopted when high removal rate is required. The penetration of selected control measures assumed for key sources are summarized in Table 4.

3.2.3 Residential sector

Emission control policies have seldom been proposed for the residential sector in China. In the BAU[0]/PC[0] scenarios, we assume no control measures except for the continued application of CYC and WET for residential boilers. In BAU[1]/PC[1], HED and low-sulfur derived coal are assumed to be deployed gradually, both penetrating 20% and 40% of the total capacity by 2020 and 2030, respectively. In addition, we assume gradual adoption of advanced coal stoves and advanced biomass stoves (e.g., those with more efficient combustion or catalytic devices) where applicable, which reduce emissions of PM and NMVOC. The BAU[2]/PC[2] scenarios assume the application of best-available technology without considering economic cost.

3.2.4 Transportation sector

In the BAU[0]/PC[0] scenarios, only the existing standards (released before the end of 2010) are considered. In the BAU[1]/PC[1] scenarios, all of the current standards in Europe are assumed to be implemented in China gradually, and the time intervals between the releases of standard stages would be a little shorter than those of Europe. The implementation timeline of the emission standards is given in Figure 1. The removal efficiencies of the future emission standards are from the GAINS-Asia model of IIASA (Amann et al., 2008; Amann et al., 2011). The BAU[2]/PC[2] scenarios assume the same implementation timeline for new standards as the BAU[1]/PC[1] scenariod. In addition, old vehicles with high emissions are phased out at a faster pace through compulsory measures and economic subsidies. The proportions of vehicles subject to different emission standards are summarizd in Table 5.

3.2.5 Solvent use and biomass open burning

For emissions from solvent use, the BAU[0]/PC[0] scenarios consider only several national standards limiting the NMVOCs content of some solvent products (see Sect. 2.2.5). Major assumptions for the BAU[1]/PC[1] scenarios are consistent with the NMVOC emission sources in the industrial sector, i.e., implementation of the EU Directives 1999/13/EC and 2004/42/EC as of 2015-2020, followed by gradually strengthened regulations afterwards. Potential mitigation measures to attain the European standards differ greatly for different emissions sources because of various spraying technologies and chemical proporties of the solvent used. However, similar to the industrial sources, these measures can be catetogrized into two kinds: use of environmentally friendly substitutes (e.g., water-based or UV products) or end-of-pipe control technologies. Substitution measures are assumed where applicable, while end-of-pipe control technologies would be mainly installed in newly built factories. The penetration of selected control measures assumed for key sources are summarized in Table 6.

We assume a ban of biomass open burning in the BAU[2]/PC[2] scenarios.

3.3 Future emission trends and effects of control measures

The air pollutant emissions in each scenario are estimated based on the assumptions in Sect. 3.1 and Sect. 3.2. Table 8 shows the national air pollutant emissions in East Asia under each scenario. Figure 2 shows the emissions by sector in China, and Figure 3 shows the emissions by sector in Japan and South Korea. Table S4 shows the provincial emissions in China.

3.3.1 NO_X

Under current regulations and implementation status (the BAU[0] scenario), NO_X emissions in East Asia are projected to increase by 28% in 2030 from the 2010 levels. The implementation of assumed energy-saving measures (reflected by the difference between the BAU[0] and the PC[0] scenarios) and progressive end-of-pipe control measures (reflected by the difference between the PC[0] and the PC[1] scenarios) are expected to reduce NO_X emissions by 28% and 36%, respectively, from the baseline projection (the BAU[0] scenario). With the full enforcement of technically feasible control measures (the PC[2] scenario), the remaining emissions account for only 21% of the baseline projection, or 27% of the 2010 levels.

China's growth potential under current regulations (36%) is significantly larger than the average of East Asia (28%), resulting from a great increase in energy consumption and weak existing control measures. The share of China in East Asia's NO_X emissions would increase to 93% under the baseline projection. The enforcement of energy-saving measures (the PC[0] scenario) leads to a 29% reduction from the baseline projection. With the implementation of the 12^{th} Five Year Plan and slowly strengthened end-of-pipe control policies after 2015 (reflected by the difference between the PC[0] and the PC[1] scenarios), China's NO_X emissions could be reduced by nearly 40% (compared to the baseline projection). The most effective control measures are the installation of SCR and SNCR and the application of stringent vehicle standards, which together achieve nearly 80% of this reduction. The full application of technically feasible control measures (the PC[2] scenario) could reduce China's NO_X emissions to 20% of the baseline projection, or 28% of the 2010 levels. It should be noted that the NO_X emissions are projected at 22.9 Mt in 2015 under the BAU[1] scenario, 12.2% lower than that of 2010. This implies that if the control policies in the 12th Five-Year Plan can be implemented successfully (as assumed in the BAU[1] scenario), the national target to reduce the NO_X emissions by 10% during 2011-2015 would be achieved.

Under current regulations and implementation status, the NO_X emissions in East Asia other than China are expected to decrease by 27%, with especially rapid decline in Japan (47%) and South Korea (34%). The decrease is mainly attributable to the continuously increasing proportion of vehicles subject to stringent emission standards. With the enforcement of energy-saving policies intended to limit global temperature increase to 2ºC (reflected by the difference between the BAU[0] and the PC[0] scenarios), NO_X emissions in East Asia outside of China, and of the two major energy consumers therein (Japan and South Korea), are all expected to decline by 15%-17% in 2030 compared with the baseline projection. These policies are most effective in the power sector, due to negligible emissions from renewable and nuclear power generation compared with traditional coal-fired power. The full application of technically feasible control measures (the PC[2] scenario) would reduce the NO_X emissions in East Asia except China, and Japan and South Korea individually to only 30%, 46% and 30% of the baseline projection, or 22%, 24% and 20% of the 2010 levels, respectively.

3.3.2 SO_2

The SO_2 emissions in East Asia are predicted to grow 24% from 2010 to 2030 under current regulations and implementation status (the BAU[0] scenario). The enforcement of advanced energy-saving measures (the PC[0] scenario) could lead to a substantial 36% reduction in SO_2 emissions from the baseline projection, exceeding the effect of progressively implemented end-of-pipe control measures, 25% (reflected by the difference between the PC[0] and the PC[1] scenarios). FGD facilities had been intensively deployed by 2010 in most industrial sources of Japan and in the power plants of China and South Korea. Therefore, the reduction potential through the installation of end-of-pipe control technologies will likely decline in the future, spotlighting the importance of energy-saving measures for further reduction of SO_2 emissions. With the full application of best-available technologies (the PC[2] scenario), the remaining SO_2 emissions in East Asia would account for only 27% of the baseline projection, or 34% of the 2010 levels.

Similar to NO_X, China's SO_2 emissions have a larger growth potential than the average of East Asia during 2010-2030 under the current policy and implementation status. Implementation of new energy-saving measures (reflected by the difference between the BAU[0] and the PC[0] scenarios) and progressive end-of-pipe control measures (reflected by the difference between the PC[0] and the PC[1] scenarios) could lead to 36% and 26% reductions of China's SO_2 emissions, respectively (compared with the baseline projection). Consistent with the total emissions in East Asia, the contribution of energy-saving measures clearly exceeds the planned end-of-pipe control policies. As the power sector had largely been equipped with FGD facilities by the base year, industrial boilers and industrial process contribute 82% of the SO_2 emission reduction achieved through progressive end-of-pipe control policies. Assuming the full enforcement of technically feasible control measures (PC[2]), SO_2 emissions are estimated to reach only 27% of the baseline projection, or 34% of the 2010 levels.

We also note that China's SO_2 emissions are projected to be 21.7 Mt in 2015 under the BAU[1] scenario, 11.1% lower than those of 2010. This implies that if the control policies in the 12^{th} Five-Year Plan could be implemented successfully (as assumed in the BAU[1] scenario), the national target to reduce the SO_2 emissions by 8% during 2011-2015 would be achieved.

The SO_2 emissions in East Asia outside of China, including Japan and South Korea individually, are expected to stay relatively stable until 2030 under current regulations. The implementation of new energy-saving polices (the PC[0] scenario) could lead to a 9-18% reduction in SO_2 emissions from the levels of the baseline projection. The reduction is mainly achieved thorough the promotion of nuclear and renewable power generation and replacement with cleaner fuels in the industrial sector. Under the full application of technically feasible reduction measures (the PC[2] scenario), the SO_2 emissions in East Asia except China, and Japan and South Korea individually would be reduced to 33%, 52% and 39% of the baseline projection, respectively.

3.3.3 PM_{10} and $PM_{2.5}$

PM_{10} and $PM_{2.5}$ emissions in East Asia are projected to remain relatively stable up to 2030 under the current policies (the BAU[0] scenario), resulting from growth in energy consumption offset by reduction from existing control policies (in particular, vehicle emission standards). New energy-saving policies (reflected by the difference between the BAU[0] and the PC[0] scenarios) and progressive end-of-pipe control measures (reflected by the difference between the PC[0] and the PC[1] scenarios) result in about 28% and 23% reduction in PM_{10}/$PM_{2.5}$ emissions from the levels of baseline projection, respectively. Full application of best-available technologies (the PC[2] scenario) could reduce PM_{10} and $PM_{2.5}$ emissions to about one quarter of the levels of the baseline projection or the base year.

China's future PM_{10} and $PM_{2.5}$ emission trends under the studied scenarios are quite similar to those of East Asia as a whole. Similar to SO_2, the effects of advanced energy-saving polices (resulting in about 29% reduction of $PM_{2.5}$ emissions from the baseline projection) exceeds the planned end-of-pipe control measures (about a 25% reduction). With the energy-saving measures applied, the reduction in emissions from the residential sector is especially pronounced (nearly 60%), resulting from the replacement of coal and biomass with cleaner fuel types. The most effective end-of-pipe control policies are the application of recently released new emission standards for various industrial sources. We estimate that these new industrial standards lead to over 20% reduction of China's total PM_{10} and $PM_{2.5}$ emissions. If the best-available technologies are fully applied (the PC[2] scenario), the PM_{10} and $PM_{2.5}$ emissions would be reduced to about one quarter of the levels of baseline projection or the levels of the base year.

The total PM_{10} and $PM_{2.5}$ emissions in East Asia other than China are also expected to remain relatively stable up to 2030 under the current policies. An exception is Japan, whose PM_{10} and $PM_{2.5}$ emissions are projected to decrease about one quarter by 2030. The major driving force underlying this decline would be an increasing proportion of vehicles regulated by newer emission standards. The implementation of new energy-saving policies (the PC[0] scenario) is expected to reduce the $PM_{2.5}$ emissions of East Asia other than China, and Japan and South Korea individually by about 20%, 17%, and 5%, respectively, from the baseline projection. With full application of best-available control technologies (the PC[2] scenario), the $PM_{2.5}$ emissions in

East Asia except China, and Japan and South Korea individually would account for about one quarter, one half, and one half of the levels of the baseline projection, respectively.

3.3.4 NMVOC

Under current regulations and implementation status (the BAU[0] scenario), NMVOC emissions in East Asia are projected to increase by 24% by 2030 from the 2010 levels. The implementation of assumed energy-saving measures (reflected by the difference between the BAU[0] and the PC[0] scenarios) and progressive end-of-pipe control measures (reflected by the difference between the PC[0] and the PC[1] scenarios) are expected to reduce NMVOC emissions by 15% and 23%, respectively, from the baseline projection. Up to 62% of the total NMVOC emissions are expected to remain even with the assumed energy-saving measures and progressive end-of-pipe controls enforced together. There remains large potential to reduce NMVOC emissions beyond the progressive control strategies, since the full application of best-available technologies (the PC[2] scenario) could reduce NMVOC emissions to only 35% of the baseline projection.

China's NMVOC emissions are estimated to increase by 27% from 2010 to 2030 under the current policy and implementation status. This upward trend is stronger than the East Asia average but weaker than China's NO_X emissions. The emissions from the transportation and residential sectors are expected to decline as a result of existing emission standards for vehicles and the dwindling direct combustion of biomass in the residential sector. By carrying out a series of energy-saving policies (the PC[0] scenario), total emissions are expected to decrease by 16% from the baseline projection. Emissions from the residential sector decrease most notably because of the substitution of biomass with cleaner fuels. Another 26% could be reduced if progressive end-of-pipe control measures are implemented (reflected by the difference between the PC[0] and the PC[1] scenarios), and the most effective measures are the substitution with low-solvent products and end-of-pipe removal technologies such as incineration and adsorption in the industrial sector and the use of solvents. With full implementation of the best-available technologies (the PC[2] scenario), the NMVOC emissions could be reduced to about one third of the levels of the baseline scenario.

The emissions in East Asia outside of China are expected to increase by 5% from 2010 to 2030 under current regulations. The growth rates in Japan and South Korea are 4% and 9%, respectively. This slight upward trend is an integrated effect of the reduction in transportation emissions due to increased share of low-emission vehicles, and the increase of emissions from solvent use due to inadequate control policies. By 2030, solvent use contributes about 80% of total NMVOC emissions in both Japan and Korea under the baseline projection. As solvent use has little to do with fuel consumption, the implementation of energy-saving policies has very limited effects on the reduction of NMVOC emissions. In contrast, the full application of end-of-pipe control measures (the PC[2] scenario) would reduce the emissions from solvent use dramatically, to about one quarter of the baseline projection.

