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Emission trends and mitigation options for air pollutants in East Asia

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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 matters (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 11 %, respectively, mainly attributable to the large scale deployment of FGD for China's power plants, and the promotion of high-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 the rapid increase in the emissions from China owing 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 tight vehicle emission standards in Japan and South Korea. Under current legislation and current implementation status, 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 the "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 for SO_2, $PM_{2.5}$, and NMVOC. With the full implementation of maximum feasible reduction measures, the emissions of NO_x, SO_2, and $PM_{2.5}$ in East Asia are expected to 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 reduction in NO_x and SO_2 emissions by considering aggressive govermental 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) reports that East Asia contribute 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 and Europe. Moreover, both emission calculation and satellite observations indicate that NO_x emissions in China have experienced rapid increase during 1995–2010, with annual average growth rate ranging between 5.5–7 % (Zhao et al., 2013c; Zhang et al., 2007, 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 global air quality and climate 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 global warming mitigation, 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 are stringent and have been rapidly upgraded. During 2006–2010, China set a target to reduce the energy use per unit Gross Domestic Production (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 aims at further 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 toward the committed targets in Kyoto Protocol, which requires 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 continuously in the past decade. A number of researches have studied the recent emission trends in East Asia (or 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 estimation (Lu et al., 2010, 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 matters (PM) (Lin et al., 2010a; Lu et al., 2011). Kurokawa et al. (2013) and Zhao et al. (2013a, d) 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, 2009; Cofala et al., 2007, 2012; Ohara et al., 2007; Xing et al., 2011; Zhao et al., 2013c). However, most of these projections were based on the emissions for the year 2005 or earlier and did not consider the dramatic recent changes. Latest projections include Cofala et al. (2012) and Zhao et al. (2013c). Cofala et al. (2012), one of the latest projections, 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 the 2010 emission inventory, and quantified the effects of various control policies, but did not include the analysis of other air pollutants.

Although there have been a number of studies on recent and future emission trends in East Asia, they are proved inadequate when serving for the development of broadly effective air quality and climate policies. Firstly, future control measures must be developed by taking full account into the latest policies. Hence a comprehensive review of recent mitigation measures in the entire region is important but has not been presented. As described above, most projections were based on the emissions for the year 2005 or earlier, and underestimated China's economic growth experienced in the last decade, especially during the period from 2006 to 2010. Besides, these early projections did not anticipate new emission control policies envisaged in China's 12th Five Year Plan published in 2011 (for the period of 2011–2015; The State Council of the People's Republic of China, 2011) and the rapidly emerging emission stardards released after 2010, which may fundamentally change the future emission pathway. The most recent projections based on up-to-date emissions (Cofala et al., 2012; Zhao et al., 2013c) incorporate only a specific pollutant or a specific set of control measures, which could not provide full insight into the future trends of major air pollutants. Secondly, the attainment of stringent ambient air quality standard (e.g. China's standard of 35 $\mu g\,m^{-3}$ for annual average $PM_{2.5}$ concentration, released in 2012) requires simultaneous reduction of multiple pollutants including SO_2, NO_x, $PM_{2.5}$, and non-methane volatile organic compounds (NMVOC) to a large extent (Wang and Hao, 2012). Therefore, it is essential that a full range of relevant pollutants is considered, and scenarios at different stringency levels from the business-as-usual case to the maximum feasible reduction case are developed, so that cost-effective emission controls can balance measures over all pollutants and over a wide range of stringency levels. Thirdly, most studies focused on either end-of-pipe control measures, or energy saving measures; their roles in integrated control policies tackling multiple pollutants and global warming simultaneously have been insufficiently studied. Considering the above, a comprehensive projection of multiple pollutants' emissions incorporating up-to-date base-year data, control measures scheduled to be implemented, 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, but has not been presented in the previous studies.

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 model performance and uncertainties in Asia.

In Sect. 2, we reviewed major control policies in East Asia in the last decade, and evaluated the impact of control measures on air pollutant emissions during 2005–2010. Compared with previous studies on emission trends, we are particularly devoted to presenting a comprehensive review of the recent mitigation measures in this region, and illuminate the driving forces underlying the emission trends. In Sect. 3, we projected future emissions of SO_2, NO_x, NMVOC, and PM up to 2030 for six emission scenarios, considering both energy-saving and end-of-pipe measures. Eventually, in Sect. 4, we compared our results with the previously developed projections. 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 China, Japan, and South Korea which are key energy consumers in the region and dominate the emissions of air pollutants. With respect to air pollution policy, Japan and Korea have the longest tradition while China's emission regulation has been emerging in the last decade at an impressive rate and has very ambitious future goals. Therefore, special attention is given to the developments in China.

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 of 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 e.g., dust collector and flue gas desulfurization installations. A smart mix of measures to simultaneously address energy conservation, air pollution 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 needs to reduce 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, 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). Chinese government has set a target to reduce CO_2 emissions per unit GDP by 40–45 % in 2020 compared with the 2005 levels (Wang and Hao, 2012). Total energy consumption in East Asia increased by 31 % during 2005–2010. China experienced the fastest increase of 43 % driven by rapid GDP growth rate, while Japan's energy consumption decreased during the five years because of lower GDP growth rate and stringent energy saving policies. The growth rate of South Korea is medium (19 %).

2.1.1 Power plants

The energy consumption in China's power sector increased remarkably by 35 % during 2005–2010 due to rapid increase in the demand of 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 comes from coal (Zhao et al., 2013c). In contrast, installed power generation capacity in Japan was well diversified, with coal, oil, natural gas, nuclear and hydro contributing about 27 %, 8 %, 27 %, 26 %, and 8 % of the total electricity generation in 2010, respectively (http://www.iea.org/statistics/). In South Korea, fossil fuels accounted for 65.7 % of the total electricity generated, followed by nuclear at 32.5 % (IEA, 2012c). Nuclear power plants have been playing a crucial role in Japan and South Korea's low-carbon policies. However, in 2011, the share of nuclear power generation in Japan dropped dramatically to less than 10 %, owing to the Fukushima nuclear power plant accident on 11 March 2011 (http://www.iea.org/statistics/). This made the future of nuclear power in Japan quite uncertain. In South Korea, nuclear power generation is expected to keep increasing in the next decade, as five reactors are under construction and six more have been announced (IEA, 2012b). Considering the coal-intensive power generation mix, Chinese government has also been promoting the development of clean energy power through subsidy policies. By 2010, the capacities of hydro power, natural gas power, wind power, and solar power have increased dramatically to 1.82, 2.25, 23.8, and 3.43 times those of 2005, respectively (China Electric Power Yearbook Committee, 2006, 2011).

China has also made efforts to improve the efficient coal-fired power generation units. Chinese government has shut down 77 GW of small coal-fired units during 2006–2010 (NDRC, 2011), and this program will be extended to phase out an additional 20 GW of small units during 2011–2015 (The State Council of the People's Republic of China, 2012). At the same time, most new units built after 2005 were ≥ 300 MW. As a result, the capacity share of units ≥ 300 MW rose from 50 % in 2005 to 73 % in 2010 (The State Council of the People's Republic of China, 2012), and share of advanced supercritical and ultra-supercritical units rose to over 13 % (Li et al., 2012). In effect, the coal consumption per unit electricity supplied decreased from 370 gce kWh^{-1} to 333 gce kWh^{-1} during the same period (The State Council of the People's Republic of China, 2012).

2.1.2 Industrial sector

During 2005–2010, China's energy consumption of 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, with the target to reduce energy intensity per GDP by 20 % during 2005–2010, China put much effort to replace out-of-date production technologies with more energy-efficient ones. For example, the penetration of precalcined cement kilns increased from 45 % in 2005 to about 80 % in 2010. During the same period, the proportion of large units ($\geq 4000\,\mathrm{t\,d^{-1}}$) in all precalcined kilns increased from 33 % to 60 % (Zhao et al., 2013c; Zhao et al., 2013d). The share of coke produced in machinery coking ovens (vs. indigenous ovens) increased from 82 % in 2005 to 87 % in 2010 (NBS, 2007, 2011; Huo et al., 2012); the share of blast furnace larger than $1000\,\mathrm{m^3}$ increased from 48 % to 61 % during 2005–2010 (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 during the five years (The State Council of the People's Republic of China, 2012).

