

# 1 Emission trends and mitigation options for air pollutants in 2 East Asia

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## 15 16 **Abstract.**

17 Emissions of air pollutants in East Asia play an important role in the regional and global  
18 atmospheric environment. In this study we evaluated the recent emission trends of sulfur dioxide  
19 (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), and non-methane volatile organic  
20 compounds (NMVOC) in East Asia, and projected their future emissions up to 2030 with six  
21 emission scenarios. The results will provide future emission projections for the modeling  
22 community of the model inter-comparison program for Asia (MICS-Asia). During 2005-2010,  
23 the emissions of SO<sub>2</sub> and PM<sub>2.5</sub> in East Asia decreased by 15% and 12%, respectively, mainly  
24 attributable to the large-scale deployment of flue gas desulfurization (FGD) at China's power  
25 plants, and the promotion of high-efficient PM removal technologies in China's power plants and  
26 cement industry. During this period, the emissions of NO<sub>x</sub> and NMVOC increased by 25% and  
27 15%, driven by rapid increase in the emissions from China due to inadequate control strategies.  
28 In contrast, the NO<sub>x</sub> and NMVOC emissions in East Asia except China decreased by 13-17%,

1 mainly due to the implementation of stringent vehicle emission standards in Japan and South  
2 Korea. Under current regulations and current levels of implementation, NO<sub>x</sub>, SO<sub>2</sub>, and NMVOC  
3 emissions in East Asia are estimated to increase by about one quarter over 2010 levels by 2030,  
4 while PM<sub>2.5</sub> emissions are expected to decrease by 7%. Assuming enforcement of new energy-  
5 saving policies, emissions of NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub> and NMVOC in East Asia are expected to  
6 decrease by 28%, 36%, 28%, and 15%, respectively, compared with the baseline case. The  
7 implementation of “progressive” end-of-pipe control measures would lead to another one-third  
8 reduction of the baseline emissions of NO<sub>x</sub>, and about one-quarter reduction of SO<sub>2</sub>, PM<sub>2.5</sub>, and  
9 NMVOC. With the full implementation of maximum feasible reduction measures, the emissions  
10 of NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> in East Asia would account for only about one quarter, and NMVOC for  
11 one third, of the levels of the baseline projection. Compared with previous projections, this study  
12 projects larger reductions in NO<sub>x</sub> and SO<sub>2</sub> emissions by considering aggressive governmental  
13 plans and standards scheduled to be implemented in the next decade, and quantifies the  
14 significant effects of detailed progressive control measures on NMVOC emissions up to 2030.

15

## 16 **1 Introduction**

17 Air pollutant emissions in East Asia contribute a large share of the global emissions. [Cofala et al.](#)  
18 [\(2012\)](#) reported that East Asia contributes about 36%, 29%, and 36% to global emissions of  
19 sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and particulate matter less than or equal to 2.5 μm  
20 (PM<sub>2.5</sub>), respectively, much more than those of the United States (U.S.) and Europe. Moreover,  
21 both emission calculations and satellite observations indicate that NO<sub>x</sub> emissions in China have  
22 experienced rapid increase during 1995-2010, with annual average growth rates ranging between  
23 5.5%-7% ([Zhao et al., 2013c](#); [Zhang et al., 2007](#); [Zhang et al., 2012a](#)). As a result, emissions in  
24 East Asia have greatly degraded regional air quality and visibility ([Wang and Hao, 2012](#); [Zhang](#)  
25 [et al., 2012c](#)) and damaged human health ([WB and SEPA, 2007](#)). They also affect air quality and  
26 climate forcing beyond the region through the outflow that travels across Pacific ([Liu et al., 2003](#)).  
27 In light of this situation, the control of emissions in East Asia is very important for the  
28 improvement of regional and global atmospheric environment.

1 With the objectives of air quality improvement and mitigation of climate change, the  
2 countries of East Asia, e.g., China, Japan, and South Korea, have taken substantial measures to  
3 improve energy efficiency and reduce emissions of air pollutants. These measures have often  
4 been stringent and have been rapidly enhanced. During 2006-2010, China set a target to reduce  
5 energy use per unit of Gross Domestic Product (GDP) and national SO<sub>2</sub> emissions by 20% and  
6 10%, respectively ([The State Council of the People's Republic of China, 2006](#)). During 2011–  
7 2015, China aims at additional 16%, 10%, and 8% reductions for energy use per unit GDP, NO<sub>x</sub>  
8 emissions, and SO<sub>2</sub> emissions, respectively ([The State Council of the People's Republic of China, 2011](#)). Japan has taken measures toward its commitment in the targets of the Kyoto Protocol,  
9 which require that annual CO<sub>2</sub> emissions during 2008-2012 should be 6% lower than those of  
10 1990 ([IEA, 2008](#)). The vehicle emission standards in China, Japan, and South Korea have also  
11 been updated repeatedly in the past decade. A number of studies have investigated the recent  
12 emission trends in East Asia (or a specific country therein) and the effects of typical control  
13 policies. For example, reductions in China's SO<sub>2</sub> emissions since 2005 both by observations from  
14 satellites ([Li et al., 2010](#)), and by bottom-up emission estimations ([Lu et al., 2010](#); [Lu et al., 2011](#);  
15 [Klimont et al., 2013](#)). Some studies also estimated the trends of the emissions of NO<sub>x</sub> ([Zhang et al., 2012a](#);  
16 [Lin et al., 2010b](#); [Zhao et al., 2013c](#)) and particulate matter (PM) ([Lin et al., 2010a](#); [Lu et al., 2011](#)).  
17 [Kurokawa et al. \(2013\)](#), [Zhao et al. \(2013d\)](#), and [Zhao et al. \(2013a\)](#) estimated the  
18 recent emission trends of multiple air pollutants. Future emissions were also predicted by  
19 previous studies ([Streets and Waldhoff, 2000](#); [Klimont et al., 2001](#); [Cofala et al., 2007](#); [Ohara et al., 2007](#);  
20 [Klimont et al., 2009](#); [Xing et al., 2011](#); [Cofala et al., 2012](#); [Zhao et al., 2013c](#)).  
21 However, most of these projections were based on emissions for 2005 or earlier and did not  
22 consider more recent, sometimes dramatic, changes. The latest projections include [Cofala et al. \(2012\)](#)  
23 and [Zhao et al. \(2013c\)](#). [Cofala et al. \(2012\)](#) projected global emissions of SO<sub>2</sub>, NO<sub>x</sub>, and  
24 PM<sub>2.5</sub> for four energy scenarios developed by [IEA \(2012a\)](#), but did not envisage further end-of-  
25 pipe mitigation measures in the future. [Zhao et al. \(2013c\)](#) developed six NO<sub>x</sub> emission scenarios  
26 up to 2030 based on a 2010 emission inventory, and quantified the effects of various control  
27 policies, but did not analyze other air pollutants.

28  
29 Although there have been a number of studies of recent and future emission trends in East  
30 Asia, they are inadequate for development of broadly effective air quality and climate mitigation

1 policies. First, future control measures must be developed while taking full account of the latest  
2 policies, and a comprehensive and up-to-date review for the entire region is currently lacking in  
3 the literature. As described above, the base years of most projections were 2005 or earlier, and  
4 therefore they underestimated China's economic growth over the last decade, especially from  
5 2006 to 2010. These early projections also did not anticipate new emission control policies  
6 announced in 2011 under China's 12<sup>th</sup> Five Year Plan (for the period of 2011-2015; [The State](#)  
7 [Council of the People's Republic of China, 2011](#)), nor a number of emission standards released  
8 after 2010, both of which may fundamentally alter the future emission pathways. The most recent  
9 projections ([Cofala et al., 2012](#); [Zhao et al., 2013c](#)) considered only a specific pollutant or a  
10 specific set of control measures, providing only partial insight into the future trends of all major  
11 air pollutants. Second, the attainment of stringent ambient air quality standards (e.g., China's  
12 standard of  $35 \mu\text{g m}^{-3}$  for the annual average  $\text{PM}_{2.5}$  concentration, released in 2012) requires  
13 simultaneous reductions of multiple pollutants including  $\text{SO}_2$ ,  $\text{NO}_x$ ,  $\text{PM}_{2.5}$ , and non-methane  
14 volatile organic compounds (NMVOC) ([Wang and Hao, 2012](#)). Therefore it is essential to  
15 consider a full range of relevant pollutants and scenarios at different stringency levels from the  
16 business-as-usual case to the maximum feasible reduction case, so that cost-effective emission  
17 controls can balance measures over all pollutants and control levels. Third, most studies focused  
18 on either end-of-pipe or energy-saving measures; their roles in integrated policies that  
19 simultaneously tackle multiple pollutants and climate forcers have been insufficiently studied.  
20 Considering the above, a comprehensive projection of emissions of multiple pollutants that  
21 incorporates the latest available base-year data, control measures scheduled for implementation,  
22 and other potential energy-saving and end-of-pipe measures at different stringency levels will  
23 contribute to both air pollution research and future decision making.

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

28 In Sect. 2, we review major control policies in East Asia over the last decade and evaluate  
29 their impact on air pollutant emissions during 2005-2010. Compared with previous studies of  
30 emission trends, we are particularly devoted to presenting a comprehensive review of the recent

1 mitigation measures in this region, and illuminate the driving forces underlying the emission  
2 trends. In Sect. 3, we project future emissions of SO<sub>2</sub>, NO<sub>x</sub>, NMVOC, and PM up to 2030 for six  
3 emission scenarios (see Table 1), considering both energy-saving and end-of-pipe measures. In  
4 Sect. 4, we compare our results with other emission estimates as well as observations. In this  
5 study, the domain of East Asia consists of seven countries/regions, i.e., mainland China (People's  
6 Republic of China except Hong Kong, Macao, and Taiwan), Japan, South Korea, North Korea,  
7 Mongolia, Hong Kong & Macao, and Taiwan. In the following text, China is short for mainland  
8 China. We focus on Japan, South Korea, and especially China, the key energy consumers in the  
9 region that dominate the emissions of air pollutants. Japan and Korea have relatively long  
10 histories of air pollution policies, while China has been enhancing its emission regulations in the  
11 last decade at an accelerating rate, have very ambitious future goals, and contribute the largest  
12 share of regional emissions. Therefore, developments in China are given special attention.