4 Comparison with other studies and observations

4.1 Comparison with other studies

In 2010, China contributed 88%, 94%, 94%, 95%, and 88% of the total NO_X, SO_2, PM_{10}, $PM_{2.5}$, and NMVOC emissions in East Asia, respectively. As a developing country, China has substantial potential to reduce air pollutant emissions with the implementation of aggressive control policies, and combined with its sheer size is therefore expected to dominate the emission trends of East Asia in the next 20 years. Many previous studies projecting emissions have focused on China. While some Asian and international studies have incorporated Japan, South Korea, and other countries to produce regional projections, they have seldom disaggregated emissions by country, making it difficult to review their projections. For these reasons, our comparisons with prior literature in this section are limited to comparisons of China's emission trends.

There are numerous studies estimating historical emissions of China. Since this study focuses on temporal trends, we exclude in our comparisons the numerous studies estimating emissions for only a single year.

As for future projections, early studies (reported before 2005) of China's emissions (van Aardenne et al., 1999; Streets and Waldhoff, 2000; Klimont et al., 2001; Klimont et al., 2002) were based on the emissions in 1995 or before. They generally substantially underestimated the rapid economic growth during 2000-2010. In addition, none of them anticipated the aggressive control policies in China since 2005. Therefore, these projections deviated greatly from the actual trends. In this study, we only compare emission projections reported since 2005 (or using the base year of 2000 or later) with our projections, which are shown in Figure 4.

4.1.1 NO_X emissions

Zhao et al. (2013d) and Kurokawa et al. (2013) have evaluated recent NO_X emission trends in China. They both presented similar temporal trends to our estimation. The estimated growth rates of China's NO_X emissions are all within the range of 20-23% for the period 2005-2008, and 34-47% for the period of 2005-2010.

Ohara et al. (2007) projected NO_X emissions in China through 2020 by using the emissions for 2000 and three scenarios: a "policy failure" scenario, a "best guess" scenario, and an optimistic scenario. The projections of all the three scenarios for 2010 were much lower than our estimates, indicating they underestimated the economic growth during 2000-2010. The three scenarios projected growth rates ranging between 51% and -10% for the period 2010-2020. In contrast, even the progressive control strategy in our study results in a larger decline of NO_X emissions (-26% in the BAU[1] scenario and -39% in the PC[1] scenario) during the same period, due to the implementation of the control measures scheduled in the 12th Five-Year Plan. Amann et al. (2008) developed three scenarios through 2030 based on the emissions in 2005. The "current legislation" scenario assumed current regulations and enforcement, while the "advanced control technology" scenario assumed across-the-board application of such technologies, largely based on existing German regulations. The optimized scenario was a least-cost optimization that would achieve the same health benefit as the advanced control technology scenario. Xing et al. (2011) projected NO_X emissions for 2020 with four scenarios based on the emissions of 2005, including one assuming current regulations and implementation status, one assuming improvement of energy efficiency and current environmental regulations, one assuming improvement of energy efficiency and better implementation of environmental regulations, and a final scenario assuming improvement of energy efficiency and strict environmental regulations. These two studies (Amann et al. and Xing et al.) were conducted cooperatively. Similar to Ohara et al. (2007), their projections for 2010 were also significantly lower than our estimations. As for the growth rates until 2020 or 2030, all the scenarios in these two studies projected a larger increase or smaller decline than our progressive control strategy assuming the enforcement of the

12th Five Year Plan, indicating these two studies did not anticipate stringent future control policies. Cofala et al. (2012) projected the NO_X emissions until 2030 based on 2010 emissions and four scenarios envisaging energy-saving measures at different stringency levels. The projected rates of change for 2010-2030 range between 16% and -24%. Since no end-of-pipe control measures beyond the baseline are considered, it is only meaningful to compare these scenarios with our BAU[0] and PC[0] scenarios, which projected the growth rates for the same period at 36% and -3%, respectively. This study predicted a stronger growth potential of China's energy consumption in the future, leading to the larger rate of growth or smaller rate of decline above.

4.1.2 SO_2 emissions

A number of studies have evaluated China's recent SO_2 emission trends (Klimont et al., 2013; Lu et al., 2011; Zhao et al., 2013d; Kurokawa et al., 2013). Although the emission estimates in different studies differ by up to 30% during the period, all of the reviewed studies and our own show declining SO_2 emissions during 2005-2010. This study estimated a slightly stronger decline (13% for 2005-2008, and 15% for 2005-2010) compared with the previous studies (2%-8% for 2005-2008, and 2%-12% for 2005-2010).

Most of the projections reviewed here have more or less envisaged China's recent SO_2 control policies. Ohara et al. (2007) predicted that SO_2 emissions would change by 27%, -11%, and -23% during 2010-2020 in their policy failure, best-guess, and optimistic scenarios, respectively, comparable to our BAU[0], PC[0], and BAU[1] scenarios, respectively. Amann et al. (2008) failed to reproduce the declining trend during 2005-2010, but the control policies assumed in its most aggressive scenario (the advanced control technology scenario) resulted in a similar rate of decline as of 2030 as our progressive control strategy. The growth rates projected in all four scenarios of Xing et al. (2011) are higher than our BAU[1] scenario, indicating that their assumptions of future SO_2 control policies are more conservative than our progressive control strategy based on the 12th Five Year Plan. Cofala et al. (2012) predicted SO_2 emissions to decrease by 20%-40% during 2010-2030 under four different energy-saving policy scenarios, while our BAU[0] and PC[0] scenarios predicted rates of change at 26% and -20%, respectively.

As described in Sect. 4.1.1, the differences are also attributed to a stronger growth potential of China's energy consumption projected in our study.

4.1.3 PM emissions

Zhao et al. (2013d) and Kurokawa et al. (2013) have evaluated the recent trends of PM_{10} and $PM_{2.5}$ emissions in China. While Zhao et al. (2013d) and this study both showed a declining trend during 2005-2010, Kurokawa et al. (2013) estimated a significant upward trend after 2005. The discrepancy may be attributed mainly to the uncertainty in the penetration levels of dust collectors at industrial sources.

China has been implementing PM control policies for several decades. Therefore, all of the projections reviewed here have assumed the future application of dust collectors to some extent. The PM_{10} emissions growth rate until 2020 of the least aggressive scenario in Xing et al. (2011) is comparable to our BAU[0], and the most aggressive one is comparable to our PC[1], indicating similar stringency levels of the control policies assumed in these two studies up to 2020. Amann et al. (2008) predicted a slight increase of $PM_{2.5}$ emissions during 2005-2010, in contrast with a 12% decline estimated in our study using statistical data. However, the growth rate for the period 2010-2030 in their current legislation scenario is quite close to our BAU[0] scenario; the growth rates in their advanced control technology scenario and optimized scenario are close to our PC[1] one. Cofala et al. (2012) projected the change rate of $PM_{2.5}$ emissions for 2010-2030 between -20% and -34% under four energy scenarios, which are comparable to the projected change rates of our BAU[0] (-8%) and PC[0] (-34%). Finally, it should be noted that our maximum feasible reduction scenario (the PC[2] scenario) projects much lower emissions than any previously developed scenario.

4.1.4 NMVOC emissions

Kurokawa et al. (2013) have estimated the recent trends in China's NMVOC emissions, which showed a slightly stronger upward trend (16% growth during 2005-2008) than this study (9% growth for the same period).

Only three studies have projected China's NMVOC emissions since 2005. Compared with our study, Ohara et al. (2007) made similar estimation of NMVOC emissions in 2010, but predicted much higher growth rates for the period 2010-2020 in all three of their scenarios, as they assumed few effective control measures in any scenario. Xing et al. (2011) and Wei et al. (2011b) have considered the effect of recent vehicle emission standards on NMVOC emissions, and assumed relatively simple but progressively strengthened control polices through 2020, and therefore achieved similar growth rates to ours for both baseline and progressive strategies. Given China is still in the initial stage of NMVOC emission controls, and limited new policies are expected to emerge in the next 5-10 years, the emission trends are unlikely to deviate greatly from the baseline through 2020. However, control measures at different levels of stringency might result in dramatically different emissions by 2030. Our study is the first one to quantify the effect of potentially new policies on NMVOC emission trends through 2030 and to quantify the maximum feasible reduction potential using energy-saving policies and end-of-pipe control measures.

4.2 Comparison with observations

SO_2 and NO_2 retrievals from satellite observations are used for comparisons with trends of primary emissions estimated in this work. A more rigorous comparison would involve incorporating the emission inventory into a chemical transport model and comparing the simulated NO_2 or SO_2 column with satellite observations, which will be considered in future research. Lu et al. (2011) retrieved the satellite SO_2 vertical column density (VCD) for Eastern Central China (latitude <45ºN, longitude >100ºE), in which measurements of the Ozone Monitoring Instrument (OMI) and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) during 2005-2010 were used. Fioletov et al. (2013) developed a filtering procedure to remove local biases, in particular transient volcanic signals, and applied this method to retrieve the SO_2 VCD over an area of Eastern China during 2005-2010. The data sources include OMI, SCIAMACHY, the Global Ozone Monitoring Experiment-2 (GOME-2) German Aerospace Center (DLR) product, and the GOME-2 Smithsonian Astrophysical Observatory (SAO) product. It should be noted that the data of GOME-2 are only available since 2007. The comparison of SO_2 VCDs derived by Lu et al. (2011) and Fioletov et al. (2013) with the estimated SO_2 emissions are shown in Figure 5(a) and Figure 5(b), respectively. It can be seen that the temporal trends of SO_2 VCD retrieved by Fioletov et al. (2013) from all four data sources (OMI, SCIAMACHY, GOME-2 DLR, and GOME-2 SAO) agree well with each other.

In addition, the trends of SO_2 VCD retrieved by Lu et al. (2011) agree well with that of Fioletov et al. (2013) during 2005-2009. However, Lu et al. (2011) shows a significant increase in SO_2 VCD between 2009 and 2010 (especially that retrieved from SCIAMACHY), while Fioletov et al. (2013) shows a slight increase. Fioletov et al. (2013) implies that the pronounced increase between 2009 and 2010 arises from time-dependent bias in the retrieval algorithms. When the filtering procedure developed in Fioletov et al. (2013) was applied, the pronounced increase turned into a slight increase. Therefore, we exclude the SO_2 VCD in 2010 in Lu et al. (2011) in the following discussion.

As shown in Figure 5(a), during 2005-2009, SO_2 VCD from OMI, SO_2 VCD from SCIAMACHY, and estimated SO_2 emissions decreased by 20%, 21%, and 17%, respectively, in Eastern Central China. Similarly, during 2005-2010, the rate of decline of SO_2 VCD from OMI (16%), SO_2 VCD from SCIAMACHY (8%), and estimated SO_2 emissions (15%) agree fairly well with each other in the studied area of Fioletov et al. (2013). However, SO_2 VCDs from both SCIAMACHY and OMI peak in 2007, while this study shows a monotonic decline in SO_2 emissions through 2009. This may be mainly attributable to the uncertainty in the actual removal efficiency and operation status of FGD facilities. Although FGDs have been rapidly introduced since 2005, the actual operation status has been questioned before by both the government and research community (Xu et al., 2009). In response to this situation, the Chinese government began to require the installation of continuous emission monitoring systems (CEMSs) together with FGDs since July 2007 (SEPA, 2007). Therefore, the average removal efficiency should have improved subsequently, contributing to the rapid decline in SO_2 during 2007-2009. Despite the inconsistency above, the estimated overall change rate in SO_2 emissions from 2005 to 2010 agrees fairly well with satellite observations, although this agreement is very sensitive to the choice of trend start and end years.

The NO_2 VCDs were retrieved from OMI and SCIAMACHY with the method described in Zhao et al. (2013b) and Zhang et al. (2012a), respectively. Figure 5(c) compares the average NO_2 VCD in Eastern Central China and the total NO_X emissions in this area. It can be seen that the growing trend of NO_X emissions are well captured by both the observations of OMI and SCIAMACHY. The growth rates of NO_2 VCD from OMI, NO_2 VCD from SCIAMACHY, and NO_X emissions are 27%, 34%, and 31%, respectively.

The trends in PM concentrations are not directly comparable with primary emissions, as secondary PM is formed through complex chemical reactions of primary pollutants. Our previous study (Zhao et al., 2013a) simulated the concentrations of air pollutants in China in 2005 and 2010 using the Community Multi-scale Air Quality (CMAQ) model and the same emission inventory as presented in this paper. The trends of air pollutant emissions were evaluated by comparing the trends of simulated air quality with observations. From 2005 to 2010, the simulated PM_{10} concentrations of 58 Chinese cities decreased by 7.3%, which agreed well with the rate of decline of the observations (7.6%, http://datacenter.mep.gov.cn). In addition, the simulated changes of Aerosol Optical Depth (AOD) during 2005-2010 can well reproduce the spatial pattern of the AOD changes observed by Moderate Resolution Imaging Spectroradiometer (MODIS). During 2005-2010, AOD decreased in some areas such as the southeast coast of China, but increased in a large part of China, with especially pronounced increases in the Sichuan Basin and the southern part of the North China Plain (Zhao et al., 2013a).