Contrasted by the swift increase of China, Japan's industrial sector has played a central role in energy conservation in the past decades (IEA, 2008). Major policies include compulsory submission of energy saving plans for large energy consumers, frequent on-site inspection, 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 production of cement and crude steel by 6.3 % and 5.6 % respectively (Wang, 2010). Japan's industrial energy use as a proportion of the total has declined from 26 % in 2000 to 18 % in 2010 (IEA, 2002, 2012c), and the share of coal and petroleum products has decreased from 64 % to 56 % during 2000–2010 (IEA, 2002, 2012c).

The industrial energy consumption in South Korea has been increasing steadily in the last decade since its energy intensity of GDP was not notably improved from the 1990s to 2006 (IEA, 2006). In 2008, South Korea set a new target for energy intensity in the Strategy for Green Growth (from 0.328 toe/1000 USD in 2007 to 0.290 toe/1000 USD in 2013, and 0.233 toe/1000 USD in 2020). These policies are expected to be enforced mainly through "voluntary agreement" between the government and large companies (IEA, 2006, 2012b; UNEP, 2010).

2.1.3 Residential sector

The residential energy consumption in China and South Korea has been increasing steadily during 2005–2010, driven by the increase in 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 stable demand for buildings and aggressive energy saving policies (IEA, 2008; http://www.iea.org/statistics/).

By the end of 2006, 96 % of China's newly-built buildings have complied with the energy saving standard for the design of buildings released in 1996 (THUBERC, 2009). A more stringent standard was released in 2010 (The State Council of the People's Republic of China, 2012). Japan's energy efficiency standards in the building codes, first released in 1980 and strengthened in 1992 and 1999, were all voluntary. As of 2005, 30 % of newly-built houses and 85 % of buildings larger than 2 000 m^2 complied with the voluntary standards (IEA, 2008). In Korea, the building energy codes have been at a relatively low level for a long time, until a performance based strong building design code applied to large commercial buildings in 2011 (IEA, 2006, 2012b).

Japan is a world leader for the energy efficiencies of appliances in residential and commercial buildings. "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 % (1997–2004) and 55 % (1998–2004), both exceeding the targets of 66 % and 31 % (IEA, 2008; Energy Conservation Center of Japan, 2011). Similar programs have been promoted in South Korea and China recently (UNEP, 2010).

Due to the coal-intensive energy structure, China has been promoting clean energy in residential sector. Direct combustion of biomass 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 and ownership of solar water heater both doubled during 2005–2010 owing to subsidy policies.

2.1.4 Transportation sector

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

The decline in Japan's vehicle energy consumption is largely due to its fuel efficiency standards, which are among the most aggressive ones in the world. For passenger vehicles, there has been a consistent improvement in the average fuel economy from 13.5 km L^{-1} in 2000 to 17.8 km L^{-1} in 2009 (Energy Conservation Center of Japan, 2011). Japan was the first country in the world implementing fuel efficiency standards for heavy-duty vehicles. The fuel efficiency of freight vehicles 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. During 2005–2010, the fuel efficiency of new gasoline passenger cars increased from 11.0 km L^{-1} to 13.5 km L^{-1} (Zhao et al., 2013c). An updated standard (14.3 km L^{-1} by 2015) for passenger cars was issued in 2011. In 2006, South Korean government introduced its first mandatory fuel economy standards requiring car manufacturers to meet average fuel economy standards of 12.4 km L^{-1} for vehicles with engines of less than 1500 cubic centimeters (IEA, 2006). In July 2009, a new fuel economy standard of 17 km L^{-1} was announced (IEA, 2012b).

Korea has been systematically promoting compressed natural gas (CNG) buses since 2000. As of 2008, 19 thousand intra-city buses and 429 garbage trucks have utilized CNG. 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

Power plants, due to their relatively large scale, are usually subject to the most stringent control measures. The penetrations of major control technologies in the power sector of China, Japan, and South Korea are summarized in Table 2.

In 2006, China set targets to reduce the national SO_2 emissions by 10 % by 2010 (Wang and Hao, 2012). By the year 2010, over 83 % of coal-fired power plants (about 88 % of pulverized coal combustion plants) or up to 560 gigawatts (GW) installed flue gas desulfurization (FGD) (MEP, 2011). The recently released 12th Five-Year Plan aims at another 8 % reduction in total SO_2 emissions, which requires nearly all coal-fired power plants to be equipped with high efficiency FGD facilities (95 % removal efficiency).

Low NO_x combustion technology (mainly Low NO_x Burner, 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 Selective Non-Catalytic Reduction, SNCR) was only 1.1 % in 2005 and 12.8 % in 2010 (MEP, 2011). In the 12th Five-Year Plan, Chinese government aims to reduce the national 2010 NO_x emissions by 10 % by the year 2015, and the key measures to fulfill this target is large scale deployment of SCR/SNCR facilities. The NO_x emission control policies are described in more details in our previous paper (Zhao et al., 2013c).

The emission control of particulate matter in China's power sector has achieved noticeable progress in the last decade. Since 2003, all new and rebuilt units have to attain the PM in-stack concentration standard of 50 $\mathrm{mg\,m^{-3}}$ (GB13223-2003). As a result, over 92 % of pulverized coal units installed electrostatic precipitators (ESP) by 2005. In addition, fabric filters (FF) have been put into commercial use in the past five years, and its penetration increased to 7 % by 2010 (Zhao et al., 2013a). Furthermore, the rapid deployment of wet-FGD also helped to reduce PM emissions owing to its ancillary benefit on PM removal (Zhao et al., 2010). In 2011, China's Ministry of Environmental

Protection (MEP) announced a PM in-stack concentration standard 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 deduster (HED, e.g., FF, and electrostatic-fabric integrated precipitator) are all as high as 90–100 %, and increased slightly during 2005–2010 (Klimont et al., 2009).

In South Korea, FGD systems have been installed for 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 have been equipped with HED by 2010, and the rest was equipped with ESP (NIER, 2010, 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, respectively.

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 for small number of coal-fired boilers and sintering plants in selected regions. The application of NO_x control technologies is described in more details 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. However, the emission standards for industrial sources have been updated slowly before 2010 (see details in Lei et al., 2011). The 11th Five-Year Plan requested to promote high efficiency FF in some high-emission industries. Most industrial boilers were historically equipped with wet scrubbers (WET) and cyclone dust collectors (CYC), while high efficiency FF began to penetrate recently (Lei et al., 2011; Zhao et al., 2013a). The blast furnaces in China are usually equipped with washing tower and double venturi, which have approximately the same removal efficiency as the combination of ESP and WET. ESP and FF have gradually become the major control technologies for cement plants, sintering plants and basic oxygen furnace by 2010, while large numbers of electric arc furnace 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 requires: (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 vapor balancing system between a vehicle and service station tank (Stage II control); (3) installation of internal floating covers (IFC) or secondary seals for new-built or retrofitted storage tanks. These standards were scheduled to be implemented in relatively large cities of "key regions" from 2008–2010 onwards, and in relatively large cities in other provinces from 2012–2015 onwards. We estimated vapor recycling systems have been installed for about 15 % of all the 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 changed very slightly since 1995, but they are still among the most stringent in the world (Ministry of the Environment of Japan, 2013). Under the strict regulations, the vast majority of blast furnace, basic oxygen furnace, electric arc furnace, and cement kilns are controlled with HED. The control measures portfolio for industrial boilers, sintering plants, glass production, and coke oven is a mix of ESP and HED. Effective SO_2 removal technologies (70–80 % removal efficiency) are applied for various industries, including sintering, cement production, coke oven, sulfuric acid production, etc (Gains-Asia model of the International Institute for Applied System Analysis, IIASA, http://gains.iiasa.ac.at/models/). The average efficiency of the removal equipment kept increasing slowly as old facilities retired. Dominant control measures for NO_x emissions are low NO_x combustion technologies by 2010. Flue gas denitrification facilities are not wide-spread owing to relatively high cost.

Emission standards for industrial sources in South Korea are generally less stringent than those of Japan and more stringent than those of China (Ministry of Environment of South Korea, 2013). In contrast with Japan, the control measure portfolio for cement kilns is an equal mix of ESP and HED; ESPs still dominated the PM removal technologies for industrial boilers and sintering machines, and HEDs have not been widely applied. FGD system was widely applied for some high-emitting sources like industrial boilers and sintering plants, while penetrations of 85 % and 100 % respectively by 2010 (NIER, 2010, 2013). Similar to Japan, dominant control measures for NO_x emissions are low NO_x combustion technologies by 2010.