## 13 **2 Recent control measures and emission trends**

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

### 23 **2.1 Energy-saving measures**

24 Japan, South Korea, and China have released a number of policies addressing energy  
25 conservation and climate change mitigation. Under the Kyoto Protocol, Japan committed to  
26 reduction of its greenhouse gas (GHG) emissions by 6% during 2008-2012 from the base year of  
27 1990. In the "New National Energy Strategy" formulated in May 2006, the Japanese government  
28 set a long-term target to improve energy intensity of GDP by an additional 30% by 2030 (IEA,  
29 2008). The government of South Korea has made a commitment to reduce its GHG emissions by

1 30% compared to its business as usual projection by 2020 (IEA, 2012b). The Chinese  
2 government has set a target to reduce CO<sub>2</sub> emissions per unit GDP by 40%-45% in 2020  
3 compared with 2005 levels (Wang and Hao, 2012). Total energy consumption in East Asia  
4 increased by 31% during 2005-2010. China experienced the fastest increase, 43%, driven by its  
5 rapid GDP growth rate, while Japan's energy consumption decreased during these five years due  
6 to a lower GDP growth rate and stringent energy-saving policies. The growth rate of South  
7 Korean energy consumption was intermediate between those of China and Japan, at 19%.

### 8 2.1.1 Power plants

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

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

28 China has also undertaken major efforts to improve the efficiency of coal-fired power  
29 generation. Its government forced the closure of 77 GW of small and inefficient coal-fired units

1 during 2006-2010 (NDRC, 2011), with an additional 20 GW of small units scheduled for early  
2 retirement during 2011-2015 (The State Council of the People's Republic of China, 2012). At the  
3 same time, the capacities of most new units built after 2005 have been  $\geq 300$  MW, driving their  
4 capacity share from 50% in 2005 to 73% in 2010 (The State Council of the People's Republic of  
5 China, 2012). The share of advanced supercritical and ultra-supercritical units, moreover, rose to  
6 over 13% (Li et al., 2012). As a result of these changes, the coal consumption per unit electricity  
7 supplied by thermal power plants decreased from 370 gce/kWh to 333 gce/kWh during the same  
8 period (The State Council of the People's Republic of China, 2012).

### 9 2.1.2 Industrial sector

10 During 2005-2010, the energy consumption of China's industrial sector increased dramatically, at  
11 an annual average rate of 9.0% (cf. 7.4% for total energy consumption), due largely to the rapid  
12 increase of energy-intensive products, e.g., cement and steel (NBS, 2007, 2011a). However,  
13 driven by a target to reduce energy intensity per unit GDP by 20% from 2005 to 2010, China  
14 mandated widespread replacement of outmoded production technologies with more energy-  
15 efficient ones. For example, the share of cement produced by precalciner kilns increased from  
16 45% in 2005 to about 80% in 2010. During the same period, the proportion of large units ( $\geq 4000$   
17 t/d) of all precalciner kilns increased from 33% to 60% (Zhao et al., 2013c; Zhao et al., 2013d).  
18 The share of coke produced in machinery coking ovens (versus indigenous ovens) increased from  
19 82% in 2005 to 87% in 2010 (NBS, 2007, 2011; Huo et al., 2012); the share of blast furnaces  
20 larger than 1000 m<sup>3</sup> increased from 48% to 61% over the same time period (The State Council of  
21 the People's Republic of China, 2012). In effect, the average energy intensity of cement and crude  
22 steel production decreased by 29% and 12%, respectively, from 2005 to 2010 (The State Council  
23 of the People's Republic of China, 2012).

24 While China's industrial sector has grown swiftly but only recently undertaken aggressive  
25 energy efficiency improvements, Japan's industrial sector has played a central role in national  
26 energy conservation for several decades (IEA, 2008). Major policies have included compulsory  
27 submission of energy-saving plans for large energy consumers, frequent on-site inspections, and  
28 subsidies to assist small companies to introduce energy-efficient equipment (IEA, 2008; Energy  
29 Conservation Center of Japan, 2011). These measures decreased the average energy consumption

1 per ton of production of cement and crude steel by 6.3% and 5.6%, respectively, from 2000 to  
2 2010 (Wang, 2010). Japan’s industrial energy use as a proportion of total energy use has declined  
3 from 26% in 2000 to 18% in 2010 (IEA, 2002, 2012c), and the share of coal and petroleum  
4 products of total energy consumption has decreased from 64% to 56% during 2000-2010 (IEA,  
5 2002, 2012c).

6 Industrial energy consumption in South Korea increased steadily in recent years, in part  
7 because its energy intensity (energy consumption per unit GDP) did not notably improve from  
8 the 1990s to 2006 (IEA, 2006). In 2008, South Korea set new targets for national energy intensity  
9 in its “Strategy for Green Growth”: from 0.328 toe/US\$1000 in 2007 to 0.290 toe/US\$1000 in  
10 2013, and 0.233 toe/US\$1000 in 2020. Enforcement of these policies is expected to occur mainly  
11 through “voluntary agreements” between the government and large companies (IEA, 2006, 2012b;  
12 UNEP, 2010).

### 13 2.1.3 Residential sector

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

19 By the end of 2006, 96% of China’s new buildings complied with the energy-saving design  
20 standard released in 1996 (THUBERC, 2009); this was succeeded by a more stringent standard in  
21 2010 (The State Council of the People’s Republic of China, 2012). The energy efficiency  
22 standards in Japan’s building codes, first released in 1980 and strengthened in 1992 and 1999,  
23 have all been voluntary. As of 2005, 30% of new houses and 85% of new buildings larger than  
24 2000 m<sup>2</sup> complied with the voluntary standards (IEA, 2008). In Korea, energy efficiency codes  
25 for buildings had long been relatively weak until a strong, performance-based design code  
26 applicable to large commercial buildings was issued in 2011 (IEA, 2006, 2012b).

27 Japan is a world leader in the energy efficiency of residential and commercial appliances. The  
28 “Top Runner program,” which set energy-efficiency targets for appliances based on the most  
29 energy-efficient products on the market, has been successfully enforced. For example, the



1 efficiency of air conditioners and refrigerators increased by 68% (over 1997-2004) and 55%  
2 (1998-2004), respectively, both exceeding the targets of 66% and 31% (IEA, 2008; Energy  
3 Conservation Center of Japan, 2011). Similar programs have recently been promoted in South  
4 Korea and China (UNEP, 2010).

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

#### 10 2.1.4 Transportation sector

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

15 The reduction in Japan's vehicle energy consumption is largely due to its fuel-efficiency  
16 standards, which are among the most aggressive in the world. For passenger vehicles, there was a  
17 consistent improvement in the average fuel economy from 13.5 km/L in 2000 to 17.8 km/L in  
18 2009 (Energy Conservation Center of Japan, 2011). Japan was also the first country in the world  
19 to implement fuel efficiency standards for heavy-duty (freight) vehicles, which decreased from  
20 851 kcal/t-km in 2000 to 722 kcal/t-km in 2008 (Institute of Energy Economics of Japan, 2010).  
21 China has also implemented fuel-efficiency standards for light-duty vehicles since 2004, leading  
22 to an increase in the efficiency of new gasoline passenger cars from 11.0 km/L in 2005 to 13.5  
23 km/L in 2010 (Zhao et al., 2013c). An updated standard (14.3 km/L by 2015) for passenger cars  
24 was issued in 2011. In 2006, the South Korean government introduced its first mandatory fuel-  
25 economy standards, requiring car manufacturers to meet average fuel economy standards of 12.4  
26 km/L for vehicles with engines of less than 1500 cubic centimeters (IEA, 2006). In July 2009, a  
27 new fuel-economy standard of 17 km/L was announced (IEA, 2012b).

28 China has also launched several initiatives to promote electric vehicles, and their population  
29 reached 12,000 by 2010 (Yang, 2012). The most recent development plan for new-energy

1 vehicles (issued in 2012) aimed to increase the population of electric vehicles to 0.5 million and 5  
2 million in 2015 and 2020, respectively, through a series of subsidy policies.

## 3 **2.2 End-of-pipe control measures**

### 4 2.2.1 Power plants

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

8 In 2006, China set a target to reduce national SO<sub>2</sub> emissions by 10% by 2010 over 2005 levels  
9 ([Wang and Hao, 2012](#)). By 2010, over 83% of coal-fired power plants (about 88% of pulverized  
10 coal combustion plants, representing 560 GW) had installed flue gas desulfurization (FGD) ([MEP,  
11 2011](#)). The recently released 12<sup>th</sup> Five-Year Plan aims at another 8% reduction in total SO<sub>2</sub>  
12 emissions by 2015, which would require nearly all coal-fired power plants to be equipped with  
13 high-efficiency FGD facilities (i.e., with at least 95% removal efficiency).

14 Low-NO<sub>x</sub> combustion technology (mainly Low-NO<sub>x</sub> Burners, LNB) was the major NO<sub>x</sub>  
15 control technology in China's coal-fired power plants by 2010. The penetration of flue gas  
16 denitrification (Selective Catalytic Reduction, SCR, and/or Selective Non-Catalytic Reduction,  
17 SNCR) was only 1.1% in 2005 and 12.8% in 2010 ([MEP, 2011](#)). In the 12<sup>th</sup> Five-Year Plan, the  
18 Chinese government aims to reduce the national NO<sub>x</sub> emissions by 10% from 2010 to 2015, and  
19 the key measures to meet this target is large-scale deployment of SCR/SNCR facilities. The NO<sub>x</sub>  
20 emission control policies are described in more detail in our previous paper ([Zhao et al., 2013c](#)).