As described above, both observation and simulation results indicate that annual average PM_{10} concentrations in major cities of Eastern China decreased since 2005. However, based on our simulation results (Zhao et al., 2013a), the control policies had not been successful in reducing concentrations of fine particles over a large part of China. One of the important reasons for the increase of fine particles during 2005-2010 is that nitrate concentrations increased in most of China driven by the increase of NO_X and NH_3 emissions. Although sulfate concentrations in East China decreased due to the decline of SO_2 emissions, the concentrations of secondary inorganic aerosol (SIA) increased in most of China, especially in the Sichuan Basin and eastern Hubei province. In addition, the increase in the emissions of NMVOC led to the increase of secondary organic aerosols. The increase in secondary $PM_{2.5}$ concentrations offset the decline of primary $PM_{2.5}$ concentrations and led to the increase of total $PM_{2.5}$ concentrations in a large part of China. Given above, although the emissions of primary PM and SO_2 decreased in most of China, the modeling results indicated that total $PM_{2.5}$ concentrations still increased in a large part of China (Zhao et al., 2013a).

5 Conclusions and policy implications

In this study we reviewed the application status of air pollution control measures in East Asia in the last decade, evaluated the impact of control policies on the emission trends during 2005-2010, and projected future emissions of SO_2, NO_X, PM_{10}, $PM_{2.5}$, and NMVOC up to 2030 under six emission scenarios based on a range of energy-saving and end-of-pipe emission control measures.

During 2005-2010, the emissions of SO_2 and $PM_{2.5}$ in East Asia decreased by 15% and 12%, respectively, mainly attributable to the large scale deployment of FGD in China's power plants, and the deployment of more efficient PM removal technologies in China's power and cement plants. During this period, the emissions of NO_X and NMVOC increased by 25% and 15%, respectively, driven by the rapid increase in the emissions from China due to inadequate control strategies. In contrast, the NO_X and NMVOC emissions in East Asia other than China decreased by 13-17% mainly due to the implementation of stringent vehicle emission standards in Japan and South Korea.

Under current regulations and implementation status (the BAU[0] scenario), NO_X, SO_2, and NMVOC emissions in East Asia are estimated to increase by about one quarter by 2030 from the 2010 levels, while $PM_{2.5}$ emissions are expected to decrease by 7%. Assuming enforcement of new energy-saving policies, emissions of NO_X, SO_2, $PM_{2.5}$, and NMVOC in East Asia are expected to decrease by 28%, 36%, 28%, and 15%, respectively, compared with the baseline case. The implementation of progressive end-of-pipe control measures is expected to lead to another one-third reduction of the baseline emissions of NO_X, and about one-quarter reduction of SO_2, $PM_{2.5}$, and NMVOC. Exploring the potential of currently known best-available technologies, their full implementation could reduce the emissions of NO_X, SO_2, and $PM_{2.5}$ in East Asia to only about one quarter, and NMVOC to one third, of the levels of the baseline projection.

Comparison with emission projections in the literature indicates that this study: (1) estimates similar recent emission trends until 2010; (2) projects larger reductions in NO_X and SO_2 emissions by assuming aggressive governmental plans and standards scheduled to be implemented in the next decade; (3) accounts for the significant effects of detailed progressive control measures on NMVOC emissions up to 2030; and (4) quantifies technically feasible reduction potentials. The results of this study provide future emission projections for the modeling community of the MICS-Asia program, allowing modelers to assess the impact of emission changes on future air quality. In addition, the emission projections at various stringency levels from a business-as-usual case to a maximum feasible reduction case provide a basis for further studies on cost-effective emission control strategies, which can balance control measures over all pollutants and control levels.

The results of this study have important policy implications. First, this study indicates that the successful implementation of the control policies set in China's 12th Five Year Plan, the recently released emission standards for various industrial sources, and slowly strengthened control measures after 2015 (as assumed in the "progressive" end-of-pipe control strategy) could reduce China's emissions of NO_X, SO_2, and $PM_{2.5}$ significantly. The resulting NO_X, SO_2, and $PM_{2.5}$ emissions would be 16-26% lower than the 2010 levels by 2020, and even lower by 2030, demonstrating a high mitigation potential when this legislation and associated regulations are enforced efficiently. Therefore we believe it is essential to support and monitor the progress of implementation of these measures. Second, the contributions of advanced energy-saving measures to the reduction of SO_2 and $PM_{2.5}$ emissions exceeds those of progressive end-of-pipe control measures by 2030. Since end-of-pipe control technologies (e.g., FGD facilities and high-efficiency dedustors) have already been widely applied in typical sources in the base year, their reduction potential will diminish in the future. The energy-saving measures would play an essential role for further reduction of air pollutant emissions. Third, control policies for NMVOC emissions are unfortunately lacking in China and South Korea at present; this study indicates that the simultaneous enforcement of energy-saving measures and progressive end-of-pipe control measures (mainly assuming enforcement of European standards) could reduce 38% of the total NMVOC emissions from the levels of baseline projection. Nevertheless, large reduction potential still remains, and additional policies to reduce NMVOC emissions efficiently and effectively warrant careful consideration .

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References

Amann, M., Jiang, K. J., Hao, J. M., and Wang, S. X.: Scenarios for cost-effective control of air pollution and greenhouse gases in China, International Institute for Applied Systems Analysis, Laxenburg, Austria, 51, 2008.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Hoglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schopp, W., Wagner, F., and Winiwarter, W.: Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, Environ. Modell. Softw., 26, 1489-1501, doi: 10.1016/j.envsoft.2011.07.012, 2011.

Bo, Y., Cai, H., and Xie, S. D.: Spatial and temporal variation of historical anthropogenic NMVOCs emission inventories in China, Atmos. Chem. Phys., 8, 7297–7316, 2008.

China Electric Power Yearbook Committee: China Electric Power Yearbook 2006, China Electric Power Press, Beijing, China, 2006 (in Chinese).

China Electric Power Yearbook Committee: China Electric Power Yearbook 2011, China Electric Power Press, Beijing, China, 2011 (in Chinese).

Cofala, J., Amann, M., Klimont, Z., Kupiainen, K., and Hoglund-Isaksson, L.: Scenarios of global anthropogenic emissions of air pollutants and methane until 2030, Atmos. Environ., 41, 8486-8499, doi: 10.1016/j.atmosenv.2007.07.010, 2007.

Cofala, J., Bertok, I., Borken-Kleefeld, J., Heyes, C., Klimont, Z., Rafaj, P., Sander, R., Schöpp, W., and Amann, A.: Emissions of Air Pollutants for the World Energy Outlook 2012 Energy Scenarios, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012.

Delphi Company: Worldwide Emission Standard: Heavy Duty and Off-Highway Vehicles, available at www.delphi.com/emissions-hd, access: 1 November 2013, Delphi company, Troy, Michigan, U.S., 100 pp., 2013a.

Delphi Company: Worldwide Emission Standard: Passenger Cars and Light Duty Vehicles, available at www.delphi.com/emissions-pc, access: 1 November 2013, Delphi company, Troy, Michigan, U.S., 100 pp., 2013b.

Energy Conservation Center of Japan: Japan Energy Conservation Handbook 2011, available at http://www.asiaeec-col.eccj.or.jp/databook/2011/, access: 1 October 2013, Energy Conservation Center of Japan, Tokyo, Japan, 145 pp., 2011.

Fioletov, V. E., McLinden, C. A., Krotkov, N., Yang, K., Loyola, D. G., Valks, P., Theys, N., Van Roozendael, M., Nowlan, C. R., Chance, K., Liu, X., Lee, C., and Martin, R. V.: Application of OMI, SCIAMACHY, and GOME-2 satellite SO2 retrievals for detection of large emission sources, J. Geophys. Res-Atmos., 118, 11399-11418, doi:10.1002/jgrd.50826, 2013.

Huo, H., Lei, Y., Zhang, Q., Zhao, L. J., and He, K. B.: China's coke industry: Recent policies, technology shift, and implication for energy and the environment, Energ. Policy., 51, 397–404, 2012.

Institute of Energy Economics of Japan: Handbook of Energy & Economic Statistics in Japan, Institute of Energy Economics of Japan, Tokyo, Japan, 370 pp., 2010.

International Energy Agency (IEA): Energy Balances of OECD Countries 1999-2000, International Energy Agency, Head of Publications Service, Paris, France, 249 pp., 2002.

International Energy Agency (IEA): Energy policy of IEA countries: Korea 2006 Review, International Energy Agency, Paris, France, 2006.

International Energy Agency (IEA): Energy Balances of OECD Countries 2004-2005, International Energy Agency, Head of Publications Service, Paris, France, 249 pp., 2007.

International Energy Agency (IEA): Energy policy of IEA countries: Japan 2008 Review, International Energy Agency, Paris, France, 2008.

International Energy Agency (IEA): World Energy Outlook 2009, International Energy Agency, Paris, France, 2009.

International Energy Agency (IEA): Energy policy of IEA countries: Korea 2012 Review, International Energy Agency, Paris, France, 2012a.

International Energy Agency (IEA): Energy Balances of OECD Countries 2009-2010, International Energy Agency, Head of Publications Service, Paris, France, 249 pp., 2012b.

Japan Automobile Manufacturers Association: PM/PM2.5 in Ambient Air & Related Activities in Japan, Japan Automobile Manufacturers Association, Tokyo, Japan, 51 pp., 2011.

Japan Petroleum Energy Center (JPEC): Emission inventory of road transport in Japan, Japan Petroleum Energy Center, Tokyo, 136, 2012a (in Japanese).

Japan Petroleum Energy Center (JPEC): Emission inventory of sources other than road transport in Japan, Japan Petroleum Energy Center, Tokyo, 288, 2012b (in Japanese).

Japan Petroleum Energy Center (JPEC): Speciation profiles of VOC, PM, and NOx emissions for atmospheric simulations of $PM_{2.5}$, Japan Petroleum Energy Center, Tokyo, 69, 2012c (in Japanese).

Klimont, Z., Cofala, J., Schopp, W., Amann, M., Streets, D. G., Ichikawa, Y., and Fujita, S.: Projections of SO2, NOx, NH3 and VOC emissions in East Asia up to 2030, Water. Air. Soil. Poll., 130, 193-198, 2001.

Klimont, Z., Streets, D. G., Gupta, S., Cofala, J., Fu, L. X., and Ichikawa, Y.: Anthropogenic emissions of non-methane volatile organic compounds in China, Atmos. Environ., 36, 1309-1322, doi: 10.1016/S1352-2310(01)00529-5, 2002.

Klimont, Z., Cofala, J., Xing, J., Wei, W., Zhang, C., Wang, S., Kejun, J., Bhandari, P., Mathur, R., Purohit, P., Rafaj, P., Chambers, A., and Amann, M.: Projections of SO(2), NO(x) and carbonaceous aerosols emissions in Asia, Tellus. B., 61, 602-617, doi: 10.1111/j.1600-0889.2009.00428.x, 2009.

Klimont, Z., Smith, S. J., and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environ. Res. Lett., 8, 1-6, doi:10.1088/1748-9326/8/1/014003, 2013.

Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Greet, J.-M., Fukui, T., Kawashima, K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmos. Chem. Phys. Discuss., 13, 10049-10123, doi:10.5194/acpd-13-10049-2013, 2013.

Lei, Y., Zhang, Q., He, K. B., and Streets, D. G.: Primary anthropogenic aerosol emission trends for China, 1990-2005, Atmos. Chem. Phys., 11, 931-954, doi: 10.5194/acp-11-931-2011, 2011.