2.2.3 Residential sector

There are only limited legislations addressing residential sources. In Japan, about half of residential and commercial boilers are equipped with HED, driven by the stringent regulation 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 regulation (released in 2000) with the purpose of mitigating dioxin pollution (Ministry of the Environment of Japan, 2013; Wakamatsu et al., 2013). Previous research found briquette stoves have lower emission factors for SO_2 and PM (Lei et al., 2011). We estimate briquette 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 could be further reduced by switching to a newer type of installation, e.g., installing a catalyst or non-catalyst insert, using primary and secondary air deflectors, etc. Such kinds of improved stoves have been gradually spreading 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 European Union Standards since 2000; the implementation time and penetrations of major emission standards is shown in Fig. 1 and Table 6. At 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 were implemented in 2011. Euro IV standard for heavy duty diesel vehicles was first planned to be implemented in 2010. However, it 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 yr ahead of the national legislation. Recently, Beijing EPB announced to enforce Euro V in 2012 and Euro VI in 2016. Except for the emission regulations for new vehicles, emission reductions are also achieved through control of in-use vehicles 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 emission standards of Japan have been continuously strengthened. For light duty vehicles, the prevailing emission standard for NO_x and NMVOC during 2005–2010 (New Long-term Regulation) was comparable to that in US (Tier II), and more stringent than that of European Union (Euro IV) before Euro V took into effect since the second half of 2009. The latest "Post-New Long-term Regulation" released in 2009 added a limit for PM comparable to US Tier II, while the limits for other pollutants remained the same as the "New Long-term Regulation". For heavy duty vehicles, Japan's NO_x emission regulations before 2005 had been stricter than in Europe and the United States (Japan Automobile Manufacturers Association, 2011). During 2005–2010, Japan's prevailing standard (New Long-term Regulation) is comparable to Euro V (issued in 2008), and between the 2004 and 2007 standards in US. By the early 2010s, European, US and Japanese regulatory values 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 the vehicle emission standards to the level of advanced countries. In December 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. These standards took into effects 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). Penetrations of vehicle emission standards in Japan and South Korea are given in Table 6.

2.2.5 Non-energy related sectors

Chinese government have released standards to limit the solvent content in some products, including wood paint, interior wall paints, adhesives for shoes production, decorative adhesives, and printing inks. Driven by these standards, the solvent contents of some products decreased, and the penetration of low-solvent products increased during 2005–2010. Tables 5 and S2 show the penetrations of major control measures for solvent use; Table S3 shows the changes in the emission factors of typical sources (especially those regulated) during 2005–2010. Despite the existing standards, most of the emissions from solvent use remain uncontrolled in China.

In 2004, Japan Ministry of Environment set target to reduce the 2000 NMVOC emissions by 30 % as of 2010 using both regulations (10 %) and voluntary efforts (20 %), with a focus on solvent use emissions (Ministry of the Environment of Japan, 2013). It was estimated that the actually achieved reductions were 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 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 with a model structure developed in our previous paper (Zhao et al., 2013c). The emissions from each sector in each province were calculated from the activity data (energy consumption, industrial products, etc.), technology-based uncontrolled emission factors, and penetrations of control technologies. The data sources for China are described in our previous paper (Zhao et al., 2013b).

The historical emissions of Japan are consistent with the JATOP Emission Inventory-Data Base (JEI-DB), developed by Japan Petroleum Energy Center (JPEC) (JPEC, 2012a–c). Special attention was paid to the road vehicle emissions. The basic concept of estimation is multiplying the traffic volume (considering vehicle type mix ratio by regulations), and the emission factor. JPEC adjusts that value with correction factors: a deterioration correction factor depending on accumulated mileage, a temperature correction factor and a humidity correction factor. It also includes original research data including start emission factor, evaporative emission factors, high emission vehicle ratio, and vehicle usage profile from a questionnaire survey (JPEC, 2012c). The emissions from other sources was calculated using local statistical information and emission factors, and allocated to area (1 km × 1 km) and time (hourly) (JPEC, 2012a).

The historical emissions of South Korea were calculated by the National Institute of Environmental Research (NIER) in South Korea, and the data sources are described in some research reports and a web-based database (NIER, 2010, 2013; CAPSS, http://airemiss.nier.go.kr/). It should be noted that Continuous emissions monitoring systems (CEMSs) were installed the most of large point sources from the year 2002.

The emission for those stacks have been estimated using CEMSs for years 2007–2010 (pre-2007, the emission factor method). There are “not-so-small” emission gaps before and after 2007 due to this methodological change. We, therefore, substituted pre-2007 emissions for those stacks using extrapolation of 2007–2010 “CEMS-based” estimation considering the changes of control measures.

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

National air pollutant emissions in East Asia are summarized in Table 8. The sectoral emissions in China are given in Fig. 2, and those in Japan and South Korea are shown in Fig. 3.

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, since China 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 emission from power plants stopped growing by 2010 owing to the application of LNBs and promotion of clean energy power. But the emissions from industry and transportation kept growing rapidly because of the swift growth in industrial energy consumption and vehicle populations.

NO_x emissions from East Asia except China decreased by 13 % during the five years, mainly attributed to the reductions in emissions from Japan (21 % reduction). The implementation of tight emission standard for new vehicles, and subsequently the large reduction in Japan’s transportation sector is the main driving force to this decline. The emissions of South Korea decreased slightly by 5 %, also owing to the implementation of new vehicle standards.

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. The emissions from China accounts for as large as 94 % of the total SO_2 emissions in East Asia. During 2005–2010, both China and the regions except China experienced a 15 % decline in SO_2 emissions.

The decline in China's SO_2 emissions is mainly attributable to the large scale deployment of FGD for power plants. In comparison, SO_2 emissions from China's industrial sector kept increasing during this period, slowing down the declining rate of total SO_2 emissions; 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 high-efficient desulfurization technologies in the industrial sector, and the replacement of coal and oil with clean and renewable energy. South Korea's SO_2 emissions roughly remained constant, because the reduction of the emissions from power plants (owing 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 15.8 Mt and 11.8 Mt respectively. During 2005–2010, the PM_{10} and $PM_{2.5}$ emissions decreased by 15 % and 11 % respectively. This trend was also donimated by the trend in emissions from China, as China's $PM_{10}/PM_{2.5}$ emissions represent 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 cement industry experienced the fastest decrease (43–47 % reduction from 2005–2010), as a result of the rapid evolution of end-of-pipe removal equipments (see Tables 2 and 4). The emissions of industrial combustion and steel industry increased by 14–32 %, while the emissions of other sectors kept relatively stable.

PM_{10} and $PM_{2.5}$ emissions decreased by 7 % and 8 % in East Asia except China. The declining rate is as large as 19–28 % in Japan, and transportation sector contributes 70 % of this decline. Emissions from South Korea increased somewhat due to the increase in industrial fuel consumption, which is further a result of the relatively stable energy intensity of industrial sector (see Sect. 2.1.2).

2.3.4 NMVOC

The total NMVOC emissions in East Asia were 22.9 Mt in 2010, and experienced a 15 % growth during 2005–2010, as an integrated effect of a 21 % increase in emission 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 owing to improving vehicle emission standards and the replacement of biomass with cleaner energy sources. However, these reductions were offset by the dramatic increase of emissions from industrial process (+46 %) and solvent use (+102 %), leading to a 21 % increase of the total NMVOC emissions.

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

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 the 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, population). The future technology distribution and energy efficiencies are assumed and the energy consumption is calculated. Both historical and future emissions are derived from energy consumption, emission factors and assumptions on the penetration of control technologies. For details, please refer to 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 legislations and implementation status (until the end of 2010). In the PC scenario, we assume the introduction and strict enforcement of new energy-saving policies, including life style changes, structural adjustment, and energy efficiency improvement. Life style changes imply slower growth of energy service demand, including energy-intensive industrial products, building area and residential service demand, vehicle population, electricity production, and heat supply, due to more conservative life styles. Structural adjustment includes promotion of clean and renewable fuels and energy-efficient technologies, such as renewable energy power and CHP for power plants and heat supply sector respectively, arc furnace and large precalcined kilns for industrial sector, biogas stoves and heat pumps for residential sector, electric vehicles and bio-fuel vehicles for transportation sector, etc. Assumed energy efficiency improvement includes the improvement of the energy efficiencies of single technologies in each sector.