21 The emission control of primary particulate matter in China's power sector has achieved  
22 noticeable progress in the last decade. Since 2003, all new and rebuilt units have to attain the in-  
23 stack concentration standard for PM of 50 mg/m<sup>3</sup> (GB13223-2003). As a result, over 92% of  
24 pulverized coal units had installed electrostatic precipitators (ESP) by 2005. In addition, fabric  
25 filters (FF) have been put into commercial use in recent years, and their penetration increased to  
26 7% by 2010 ([Zhao et al., 2013a](#)). Furthermore, the rapid deployment of wet-FGD also helped to  
27 reduce PM emissions due to its ancillary benefit on PM removal ([Zhao et al., 2010](#)). In 2011,  
28 China's Ministry of Environmental Protection (MEP) announced a revised in-stack concentration

1 standard for PM of 20 mg/m<sup>3</sup> for environmentally sensitive regions and 30 mg/m<sup>3</sup> for other  
2 regions.

3 In Japan, application of best-available technologies to control SO<sub>2</sub>, NO<sub>x</sub>, and PM is required  
4 for most power generation units across the country. The penetrations of wet-FGD, LNB+SCR  
5 and high-efficiency deduster (HED, e.g., FF and electrostatic-fabric integrated precipitator) are  
6 all over 90%, having increased slightly during 2005-2010 (Klimont et al., 2009).

7 In South Korea, FGD systems have been installed at most power generation units; the  
8 penetration increased slightly, from 95% to 97%, during 2005-2010. For NO<sub>x</sub>, SCR has been the  
9 dominant control technology, with its share increasing from 56% in 2005 to 68% in 2010. About  
10 one third of coal-fired power generation units had been equipped with HED systems by 2010, and  
11 the rest was equipped with ESP equipment (NIER, 2010; NIER 2013; Clean Air Policy  
12 Supporting System, CAPSS, <http://airemiss.nier.go.kr/>).

### 13 2.2.2 Industrial sector

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

16 In China, SO<sub>2</sub> and NO<sub>x</sub> control technologies have been rarely installed in the industry sector.  
17 In recent years, FGD units to control SO<sub>2</sub> have been installed at a small number of coal-fired  
18 boilers and sintering plants in selected regions. The application of NO<sub>x</sub>-control technologies is  
19 described in more detail in our previous paper (Zhao et al., 2013c). In contrast with SO<sub>2</sub> and NO<sub>x</sub>,  
20 China has been controlling PM emissions from industrial sources since late 1980s; the emission  
21 standards for industrial sources, however, were updated only gradually until 2010 (see details in  
22 Lei et al., 2011). The 11<sup>th</sup> Five-Year Plan promoted high-efficiency FF in some high-emission  
23 industries. Most industrial boilers were historically equipped with wet scrubbers (WET) and  
24 cyclone dust collectors (CYC), while penetration of high-efficiency FF began recently (Lei et al.,  
25 2011; Zhao et al., 2013a). Blast furnaces in China are usually equipped with washing towers and  
26 double venturi scrubbers, which have approximately the same removal efficiency as the  
27 combination of ESP and WET. ESP and FF had gradually become the major control technologies  
28 applied at cement plants, sintering plants and basic oxygen furnaces by 2010, while large

1 numbers of electric arc furnaces and coking ovens were still equipped with WET (Lei et al., 2011;  
2 Zhao et al., 2013a).

3 The only control measures for NMVOC emissions in China's industry sector are associated  
4 with fossil-fuel exploitation and distribution. Emission standards for gasoline distribution  
5 released in 2007 require: (1) installation of vapor-recovery systems and modified loading  
6 techniques (Stage IA control) for loading and unloading operations; (2) improvement in the  
7 service station tank (Stage IB control) and installation of a vapor-balancing system between a  
8 vehicle and service station tank (Stage II control); (3) installation of internal floating covers (IFC)  
9 or secondary seals for newly-built or retrofitted storage tanks. These standards were scheduled to  
10 be implemented in relatively large cities of "key regions" (areas defined by the government as  
11 environmentally sensitive, including the Greater Beijing region, the Yangtze River Delta, and the  
12 Pearl River Delta) from 2008-2010 onwards, and in relatively large cities in other provinces from  
13 2012-2015 onwards. We estimated that vapor-recycling systems had been installed at about 15%  
14 of all gasoline storage and distribution operations by 2010 (see Table 4 for details).

15 In Japan, industrial emissions are limited strictly by the Air Pollution Control Act. The  
16 thresholds have changed only very slightly since 1995, but are still among the most stringent in  
17 the world (Ministry of the Environment of Japan, 2013). Under such strict regulations, the vast  
18 majority of blast furnaces, basic oxygen furnaces, electric arc furnaces, and cement kilns are  
19 controlled with HEDs. The PM control portfolio for industrial boilers, sintering plants, glass  
20 production plants, and coke ovens is typically a mix of ESPs and HEDs. Effective SO<sub>2</sub> removal  
21 technologies (70-80% removal efficiency) are applied in various industries, including sintering,  
22 cement production, coke ovens, sulfuric acid production, and a number of lesser production  
23 processes (Gains-Asia model of the International Institute for Applied System Analysis, IIASA,  
24 <http://gains.iiasa.ac.at/models/>). The average efficiency of such removal equipment increased  
25 gradually as old facilities were retired. The dominant controls for NO<sub>x</sub> emissions as of 2010 were  
26 low-NO<sub>x</sub> combustion technologies; flue gas denitrification has not been widespread due to  
27 relatively high cost.

28 Emission standards for industrial sources in South Korea are generally less stringent than  
29 those of Japan but more stringent than those of China (Ministry of Environment of South Korea,  
30 2013). In contrast with Japan, the PM control portfolio for cement kilns is an equal mix of ESPs

1 and HEDs; ESPs still dominate PM removal for industrial boilers and sintering machines, and  
2 HEDs are not widely applied. FGD systems were widely applied at some high-emitting sources  
3 such as industrial boilers and sintering plants by 2010, with penetrations of 85% and 100%,  
4 respectively, (NIER, 2013; NIER 2010). Similar to Japan, the dominant control measures for  
5 NO<sub>x</sub> emissions were low-NO<sub>x</sub> combustion technologies by 2010.

### 6 2.2.3 Residential sector

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

11 Compared with boilers, emissions from small stoves are more difficult to control. In Japan,  
12 small incinerators dwindled rapidly in the last decade due to a 2000 regulation designed to  
13 mitigate dioxin pollution (Ministry of the Environment of Japan, 2013; Wakamatsu et al., 2013).  
14 A previous study found briquette stoves have lower emission factors for SO<sub>2</sub> and PM (Lei et al.,  
15 2011). We estimate briquette use accounted for 6-7% of total residential coal consumption in  
16 China during 2005-2010 (NBS, 2007, 2008a, b, 2009, 2011a, b). Emissions from small stoves can  
17 be further reduced by switching to new technologies, e.g., those using catalyst or non-catalyst  
18 inserts and/or primary and secondary air deflectors. These types of improved stoves have been  
19 spreading gradually in Japan and Korea (see Table 3).

### 20 2.2.4 Transportation sector

21 China has issued a series of emission standards for new vehicles and engines based on the  
22 European Union (EU) “Euro” Standards since 2000; the implementation years and penetrations  
23 of major emission standards are shown in Figure 1 and Table 5. At the national level, Euro I, II,  
24 and III standards began to be put into effect in 2000, 2004, and 2007, respectively. The Euro IV  
25 standard for light-duty vehicles was implemented in 2011. The Euro IV standard for heavy-duty  
26 diesel vehicles was originally planned for implementation in 2010, but was postponed until July  
27 2013 by the MEP due largely to an insufficient supply of low-sulfur fuel (Wu et al., 2012).  
28 Megacities including Beijing and Shanghai are subject to greater pressure for regulating vehicle  
29 emissions, and are therefore 2-3 years ahead of the national regulation. Recently, the Beijing

1 Environmental Protection Bureau announced enforcement of Euro V in 2012 and Euro VI in  
2 2016. Aside from regulations for new vehicles, emission reductions are also achieved with  
3 control of in-use vehicle emissions and improvement of fuel quality (Wang and Hao, 2012).

4 Japan's emission standards for new vehicles have been among the most stringent in the world.  
5 Since the introduction of the first regulation in 1981, the standards have been repeatedly  
6 strengthened. For light-duty vehicles, the prevailing emission standard for NO<sub>x</sub> and NMVOC  
7 during 2005-2010 (under the "New Long-term Regulation") was comparable to that in U.S. (Tier  
8 II), and more stringent than that of the EU (Euro IV) before Euro V took effect in the second half  
9 of 2009. A more recent "Post New Long-term Regulation" released in 2009 added a limit for PM  
10 comparable to U.S. Tier II, while maintaining the prior limits for other pollutants. For heavy-duty  
11 vehicles, Japan's NO<sub>x</sub> emission regulations before 2005 had been stricter than those of Europe  
12 and U.S. (Japan Automobile Manufacturers Association, 2011). During 2005-2010, Japan's  
13 prevailing standard was comparable to Euro V (issued in 2008), and between the 2004 and 2007  
14 standards of the U.S. By the early 2010s, European, U.S. and Japanese regulatory values for NO<sub>x</sub>  
15 and PM emissions for diesel vehicles have been roughly similar (Ministry of the Environment of  
16 Japan, 2013; Delphi Company, 2013a, b).