Li, C., Zhang, Q., Krotkov, N. A., Streets, D. G., He, K. B., Tsay, S. C., and Gleason, J. F.: Recent large reduction in sulfur dioxide emissions from Chinese power plants observed by the

Ozone Monitoring Instrument, Geophys. Res. Lett., 37, L08807, doi:10.1029/2010GL042594, 2010.
Li, Y.: Dynamics of clean coal-fired power generation development in China, Energ. Policy., 51, 138-142, doi: 10.1016/j.enpol.2011.06.012, 2012.
Lin, J., Nielsen, C. P., Zhao, Y., Lei, Y., Liu, Y., and McElroy, M. B.: Recent Changes in Particulate Air Pollution over China Observed from Space and the Ground: Effectiveness of Emission Control, Environ. Sci. Technol., 44, 7771-7776, Doi 10.1021/Es101094t, 2010a.
Lin, J. T., McElroy, M. B., and Boersma, K. F.: Constraint of anthropogenic NOx emissions in China from different sectors: a new methodology using multiple satellite retrievals, Atmos. Chem. Phys., 10, 63-78, doi:10.5194/acp-10-63-2010, 2010b.
Liu, H. Y., Jacob, D. J., Bey, I., Yantosca, R. M., Duncan, B. N., and Sachse, G. W.: Transport pathways for Asian pollution outflow over the Pacific: Interannual and seasonal variations, J. Geophys. Res-Atmos., 108, D20, 8786, doi:10.1029/2002JD003102, 2003.
Lu, Z., Streets, D. G., Zhang, Q., Wang, S., Carmichael, G. R., Cheng, Y. F., Wei, C., Chin, M., Diehl, T., and Tan, Q.: Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000, Atmos. Chem. Phys., 10, 6311–6331, doi:10.5194/acp-10-6311-2010, 2010.
Lu, Z., Zhang, Q., and Streets, D. G.: Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996-2010, Atmos. Chem. Phys., 11, 9839–9864, doi:10.5194/acp-11-9839-2011, 2011.
Ministry of Environment of South Korea: Air & Climate Change Policies in South Korea: http://eng.me.go.kr/eng/web/index.do?menuId=64&findDepth=1, access: 23 January, 2014, 2013.
Ministry of Environmental Protection of China (MEP): Bulletin of urban sewage treatment facilities, and flue gas desulfurization/denitrification facilities of coal-fired power plants: http://www.mep.gov.cn/gkml/hbb/bgg/201104/t20110420_209449.htm, access: 5 May 2012, 2011 (in Chinese).
Ministry of the Environment of Japan: Air & Transportation Policies in Japan: http://www.env.go.jp/en/air/, access: 01 August, 2013, 2013.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2006, China Statistics Press, Beijing, 2007.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2007, China Statistics Press, Beijing, 2008a.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2008, China Statistics Press, Beijing, 2008b.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2009, China Statistics Press, Beijing, 2009.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2011, China Statistics Press, Beijing, 2011a.
National Bureau of Statistics (NBS): China Energy Statistical Yearbook 2010, China Statistics Press, Beijing, 2011b.
National Development and Reform Commission (NDRC): Bulletin of the progress in shutting down small power generation units: http://www.sdpc.gov.cn/zcfb/zcfbgg/2011gg/t20110422_407267.htm, access: 5 May 2012, 2011 (in Chinese).

Natlonal Institute of Environmental Research (NIER): The methodology of national air pollutants emission estimation II, 2010, National Institute of Environmental Research, Inchon, South Korea, 2010 (in Korean).

Natlonal Institute of Environmental Research (NIER): A Study on the Characteristics of the Process Facilities using SEMS Data, National Institute of Environmental Research, Inchon, South Korea, 2013 (in Korean).

Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980-2020, Atmos. Chem. Phys., 7, 4419-4444, 2007.

Shindell, D., Kuylenstierna, J. C. I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S. C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Hoglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N. T. K., Milly, G., Williams, M., Demkine, V., and Fowler, D.: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security, Science, 335, 183-189, DOI 10.1126/science.1210026, 2012.

State Environmental Protection Administration (SEPA): Administrative regulations for the application of desulfurization electricity price and the operation of flue gas desulfurization facilities in coal-fired power generation units: http://www.sdpc.gov.cn/zcfb/zcfbtz/2007tongzhi/t20070612_140883.htm, access: 1 Jan 2014, 2007 (in Chinese).

Streets, D. G., and Waldhoff, S. T.: Present and future emissions of air pollutants in China: SO2, NOx, and CO, Atmos. Environ., 34, 363-374, 2000.

The State Council of the People's Republic of China: The Eleventh Five-Year Plan for National Economic and Social Development of the People's Republic of China: http://www.gov.cn/gongbao/content/2006/content_268766.htm, access: 2 Feb 2013, 2006 (in Chinese).

The State Council of the People's Republic of China: Integrated Work Plan for Energy Saving and Emission Reduction During the Twelfth Five-Year Plan: http://www.gov.cn/zwgk/2011-09/07/content_1941731.htm, access: 2 Feb 2013, 2011 (in Chinese).

The State Council of the People's Republic of China: The Twelfth Five-Year Plan for Energy Saving and Emission Reduction: http://www.gov.cn/zwgk/2012-08/21/content_2207867.htm, access: 2 Feb 2013, 2012 (in Chinese).

Tsinghua University Building Energy Research Center (THUBERC): Annual Report on China Building Energy Efficiency, China Architecture & Building Press, Beijing, 2009 (in Chinese).

United Nations Environment Programme (UNEP): Overview of the Republic of Korea's National Strategy for Green Growth, United Nations Environment Programme, Geneva, Switzerland, 54 pp., 2010.

United Nations Environment Programme (UNEP), and World Meteorological Organization (WMO): Integrated Assessment of Black Carbon and Tropospheric Ozone, United Nations Environment Programme and World Meteorological Organization, Nairobi, Kenya, 2011.

van Aardenne, J. A., Carmichael, G. R., Levy, H., Streets, D., and Hordijk, L.: Anthropogenic NOx emissions in Asia in the period 1990-2020, Atmos. Environ., 33, 633-646, 1999.

Wakamatsu, S., Morikawa, T., and Ito, A.: Air Pollution Trends in Japan between 1970 and 2012 and Impact of Urban Air Pollution Countermeasures, Asian J. Atmos. Environ., 7, 177-190, doi: 10.5572/ajae.2013.7.4.177, 2013.

Wang, Q. Y.: Chinese Energy Data 2010, The Energy Foundation, Beijing, 109 pp., 2010.
Wang, S. X., and Hao, J. M.: Air quality management in China: Issues, challenges, and options, J. Environ. Sci-China., 24, 2-13, doi: 10.1016/S1001-0742(11)60724-9, 2012.
Wei, W., Wang, S. X., Chatani, S., Klimont, Z., Cofala, J., and Hao, J. M.: Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China, Atmos. Environ., 42, 4976–4988, 2008.
Wei, W., Wang, S. X., and Hao, J. M.: Uncertainty Analysis of Emission Inventory for Volatile Organic Compounds from Anthropogenic Sources in China, Environmental Science, 32, 305-312, 2011a (in Chinese).
Wei, W., Wang, S. X., Hao, J. M., and Cheng, S. Y.: Projection of anthropogenic volatile organic compounds (VOCs) emissions in China for the period 2010-2020, Atmos. Environ., 45, 6863-6871, doi: 10.1016/j.atmosenv.2011.01.013, 2011b.
World Bank (WB), and State Environmental Protection Administration (SEPA): Cost of Pollution in China: Economic Estimates of Physical Damages, available at www.worldbank.org/eapenvironment, access: 1 October, 2013, 2007.
Wu, Y., Zhang, S. J., Li, M. L., Ge, Y. S., Shu, J. W., Zhou, Y., Xu, Y. Y., Hu, J. N., Liu, H., Fu, L. X., He, K. B., and Hao, J. M.: The challenge to NOx emission control for heavy-duty diesel vehicles in China, Atmos. Chem. Phys., 12, 9365–9379, doi: 10.5194/acp-12-9365-2012, 2012.
Xing, J., Wang, S. X., Chatani, S., Zhang, C. Y., Wei, W., Hao, J. M., Klimont, Z., Cofala, J., and Amann, M.: Projections of air pollutant emissions and its impacts on regional air quality in China in 2020, Atmos. Chem. Phys., 11, 3119-3136, doi: 10.5194/acp-11-3119-2011, 2011.
Xu, Y., Williams, R. H., and Socolow, R. H.: China's rapid deployment of SO2 scrubbers, Energ. Environ. Sci., 2, 459–465, 2009.
Yang, Z. D.: Well-to-wheels analysis of energy consumption and CO2 emissions of electric-powered vehicles in China, Master thesis, School of Environment, Tsinghua University, Beijing, China, 83 pp., 2012 (in Chinese).
Zhang, Q., Streets, D. G., He, K., Wang, Y., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z., and Lei, Y.: NOx emission trends for China, 1995-2004: The view from the ground and the view from space, J. Geophys. Res-Atmos., 112, D22306, doi: 10.1029/2007jd008684, 2007.
Zhang, Q., Geng, G. N., Wang, S. W., Richter, A., and He, K. B.: Satellite remote sensing of changes in NO (x) emissions over China during 1996-2010, Chinese. Sci. Bull., 57, 2857-2864, DOI 10.1007/s11434-012-5015-4, 2012a.
Zhang, Q., He, K. B., and Huo, H.: Cleaning China's air, Nature, 484, 161-162, 2012b.
Zhang, X. Y., Wang, Y. Q., Niu, T., Zhang, X. C., Gong, S. L., Zhang, Y. M., and Sun, J. Y.: Atmospheric aerosol compositions in China: spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols, Atmos. Chem. Phys., 12, 779-799, DOI 10.5194/acp-12-779-2012, 2012c.
Zhao, B., Wang, S. X., Dong, X. Y., Wang, J. D., Duan, L., Fu, X., Hao, J. M., and Fu, J.: Environmental effects of the recent emission changes in China: implications for particulate matter pollution and soil acidification, Environ. Res. Lett., 8, 024031, doi:10.1088/1748-9326/8/2/024031, 2013a.
Zhao, B., Wang, S. X., Wang, J. D., Fu, J., Liu, T. H., Xu, J. Y., Fu, X., and Hao, J. M.: Impact of national NOX and SO2 control policies on particulate matter pollution in China, Atmos. Environ., 77, 453-463, 2013b.

Zhao, B., Wang, S. X., Xu, J. Y., Fu, K., Klimont, Z., Hao, J. M., He, K. B., Cofala, J., and Amann, M.: NOx emissions in China: historical trends and future perspectives, Atmos. Chem. Phys., 13, 9869-9897, doi:10.5194/acp-13-9869-2013, 2013c.

Zhao, Y., Wang, S. X., Nielsen, C. P., Li, X. H., and Hao, J. M.: Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants, Atmos. Environ., 44, 1515-1523, doi: 10.1016/j.atmosenv.2010.01.017, 2010.

Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO2 in China, Atmos. Chem. Phys., 13, 487–508, doi:10.5194/acp-13-487-2013, 2013d.

Tables and figures

Table 1. Definition of the energy and emission scenarios in this study.

Energy scenario name	Energy scenario definition	Emission scenario name	Emission scenario definition
Business-as-usual (abbr. BAU)	The BAU scenario is based on current regulations and implementation status (until the end of 2010).	BAU[0]	The BAU[0] scenario assumes the energy-saving policies of the BAU scenario. For an end-of-pipe control strategy, it assumes that all current regulations (until the end of 2010) and the current implementation status in all countries will be continued during 2011-2030.
		BAU[1]	The BAU[1] scenario assumes the energy-saving policies of the BAU scenario. For an end-of-pipe control strategy in China, it assumes that new pollution control policies will be released and implemented, representing a progressive approach towards future environmental protection. For the other countries in East Asia, the assumptions of the BAU[1] scenario are exactly the same as the BAU[0] scenario.
		BAU[2]	The BAU[2] scenario assumes the energy-saving policies of the BAU scenario. For an end-of-pipe control strategy, it assumes that the maximum technically feasible control technologies would be fully applied by 2030, regardless of the economic cost.
Alternative policy (abbr. PC)	The PC scenario assumes that new energy-saving policies will be released and more strongly enforced, resulting in lifestyle changes, structural adjustment, and energy efficiency improvement.	PC[0]	The PC[0] scenario assumes the energy-saving policies of the PC scenario, and the same end-of-pipe control strategy as the BAU[0] scenario.
		PC[1]	The PC[1] scenario assumes the energy-saving policies of the PC scenario, and the same end-of-pipe control strategy as the BAU[1] scenario.
		PC[2]	The PC[2] scenario assumes the energy-saving policies of the PC scenario, and the same end-of-pipe control strategy as the BAU[2] scenario.

Table 2. Penetrations of major control technologies in the power sectors in China, Japan, and South Korea (% of fuel use).

Energy technology	Control technology	Base year						BAU[0]/PC[0]						BAU[1]/PC[1]						BAU[2]/PC[2]		
		2005			2010			2020			2030			2020			2030			2030		
	Country	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea
Grate boilers	CYC (PM)	12	-	-	12	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-
	WET (PM)	88	-	-	88	-	-	100	-	-	100	-	-	100	-	-	100	-	-	0	-	-
	HED (PM)	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	100	-	-
Pulverized coal combustion	WET (PM)	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ESP (PM)	92	3	72	93	2	67	90	0	64	80	0	61	65	0	64	50	0	61	0	0	0
	HED (PM)	0	97	28	7	98	33	10	100	36	20	100	39	35	100	36	50	100	39	100	100	100
	FGD (SO_2)	12	97	95	88	98	97	93	100	98	96	100	98	100	100	98	100	100	98	100	100	100
	LNB (NO_X)	53	10	23	75	0	13	82	0	13	84	0	13	8	0	13	0	0	13	0	0	0
	LNB+SNCR (NO_X)	0	0	5	1	0	5	1	0	5	1	0	5	6	0	5	7	0	5	0	0	0
	LNB+SCR (NO_X)	1	90	56	12	100	68	12	100	72	12	100	76	86	100	72	94	100	76	100	100	100
Fluidized bed combustion	WET (PM)	8	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-
	ESP (PM)	92	-	-	100	-	-	90	-	-	80	-	-	65	-	-	50	-	-	0	-	-
	HED (PM)	0	-	-	0	-	-	10	-	-	20	-	-	35	-	-	50	-	-	100	-	-
	CFB-FGD (SO_2)	17	-	-	53	-	-	66	-	-	80	-	-	100	-	-	100	-	-	100	-	-
	SNCR (NO_X)	0	-	-	0	-	-	0	-	-	0	-	-	30	-	-	80	-	-	70	-	-
	SCR (NO_X)	0	-	-	0	-	-	0	-	-	0	-	-	5	-	-	20	-	-	30	-	-
Natural gas power	LNB (NO_X)	30	80	20	74	61	15	87	52	15	91	50	15	50	52	15	10	50	15	0	0	0
	LNB+SNCR (NO_X)	0	0	0	1	0	0	1	0	0	1	0	0	5	0	0	9	0	0	10	0	0
	LNB+SCR (NO_X)	0	20	30	5	39	46	5	48	50	5	50	54	45	48	50	81	50	54	90	100	100

Notes: CYC, cyclone dust collector; WET, wet scrubber; ESP, electrostatic precipitator; HED, high efficiency deduster; FGD, flue gas desulfurization; CFB-FGD, flue gas desulfurization for circulated fluidized bed; LNB, low-NO_X combustion technology; SCR, selective catalytic reduction; SNCR, selective non-catalytic reduction. The table gives the national average penetrations of major control technologies. Note, however, that the penetrations vary with provinces and the penetration in "key regions" as defined by the Chinese government, is usually larger than that of other regions.