We developed three end-of-pipe control strategies for each energy scenario, including baseline (abbr. [0]), progressive (abbr. [1]), and maximum feasible control strategies (abbr. [2]), thereby constituting six emission scenarios (BAU[0], BAU[1], BAU[2], PC[0], PC[1], and PC[2]). The control strategy [0] assumes that all current pollution control legislation (until the end of 2010) and the current implementation status would be followed during 2011–2030. The control stategy [1] assumes that new pollution control policies would be released and implemented in China, representing progressive approach towards future environmental policies. For other countries, we assume the same assumption as strategy [0]. The control strategy [2] assumes the 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) (UNEP and WMO, 2011). Both the energy consumption and air pollutant emissions were calculated with a 5-year resolution, though 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 except for China, our BAU and PC scenarios are consistent with the energy pathways of the reference scenario and 450 ppm scenario in 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 considers the current energy and climate related policies, the 450 ppm scenario explores what the global energy consumption could envolve if countries take coordinated action to restrict the global temperature increase to 2 °C. The details of energy scenarios are described in UNEP and WMO (2011) and IEA (2009).

For China, we have developed two energy scenarios consistent our previous paper (Zhao et al., 2013c). Presented below is a brief description of the assumptions and results of the energy scenarios. Please refer to Zhao et al. (2013c) for detailed information.

We assumes the annual average GDP growth rate to decrease gradually from 8.0 % during 2011–2015 to 5.5 % during 2026–2030, respectively. 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 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 PC scenarios that of 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 PC scenarios, contrasted by 73 % in BAU scenario.

We projected lower yields of energy-intensive industrial products in PC scenario than those of BAU scenario because of a more conservative life style. The shares of less energy-intensive technologies are assumed to be higher in PC scenario than BAU scenario.

For residential sector, China's building area per capita in PC scenario is expected to be 3–4 m^2 lower than that of BAU scenario in both urban and rural area. The energy demand for heating per unit area is somewhat lower in our PC scenario because of implementation of new energy conservation standards for 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 BAU and PC scenarios, respectively. The PC scenario assumes an aggressive plan to promote 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.

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 % larger 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 economic structure adjustment. In contrast, the energy consumption of transportation is projected to increase dramatically by 200 % and 101 % in 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 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 except China is projected to increase slightly by 12 % and 2 % from the 2010 level in BAU and PC scenarios, respectively. Japan and South Korea are two major energy consumers except China. Under current policies, Japan's energy consumption are projected to increase very slightly by 2 % from 2010 to 2030, because of slow economic growth rate and a tendency towards higher energy efficiency resulting from current legislaion. Due to the 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 from the 2010 level. This reduction is mainly attributed to the decline in energy consumption of 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 % from the 2010 level, respectively. Similar to China, there is also an evident trend 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 BAU scenarios, and further to 12 % and 29 % under PC scenario. In contrast, the proportion of renewable energy would increase from 16 % in 2010 to 23 % and 33 % in 2030 under BAU and PC scenarios, respectively.

3.2 Development of emission scenarios

For the countries except for China, our control strategies [0] and [2] are consistent with the control strategies of the reference scenario and maximum feasible reduction scenario in UNEP and WMO (2011), respectively. While control strategy [1] assumes new pollution control policies would be implemented progressively in China, it has the same assumption as control strategy [0] for other countries for the following reasons: (1) China accounts for 89 %, 95 %, 94 %, 94 %, and 90 % of the total NO_x, SO_2, PM_{10}, $PM_{2.5}$, and NMVOC emissions in East Asia; (2) Japan and Korea already have stringent environmental policies in the base year, the progressive control strategy for other countries expect China is not that meaningful. The major assumptions underlying control strategies [0] and [2] are simple and straight forward. Control strategy [0] assumes current legislation and implementation status, which has already been documented in detail in Sect. 2.2. Control strategy [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 leave out the details for other countries. The penetrations of major control technologies in China, Japan and South Korea are summarized in Tables 2–6.

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. For PM emissions, the government did not set total emission target, but set a strict PM in-stack concentration standard in 2011 (30 $mg\,m^{-3}$ for the whole country and 20 $mg\,m^{-3}$ for “key regions”). Power plants burning low ash content coal could attain the 30 $mg\,m^{-3}$ threshold by installing ESP and wet-FGD simultaneously. For units burning high ash coal, or when the 20 mg m^{-3} threshold applies, high efficiency deduster (HED, including FF and electrostatic-fabric integrated precipitator), proves to be the only commercially available control technology.

BAU[0]/PC[0] scenario considers 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] scenario is designed based on the 12th Five-Year Plan and 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 is assumed to approach 100 % by 2015. All new-built thermal power plants should be equipped with low NO_x combustion technologies and flue gas denitrification (SCR/SNCR) from 2011 onwards. Existing thermal power plants should be upgraded with low NO_x combustion technologies, and large units (≥ 300 MW) should be upgraded with flue gas denitrification during 2011–2015. SCR/SNCR will gradually penetrate to smaller units after 2015. More ambitious application of measures is required in the "key regions". For PM, HED would spread much more rapidly, with its share approaching 35 % and 50 % in 2020 and 2030, respectively. In the BAU[2]/PC[2] scenario, the best available technologies, i.e. FGD, LNB+SCR, 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). Several provinces including Beijing and Guangdong have issued local standards recently. The BAU[0]/PC[0] scenario was designed based on current legislation, i.e. nearly no control measures are utilized for SO_2 and NO_x emissions, and WET remains dominant control technology for PM emissions. The BAU[1]/PC[1] scenario is 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 promoted in large scales, penetrating 20 %, 40 %, and 80 % of the total capacity by 2015, 2020, and 2030 respectively. For NO_x, newly built industrial boilers are required to be equipped with LNB, and existing boilers in the "key regions" are beginning 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 would be gradually promoted to replace the relatively low-efficient WET. In the BAU[2]/PC[2] scenario, the most efficient removal technologies, including FGD, LNB+SCR, and HED would be fully applied.

The emissions from "industry process" were mainly regulated by the "emission standard for industrial kiln and furnace" before 2010. Standards for specific industry were only issued for cement plants (GB4915-2004), and coking oven (GB16171-1996). However, new emission standards for various industries were issued explosively during 2010–2012, which might significantly alter the emission pathways in the future.

A series of new emission standards for iron and steel industry were released in 2012, including the standards for sintering, iron production, steel production, steel rolling and so on. Sintering machine acts as the main source for SO_2 and NO_x emissions in iron and steel industry, and also an important source for PM emissions. Wet-FGDs are required to be installed in order to attain the SO_2 concentration threshold, 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. However, the 12th Five-Year Plan requests newly built sintering plants to be equipped with flue gas denitrification (SCR/SNCR). Most sintering plants could meet the PM threshold with simultaneous installation of FGD and ESP. However, HED is required for those in "key regions" and those with poor raw material quality. The BAU[0]/PC[0] scenario assumes the control legislations as of 2010. The BAU[1]/PC[1] scenario is developed on the basis of the 2012 standard and the 12th Five-Year Plan. FGD would be installed for most sintering machines and SCR/SNCR for newly built machines during the 2011–2015; the penetrations would increase gradually afterwards. While ESP remains the donimant PM removal technology, HED is assumed be promoted gradually. FGD, SCR, and HED would be fully applied in BAU[2]/PC[2] scenario. The blast furnaces (for pig iron production) in China are usually equipped with washing tower and double venturi, which remains the best available technology nowadays. The 2012 emission standard for steel production (with basic oxygen furnace and electric arc furnace being the major technology) 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] assumes the emission standard before 2010, BAU[1]/PC[1] assumes the retirement of WET and gradual promotion of HED, according to the 2012 emission standard. BAU[2]/PC[2] assumes full utilization of HED.

Current emission standard for cement industry was released in 2004. The SO_2 and NO_x threshold could be met without additional control measures, and the PM threshold could be met with both ESP and HED. Therefore, we assume the control technology mix of 2010 would be kept in BAU[0]/PC[0] scenario. In 2012, MEP published a draft new emission standard to seek for the suggestions of public. As cement clinker could absorb most SO_2 produced due to its basic nature, even the strenghthend SO_2 limit could be attained under good technical conditions. The attainment of the NO_x limit calls for the update with low NO_x combustion technology (or installation of SNCR if the update is not applicable) for existing kilns, and simutaneous utilization of low NO_x combustion technology and SNCR/SCR for new kilns. The BAU[1]/PC[1] scenario is designed based on the 2012 draft standard and the 12th Five-Year Plan. Newly built precalcined kilns (mostly $\geq 4000\,\mathrm{t\,d^{-1}}$) are required to be equipped with flue gas denitrification (SCR/SNCR), and existing precalcined 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 promoted gradually to meet the strengthened PM threshold for new kilns. BAU[2]/PC[2] scenario assumes full application of desulfurization facilities, LNB+SCR, and HED.