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

25 The penetrations of vehicle emission standards in Japan and South Korea are given in Table 5.

### 26 2.2.5 Solvent use

27 The Chinese government has released standards to limit the solvent content of some products,  
28 including wood paint, interior wall paint, adhesives for shoe production, decorative adhesives,  
29 and printing inks. Driven by these standards, the solvent content of some products declined, and

1 the penetration of low-solvent products increased during 2005-2010. Table 6 and Table S2 show  
2 the penetrations of major control measures for solvent use; Table S3 shows the changes in the  
3 emission factors of typical sources (especially regulated ones) during 2005-2010. Despite the  
4 existing standards, most emissions from solvent use remain uncontrolled in China.

5 In 2004, Japan's Ministry of Environment set a target to reduce NMVOC emissions by 30%  
6 from 2000 levels by 2010 using both regulations (10%) and voluntary efforts (20%), with a focus  
7 on emissions from solvent use ([Ministry of the Environment of Japan, 2013](#)). The actual  
8 reductions are estimated to be higher, but the O<sub>3</sub> and PM concentrations have not declined as  
9 expected ([Wakamatsu et al., 2013](#)).

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

### 15 **2.3 Effect of control measures on recent emission trends**

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

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

1 estimation of China's emissions (JPEC, 2012a).

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

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

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

### 16 2.3.1 NO<sub>x</sub>

17 The total NO<sub>x</sub> emissions in East Asia were 29.7 Mt in 2010 and the growth rate was 25% during  
18 2005-2010. This trend was dominated by the increase in emissions from China, which  
19 contributed 82-88% of total NO<sub>x</sub> emissions in East Asia.

20 During this period, NO<sub>x</sub> emissions in China increased by 34%, driven by the rapid increase of  
21 industry and transportation. The emissions from power plants stopped growing by 2010 due to  
22 the application of LNBS and penetration of non-fossil energy sources in the sector. But emissions  
23 from industry and transportation continued to grow rapidly due to swiftly expanding industrial  
24 energy consumption and vehicle populations.

25 NO<sub>x</sub> emissions from the rest of East Asia decreased by 13% during the five years, mainly  
26 attributed to a 21% reduction in emissions from Japan due chiefly to the implementation of tight  
27 emission standards for new vehicles. The emissions of South Korea decreased slightly, by 5%,  
28 for the same reason.



### 1 2.3.2 SO<sub>2</sub>

2 The total SO<sub>2</sub> emissions in East Asia decreased by 15%, from 30.4 Mt in 2005 to 25.9 Mt in 2010,  
3 with both China and the rest of East Asia experiencing the same 15% rate of decline and Chinese  
4 emissions accounting for as much as 94% of the regional total.

5 The decline in China's SO<sub>2</sub> emissions is mainly attributable to the widespread deployment of  
6 FGD at power plants, even as emissions from China's industrial sector continued to rise during  
7 this period; this is consistent with the recent estimates by [Zhang et al. \(2012b\)](#), [Lu et al. \(2011\)](#),  
8 [Klimont et al. \(2013\)](#).

9 SO<sub>2</sub> emissions of Japan decreased by 20%, mainly attributed to the increasing penetration of  
10 higher-efficiency desulfurization technologies in the industrial sector, and the replacement of coal  
11 and oil with cleaner energy sources. South Korea's SO<sub>2</sub> emissions remained roughly constant,  
12 because the reduction of the emissions from power plants (due to the deployment of FGDs) was  
13 offset by the increasing emissions from industrial sources.

### 14 2.3.3 PM<sub>10</sub> and PM<sub>2.5</sub>

15 In 2010, the total PM<sub>10</sub> and PM<sub>2.5</sub> emissions in East Asia were 16.8 Mt and 12.5 Mt, respectively,  
16 decreasing 15% and 12% from 2005 levels. This trend was also dominated by emission trends in  
17 China, as its PM<sub>10</sub> and PM<sub>2.5</sub> emissions represent about 94% of those of East Asia.

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

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

#### 1 2.3.4 NMVOC

2 The total NMVOC emissions in East Asia were 25.9 Mt in 2010, reflecting 15% growth over  
3 2005 levels, an integrated effect of a 21% increase in emissions from China (contributing 84-88%  
4 of the total emissions) and a 17% reduction in emissions from other countries.

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

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

#### 14 **2.4 Uncertainty analysis**

15 A Monte Carlo uncertainty analysis was performed on the emission inventories of East Asia  
16 during 2005-2010, following the methodology described in [Bo et al. \(2008\)](#) and [Wei et al. \(2008\)](#).  
17 Table S5 shows the calculated uncertainties by sector.

18 During 2005-2010, the average 90% confidence interval of the total NO<sub>x</sub> emissions is [-31%,  
19 44%]. The coefficient of variation (CV) is  $\pm 25\%$  on average. The uncertainties of emissions  
20 vary with emission sectors (see Table S5), attributable to the different magnitudes of  
21 uncertainties associated with activity levels and emission factors. Biomass open burning has the  
22 largest CV ( $\pm 177\%$ ) because both the activity levels and the emission factors are quite uncertain.  
23 The transportation sector has the second highest uncertainty (CV=  $\pm 66\%$ ), as its fuel  
24 consumption is calculated from vehicle population, annual average mileage travelled, and fuel  
25 economy, rather than the energy statistics.

26 The average 90% confidence interval and CV of the total SO<sub>2</sub> emissions are [-29%, 45%] and  
27  $\pm 28\%$ , respectively, during 2005-2010. Similar to that of NO<sub>x</sub> emissions, the SO<sub>2</sub> emissions  
28 from biomass open burning have the highest uncertainty (CV=  $\pm 179\%$ ). The uncertainties of the

1 industrial, residential, and transportation sectors are quite close to each other, with CVs at a range  
2 of  $\pm 48\%$ - $\pm 51\%$ .

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

8 The average 90% confidence interval and CV of the total NMVOC emissions are  $[-42\%, 67\%]$   
9 and  $\pm 42\%$ , respectively. The “other sectors”, which include biomass open burning, waste  
10 treatment, cooking, and smoking, with biomass open burning contributing over 80% of NMVOC  
11 emissions, have the highest uncertainty (CV= $\pm 184\%$ ), followed by solvent use (CV= $\pm 78\%$ ),  
12 for which the activity levels are not directly available from statistics and the emission factor  
13 measurements are lacking. The CVs for the industrial, residential, and transportation sectors are  
14 all within the range of  $\pm 57\%$ - $\pm 65\%$ .

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

### 22 **3 Future emission scenarios for air pollutants**

23 To quantify the effects of various measures on future air pollutant emissions, in this study we  
24 developed emission scenarios for  $SO_2$ ,  $NO_x$ , PM, and NMVOC based on energy-saving policies  
25 and end-of-pipe control strategies. The scenarios are developed with the same model structure as  
26 that for the estimation of historical emissions developed in our previous paper (Zhao et al.,  
27 2013c). The energy service demand is estimated based on driving forces (e.g., GDP and  
28 population). The future technology distribution and energy efficiencies are assumed and the  
29 energy consumption is calculated accordingly. Both historical and future emissions are derived

1 from energy consumption, emission factors, and assumptions on the penetration of control  
2 technologies. For details, see [Zhao et al. \(2013c\)](#).

3 We developed two energy scenarios, a business as usual scenario (BAU) and an alternative  
4 policy scenario (PC). The BAU scenario is based on current regulations and implementation  
5 status (as of the end of 2010). In the PC scenario, we assume the introduction and strict  
6 enforcement of new energy-saving policies, including ones leading to a more energy-conserving  
7 lifestyle, structural adjustment, and energy efficiency improvement. Energy-conserving lifestyle  
8 implies a slower growth of energy service demand, including energy-intensive industrial products,  
9 building area and residential services, vehicle population, electricity production, and heat supply.  
10 Structural adjustment includes promotion of clean and renewable fuels and energy-efficient  
11 technologies. Examples include: renewable energy sources and CHP for power plants and heat  
12 supply; arc furnaces and large precalciner kilns for the industrial sector; biogas stoves and heat  
13 pumps for the residential sector; and electric and biofuel vehicles for the transportation sector.  
14 Assumed energy efficiency improvement targets individual technologies in each sector.

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

26 In this paper we focus on the development of energy scenarios and emission scenarios for  
27 China. The scenarios for other countries are adapted from those developed by IIASA in a project  
28 funded by United Nations Environment Programme (UNEP) and World Meteorological  
29 Organization (WMO) ([UNEP and WMO, 2011](#)). Both the energy consumption and air pollutant  
30 emissions were calculated with a 5-year time step, although the parameters and results are

1 presented for selected years only. Detailed assumptions of the energy scenarios and emission  
2 scenarios are documented below.

### 3 **3.1 Development of energy scenarios**

4 For countries other than China, our BAU and PC scenarios are consistent with the energy  
5 pathways of the reference and 450-ppm scenarios in [UNEP and WMO \(2011\)](#), which were based  
6 on the reference and 450-ppm scenarios presented in the World Energy Outlook 2009 ([IEA,](#)  
7 [2009](#)), respectively. While the reference scenario is based on current energy and climate-related  
8 policies, the 450-ppm scenario explores the global energy consumption if countries take  
9 coordinated action to restrict the global temperature increase to 2°C. The details of energy  
10 scenarios are described in [UNEP and WMO \(2011\)](#) and [IEA \(2009\)](#).

11 For China, we have developed two energy scenarios that are consistent our previous paper  
12 ([Zhao et al., 2013c](#)). Presented below is a brief description of the assumptions and results of the  
13 energy scenarios; see [Zhao et al. \(2013c\)](#) for detailed information. Note that because that paper  
14 focused on the emission trends of NO<sub>x</sub>, it did not project activity data in terms of fossil fuel  
15 distribution (included in the industrial sector for this study) nor the use of solvents. These two  
16 projections are incorporated below.