Table 3. Penetrations of major control technologies in industrial and residential combustion sources in China, Japan, and South Korea (% of fuel use).

Energy technology	Control technology	Base year						BAU[0]/PC[0]						BAU[1]/PC[1]						BAU[2]/PC[2]		
		2005			2010			2020			2030			2020			2030			2030		
	Country	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea
Industrial grate boilers	CYC (PM)	23	0	25	0	0	23	0	0	20	0	0	17	0	0	20	0	0	17	0	0	0
	WET (PM)	73	0	12	95	0	9	95	0	9	95	0	9	60	0	9	20	0	9	0	0	0
	ESP (PM)	0	50	16	0	50	16	0	50	16	0	50	16	20	50	16	40	50	16	0	0	0
	HED (PM)	0	50	47	5	50	52	5	50	55	5	50	58	20	50	55	40	50	58	100	100	100
	FGD (SO2)	0	42	80	1	42	85	1	42	88	1	42	90	40	42	88	80	42	90	100	100	100
	LNB (NOX)	0	65	0	0	80	0	0	80	0	0	80	0	91	80	0	100	80	0	0	0	0
	LNB+SCR (NOX)	0	20	0	0	20	0	0	20	0	0	20	0	0	20	0	0	20	0	100	100	100
Residential boilers	CYC (PM)	23	50	60	14	50	51	12	50	45	10	50	40	0	50	45	0	50	40	0	50	50
	WET (PM)	63	0	40	78	0	49	81	0	55	85	0	60	80	0	55	60	0	60	50	0	0
	HED (PM)	0	50	0	0	50	0	0	50	0	0	50	0	20	50	0	40	50	0	50	50	50
	DC (SO2)	0	0	0	0	0	0	5	0	0	10	0	0	20	0	0	40	0	0	100	100	100
Coal stoves	STV_ADV_C	0	25	10	0	50	13	0	50	18	0	50	20	10	50	18	30	50	20	100	100	100
Biomass stoves	STV_ADV_B	0	35	30	0	48	35	0	70	35	0	78	35	10	70	35	30	78	35	50	50	50
	STV_PELL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	50

Notes: DC, application of (low-sulfur) derived coal; STV_ADV_C, replacement of advanced coal stove; STV_ADV_B, replacement of advanced biomass stove (e.g. better combustion condition, catalytic stove); STV_PELL, biomass pellet stove.

Table 4. Penetrations of major control technologies for selected industrial process in China.

(a) SO_2

Industrial process	Control technology	Base year 2005	Base year 2010	BAU[0]/PC[0] 2020	BAU[0]/PC[0] 2030	BAU[1]/PC[1] 2020	BAU[1]/PC[1] 2030	BAU[2]/PC[2] 2030
Sintering	FGD	0	10	20	40	95	100	100
Coke oven	FGD for coal-charging process	0	0	0	0	10	10	0
	FGD for coke oven gas	0	0	0	0	10	10	0
	Combination of the technologies above	0	0	0	0	30	50	100
Glass production (float process)	FGD	0	0	0	0	50	90	100
Sulfuric acid production	Ammonia acid desulfurization method	0	0	0	0	40	80	100

(b) NO_X

Industrial process	Control technology	Base year 2005	Base year 2010	BAU[0]/PC[0] 2020	BAU[0]/PC[0] 2030	BAU[1]/PC[1] 2020	BAU[1]/PC[1] 2030	BAU[2]/PC[2] 2030
Sintering	SNCR	0	0	0	0	36	54	20
	SCR	0	0	0	0	24	36	80
Precalciner cement kiln	LNB	30	35	35	35	30	25	0
	LNB+SNCR	0	0	0	0	30	45	0
	LNB+SCR	0	0	0	0	20	30	100
Glass production (float process)	OXFL	0	0	0	0	80	88	70
	SCR	0	0	0	0	10	12	30
Nitric acid (dual pressure process)	ABSP	10	12	12	12	18	18	18
	SCR	15	18	18	18	72	82	82
	ABSP+SCR	0	0	0	0	0	0	0
Nitric acid (other process)	ABSP	60	63	66	66	5	5	0
	SCR	30	32	34	34	15	15	0
	ABSP+SCR	0	0	0	0	80	80	100

Notes: ABSP, absorption method; OXFL, oxy-fuel combustion technology.

(c) PM

Industrial process	Control technology	Base year 2005	Base year 2010	BAU[0]/PC[0] 2020	BAU[0]/PC[0] 2030	BAU[1]/PC[1] 2020	BAU[1]/PC[1] 2030	BAU[2]/PC[2] 2030
Sintering (flue gas)	CYC	5	0	0	0	0	0	0
	WET	20	5	0	0	0	0	0
	ESP	65	75	80	80	70	60	0
	HED	10	20	20	20	30	40	100
Blast furnace (flue gas)	WET	100	100	100	100	100	100	100
	ESP	100	100	100	100	100	100	100
Basic oxygen furnace	ESP	40	30	20	20	10	0	0
	HED	60	70	80	80	90	100	100
Electric arc furnace	WET	60	30	20	20	0	0	0
	ESP	30	50	50	50	40	20	0
	HED	10	20	30	30	60	80	100
Coke oven	WET	100	100	100	100	50	30	0
	HED	0	0	0	0	50	70	100
Precalciner cement kiln	WET	1	0	0	0	0	0	0
	ESP	52	40	35	30	20	5	0
	HED	47	60	65	70	80	95	100
Glass production	CYC	5	0	0	0	0	0	0
	WET	25	20	20	20	0	0	0
	ESP	68	75	75	75	85	75	0
	HED	3	5	5	5	15	25	100
Brick production	CYC	40	30	30	30	20	0	0
	WET	8	20	20	20	40	50	0
	ESP	0	20	20	20	40	50	0
	HED	0	0	0	0	0	0	100

Notes: CMN, common control of fugitive emissions; HIEF, high-efficiency control of fugitive emissions.

(d) NMVOC

Industrial process	Control technology	Base year		BAU[0]/PC[0]		BAU[1]/PC[1]		BAU[2]/PC[2]
		2005	2010	2020	2030	2020	2030	2030
Coke oven	No control	100	100	100	100	55	20	0
	End of pipe control measures	0	0	0	0	45	80	100
Refinery	No control	100	100	87	80	20	0	0
	Leak detection and repair program	0	0	10	15	30	15	0
	Covers on oil and water separators	0	0	3	5	10	5	0
	Combination of the above options	0	0	0	0	40	80	100
Plant oil extraction	No control	95	90	84	80	20	0	0
	Activated carbon adsorption	5	10	13	15	50	50	0
	Schumacher type DTDC and activated carbon adsorption	0	0	3	5	25	35	0
	Schumacher type DTDC and new recovery section	0	0	0	0	5	15	100
Pharmacy	No control	100	100	90	85	15	0	0
	Primary measures and low-level end-of-pipe measures	0	0	10	15	50	30	0
	Primary measures and high-level end-of-pipe measures	0	0	0	0	35	70	100
Gasoline storage	No control	100	95	75	60	25	0	0
	IFC (Internal floating covers or secondary seals)	0	5	25	40	75	100	100
Gasoline loading and unloading	No control	100	85	50	50	25	0	0
	Stage IA (Vapor recovery systems and modified loading techniques)	0	15	50	50	75	100	100
Service station	No control	100	85	50	50	25	0	0
	Stage IB + Stage II (Improvement in service station tank and vapor balancing system between a vehicle and service station tank)	0	15	50	50	75	100	100
Crude oil storage and distribution	No control	100	100	100	100	75	50	0
	IFC + Stage IA + Stage IB + Storage II	0	0	0	0	25	50	100

Table 5. Penetrations of vehicle emission standards in China, Japan, and South Korea (%).

(a) China

Vehicle	Standard	Base year		BAU[0]/PC[0]		BAU[1]/PC[1]		BAU[2]/PC[2]
		2005	2010	2020	2030	2020	2030	2030
HDT-D	NOC	19	1	0	0	0	0	0
	HDEUI	42	8	0	0	0	0	0
	HDEUII	39	22	0	0	0	0	0
	HDEUIII	0	70	7	0	7	0	0
	HDEUIV	0	0	19	0	19	0	0
	HDEUV	0	0	75	100	41	0	0
	HDEUVI	0	0	0	0	32	100	100
HDB-D	NOC	28	8	0	0	0	0	0
	HDEUI	40	18	0	0	0	0	0
	HDEUII	32	24	3	0	3	0	0
	HDEUIII	0	51	20	0	22	0	0
	HDEUIV	0	0	18	2	18	2	0
	HDEUV	0	0	59	98	32	8	0
	HDEUVI	0	0	0	0	25	90	100
LDT-D	NOC	11	0	0	0	0	0	0
	MDEUI	65	13	0	0	0	0	0
	MDEUII	23	30	0	0	0	0	0
	MDEUIII	0	58	1	0	2	0	0
	MDEUIV	0	0	99	100	26	0	0
	MDEUV	0	0	0	0	57	1	0
	MDEUVI	0	0	0	0	16	100	100
LDT-G	NOC	27	0	0	0	0	0	0
	LFEUI	56	13	0	0	0	0	0
	LFEUII	16	29	0	0	0	0	0
	LFEUIII	0	58	2	0	2	0	0
	LFEUIV	0	0	98	100	28	0	0
	LFEUV	0	0	0	0	56	1	0
	LFEUVI	0	0	0	0	14	99	100
LDB-G	NOC	31	6	0	0	0	0	0
	LFEUI	54	22	1	0	1	0	0
	LFEUII	15	23	4	0	4	0	0
	LFEUIII	0	48	14	0	15	0	0
	LFEUIV	0	0	81	100	35	6	0
	LFEUV	0	0	0	0	36	25	0
	LFEUVI	0	0	0	0	8	70	100
CAR-G	NOC	23	3	0	0	0	0	0
	LFEUI	55	16	0	0	0	0	0
	LFEUII	23	28	3	0	3	0	0
	LFEUIII	0	53	9	0	10	0	0
	LFEUIV	0	0	88	100	30	1	0
	LFEUV	0	0	0	0	44	11	0
	LFEUVI	0	0	0	0	13	87	100

Notes: HDT-D, heavy duty diesel truck; HDB-D, heavy duty diesel bus; LDT-D, light duty diesel truck; LDT-G, light duty gasoline truck; LDB-G, light duty gasoline bus; CAR-G, gasoline car; HDEUI~ HDEUIII, EURO I~III standards on heavy duty diesel road vehicles; MDEUI~ MDEUIII, EURO I~III standards on light duty diesel road vehicles; LFEUI~ LFEUIII, EURO I~III standards on light duty spark ignition road vehicles (4-stroke engines).

(b) Japan

Vehicle	Standard	Base year		BAU[0]/ BAU[1]/ PC[0]/ PC[1]		BAU[2]/ PC[2]	Vehicle	Standard	Base year		BAU[0]/ BAU[1]/ PC[0]/ PC[1]		BAU[2]/ PC[2]
		2005	2010	2020	2030	2030			2005	2010	2020	2030	2030
HDT-D	BST	41%	25%	0%	0%	0%	LDT-G	BST	38%	16%	1%	0%	0%
	ST	27%	19%	1%	0%	0%		ST	4%	2%	0%	0%	0%
	LT	26%	25%	22%	0%	0%		LT	10%	6%	0%	0%	0%
	NST	7%	11%	10%	0%	0%		1998R	14%	10%	6%	0%	0%
	NLT	0%	20%	22%	7%	0%		NST	34%	31%	19%	0%	0%
	PNLT	0%	0%	44%	93%	100%		NLT	0%	34%	24%	8%	0%
HDB-D	BST	52%	32%	0%	0%	0%		PNLT	0%	0%	49%	92%	100%
	ST	19%	15%	2%	0%	0%	LDB-B	BST	12%	4%	0%	0%	0%
	LT	25%	24%	23%	0%	0%		ST	4%	1%	0%	0%	0%
	NST	5%	8%	8%	0%	0%		LT	4%	1%	0%	0%	0%
	NLT	0%	20%	22%	8%	0%		1998R	16%	6%	3%	0%	0%
	PNLT	0%	0%	45%	92%	100%		NST	63%	35%	17%	0%	0%
LDT-D	BST	41%	27%	0%	0%	0%		NLT	0%	52%	27%	10%	0%
	ST	27%	20%	0%	0%	0%		PNLT	0%	0%	53%	90%	100%
	LT	27%	23%	22%	0%	0%	CAR	1983R	72%	32%	8%	0%	0%
	NST	5%	11%	10%	0%	0%		NST	28%	37%	24%	0%	0%
	NLT	0%	20%	23%	7%	0%		NLT	0%	31%	23%	9%	0%
	PNLT	0%	0%	46%	93%	100%		PNLT	0%	0%	46%	91%	100%

Notes: BST, before short term target; ST, short term target; LT, long term target; NST, new-short term target; NLT, new-long term target; PNLT, post new-long term target; 1998R, 1998 regulation; 1983R, 1983 regulation.