As for coke oven, we assume no control measures for SO_2 and NO_x emissions, and continuous application of WET for PM emissions in BAU[0]/PC[0] scenario. In

BAU[1]/PC[1] scenario, we assume the installation of FGD for coal filling process (contributing about 50 % emissions), or FGD for coke oven gas (contributing about 30 % emissions) for newly built plants 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. BAU[2]/PC[2] scenario assumes full application of best desulfurization, denitrification, and PM removal facilities.

As for glass production, BAU[0]/PC[0] scenario assumes no control measures for SO_2 and NO_x emissions, and current mix of PM removal technologies. BAU[1]/PC[1] scenario is 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 for both existing and new plants. Out-of-date PM removal technologies, e.g. WET, would be phased out. For brick industry, about 30 % plants remain uncontrolled by 2010. The draft new emission standard in 2009 calls for PM removal efficiency over 60 % for existing plants, and over 80 % for new plants. In BAU[1]/PC[1] scenario, PM emissions from brick plants are assumed to be controlled according to the standard, though enforced leniently due to difficulty in inspection.

To attain the new emission standard for the nitric acid industry (GB26131-2010), the dual-pressure process should be equipped with absorption method (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 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 BAU[1]/PC[1] scenario, the enforcement of Stage IA, Stage IB, and Stage II controls would be extended to all cities in China, and IFC would be applied for both new-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 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 BAU[0]/PC[0] scenario. In BAU[1]/PC[1] scenario, we assume that new NMVOC emission standards (similar to or slightly less stringent than EU Directive 1999/13/EC and 2004/42/EC, depending on specific industry) will be released and implemented in key provinces as of 2015, and in other provinces as of 2020. Afterwards, the emission standards will become more stringent gradually. In terms of technologies, we would prefer basic management techniques (e.g., leakage detection and repair system for refinery, improved solvent management for paint production) when they are applicable. End-of-pipe measures (condensation, adsorption, absorption, incineration etc.) 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

Control policies have seldom been proposed for residential sector in China. In BAU[0]/PC[0] scenario, we assume no control measures except for the continuous application of CYC and WET for residential boilers. In BAU[1]/PC[1], HED and low-sulfur derived coal are assumed to be promoted gradually, both penetrating 20 % and 40 % of the total capacity by 2020 and 2030 respectively. In addition, we take into consideration the replacement with advanced coal stove, and advanced biomass stove (e.g. better combustion condition, catalytic stove) where applicable, which are beneficial for the reduction of PM and NMVOC. The BAU[2]/PC[2] scenario, assumes the application of best-available technology without considering economic cost.

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3.2.4 Transportation sector

In BAU[0]/PC[0] scenario, only existing standards (released before the end of 2010) are considered. In BAU[1]/PC[1] scenario, all the current standards in Europe are assumed to be implemented in China gradually, and the time intervals between the releases of two stage standards would be a little shorter than those of Europe. The implementation timeline of the emission standards is given in Fig. 1. The removal efficiencies of the future emission standards are from the GAINS-Asia model of IIASA (Amann et al., 2008, 2011). The BAU[2]/PC[2] scenario assumes the same assumptions on the implementation timeline of new standards as BAU[1]/PC[1] scenario. In addition, old vehicles with high emissions are phased out at a faster pace through forcible measures and economic subsidies. The proportions of vehicles subject to different emission standards are summarizd in Table 6.

3.2.5 Non-energy related sector

For emissions from solvent use, BAU[0]/PC[0] scenario considers only several national standards limiting the NMVOCs contents in some solvent products (see Sect. 2.2.5). BAU[1]/BAU[1] scenario assumes that new NMVOC emission standards (similar to or slightly less stringent than EU Directive 1999/13/EC and 2004/42/EC, depending on specific industry) will be released and implemented in key provinces as of 2015, and in other provinces as of 2020. Afterwards, the emission standards will become more stringent gradually. Potential mitigation measures to attain the European standards differ greatly for different emissions sources because of discrepant spraying technologies and various chemical properties of the solvent used. However, these measures could be catetogried into two kinds, i.e. substitution with environmentally friendly products (including high solids product, water-based product, and UV product, etc.) and add-on control technologies (including condensation, adsorption, absorption, incineration, etc.). Substitution measures are preferred when applicable, and add-on control technologies would be mainly installed in the newly-built factories. The penetration of selected control measures assumed for key sources are summarized in Table 5.

We consider ban of biomass open burning in BAU[2]/PC[2] scenario.

3.3 Future emission trends and effects of control measures

The air pollutant emissions in each scenario are estimated based on the assumptions in Sects. 3.1 and 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 Fig. 3 shows the emissions by sector in Japan and South Korea.

3.3.1 NO_x

Under current legislation and current implementation status, NO_x emissions in East Asia are projected to increase by 28 % by 2030 from the 2010 levels. The implementation of assumed energy saving measures and “progressive” end-of-pipe control measures are expected to reduce NO_x emissions by 28 % and 36 % respectively from the baseline projection. With the enforcement of maximum feasible reduction measures, the remaining emissions account for only 21 % of the baseline projection, or 27 % of the 2010 levels.

Special attention is paid to China given its huge emissions. China’s growth potential under current legislations (36 %) is significantly larger than the average of East Asia (28 %), resulting from the great increase in energy consumption and weak control measures already in effect. The share of China in East Asia’s NO_x emissions would increase to 93 % under baseline projection. The enforcement of energy saving measures leads to 29 % reduction from the baseline projection. With the implementation of the 12th Five Year Plan and slowly strengthened end-of-pipe control policies after 2015, China’s NO_x emissions could be reduced by nearly 40 % (of the baseline projection). The most effective control measures are the installation of SCR/SNCR and the application of tight vehicle standards, which together contribute to nearly 80 % of this reduction. The maximum feasible control measures 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 could 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 legislation and implementation status, the NO_x emissions in East Asia except 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 2 °C, NO_x emissions in East Asia except China, and two major energy consumers therein (Japan and South Korea) are all expected to be reduced by 15–17 % in 2030 compared with the baseline projection. These policies are most effective for the power sector, as renewable and nuclear power generation are almost "zero emissions" compared with traditional coal power. The full application of maximum feasible control measures would reduce the NO_x emissions in East Asia except China, Japan and South Korea 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 have a 24 % growth from 2010 to 2030 if we stick to current legislation and current implementation status. The enforement of advanced energy-saving measures could lead to substantial reduction in SO_2 emissions (36 % reduction) from the baseline projection, exceeding the effect of progressively implemented end-of-pipe control measures (25 %). FGD facilities have been intensively installed by 2010 in most industrial sources of Japan and power plants of China and South Korea. Therefore, the reduction potential through the installtion of end-of-pipe control technologies would be less and less in the future, revealing the importance of energy-saving measures for further reduction of SO_2 emissions. With the full application of best available technologies, the remaining SO_2 emissions in East Asia 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 current policy and current implementation status. Implementation of new energy saving measures and "progressive" end-of-pipe control measures could lead to 36 % and 26 % reductions of China's SO_2 emissions (compared with the baseline projection). Consistent with the total emissions in East Asia, the contribution of energy saving measures evidently exceeds the planned end-of-pipe control policies. As the power sector has largely been equipped with FGD facilities in the base year, industrial boilers and industrial process contribute 82 % of the SO_2 emission reduction achieved through installation of desulfurization facilites. In the maximum feasible reduction scenario, SO_2 emissions are estimated at only 27 % of the baseline projection, or 34 % of the 2010 levels.

We also note that the SO_2 emissions are projected to be 21.7 Mt in 2015 under the BAU[1] scenario, 11.1 % lower than that of 2010. This implies that if the control policies in the 12th 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 except China, and two major energy consumers therein (Japan and South Korea) are expected to stay relatively stable until 2030 under current legislations. The implementation of new energy saving polices could lead to 9–18 % reduction in SO_2 emissions from the levels of baseline projection. The reduction is mainly achieved thorough the promotion of nuclear and renewable power generation and replacement with cleaner fuel type in the industrial sector. Under the maximum feasible reduction measures, the SO_2 emissions in East Asia except China, Japan and South Korea would be reduced to 33 %, 52 % and 39 % of the baseline projection, respectively.