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

22 The total electricity production is projected to be 10%-12% lower in the PC scenario than that  
23 of the BAU senario. The PC scenario considers aggressive development plans for clean and  
24 renewable energy power generation; therefore, the proportion of electricity production from coal-  
25 fired power plants is expected to decrease to 57% in 2030 in the PC scenario, contrasted with  
26 73% in the BAU scenario.

27 We used elasticity coefficient method to estimate future production of industrial products.  
28 Production of most energy-intensive commodities used in construction of infrastructure are  
29 expected to increase until 2020, and then to stabilize or even decline after 2020, whereas products

1 associated with household consumption are expected to increase through 2030, although at a  
2 declining rate. We projected lower production of industrial products in the PC scenario than those  
3 of the BAU scenario because of more energy-conserving lifestyles. The penetrations of less  
4 energy-intensive technologies are assumed to be higher in the PC scenario than the BAU scenario.

5 For the residential sector, China's building area per capita in the PC scenario is expected to be  
6 3-4 m<sup>2</sup> lower than that of the BAU scenario in both urban and rural areas. The heating energy  
7 demand per unit area is somewhat lower in our PC scenario because of the implementation of  
8 new energy-conservation standards in the design of buildings. Replacement of coal and direct  
9 biomass burning with clean fuels are assumed in both urban and rural areas, with faster progress  
10 in the PC scenario.

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

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

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

$$23 \quad A_{t1} = \sum_j \left( A_{t0,j} \times \frac{Y_{t1,j}}{Y_{t0,j}} \right) \quad (1)$$

24 where,  $t0$ ,  $t1$  are time periods, e.g.,  $t0=2010$ , and  $t1=2030$ ;  $j$  represents the industries using a  
25 specific solvent product;  $A_{t1}$  is the consumption of this solvent product in the year  $t1$ ;  $A_{t0,j}$  is the  
26 consumption of this solvent product in industry  $j$  in the year  $t0$ ;  $Y_{t0,j}$  and  $Y_{t1,j}$  are the yields of  
27 the major products (e.g., crude steel for the iron and steel industry) for industry  $j$  in the year  $t0$

1 and  $\epsilon_1$ , respectively. The yields of industrial products were projected using the elasticity  
2 coefficient method as described above.

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

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

24 By 2030, the energy consumption of East Asia other than China is projected to increase  
25 slightly by 12% and 2% over the 2010 level in the BAU and PC scenarios, respectively. Under  
26 current policies, Japan's energy consumption is projected to increase very slightly by 2% from  
27 2010 to 2030, because of slow economic growth rate and a trend towards higher energy  
28 efficiency resulting from current legislation. Under implementation of low-carbon policies  
29 intended to limit CO<sub>2</sub> concentrations to 450 ppm, Japan's energy consumption would be reduced  
30 by 6% by 2030 over the 2010 level. This reduction is mainly attributed to the decline in energy

1 consumption of the transportation sector, resulting from improved fuel economy and reduced  
2 mileage travelled. By 2030, South Korea's energy consumption is expected to increase by 26%  
3 and 15% over the 2010 level under the two energy scenarios, respectively. Similar to China, there  
4 are also evident trends towards clean and renewable energy in Japan and South Korea. For  
5 example, from 2010 to 2030, the shares of coal and petroleum products in Japan's energy  
6 consumption are expected to decrease from 22% and 40% to 20% and 31% under the BAU  
7 scenario, respectively, and to 12% and 29% under the PC scenario. In contrast, the proportion of  
8 renewable energy would increase from 16% in 2010 to 23% and 33% in 2030 under the BAU and  
9 PC scenarios, respectively.

## 10 **3.2 Development of emission control scenarios**

11 For the countries other than China, our control strategies [0] and [2] are consistent with the  
12 control strategies of the reference scenario and the maximum feasible reduction scenario in  
13 [UNEP and WMO \(2011\)](#), respectively. While control strategy [1] assumes new pollution control  
14 policies would be implemented progressively in China, it has the same assumptions as control  
15 strategy [0] for the other countries for the following reasons: (1) China accounts for 88%, 94%,  
16 94%, 95%, and 88% of the total NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, and NMVOC emissions in East Asia in  
17 2010; (2) Japan and South Korea already have stringent environmental policies in the base year,  
18 and the progressive control strategy for countries other than China will have negligible effect on  
19 the regional outcomes. The major assumptions underlying control strategies [0] and [2] are  
20 straightforward: [0] assumes current regulations and implementation status, as already  
21 documented in detail in Sect. 2.2, while [2] assumes full application of best-available  
22 technologies in the world. Therefore, in the following text, we will focus on the assumptions for  
23 China and omit details for other countries. The penetrations of major control technologies in  
24 China, Japan, and South Korea are summarized in Table 2 through Table 5.

### 25 **3.2.1 Power plants**

26 As documented in Sect. 2.2.1, the recently released 12<sup>th</sup> Five-Year Plan set specific targets and  
27 proposed detailed technological roadmaps for the reduction of SO<sub>2</sub> and NO<sub>x</sub> emissions from  
28 power plants. The government did not set a total PM emission target, but rather a strict in-stack  
29 PM concentration standard in 2011 (30 mg m<sup>-3</sup> for the whole country and 20 mg m<sup>-3</sup> for key



1 regions, as defined in Sect. 2.2.2). Power plants burning coal with low ash content could attain  
2 the 30 mg m<sup>-3</sup> threshold by installing ESP and wet-FGD simultaneously. For units burning coal  
3 with high ash content, or when the 20 mg m<sup>-3</sup> threshold applies, HEDs (including FFs and  
4 electrostatic-fabric integrated precipitators) would be the only commercially available control  
5 technology.

6 The BAU[0]/PC[0] scenarios consider only the control policies released before the end of  
7 2010. In other words, NO<sub>x</sub> and PM emissions are mainly controlled with LNB and ESP,  
8 respectively. The penetration of FGD would increase quite slowly. The BAU[1]/PC[1] scenarios  
9 are based on the 12<sup>th</sup> Five-Year Plan (including the 2011 emission standard for 2011-2015) and  
10 the assumption that high-efficiency control technologies will continue to spread gradually after  
11 2015. The penetration of FGD in coal-fired units is assumed to approach 100% by 2015. All  
12 newly built thermal power plants will be equipped with low-NO<sub>x</sub> combustion technologies and  
13 flue gas denitrification (SCR or SNCR) from 2011 onwards. Existing thermal power plants will  
14 be upgraded with low-NO<sub>x</sub> combustion technologies, and large units ( $\geq 300$  MW) will be  
15 upgraded with SCR or SNCR during 2011-2015. SCR and SNCR will gradually penetrate to  
16 smaller units after 2015. More ambitious measures will be required in the key regions. For PM,  
17 HED will spread much more rapidly, with its share in coal-fired units approaching 35% and 50%  
18 in 2020 and 2030, respectively. In the BAU[2]/PC[2] scenarios, the best-available technologies  
19 (i.e., FGD, LNB+SCR, and HED for PM) are assumed to be fully applied by 2030. Table 2 gives  
20 the national average penetration of control technologies. Note that the penetrations in the key  
21 regions are usually larger than those of other regions.

### 22 3.2.2 Industrial sector

23 The latest national emission standard for industrial boilers was released in 2001 (GB13271-2001),  
24 although several provinces including Beijing and Guangdong have recently issued local standards.  
25 As the BAU[0]/PC[0] scenarios are based only on current regulations, i.e., nearly no measures  
26 implemented to control SO<sub>2</sub> and NO<sub>x</sub> emissions, and WET remains dominant control technology  
27 for PM emissions. The BAU[1]/PC[1] scenarios are based on the 12<sup>th</sup> Five-Year Plan during  
28 2011-2015; progressive control measures would be enforced after 2015 as an extension of the  
29 12<sup>th</sup> Five-Year Plan. For SO<sub>2</sub>, FGDs are assumed to be widely deployed, penetrating 20%, 40%,

1 and 80% of the total capacity by 2015, 2020, and 2030, respectively. For NO<sub>x</sub>, LNB will be  
2 required at newly built industrial boilers, and existing boilers in the key regions will begin to be  
3 retrofitted with LNB during 2011-2015. The vast majority of existing boilers are expected to be  
4 equipped with LNB by 2020. For PM, ESP and HED will be gradually deployed to replace the  
5 less-efficient WET. In the BAU[2]/PC[2] scenarios, the most efficient removal technologies,  
6 including FGD, LNB+SCR, and HED, will be fully applied.

7 The emissions from industry processes (i.e., other than boilers) were mainly regulated by the  
8 “Emission Standard for Industrial Kilns and Furnaces” before 2010. Standards for specific  
9 industries were only issued for cement plants (GB4915- 2004) and coking ovens (GB16171-  
10 1996). However, new emission standards for a variety industries were rapidly issued during  
11 2010-2012, which may significantly alter their future emission pathways.