(c) South Korea

Vehicle	Standard	Base year		BAU[0]/ BAU[1]/ PC[0]/ PC[1]		BAU[2]/ PC[2]	Vehicle	Standard	Base year		BAU[0]/ BAU[1]/ PC[0]/ PC[1]		BAU[2]/ PC[2]
		2005	2010	2020	2030	2030			2005	2010	2020	2030	2030
HDT-D	NOC	0	0	0	0	0	LDT-G	NOC	0	0	0	0	0
	HDEUI	13	10	0	0	0		LFEUI	15	10	0	0	0
	HDEUII	15	13	0	0	0		LFEUII	33	12	0	0	0
	HDEUIII	35	33	0	0	0		LFEUIII	30	28	0	0	0
	HDEUIV	0	24	10	0	0		LFEUIV	7	38	23	0	0
	HDEUV	0	12	48	0	0		LFEUV	0	10	77	100	0
	HDEUVI	0	0	42	100	100		LFEUVI	0	0	0	0	100
HDB-D	NOC	0	0	0	0	0	LDB-G	NOC	0	0	0	0	0
	HDEUI	13	10	0	0	0		LFEUI	15	10	0	0	0
	HDEUII	15	13	0	0	0		LFEUII	33	12	0	0	0
	HDEUIII	35	33	0	0	0		LFEUIII	30	28	0	0	0
	HDEUIV	0	24	10	0	0		LFEUIV	7	38	23	0	0
	HDEUV	0	12	48	0	0		LFEUV	0	10	77	100	0
	HDEUVI	0	0	42	100	100		LFEUVI	0	0	0	0	100
LDT-D	NOC	0	0	0	0	0	CAR-G	NOC	0	0	0	0	0
	MDEUI	30	10	0	0	0		LFEUI	15	10	0	0	0
	MDEUII	20	17	0	0	0		LFEUII	33	12	0	0	0
	MDEUIII	35	34	0	0	0		LFEUIII	30	28	0	0	0
	MDEUIV	0	27	25	0	0		LFEUIV	7	38	23	0	0
	MDEUV	0	8	35	0	0		LFEUV	0	10	77	100	0
	MDEUVI	0	0	40	100	100		LFEUVI	0	0	0	0	100

Note: South Korea adopted U.S. emission standards for gasoline vehicles, which were equivalent to the penetrations of European standards above in terms of removal efficiencies.

Table 6. Penetrations of major control technologies for NMVOC emissions from selected solvent use types in China.

Solvent use type	Control technology	Base year		BAU[0]/PC[0]		BAU[1]/PC[1]		BAU[2]/PC[2]
		2005	2010	2020	2030	2020	2030	2030
Paint use in interior wall of buildings	No control (GB18582-2001)	100	0	0	0	0	0	0
	Decrease of solvent content--GB18582-2008	0	100	95	90	70	0	0
	Decrease of solvent content--2004/42/EC stage 1	0	0	5	10	30	80	0
	Decrease of solvent content--2004/42/EC stage 2	0	0	0	0	5	20	100
Paint use in external wall of buildings	No control (solvent-based paint)	81.5	78	72.5	68.5	70	50	0
	Substitution with water-based paint	18.5	22	27.5	32.5	30	50	100
Paint use in vehicle manufacturing	No control (water-based primer, solvent-based paint for other parts)	100	97	91	84	35	0	0
	Substitution with water-based paint	0	2	4	6	15	30	0
	Adsorption, incineration	0	1	5	10	40	65	0
	Substitution + adsorption, incineration	0	0	0	0	0	5	100
Paint use in vehicle refinishing	No control (solvent-based paint)	95	92.5	87.5	82.5	80	40	0
	Sustitution with high solids or water-based paint	5	7.5	12.5	17.5	20	60	100
Paint use in wood coating	No control (solvent-based paint)	93.5	89	79	69	50	15	0
	Incineration	0	0	2	4	15	25	20
	Substitution with high solids paint	2	4	8	12	15	25	20
	Substitution with water-based or UV paint	4.5	7	11	15	20	35	60
Offset printing	No control (solvent-based ink)	94	90	85	80	60	15	0
	Substitution with water-based or UV ink	6	10	15	20	20	30	10
	Add-on control technology	0	0	0	0	20	55	90
Flexography and rotogravure printing (for packaging)	No control (solvent-based ink)	70	64	55	45	30	0	0
	Substitution with low solvent or water-based ink	30	35	40	45	40	30	0
	Add-on control technology	0	1	5	10	10	30	0
	Substitution + add-on control technology	0	0	0	0	20	40	100
Flexography and rotogravure printing (for publication)	No control (solvent-based ink)	90	85	80	75	62.5	5	0
	Substitution with low solvent or water-based ink	10	15	20	25	22.5	40	0
	Add-on control technology	0	0	0	0	15	50	0
	Substitution + add-on control technology	0	0	0	0	0	5	100
Screen printing	No control (solvent-based ink)	90	85	80	75	62.5	5	0
	Substitution with low solvent or water-based ink	10	15	20	25	22.5	40	0
	Add-on control technology	0	0	0	0	15	50	0
	Substitution + add-on control technology	0	0	0	0	0	5	100
Adhesive use in wood processing	No control	100	97.5	92.5	87.5	90	60	0
	Add-on control technology	0	2.5	7.5	12.5	10	40	100
Adhesive use in manufacturing of shoes	No control (solvent-based adhesive)	90	87	82.5	80	70	50	10
	Substitution with low solvent adhesive	10	13	17.5	20	30	50	90
	Add-on control technology	0	0	0	0	0	0	0

Table 7. Summary of national energy consumption in East Asia (Unit: EJ/year).

	2005	2010	BAU		PC	
			2020	2030	2020	2030
China, mainland	85.31	121.75	169.41	199.55	144.39	155.01
Power plants	18.87	25.52	37.45	43.93	32.23	36.07
Other conversion	3.11	5.30	5.98	6.49	5.07	4.84
Industry	37.79	58.16	73.64	81.68	62.83	66.51
Residential	18.12	20.79	28.05	32.78	22.96	24.01
Transportation	6.73	11.00	22.91	33.02	20.04	22.11
Loss	0.69	0.98	1.37	1.64	1.26	1.46
Coal	58.01	82.93	106.83	118.80	83.84	80.31
Oil	12.48	18.28	33.36	45.31	28.62	29.68
Gas	1.80	4.19	7.87	10.99	8.40	14.35
Biomass	7.60	7.21	7.35	6.74	6.30	6.21
Other renewables and nuclear	5.43	9.15	14.01	17.71	17.24	24.45
Japan	22.03	21.36	21.78	21.86	20.93	20.09
Power plants	5.59	5.22	5.63	6.07	5.54	5.35
Other conversion	1.62	2.25	2.27	2.21	2.13	1.93
Industry	5.61	5.32	5.62	5.57	5.45	5.30
Residential	5.03	4.86	5.17	5.48	5.02	5.28
Transportation	4.17	3.71	3.10	2.53	2.80	2.23
Coal	4.23	4.79	4.73	4.47	4.46	2.45
Oil	9.97	8.47	7.45	6.70	6.78	5.84
Gas	3.79	4.33	4.92	5.12	4.43	4.46
Biomass	0.29	0.30	0.42	0.54	0.50	0.68
Other renewables and nuclear	3.76	3.50	4.30	5.07	4.82	6.68
South Korea	8.90	10.59	12.33	13.31	11.81	12.22
Power plants	2.33	2.85	3.52	4.00	3.40	3.65
Other conversion	0.48	0.98	1.03	1.03	0.95	0.89
Industry	3.01	3.58	3.99	4.17	3.87	3.95
Residential	1.71	1.83	2.19	2.40	2.11	2.25
Transportation	1.37	1.34	1.61	1.70	1.48	1.49
Coal	2.05	3.17	3.22	3.31	3.00	1.75
Oil	3.90	4.10	4.43	4.45	4.26	4.16
Gas	1.23	1.59	2.16	2.29	1.93	2.13
Biomass	0.09	0.13	0.19	0.28	0.22	0.37
Other renewables and nuclear	1.62	1.64	2.37	3.02	2.49	3.91
North Korea	1.42	1.55	1.95	2.51	1.90	1.96
Mongolia	0.12	0.09	0.08	0.08	0.06	0.04
Hong Kong & Macao, China	0.76	0.93	1.30	1.39	1.16	1.08
Taiwan, China	4.43	4.24	4.27	4.43	3.94	4.16
Total	122.97	160.51	211.12	243.13	184.20	194.57
Total (except mainland China)	37.66	38.75	41.70	43.59	39.80	39.56

Table 8. Summary of national air pollutant emissions in East Asia (Unit: Mt/year).

	Base year		BAU[0]		BAU[1]		BAU[2]	PC[0]		PC[1]		PC[2]
	2005	2010	2020	2030	2020	2030	2030	2020	2030	2020	2030	2030
NO_X												
China, mainland	19.48	26.05	31.69	35.35	19.18	15.82	9.85	26.32	25.16	15.95	11.47	7.18
Japan	2.050	1.616	1.033	0.860	1.033	0.860	0.461	0.954	0.727	0.954	0.727	0.392
South Korea	1.112	1.055	0.809	0.697	0.809	0.697	0.245	0.778	0.575	0.778	0.575	0.210
North Korea	0.276	0.284	0.345	0.481	0.345	0.481	0.086	0.342	0.375	0.342	0.375	0.067
Mongolia	0.064	0.058	0.055	0.057	0.055	0.057	0.041	0.052	0.047	0.052	0.047	0.034
Hong Kong & Macao, China	0.199	0.230	0.229	0.260	0.229	0.260	0.039	0.208	0.218	0.208	0.218	0.033
Taiwan, China	0.551	0.440	0.348	0.342	0.348	0.342	0.091	0.316	0.287	0.316	0.287	0.076
Total	23.73	29.74	34.51	38.05	21.99	18.51	10.81	28.97	27.39	18.60	13.70	8.00
Total except mainland China	4.252	3.682	2.819	2.697	2.819	2.697	0.963	2.649	2.229	2.649	2.229	0.813
SO_2												
China, mainland	28.70	24.42	29.07	30.68	20.59	18.23	13.32	22.24	19.49	15.69	11.55	8.34
Japan	0.705	0.562	0.520	0.518	0.520	0.518	0.294	0.507	0.470	0.507	0.470	0.268
South Korea	0.410	0.400	0.408	0.358	0.408	0.358	0.162	0.384	0.301	0.384	0.301	0.141
North Korea	0.268	0.297	0.368	0.471	0.368	0.471	0.099	0.363	0.333	0.363	0.333	0.070
Mongolia	0.087	0.073	0.065	0.073	0.065	0.073	0.011	0.054	0.036	0.054	0.036	0.005
Hong Kong & Macao, China	0.022	0.016	0.019	0.021	0.019	0.021	0.007	0.017	0.016	0.017	0.016	0.006
Taiwan, China	0.244	0.139	0.115	0.119	0.115	0.119	0.026	0.104	0.122	0.104	0.122	0.026
Total	30.44	25.91	30.57	32.24	22.08	19.78	13.92	23.67	20.77	17.12	12.83	8.85
Total except mainland China	1.735	1.486	1.496	1.559	1.496	1.559	0.599	1.431	1.278	1.431	1.278	0.516
PM_{10}												
China, mainland	18.61	15.81	16.24	15.26	13.24	10.53	5.55	13.13	11.15	10.76	7.52	4.17
Japan	0.206	0.167	0.137	0.125	0.137	0.125	0.087	0.131	0.111	0.131	0.111	0.078
South Korea	0.093	0.116	0.115	0.117	0.115	0.117	0.062	0.112	0.111	0.112	0.111	0.059
North Korea	0.596	0.558	0.557	0.599	0.557	0.599	0.134	0.477	0.444	0.477	0.444	0.099
Mongolia	0.053	0.040	0.034	0.035	0.034	0.035	0.008	0.029	0.019	0.029	0.019	0.004
Hong Kong & Macao, China	0.039	0.043	0.049	0.046	0.049	0.046	0.012	0.043	0.033	0.043	0.033	0.009
Taiwan, China	0.095	0.085	0.078	0.081	0.078	0.081	0.035	0.072	0.066	0.072	0.066	0.029
Total	19.69	16.81	17.21	16.26	14.21	11.53	5.88	13.99	11.94	11.62	8.31	4.45
Total except mainland China	1.082	1.007	0.970	1.002	0.970	1.002	0.338	0.864	0.784	0.864	0.784	0.277
$PM_{2.5}$												
China, mainland	13.34	11.79	11.74	10.87	9.61	7.29	3.41	9.43	7.73	7.71	5.03	2.50
Japan	0.142	0.102	0.084	0.077	0.084	0.077	0.051	0.077	0.064	0.077	0.064	0.044
South Korea	0.071	0.085	0.082	0.083	0.082	0.083	0.051	0.080	0.079	0.080	0.079	0.048
North Korea	0.407	0.383	0.401	0.426	0.401	0.426	0.101	0.349	0.329	0.349	0.329	0.078
Mongolia	0.025	0.019	0.016	0.016	0.016	0.016	0.004	0.014	0.010	0.014	0.010	0.002
Hong Kong & Macao, China	0.023	0.024	0.026	0.027	0.026	0.027	0.006	0.023	0.022	0.023	0.022	0.005
Taiwan, China	0.057	0.049	0.045	0.047	0.045	0.047	0.019	0.041	0.038	0.041	0.038	0.016
Total	14.07	12.45	12.39	11.55	10.27	7.97	3.64	10.01	8.27	8.29	5.57	2.69
Total except mainland China	0.724	0.662	0.653	0.676	0.653	0.676	0.231	0.584	0.542	0.584	0.542	0.193
NMVOC												
China, mainland	18.89	22.86	26.29	28.97	22.90	20.46	12.62	23.70	24.30	20.53	16.80	10.37
Japan	1.755	1.223	1.218	1.268	1.218	1.268	0.297	1.217	1.262	1.217	1.262	0.291
South Korea	0.756	0.866	0.875	0.943	0.875	0.943	0.286	0.743	0.794	0.743	0.794	0.253
North Korea	0.401	0.389	0.463	0.577	0.463	0.577	0.081	0.423	0.481	0.423	0.481	0.068
Mongolia	0.022	0.020	0.019	0.019	0.019	0.019	0.004	0.017	0.016	0.017	0.016	0.004
Hong Kong & Macao, China	0.123	0.138	0.160	0.178	0.160	0.178	0.146	0.156	0.170	0.156	0.170	0.140
Taiwan, China	0.599	0.402	0.243	0.203	0.243	0.203	0.166	0.223	0.180	0.223	0.180	0.147
Total	22.55	25.90	29.27	32.16	25.88	23.64	13.60	26.48	27.20	23.31	19.70	11.27
Total except mainland China	3.657	3.039	2.977	3.188	2.977	3.188	0.980	2.780	2.902	2.780	2.902	0.901