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

$PM_{10}/PM_{2.5}$ emissions in East Asia are projected to remain relatively stable up to 2030 under the current policies, resulting from the balance between growing energy consumption and existing control policies (in particular, vehicle emission standards). New energy saving policies and progressive end-of-pipe control measures 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 could reduce $PM_{10}/PM_{2.5}$ emissions to about one quarter of the levels of the baseline projection or the base year.

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

The $PM_{10}/PM_{2.5}$ emissions in East Asia are also expected to remain relatively stable up to 2030 under the current policies. An exception is Japan, whose $PM_{10}/PM_{2.5}$ emissions are projected to decrease about one quarter by 2030. The major driving force underlying such a decline is increasing proportion of vehicles regulated by newer emission standards. The implementation of new energy saving policies is expected to reduce the $PM_{2.5}$ emissions of East Asia except China, Japan and South Korea by about 20 %, 17 %, and 9 % respectively. With full application of best available control technologies, the $PM_{2.5}$ emissions in East Asia except China, Japan and South Korea would account for about one quarter, half and 40 % of the levels of the baseline projection.

3.3.4 NMVOC

Under current legislation and current implementation status, NMVOC emissions in East Asia are projected to increase by 24 % by 2030 from the 2010 levels. The implementation of assumed energy saving measures and "progressive" end-of-pipe control measures are expected to reduce NO_x emissions by 15 % and 23 % respectively from the baseline projection. Up to 62 % of the total NMVOC emissions are expected to remain even the assumed energy saving measures and progressive end-of-pipe control measures are enforced together. There remains large potential to reduce the NMVOC emissions beyond the progressive control strategies, since the full application of best available technologies 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 current policy and current implementation status. This upward trend is stronger than the East Asia's average but weaker than China's NO_x emissions. The emissions from 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 residential sector. By carrying out a series of energy saving policies, total emissions are expected to decrease by 16 % from the baseline projection. Emissions from residential sector decrease most notably because of the substitution of biomass by cleaner fuels. Another 26 % could be reduced if progressive end-of-pipe control measures are implemented, and the most effective measures are the substitution with low solvent products and add-on removal technologies such as incineration and adsorption in the industrial and solvent use sectors. With full implementation of the best available technologies, the NMVOC emissions could be reduced to about one third of the levels of the baseline scenario.

The emissions in East Asia except China are expected to increase by 5 % from 2010 to 2030 under current legislation. 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 owing to increased share of low-emission vehicles, and the increase of emissions from solvent use owing 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 would reduce the emissions from solvent use dramatically, thereby reducing about three quarters of the total NMVOC emissions from the baseline projection.

4 Comparison with other studies and observations

4.1 Comparison with other studies

In 2010, China contributes 88 %, 94 %, 94 %, 94 %, 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 is therefore believed to dominate the emission trends of East Asia in the next 20 yr. In addition, many previous studies on emission projection have focused on China. Some Asian or global studies did incorporated Japan, South Korea, and other countries, but they seldom presented emissions of these countries seperately, making it difficult to review their emission projections. Given the reasons above, we would just compared the previous studies with China's emission trends in this section.

The studies estimating historical emissions of China are numerous. Since this study focuses on the temporal trends, we included in our comparison only the studies which presented China's emission trends during 2005–2010, but excluded the numerous studies estimating single year emissions.

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 usually 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 have deviated greatly from the actual status. In this study, we just compared recent emission projections reported since 2005 (or using the base year of 2000 or later) with our projection, which is shown in Fig. 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 until 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 BAU[1] scenario and −39 % in PC[1] scenario) during the same period, due to the implementation of the control measures scheduled for the 12th Five-Year Plan. Amann et al. (2008) developed three scenarios until 2030 based on the emissions in 2005. The current legislation scenario assumed current legislation and current enforcement, while the advanced control technology scenario assumed across-the-board application of advanced control technologies; principally consistent with existing German legislation. The optimized scenario was a least cost optimization scenario 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 a scenario assuming current legislation and implementation status, a scenario assuming improvement of energy efficiencies and current environmental legislation, a scenario assuming improvement of energy efficiencies and better implementation of environmental legislation, and a scenario assuming improvement of energy efficiencies and strict environmental legislation. These two studies were actually conducted in cooperation. Similar to Ohara et al. (2007), their projections for 2010 were also significantly lower than our estimation. 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 with the 2010 emissions and four scenarios envisaging energy saving measures at different stringency levels. The projected change rates for the period 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 larger growth rate or smaller declining rate 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 estimations in different studies differ by up to 30 % during the period, all the studies reviewed (including ours) showed a declining trend in SO_2 emissions during 2005–2010. This study estimated a slightly stronger decline of SO_2 emissions (13 % for the period of 2005–2008, and 15 % for the period of 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 SO_2 control policies since 2005. Ohara et al. (2007) predicted that SO_2 emissions would change by 27 %, −11 % and −23 % during 2010–2020 in the policy failure scenario, the "best-guess" scenario and the optimistic scenario 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 decline rate as our progressive control strategy. The growth rates projected in all the four scenarios of Xing et al. (2011) are higher than our BAU[1] scenario, indicating that his 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 the SO_2 emissions to decrease by 20–40 % during 2010–2030 with four scenarios assuming different energy saving policies, while our BAU[0] and PC[0] scenarios predicted the change rates 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 predicted 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 tendency after 2005. The discrepancy might be mainly attributed 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 more or less assumed PM control policies in the future. The PM_{10} emissions growth rate until 2020 of the least aggressive scenario in Xing et al. (2011) in comparable to our BAU[0] scenario, and the most aggressive scenario is comparable to our PC[1] scenario, 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 its current legislation scenario is quite close to our BAU[0] scenario; the growth rates in its advanced control technology scenario or optimized scenario are close to our PC[1] scenario. Cofala et al. (2012) projected the change rate of $PM_{2.5}$ emissions for 2010–2030 between −20 % and −34 % with four energy scenarios, which are comparable to the projected change rates of our BAU[0] (−8 %) and PC[0] (−34 %) scenarios. Finally, it should be noted that our maximum feasible reduction 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 its three scenarios, as Ohara et al. (2007) hardly assumed any effective control measures in these scenarios. Xing et al. (2011) and Wei et al. (2011) have considered the effect of recent vehicle emission standards on NMVOC emissions, and assumed pretty simple but progressively emerging control polices until 2020, and therefore achieved similar growth rates to ours for both baseline and progressive strategies. Given China is still in the starting stage of NMVOC emission controls, and new policies could only emerge slowly in the next 5–10 yr, so the emission trends should not deviate greatly from the baseline until 2020. However, control measures at different stringency levels 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 until 2030 and to quantify the maximum feasible reduction potential.

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. Lu et al. (2011) retrieved the satellite SO_2 vertical column density (VCD) for Eastern Central China (latitude $< 45^\circ$ N, longitude $> 100^\circ$ E), in which measurements of 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 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 Fig. 5a and b, respectively. It can be seen that the temporal 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, while Fioletov et al. (2013) shows a slight increase. Fioletov et al. (2013) concluded that the pronounced increase between 2009 and 2010 might be attributed to transient volcanic signals. Therefore, we excluded the SO_2 VCD in 2010 in Lu et al. (2011) in the following discussion.

As shown in Fig. 5a, 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 declining rate 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 as of 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, Chinese government began to request the installation of continuous emission monitoring systems (CEMSs) together with FGDs since July 2007 (SEPA, 2007). Therefore, the average removal efficiency should have improved ever since, 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 well with satellite observations.

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 5c 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 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 declining rate 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 increase 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, but 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 (Zhao et al., 2013a). Although sulfate concentrations in East China decreased owing 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 (Zhao et al., 2013a). Given above, although the emissions of primary PM and SO_2 decreased in most of China, total $PM_{2.5}$ concentrations still increased in a large part of China.

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 with six emission scenarios envisaging both energy-saving measures and end-of-pipe control measures.

During 2005–2010, the emissions of SO_2 and $PM_{2.5}$ in East Asia decreased by 15 % and 11 %, respectively, mainly attributable to the large scale deployment of FGD for China's power plants, and the promotion of high-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 the rapid increase in the emissions from China owing 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 tight vehicle emission standards in Japan and South Korea.

Under current legislation and current implementation status (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 the "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 for 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) reproduces the recent emission trends until 2010; (2) projects larger reduction in NO_x and SO_2 emissions by considering aggressive govermental plans and standards scheduled to be implemented in the next decade; (3) quantifies the significant effects of detailed progressive control measures on NMVOC emissions up to 2030; (4) quantifies the technologically feasible reduction potentials. The results of this study provide future emission projections for the modeling community of the MICS-Asia program. The modelers could assess the impact of emission changes on future air quality with the projected emission trends in this study. In addition, the emission projections at various stringency levels from business-as-usual case to 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 over a wide range of stringency levels.