12 A series of new emission standards for the iron and steel industry were released in 2012,  
13 including the standards for sintering, iron production, steel production, steel rolling, and other  
14 processes. Sintering is the main source of SO<sub>2</sub> and NO<sub>x</sub> emissions in the iron and steel industry,  
15 and also an important source of PM emissions. Wet-FGDs are required to be installed in order to  
16 attain the SO<sub>2</sub> concentration standard, and the 12<sup>th</sup> Five-Year Plan also requires large-scale  
17 deployment of FGD. The threshold for NO<sub>x</sub> concentration can be attained without additional  
18 control technologies, but the 12<sup>th</sup> Five-Year Plan requires newly built sintering facilities to be  
19 equipped with SCR or SNCR. Most sintering plants can meet the PM threshold with  
20 simultaneous installation of FGD and ESP, but HED is required for those in key regions and  
21 those with poor raw material quality. The BAU[0]/PC[0] scenarios assume continuation only of  
22 the control regulations as of 2010. The BAU[1]/PC[1] scenarios are developed on the basis of the  
23 2012 standard and the 12<sup>th</sup> Five-Year Plan. FGD would be installed at most sintering facilities  
24 and SCR or SNCR at newly built ones during 2011-2015; the penetrations would increase  
25 gradually afterwards. While ESP remains the dominant PM-removal technology, HED is  
26 assumed be deployed gradually. FGD, SCR, and HED would be fully applied in the  
27 BAU[2]/PC[2] scenarios. The blast furnaces (for pig iron production) in China are usually  
28 equipped with washing tower and double venturi scrubbers, which remains the best-available  
29 technology nowadays. The 2012 emission standard for steel production (with basic oxygen  
30 furnace and electric arc furnace being the major technology) implies that low-efficient WET

1 should be phased out, and HED needs to be installed for newly built facilities. While  
2 BAU[0]/PC[0] assume the emission standard before 2010, BAU[1]/PC[1] assume the retirement  
3 of WET and gradual promotion of HED, according to the 2012 emission standard. BAU[2]/PC[2]  
4 assume full utilization of HED.

5 Current emission standards for the cement industry were released in 2004. The SO<sub>2</sub> and NO<sub>x</sub>  
6 standards can be met without additional control measures, and the PM standard can be met with  
7 both ESP and HED. Therefore, we assume the control technology mix of 2010 would remain the  
8 same as in the BAU[0]/PC[0] scenarios. In 2012, MEP published a draft new emission standard  
9 for public comment. As cement clinker can absorb most SO<sub>2</sub> produced due to its basic chemistry,  
10 even the strengthened SO<sub>2</sub> limit may be attained under favorable technical conditions. The  
11 attainment of the NO<sub>x</sub> limit requires upgrading with low-NO<sub>x</sub> combustion technology for  
12 existing kilns (or installation of SNCR as an alternative), and simultaneous utilization of low-  
13 NO<sub>x</sub> combustion technology and SNCR/SCR for new kilns. The BAU[1]/PC[1] scenarios are  
14 based on the 2012 draft standard and the 12<sup>th</sup> Five-Year Plan. Newly built precalciner kilns  
15 (mostly  $\geq$  4000 t/d) are required to be equipped with SCR/SNCR, and existing precalciner kilns  
16 should be retrofitted with low-NO<sub>x</sub> combustion technology during 2011-2015. SCR/SNCR is  
17 assumed to continue to spread gradually after 2015. HED would be deployed gradually to meet  
18 the strengthened PM threshold for new kilns. The BAU[2]/PC[2] scenarios assume full  
19 application of desulfurization facilities, LNB+SCR, and HED.

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

28 As for glass production, the BAU[0]/PC[0] scenarios assume no control measures for SO<sub>2</sub>  
29 and NO<sub>x</sub> emissions, and the current mix of PM removal technologies. The BAU[1]/PC[1]  
30 scenarios are designed according to the new emission standard released in 2011, though enforced

1 leniently because of difficulty in implementation. FGD, as well as end-of-pipe NO<sub>x</sub> control  
2 technologies, typically oxy-fuel combustion technology (OXFL) or SCR, would be applied  
3 gradually at both existing and new plants. Outdated PM removal technologies, e.g. WET, would  
4 be phased out. For the brick industry, emissions from about 30% of plants remain uncontrolled in  
5 2010. A draft new emission standard in 2009 calls for a PM removal efficiency of over 60% at  
6 existing plants, and over 80% at new plants. In the BAU[1]/PC[1] scenarios, PM emissions from  
7 brick plants are assumed to be controlled according to the standard, though enforced leniently due  
8 to difficulty in inspections.

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

14 In the BAU[0]/PC[0] scenarios, we assume the emission standards for gasoline distribution  
15 (GB20950, GB20951, and GB20952) would continue to be enforced in the future. In the  
16 BAU[1]/PC[1] scenarios, the enforcement of Stage IA, Stage IB, and Stage II controls would be  
17 extended to the whole China, and IFC would be applied for both newly built and existing storage  
18 tanks. In addition, similar control technologies would be applied for crude oil distribution. As a  
19 result, the application rate of IFC, Stage IA, and Stage IB+Stage II control measures in gasoline  
20 storage and distribution would approach 75% and 100% by 2020 and 2030, respectively. The  
21 application rate in crude oil distribution would be 25% and 50% by 2020 and 2030, respectively  
22 (see Table 4). For the BAU[2]/PC[2] scenarios, these control measures would be fully applied by  
23 2030.

24 For other industries with NMVOC emissions, nearly no control measures are assumed for the  
25 BAU[0]/PC[0] scenarios. In the BAU[1]/PC[1] scenarios, we assume that new NMVOC emission  
26 standards (similar to or slightly less stringent than the EU Directives 1999/13/EC and  
27 2004/42/EC, depending on specific industry) will be released and implemented in key regions as  
28 of 2015, and in other provinces as of 2020. Afterwards, the emission standards will become more  
29 stringent gradually (see Table 4). In terms of technologies, we assume application of basic  
30 management techniques (e.g., leakage detection and repair system for refineries and improved

1 solvent management in paint production) where they are applicable. End-of-pipe controls  
2 (condensation, adsorption, absorption, and incineration) are adopted when high removal rate is  
3 required. The penetration of selected control measures assumed for key sources are summarized  
4 in Table 4.

### 5 3.2.3 Residential sector

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

### 14 3.2.4 Transportation sector

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

### 25 3.2.5 Solvent use and biomass open burning

26 For emissions from solvent use, the BAU[0]/PC[0] scenarios consider only several national  
27 standards limiting the NMVOCs content of some solvent products (see Sect. 2.2.5). Major  
28 assumptions for the BAU[1]/PC[1] scenarios are consistent with the NMVOC emission sources  
29 in the industrial sector, i.e., implementation of the EU Directives 1999/13/EC and 2004/42/EC as

1 of 2015-2020, followed by gradually strengthened regulations afterwards. Potential mitigation  
2 measures to attain the European standards differ greatly for different emissions sources because  
3 of various spraying technologies and chemical properties of the solvent used. However, similar to  
4 the industrial sources, these measures can be categorized into two kinds: use of environmentally  
5 friendly substitutes (e.g., water-based, or UV products) or end-of-pipe control technologies.  
6 Substitution measures are assumed where applicable, while end-of-pipe control technologies  
7 would be mainly installed in the newly-built factories. The penetration of selected control  
8 measures assumed for key sources are summarized in Table 6.

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

### 10 **3.3 Future emission trends and effects of control measures**

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

#### 15 **3.3.1 NO<sub>x</sub>**

16 Under current regulations and implementation status (the BAU[0] scenario), NO<sub>x</sub> emissions in  
17 East Asia are projected to increase by 28% in 2030 from the 2010 levels. The implementation of  
18 assumed energy-saving measures (reflected by the difference between the BAU[0] and the PC[0]  
19 scenario) and progressive end-of-pipe control measures (reflected by the difference between the  
20 PC[0] and the PC[1] scenario) are expected to reduce NO<sub>x</sub> emissions by 28% and 36%,  
21 respectively, from the baseline projection (the BAU[0] scenario). With the enforcement of  
22 maximum feasible reduction measures (the PC[2] scenario), the remaining emissions account for  
23 only 21% of the baseline projection, or 27% of the 2010 levels.

24 China's growth potential under current regulations (36%) is significantly larger than the  
25 average of East Asia (28%), resulting from a great increase in energy consumption and weak  
26 existing control measures. The share of China in East Asia's NO<sub>x</sub> emissions would increase to  
27 93% under the baseline projection. The enforcement of energy-saving measures (the PC[0]  
28 scenario) leads to a 29% reduction from the baseline projection. With the implementation of the  
29 12<sup>th</sup> Five Year Plan and slowly strengthened end-of-pipe control policies after 2015 (reflected by

1 the difference between the PC[0] and the PC[1] scenario), China's NO<sub>x</sub> emissions could be  
2 reduced by nearly 40% (compared to the baseline projection). The most effective control  
3 measures are the installation of SCR and SNCR and the application of stringent vehicle standards,  
4 which together contribute nearly 80% of this reduction. The maximum feasible control measures  
5 (the PC[2] scenario) could reduce China's NO<sub>x</sub> emissions to 20% of the baseline projection, or  
6 28% of the 2010 levels. It should be noted that the NO<sub>x</sub> emissions are projected at 22.9 Mt in  
7 2015 under the BAU[1] scenario, 12.2% lower than that of 2010. This implies that if the control  
8 policies in the 12<sup>th</sup> Five-Year Plan can be implemented successfully (as assumed in the BAU[1]  
9 scenario), the national target to reduce the NO<sub>x</sub> emissions by 10% during 2011-2015 would be  
10 achieved.

11 Under current regulations and implementation status, the NO<sub>x</sub> emissions in East Asia other  
12 than China are expected to decrease by 27%, with especially rapid decline in Japan (47%) and  
13 South Korea (34%). The decrease is mainly attributable to the continuously increasing proportion  
14 of vehicles subject to stringent emission standards. With the enforcement of energy-saving  
15 policies intended to limit global temperature increase to 2°C (reflected by the difference between  
16 the BAU[0] and the PC[0] scenario), NO<sub>x</sub> emissions in East Asia outside of China, and of the  
17 two major energy consumers therein (Japan and South Korea), are all expected to decline by  
18 15%-17% in 2030 compared with the baseline projection. These policies are most effective in the  
19 power sector, due to negligible emissions from renewable and nuclear power generation  
20 compared with traditional coal-fired power. The full application of maximum feasible control  
21 measures (the PC[2] scenario) would reduce the NO<sub>x</sub> emissions in East Asia except China, and  
22 Japan and South Korea individually to only 30%, 46% and 30% of the baseline projection, or  
23 22%, 24% and 20% of the 2010 levels, respectively.