(a)

Type	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Light duty vehicle	1	1	1	1	1	2	2	2	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Heavy duty diesel vehicle		1	1	1	2	2	2	3	3	3	3	3	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Heavy duty gasoline vehicle				1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Motorcycle (2&4 strokes)				1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Rural Vehicle							1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Tractors, machines									1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Train, inland water																															

(b)

Type	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Light duty vehicle	1	1	1	1	1	2	2	2	3	3	3	4	4	4	4	4	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6
Heavy duty diesel vehicle		1	1	1	2	2	2	3	3	3	3	3	3	4	4	4	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6
Heavy duty gasoline vehicle				1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Motorcycle (2&4 strokes)				1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Rural Vehicle							1	2	2	2	2	2	2	3	3	3	3	4	4	4	5	5	5	6	6	6	6	6	6	6	6
Tractors, machines									1	1	2	2	2	2	3A	3A	3A	3A	3B	3B	3B	4	4	4	4	4	4	4	4	4	4
Train, inland water															3A	3A	3A	3A	3B	3B	3B	4	4	4	4	4	4	4	4	4	4

Figure 1. The implementation time of the vehicle emission standards in China: (a) the BAU[0] and PC[0] scenarios; (b) the BAU[1], PC[1], BAU[2], and PC[2] scenarios. The Arabic numbers 1-6 represent Euro I to Euro VI vehicle emission standards. Numbers in black represent standards released by the end of 2010, and those in red represent those to be released in the future.

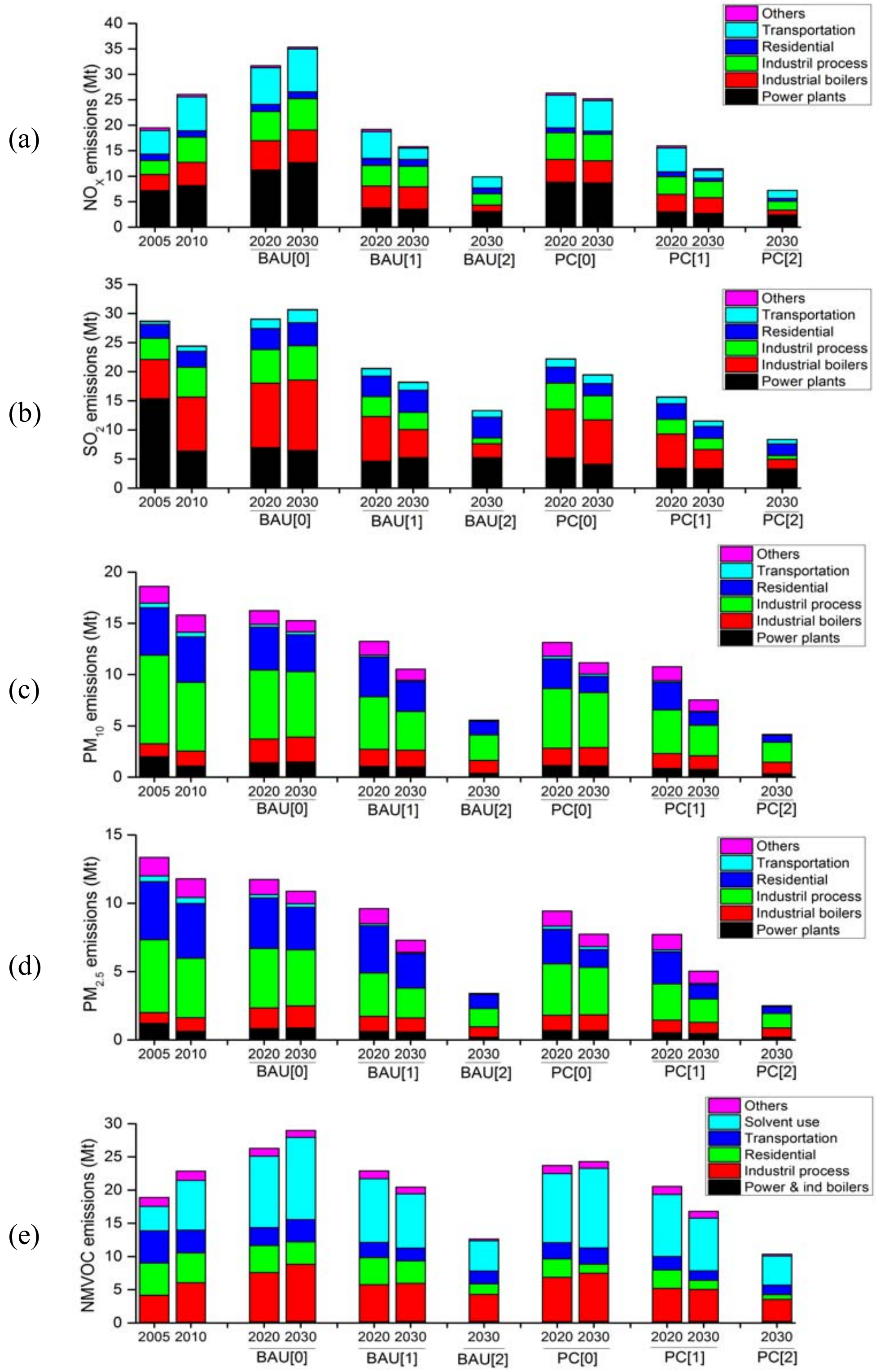


Figure 2. Emissions of major air pollutants in China and their sectoral distribution during 2005-2030: (a) NO_X; (b) SO_2; (c) PM_{10}; (d) $PM_{2.5}$; (e) NMVOC. The sector of "Others" represents biomass open burning for NO_X, SO_2, PM_{10}, and $PM_{2.5}$; for NMVOC, it includes biomass open burning, waste treatment, cooking, and smoking, with biomass open burning contributing over 80% of the total NMVOC emissions of this sector.

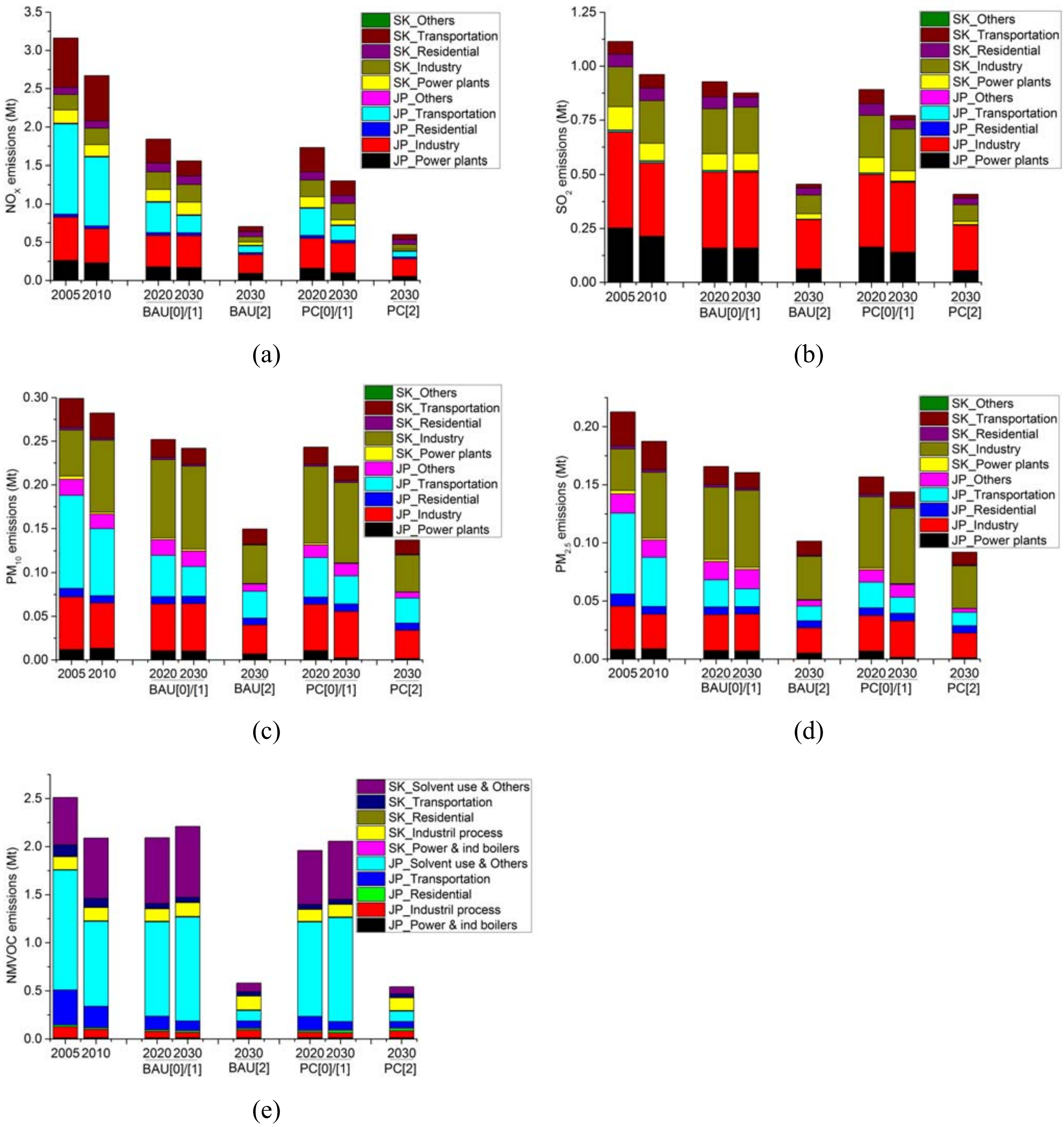
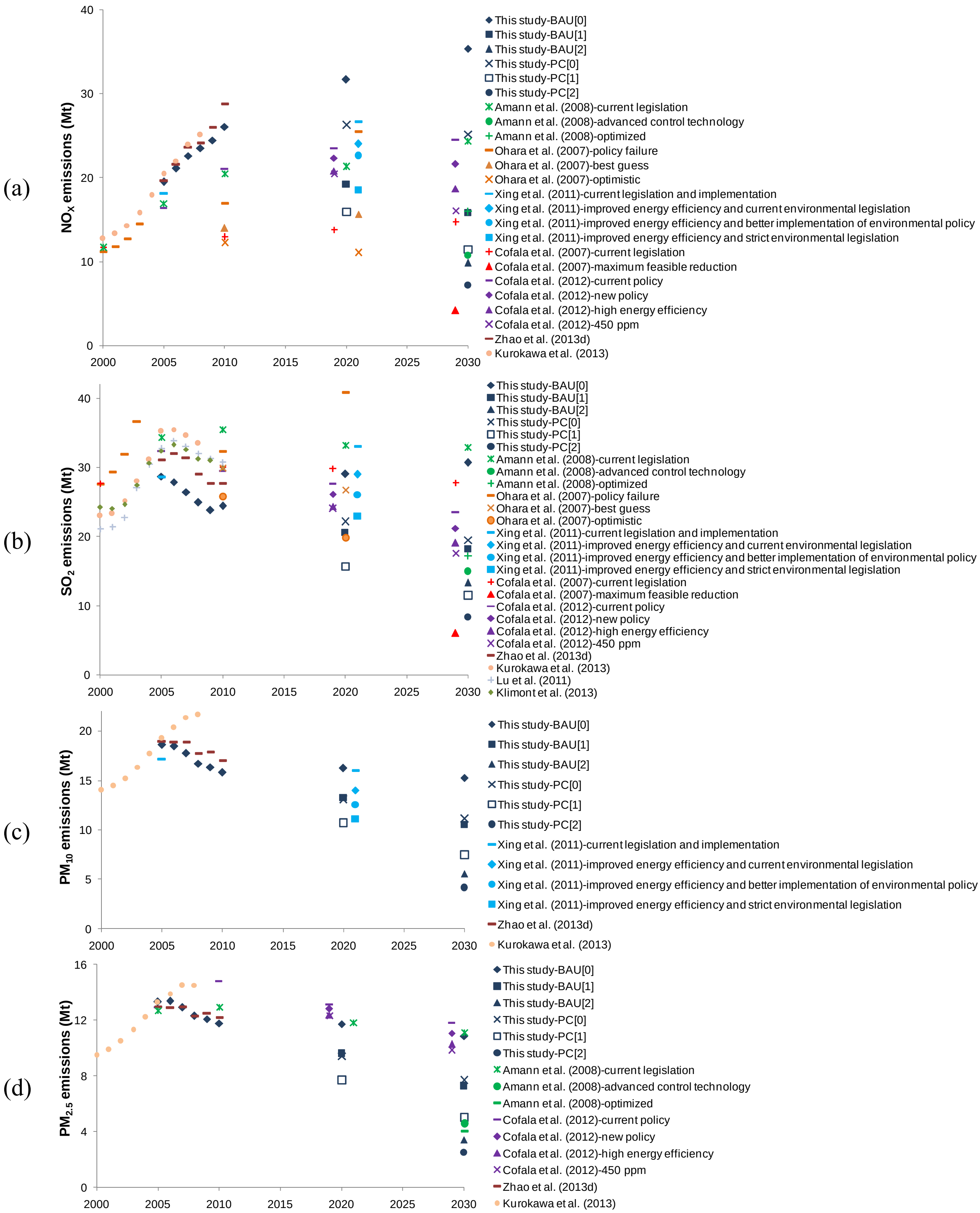