The results of this study have important policy implications. Firstly, this study indicates that the successful implementation of the control policies set in China's 12th Five Year Plan, the recently released emission stardards 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 resulted 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 these legislations are enforeced efficiently. Therefore we believe it is essential to support and monitor the progress of implementation of these legislations. Secondly, 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-efficient dedustors, have already been widely applied in typical sources in the base year, their reduction potential would become smaller and smaller in the future. The energy saving measures would play an irreplacable role for further reduction of air pollutant emissions. Thirdly, control policies for NMVOC emissions are sadly lacked in China and South Korea at present, this study demonstrate that the simultaneous enforcement of energy saving measures and progressive end-of-pipe control measures (mainly assuming enforement of European standards) could reduce 38 % of the total NMVOC emissions from the levels of baseline projection. Even though, large reduction potential still remains. Relative policies should be carefully optimized to reduce NMVOC emissions efficiently and effectively.

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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 legislations and implementation status (until the end of 2010).	BAU[0]	The BAU[0] scenario assumes the same energy saving policies as BAU scenario. For end-of-pipe control strategy, it assumes that all current legislation (until the end of 2010) and the current implementation status will be followed during 2011–2030.
		BAU[1]	The BAU[1] scenario assumes the same energy saving policies as BAU scenario. For end-of-pipe control strategy, it assumes that new pollution control policies would be released and implemented, representing progressive approach towards future environmental policies.
		BAU[2]	The BAU[2] scenario assumes the same energy saving policies as BAU scenario. For end-of-pipe control strategy, it assumes that the 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 enforced more stringently, including life style changes, structural adjustment and energy efficiency improvement.	PC[0]	The PC[0] scenario assumes the same energy saving policies as PC scenario, and the same end-of-pipe control strategy as BAU[0] scenario.
		PC[1]	The PC[1] scenario assumes the same energy saving policies as PC scenario, and the same end-of-pipe control strategy as BAU[1] scenario.
		PC[2]	The PC[2] scenario assumes the same energy saving policies as PC scenario, and the same end-of-pipe control strategy as BAU[2] scenario.

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

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

Table 2. Continued.

Energy technology	Control technology	BAU[1]/PC[1]						BAU[2]/PC[2]		
		2020			2030			2030		
	Country	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea
Grate boilers	CYC (PM)	0	–	–	0	–	–	0	–	–
	WET (PM)	100	–	–	100	–	–	0	–	–
	HED (PM)	0	–	–	0	–	–	100	–	–
Pulverized coal combustion	WET (PM)	0	0	0	0	0	0	0	0	0
	ESP (PM)	65	0	64	50	0	61	0	0	0
	HED (PM)	35	100	36	50	100	39	100	100	100
	FGD (SO_2)	100	100	98	100	100	98	100	100	100
	LNB (NO_x)	8	0	13	0	0	13	0	0	0
	LNB+SNCR (NO_x)	6	0	5	7	0	5	0	0	0
	LNB+SCR (NO_x)	86	100	72	94	100	76	100	100	100
Fluidized bed combustion	WET (PM)	0	–	–	0	–	–	0	–	–
	ESP (PM)	65	–	–	50	–	–	0	–	–
	HED (PM)	35	–	–	50	–	–	100	–	–
	CFB-FGD (SO_2)	100	–	–	100	–	–	100	–	–
	SNCR (NO_x)	30	–	–	80	–	–	70	–	–
	SCR (NO_x)	5	–	–	20	–	–	30	–	–
Natural gas power	LNB (NO_x)	50	52	15	10	50	15	0	0	0
	LNB+SNCR (NO_x)	5	0	0	9	0	0	10	0	0
	LNB+SCR (NO_x)	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. However, the penetrations vary with provinces. The penetration of the "key region" 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]					
		2005			2010			2020			2030		
	Country	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
	WET (PM)	73	0	12	95	0	9	95	0	9	95	0	9
	ESP (PM)	0	50	16	0	50	16	0	50	16	0	50	16
	HED (PM)	0	50	47	5	50	52	5	50	55	5	50	58
	FGD (SO_2)	0	42	80	1	42	85	1	42	88	1	42	90
	LNB (NO_x)	0	65	0	0	80	0	0	80	0	0	80	0
	LNB+SCR (NO_x)	0	20	0	0	20	0	0	20	0	0	20	0
Residential boilers	CYC (PM)	23	50	60	14	50	51	12	50	45	10	50	40
	WET (PM)	63	0	40	78	0	49	81	0	55	85	0	60
	HED (PM)	0	50	0	0	50	0	0	50	0	0	50	0
	DC (SO_2)	0	0	0	0	0	0	5	0	0	10	0	0
Coal stoves	STV_ADV_C	0	25	10	0	50	13	0	50	18	0	50	20
Biomass stoves	STV_ADV_B	0	35	30	0	48	35	0	70	35	0	78	35
	STV_PELL	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Continued.

Energy technology	Control technology	BAU[1]/PC[1]						BAU[2]/PC[2]		
		2020			2030			2030		
	Country	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea
Industrial grate boilers	CYC (PM)	0	0	20	0	0	17	0	0	0
	WET (PM)	60	0	9	20	0	9	0	0	0
	ESP (PM)	20	50	16	40	50	16	0	0	0
	HED (PM)	20	50	55	40	50	58	100	100	100
	FGD (SO_2)	40	42	88	80	42	90	100	100	100
	LNB (NO_x)	91	80	0	100	80	0	0	0	0
	LNB+SCR (NO_x)	0	20	0	0	20	0	100	100	100
Residential boilers	CYC (PM)	0	50	45	0	50	40	0	50	50
	WET (PM)	80	0	55	60	0	60	50	0	0
	HED (PM)	20	50	0	40	50	0	50	50	50
	DC (SO_2)	20	0	0	40	0	0	100	100	100
Coal stoves	STV_ADV_C	10	50	18	30	50	20	100	100	100
Biomass stoves	STV_ADV_B	10	70	35	30	78	35	50	50	50
	STV_PELL	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 4a. Penetrations of major control technologies for selected industrial process in China – SO_2.

Industrial process	Control technology	Base year 2005	2010	BAU[0]/PC[0] 2020	2030	BAU[1]/PC[1] 2020	2030	BAU[2]/PC[2] 2030
Sintering	FGD	0	10	20	40	95	100	100
Coke oven	FGD for coal filling 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

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

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
Sintering	SNCR	0	0	0	0	36	54	20
	SCR	0	0	0	0	24	36	80
Precalcined 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.

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

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
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
Precalcined 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.

Table 4d. Penetrations of major control technologies for selected industrial process in China – 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 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 6a. Penetrations of vehicle emission standards in China, Japan, and South Korea (%) – 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).

Table 6b. Penetrations of vehicle emission standards in China, Japan, and South Korea (%) – 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 %	LDB-B	PNLT	0 %	0 %	49 %	92 %	100 %
	ST	19 %	15 %	2 %	0 %	0 %		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 %	CAR	NLT	0 %	52 %	27 %	10 %	0 %
	ST	27 %	20 %	0 %	0 %	0 %		PNLT	0 %	0 %	53 %	90 %	100 %
	LT	27 %	23 %	22 %	0 %	0 %		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.

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Table 6c. Penetrations of vehicle emission standards in China, Japan, and South Korea (%) – 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 United States emission standards for gasoline vehicles, which were equivalent to the penetrations of European standards above in terms of removal efficiencies.

Table 7. Summary of national energy consumption in East Asia (Unit: $\mathrm{EJ\,yr^{-1}}$).

			BAU		PC	
	2005	2010	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: $\mathrm{Mt\,yr^{-1}}$).