### 24 3.3.2 SO<sub>2</sub>

25 The SO<sub>2</sub> emissions in East Asia are predicted to grow 24% from 2010 to 2030 under current  
26 regulations and implementation status (the BAU[0] scenario). The enforcement of advanced  
27 energy-saving measures (the PC[0] scenario) could lead to a substantial 36% reduction in SO<sub>2</sub>  
28 emissions from the baseline projection, exceeding the effect of progressively implemented end-  
29 of-pipe control measures, 25% (reflected by the difference between the PC[0] and the PC[1]

1 scenario). FGD facilities had been intensively deployed by 2010 in most industrial sources of  
2 Japan and in the power plants of China and South Korea. Therefore, the reduction potential  
3 through the installation of end-of-pipe control technologies will likely decline in the future,  
4 spotlighting the importance of energy-saving measures for further reduction of SO<sub>2</sub> emissions.  
5 With the full application of best-available technologies (the PC[2] scenario), the remaining SO<sub>2</sub>  
6 emissions in East Asia would account for only 27% of the baseline projection, or 34% of the  
7 2010 levels.

8       Similar to NO<sub>x</sub>, China's SO<sub>2</sub> emissions have a larger growth potential than the average of  
9 East Asia during 2010-2030 under current policy and implementation status. Implementation of  
10 new energy-saving measures (reflected by the difference between the BAU[0] and the PC[0]  
11 scenario) and progressive end-of-pipe control measures (reflected by the difference between the  
12 PC[0] and the PC[1] scenario) could lead to 36% and 26% reductions of China's SO<sub>2</sub> emissions,  
13 respectively (compared with the baseline projection). Consistent with the total emissions in East  
14 Asia, the contribution of energy-saving measures clearly exceeds the planned end-of-pipe control  
15 policies. As the power sector had largely been equipped with FGD facilities by the base year,  
16 industrial boilers and industrial process contribute 82% of the SO<sub>2</sub> emission reduction achieved  
17 through progressive end-of-pipe control policies. In the maximum feasible reduction scenario  
18 (PC[2]), SO<sub>2</sub> emissions are estimated to reach only 27% of the baseline projection, or 34% of the  
19 2010 levels.

20       We also note that China's SO<sub>2</sub> emissions are projected to be 21.7 Mt in 2015 under the  
21 BAU[1] scenario, 11.1% lower than those of 2010. This implies that if the control policies in the  
22 12<sup>th</sup> Five-Year Plan could be implemented successfully (as assumed in the BAU[1] scenario), the  
23 national target to reduce the SO<sub>2</sub> emissions by 8% during 2011-2015 would be achieved.

24       The SO<sub>2</sub> emissions in East Asia outside of China, including Japan and South Korea  
25 individually, are expected to stay relatively stable until 2030 under current regulations. The  
26 implementation of new energy-saving policies (the PC[0] scenario) could lead to a 9-18%  
27 reduction in SO<sub>2</sub> emissions from the levels of the baseline projection. The reduction is mainly  
28 achieved through the promotion of nuclear and renewable power generation and replacement  
29 with cleaner fuels in the industrial sector. Under the maximum feasible reduction measures (the



1 PC[2] scenario), the SO<sub>2</sub> emissions in East Asia except China, and Japan and South Korea  
2 individually would be reduced to 33%, 52% and 39% of the baseline projection, respectively.

### 3 3.3.3 PM<sub>10</sub> and PM<sub>2.5</sub>

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

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

24 The total PM<sub>10</sub> and PM<sub>2.5</sub> emissions in East Asia other than China are also expected to remain  
25 relatively stable up to 2030 under the current policies. An exception is Japan, whose PM<sub>10</sub> and  
26 PM<sub>2.5</sub> emissions are projected to decrease about one quarter by 2030. The major driving force  
27 underlying this decline would be an increasing proportion of vehicles regulated by newer  
28 emission standards. The implementation of new energy-saving policies (the PC[0] scenario) is  
29 expected to reduce the PM<sub>2.5</sub> emissions of East Asia other than China, and Japan and South Korea

1 individually by about 20%, 17%, and 5%, respectively, from the baseline projection. With full  
2 application of best-available control technologies (the PC[2] scenario), the PM<sub>2.5</sub> emissions in  
3 East Asia except China, and Japan and South Korea individually would account for about one  
4 quarter, one half, and one half of the levels of the baseline projection, respectively.

#### 5 3.3.4 NMVOC

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

16 China's NMVOC emissions are estimated to increase by 27% from 2010 to 2030 under  
17 current policy and implementation status. This upward trend is stronger than the East Asia  
18 average but weaker than China's NO<sub>x</sub> emissions. The emissions from the transportation and  
19 residential sectors are expected to decline as a result of existing emission standards for vehicles  
20 and the dwindling direct combustion of biomass in the residential sector. By carrying out a series  
21 of energy-saving policies (the PC[0] scenario), total emissions are expected to decrease by 16%  
22 from the baseline projection. Emissions from the residential sector decrease most notably because  
23 of the substitution of biomass with cleaner fuels. Another 26% could be reduced if progressive  
24 end-of-pipe control measures are implemented (reflected by the difference between the PC[0] and  
25 the PC[1] scenario), and the most effective measures are the substitution with low-solvent  
26 products and end-of-pipe removal technologies such as incineration and adsorption in the  
27 industrial sector and the use of solvents. With full implementation of the best-available  
28 technologies (the PC[2] scenario), the NMVOC emissions could be reduced to about one third of  
29 the levels of the baseline scenario.

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

## 11 **4 Comparison with other studies and observations**

### 12 **4.1 Comparison with other studies**

13 In 2010, China contributed 88%, 94%, 94%, 95%, and 88% of the total NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>,  
14 and NMVOC emissions in East Asia, respectively. As a developing country, China has  
15 substantial potential to reduce air pollutant emissions with the implementation of aggressive  
16 control policies, and combined with its sheer size is therefore expected to dominate the emission  
17 trends of East Asia in the next 20 years. Many previous studies projecting emissions have  
18 focused on China. While some Asian and international studies have incorporated Japan, South  
19 Korea, and other countries to produce regional projections, they have seldom disaggregated  
20 emissions by country, making it difficult to review their projections. For these reasons, our  
21 comparisons with prior literature in this section are limited to comparisons of China's emission  
22 trends.

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

26 As for future projections, early studies (reported before 2005) of China's emissions ([van](#)  
27 [Aardenne et al., 1999](#); [Streets and Waldhoff, 2000](#); [Klimont et al., 2001](#); [Klimont et al., 2002](#))  
28 were based on the emissions in 1995 or before. They generally substantially underestimated the  
29 rapid economic growth during 2000-2010. In addition, none of them anticipated the aggressive

1 control policies in China since 2005. Therefore, these projections deviated greatly from the actual  
2 trends. In this study, we only compare emission projections reported since 2005 (or using the  
3 base year of 2000 or later) with our projections, which are shown in Figure 4.

#### 4 4.1.1 NO<sub>x</sub> emissions

5 [Zhao et al. \(2013d\)](#) and [Kurokawa et al. \(2013\)](#) have evaluated recent NO<sub>x</sub> emission trends in  
6 China. They both presented similar temporal trends to our estimation. The estimated growth rates  
7 of China's NO<sub>x</sub> emissions are all within the range of 20-23% for the period 2005-2008, and 34-  
8 47% for the period of 2005-2010.

9 [Ohara et al. \(2007\)](#) projected NO<sub>x</sub> emissions in China through 2020 by using the emissions  
10 for 2000 and three scenarios: a “policy failure” scenario, a “best guess” scenario, and an  
11 optimistic scenario. The projections of all the three scenarios for 2010 were much lower than our  
12 estimates, indicating they underestimated the economic growth during 2000-2010. The three  
13 scenarios projected growth rates ranging between 51% and -10% for the period 2010-2020. In  
14 contrast, even the progressive control strategy in our study results in a larger decline of NO<sub>x</sub>  
15 emissions (-26% in the BAU[1] scenario and -39% in the PC[1] scenario) during the same period,  
16 due to the implementation of the control measures scheduled in the 12<sup>th</sup> Five-Year Plan. [Amann  
17 et al. \(2008\)](#) developed three scenarios through 2030 based on the emissions in 2005. The  
18 “current legislation” scenario assumed current regulations and enforcement, while the “advanced  
19 control technology” scenario assumed across-the-board application of such technologies, largely  
20 based on existing German regulations. The optimized scenario was a least-cost optimization that  
21 would achieve the same health benefit as the advanced control technology scenario. [Xing et al.  
22 \(2011\)](#) projected NO<sub>x</sub> emissions for 2020 with four scenarios based on the emissions of 2005,  
23 including one assuming current regulations and implementation status, one assuming  
24 improvement of energy efficiency and current environmental regulations, one assuming  
25 improvement of energy efficiency and better implementation of environmental regulations, and a  
26 final scenario assuming improvement of energy efficiency and strict environmental regulations.  
27 These two studies (Amann et al. and Xing et al.) were conducted cooperatively. Similar to [Ohara  
28 et al. \(2007\)](#), their projections for 2010 were also significantly lower than our estimations. As for  
29 the growth rates until 2020 or 2030, all the scenarios in these two studies projected a larger

1 increase or smaller decline than our progressive control strategy assuming the enforcement of the  
2 12<sup>th</sup> Five Year Plan, indicating these two studies did not anticipate stringent future control  
3 policies. [Cofala et al. \(2012\)](#) projected the NO<sub>x</sub> emissions until 2030 based on 2010 emissions  
4 and four scenarios envisaging energy-saving measures at different stringency levels. The  
5 projected rates of change for 2010-2030 range between 16% and -24%. Since no end-of-pipe  
6 control measures beyond the baseline are considered, it is only meaningful to compare these  
7 scenarios with our BAU[0] and PC[0] scenarios, which projected the growth rates for the same  
8 period at 36% and -3%, respectively. This study predicted a stronger growth potential of China's  
9 energy consumption in the future, leading to the larger rate of growth or smaller rate of decline  
10 above.