Figure 3. Emissions of major air pollutants in Japan and South Korea and their sectoral distributions during 2005-2030: (a) NO_X; (b) SO_2; (c) PM_{10}; (d) $PM_{2.5}$; (e) NMVOC. JP and SK in the legend represent Japan and South Korea, respectively. The sector of "Others" is mainly biomass open burning.


(a)
NOx emissions (Mt)
0
10
20
30
40
2000
2005
2010
2015
2020
2025
2030
This study-BAU[0]
This study-BAU[1]
This study-BAU[2]
This study-PC[0]
This study-PC[1]
This study-PC[2]
Amann et al. (2008)-current legislation
Amann et al. (2008)-advanced control technology
Amann et al. (2008)-optimized
Ohara et al. (2007)-policy failure
Ohara et al. (2007)-best guess
Ohara et al. (2007)-optimistic
Xing et al. (2011)-current legislation and implementation
Xing et al. (2011)-improved energy efficiency and current environmental legislation
Xing et al. (2011)-improved energy efficiency and better implementation of environmental policy
Xing et al. (2011)-improved energy efficiency and strict environmental legislation
Cofala et al. (2007)-current legislation
Cofala et al. (2007)-maximum feasible reduction
Cofala et al. (2012)-current policy
Cofala et al. (2012)-new policy
Cofala et al. (2012)-high energy efficiency
Cofala et al. (2012)-450 ppm
Zhao et al. (2013d)
Kurokawa et al. (2013)
(b)
SO2 emissions (Mt)
0
10
20
30
40
2000
2005
2010
2015
2020
2025
2030
This study-BAU[0]
This study-BAU[1]
This study-BAU[2]
This study-PC[0]
This study-PC[1]
This study-PC[2]
Amann et al. (2008)-current legislation
Amann et al. (2008)-advanced control technology
Amann et al. (2008)-optimized
Ohara et al. (2007)-policy failure
Ohara et al. (2007)-best guess
Ohara et al. (2007)-optimistic
Xing et al. (2011)-current legislation and implementation
Xing et al. (2011)-improved energy efficiency and current environmental legislation
Xing et al. (2011)-improved energy efficiency and better implementation of environmental policy
Xing et al. (2011)-improved energy efficiency and strict environmental legislation
Cofala et al. (2007)-current legislation
Cofala et al. (2007)-maximum feasible reduction
Cofala et al. (2012)-current policy
Cofala et al. (2012)-new policy
Cofala et al. (2012)-high energy efficiency
Cofala et al. (2012)-450 ppm
Zhao et al. (2013d)
Kurokawa et al. (2013)
Lu et al. (2011)
Klimont et al. (2013)
(c)
PM10 emissions (Mt)
0
5
10
15
20
2000
2005
2010
2015
2020
2025
2030
This study-BAU[0]
This study-BAU[1]
This study-BAU[2]
This study-PC[0]
This study-PC[1]
This study-PC[2]
Xing et al. (2011)-current legislation and implementation
Xing et al. (2011)-improved energy efficiency and current environmental legislation
Xing et al. (2011)-improved energy efficiency and better implementation of environmental policy
Xing et al. (2011)-improved energy efficiency and strict environmental legislation
Zhao et al. (2013d)
Kurokawa et al. (2013)
(d)
PM2.5 emissions (Mt)
0
4
8
12
16
2000
2005
2010
2015
2020
2025
2030
This study-BAU[0]
This study-BAU[1]
This study-BAU[2]
This study-PC[0]
This study-PC[1]
This study-PC[2]
Amann et al. (2008)-current legislation
Amann et al. (2008)-advanced control technology
Amann et al. (2008)-optimized
Cofala et al. (2012)-current policy
Cofala et al. (2012)-new policy
Cofala et al. (2012)-high energy efficiency
Cofala et al. (2012)-450 ppm
Zhao et al. (2013d)
Kurokawa et al. (2013)

(e)

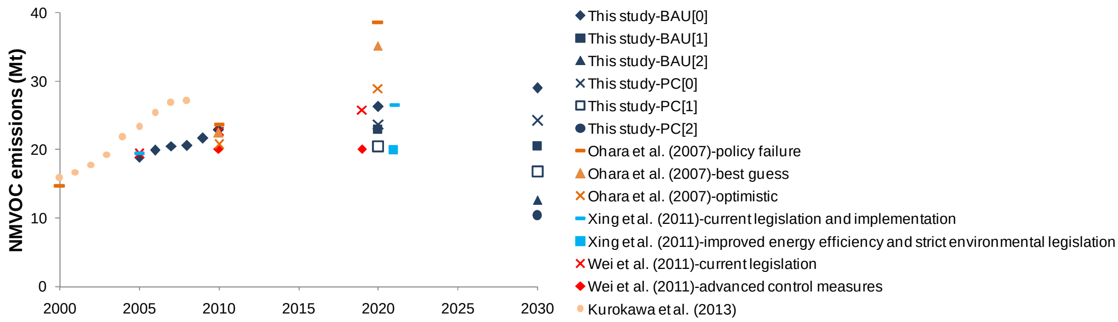


Figure 4. Comparison of estimated emissions in this study with those of other studies: (a) NO_X; (b) SO_2; (c) PM_{10}; (d) $PM_{2.5}$; (e) NMVOC. The scenarios from the same study are shown with symbols of the same colour, and since their historical emissions duplicate each other, we show just the historical values of one scenario. Some points for the years 2020 and 2030 are shifted a little left or right, in order to avoid overlapping representation. Note that the current legislation scenario in Amann et al. (2008) is consistent with the baseline scenario in Klimont et al. (2009), and the historical emission trends of Zhao et al. (2013a) is consistent with this study. Therefore, Klimont et al. (2009) and Zhao et al. (2013a) are not shown in the figures.

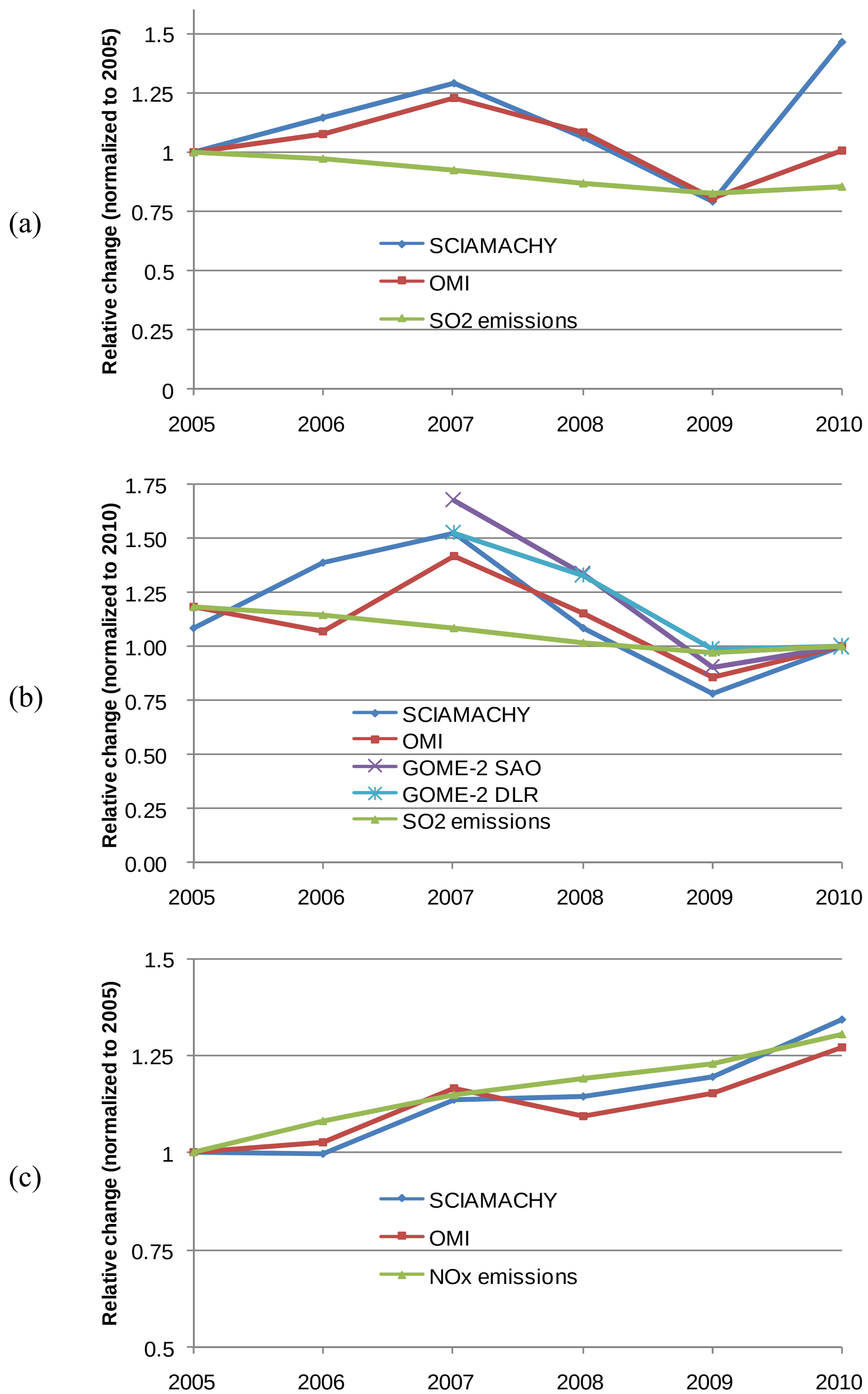


Figure 5. Inter-annual relative changes of SO_2 and NO_2 VCD from satellite observations and estimated emissions in this study. (a) Average SO_2 VCD and total SO_2 emissions in Eastern Central China (latitude <45ºN, longitude >100ºE). SO_2 VCD was derived by Lu et al. (2011). All data are normalized to 2005. (b) Average SO_2 VCD and total SO_2 emissions over an area of Eastern China (34°N–38°N, 112°E–118°E). SO_2 VCD was derived by Fioletov et al. (2013), in which a filtering procedure was applied to remove local biases, in particular volcanic signals. All data are normalized to 2010 because the data of GOME-2 are only available since 2007. (c) Average NO_2 VCD and total NO_X emissions in Eastern Central China. NO_2 VCD was retrieved from OMI and SCIAMACHY in this study. All data are normalized to 2005.