	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	10.18	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	11.14	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	13.37	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	13.97	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	6.64	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	6.98	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	4.31	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	0.112	0.128	0.128	0.134	0.128	0.134	0.054	0.119	0.121	0.119	0.121	0.051
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	14.11	12.49	12.44	11.60	10.31	8.02	4.54	10.05	8.31	8.33	5.61	2.70
Total except mainland China	0.766	0.705	0.700	0.727	0.700	0.727	0.234	0.622	0.584	0.622	0.584	0.195
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

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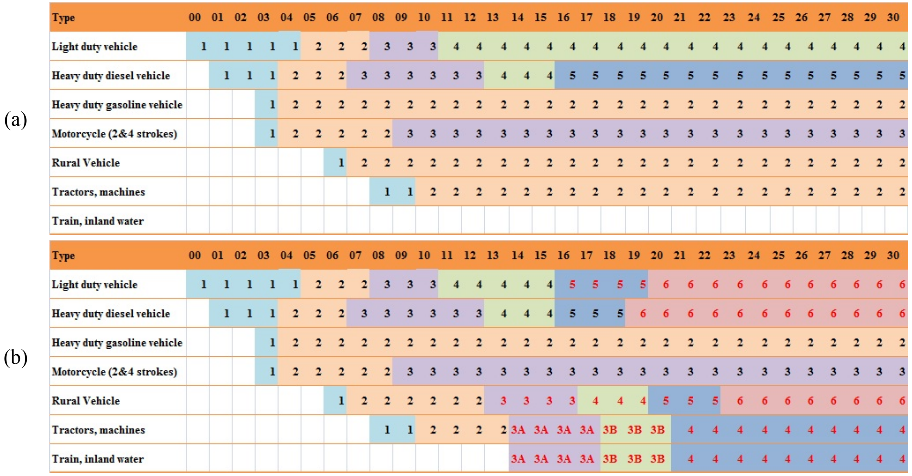


(a)

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

Fig. 1. The implementation time of the vehicle emission standards: **(a)** BAU[0]/PC[0] scenario; **(b)** BAU[1]/PC[1]/BAU[2]/PC[2] scenario. 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 that in red represent those to be released in the future.

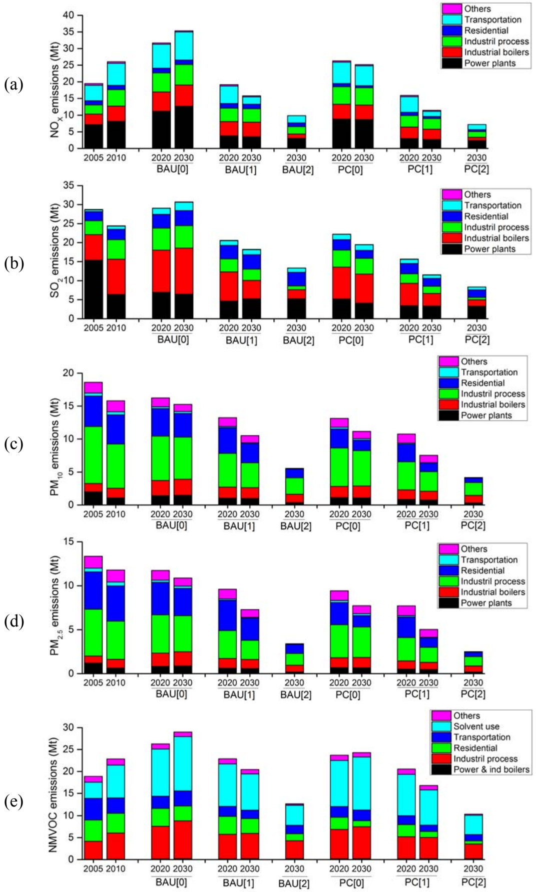
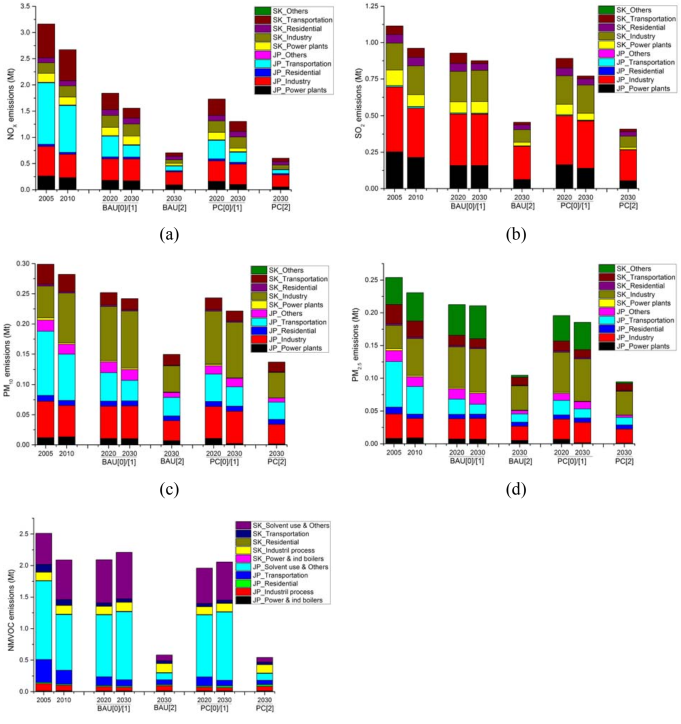


Fig. 2. Emissions of major air pollutants in China and their sectoral distribution during 2005–2030: **(a)** NO$_x$; **(b)** SO$_2$; **(c)** PM$_{10}$; **(d)** PM$_{2.5}$; **(e)** NMVOC.



(a) (b) (c) (d) (e)

Fig. 3. Emissions of major air pollutants in Japan and South Korea and their sectoral distribution 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.

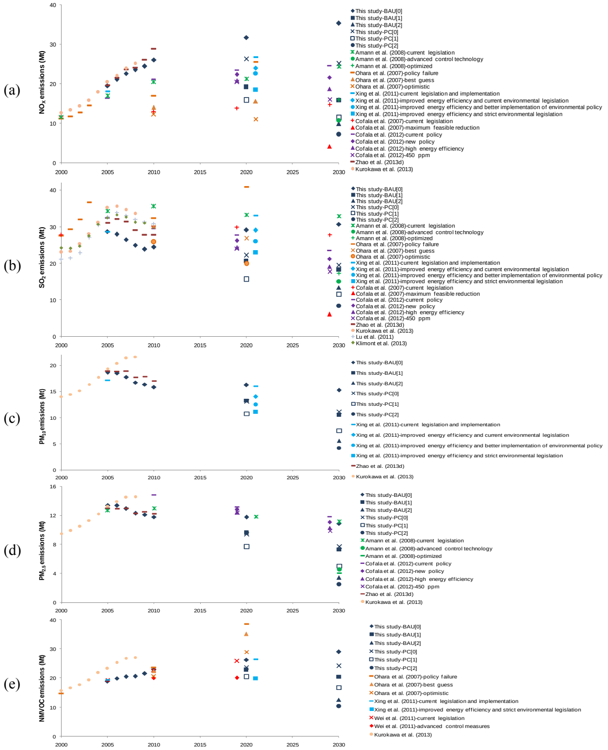


Fig. 4. Comparison of emission estimation in this study with other studies: **(a)** NO$_x$; **(b)** SO$_2$; **(c)** PM$_{10}$; **(d)** PM$_{2.5}$; **(e)** NMVOC. Scenarios from the same study are shown with symbols of the same colour, and only the historical emissions for the first scenario are shown. Some points for the years 2020 and 2030 are shifted a little left or right, in order to avoid overlapping. 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.

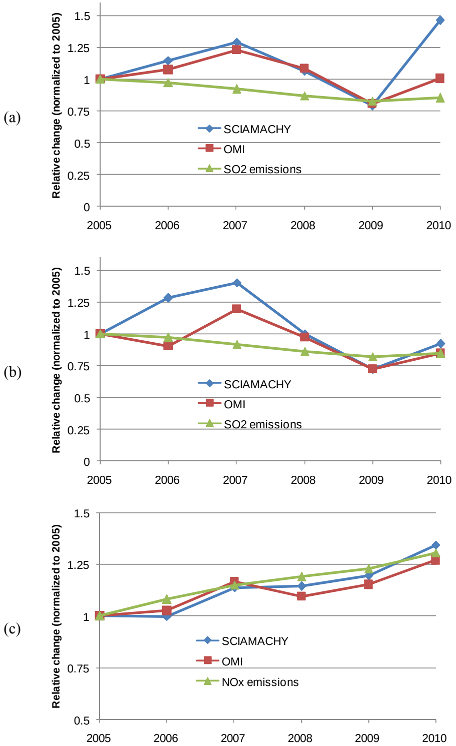


Fig. 5. Inter-annual relative changes of SO_2 and NO_2 VCD from satellite observations and emission estimation in this study. All data are normalized to 2005. **(a)** Average SO_2 VCD and total SO_2 emissions in Eastern Central China (latitude < 45° N, longitude > 100° E). SO_2 VCD was derived by Lu et al. (2011). **(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. **(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.