#### 11 4.1.2 SO<sub>2</sub> emissions

12 A number of studies have evaluated China's recent SO<sub>2</sub> emission trends ([Klimont et al., 2013](#); [Lu](#)  
13 [et al., 2011](#); [Zhao et al., 2013d](#); [Kurokawa et al., 2013](#)). Although the emission estimates in  
14 different studies differ by up to 30% during the period, all of the reviewed studies and our own  
15 show declining SO<sub>2</sub> emissions during 2005-2010. This study estimated a slightly stronger decline  
16 (13% for 2005-2008, and 15% for 2005-2010) compared with the previous studies (2%-8% for  
17 2005-2008, and 2%-12% for 2005-2010).

18 Most of the projections reviewed here have more or less envisaged China's recent SO<sub>2</sub>  
19 control policies. [Ohara et al. \(2007\)](#) predicted that SO<sub>2</sub> emissions would change by 27%, -11%,  
20 and -23% during 2010-2020 in their policy failure, best-guess, and optimistic scenarios,  
21 respectively, comparable to our BAU[0], PC[0], and BAU[1] scenarios, respectively. [Amann et al.](#)  
22 [\(2008\)](#) failed to reproduce the declining trend during 2005-2010, but the control policies assumed  
23 in its most aggressive scenario (the advanced control technology scenario) resulted in a similar  
24 rate of decline as of 2030 as our progressive control strategy. The growth rates projected in all the  
25 four scenarios of [Xing et al. \(2011\)](#) are higher than our BAU[1] scenario, indicating that their  
26 assumptions of future SO<sub>2</sub> control policies are more conservative than our progressive control  
27 strategy based on the 12<sup>th</sup> Five Year Plan. [Cofala et al. \(2012\)](#) predicted SO<sub>2</sub> emissions to  
28 decrease by 20%-40% during 2010-2030 under four different energy-saving policy scenarios,  
29 while our BAU[0] and PC[0] scenarios predicted rates of change at 26% and -20%, respectively.

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

### 3 4.1.3 PM emissions

4 [Zhao et al. \(2013d\)](#) and [Kurokawa et al. \(2013\)](#) have evaluated the recent trends of PM<sub>10</sub> and  
5 PM<sub>2.5</sub> emissions in China. While [Zhao et al. \(2013d\)](#) and this study both showed a declining trend  
6 during 2005-2010, [Kurokawa et al. \(2013\)](#) estimated a significant upward trend after 2005. The  
7 discrepancy may be attributed mainly to the uncertainty in the penetration levels of dust  
8 collectors at industrial sources.

9 China has been implementing PM control policies for several decades. Therefore, all of the  
10 projections reviewed here have assumed the future application of dust collectors to some extent.  
11 The PM<sub>10</sub> emissions growth rate until 2020 of the least aggressive scenario in [Xing et al. \(2011\)](#)  
12 is comparable to our BAU[0], and the most aggressive one is comparable to our PC[1], indicating  
13 similar stringency levels of the control policies assumed in these two studies up to 2020. [Amann  
14 et al. \(2008\)](#) predicted a slight increase of PM<sub>2.5</sub> emissions during 2005-2010, in contrast with a  
15 12% decline estimated in our study using statistical data. However, the growth rate for the period  
16 2010-2030 in their current legislation scenario is quite close to our BAU[0] scenario; the growth  
17 rates in their advanced control technology scenario and optimized scenario are close to our PC[1]  
18 one. [Cofala et al. \(2012\)](#) projected the change rate of PM<sub>2.5</sub> emissions for 2010-2030 between -  
19 20% and -34% under four energy scenarios, which are comparable to the projected change rates  
20 of our BAU[0] (-8%) and PC[0] (-34%). Finally, it should be noted that our maximum feasible  
21 reduction scenario (the PC[2] scenario) projects much lower emissions than any previously  
22 developed scenario.

### 23 4.1.4 NMVOC emissions

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

27 Only three studies have projected China's NMVOC emissions since 2005. Compared with  
28 our study, [Ohara et al. \(2007\)](#) made similar estimation of NMVOC emissions in 2010, but  
29 predicted much higher growth rates for the period 2010-2020 in all three of their scenarios, as

1 they assumed few effective control measures in any scenario. [Xing et al. \(2011\)](#) and [Wei et al.](#)  
2 [\(2011\)](#) have considered the effect of recent vehicle emission standards on NMVOC emissions,  
3 and assumed relatively simple but progressively strengthened control polices through 2020, and  
4 therefore achieved similar growth rates to ours for both baseline and progressive strategies. Given  
5 China is still in the initial stage of NMVOC emission controls, and limited new policies are  
6 expected to emerge in the next 5-10 years, the emission trends are unlikely to deviate greatly  
7 from the baseline through 2020. However, control measures at different levels of stringency  
8 might result in dramatically different emissions by 2030. Our study is the first one to quantify the  
9 effect of potentially new policies on NMVOC emission trends through 2030 and to quantify the  
10 maximum feasible reduction potential.

## 11 **4.2 Comparison with observations**

12 SO<sub>2</sub> and NO<sub>2</sub> retrievals from satellite observations are used for comparisons with trends of  
13 primary emissions estimated in this work. A more rigorous comparison would involve  
14 incorporating the emission inventory into a chemical transport model and comparing the  
15 simulated NO<sub>2</sub> or SO<sub>2</sub> column with satellite observations, which will be considered in future  
16 research. [Lu et al. \(2011\)](#) retrieved the satellite SO<sub>2</sub> vertical column density (VCD) for Eastern  
17 Central China (latitude <45°N, longitude >100°E), in which measurements of Ozone Monitoring  
18 Instrument (OMI) and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography  
19 (SCIAMACHY) during 2005-2010 were used. [Fioletov et al. \(2013\)](#) developed a filtering  
20 procedure to remove local biases, in particular transient volcanic signals, and applied this method  
21 to retrieve the SO<sub>2</sub> VCD over an area of Eastern China during 2005-2010. The data sources  
22 include OMI, SCIAMACHY, the Global Ozone Monitoring Experiment-2 (GOME-2) German  
23 Aerospace Center (DLR) product, and the GOME-2 Smithsonian Astrophysical Observatory  
24 (SAO) product. It should be noted that the data of GOME-2 are only available since 2007. The  
25 comparison of SO<sub>2</sub> VCDs derived by [Lu et al. \(2011\)](#) and [Fioletov et al. \(2013\)](#) with the  
26 estimated SO<sub>2</sub> emissions are shown in Figure 5(a) and Figure 5(b), respectively. It can be seen  
27 that the temporal trends of SO<sub>2</sub> VCD retrieved by [Fioletov et al. \(2013\)](#) from all four data sources  
28 (OMI, SCIAMACHY, GOME-2 DLR, and GOME-2 SAO) agree well with each other. In  
29 addition, the trends of SO<sub>2</sub> VCD retrieved by [Lu et al. \(2011\)](#) agree well with that of [Fioletov et](#)

1 al. (2013) during 2005-2009. However, Lu et al. (2011) shows a significant increase in SO<sub>2</sub> VCD  
2 between 2009 and 2010 (especially that retrieved from SCIAMACHY), while Fioletov et al.  
3 (2013) shows a slight increase. Fioletov et al. (2013) implies that the pronounced increase  
4 between 2009 and 2010 arises from time-dependent bias in the retrieval algorithms. When the  
5 filtering procedure developed in Fioletov et al. (2013) was applied, the pronounced increase  
6 turned into a slight increase. Therefore, we exclude the SO<sub>2</sub> VCD in 2010 in Lu et al. (2011) in  
7 the following discussion.

8 As shown in Figure 5(a), during 2005-2009, SO<sub>2</sub> VCD from OMI, SO<sub>2</sub> VCD from  
9 SCIAMACHY, and estimated SO<sub>2</sub> emissions decreased by 20%, 21%, and 17%, respectively, in  
10 Eastern Central China. Similarly, during 2005-2010, the rate of decline of SO<sub>2</sub> VCD from OMI  
11 (16%), SO<sub>2</sub> VCD from SCIAMACHY (8%), and estimated SO<sub>2</sub> emissions (15%) agree fairly  
12 well with each other in the studied area of Fioletov et al. (2013). However, SO<sub>2</sub> VCDs from both  
13 SCIAMACHY and OMI peak in 2007, while this study shows a monotonic decline in SO<sub>2</sub>  
14 emissions as of 2009. This may be mainly attributable to the uncertainty in the actual removal  
15 efficiency and operation status of FGD facilities. Although FGDs have been rapidly introduced  
16 since 2005, the actual operation status has been questioned before by both the government and  
17 research community (Xu et al., 2009). In response to this situation, the Chinese government  
18 began to require the installation of continuous emission monitoring systems (CEMSs) together  
19 with FGDs since July 2007 (SEPA, 2007). Therefore, the average removal efficiency should have  
20 improved subsequently, contributing to the rapid decline in SO<sub>2</sub> during 2007-2009. Despite the  
21 inconsistency above, the estimated overall change rate in SO<sub>2</sub> emissions from 2005 to 2010  
22 agrees well with satellite observations.

23 The NO<sub>2</sub> VCDs were retrieved from OMI and SCIAMACHY with the method described in  
24 Zhao et al. (2013b) and Zhang et al. (2012a), respectively. Figure 5(c) compares the average NO<sub>2</sub>  
25 VCD in Eastern Central China and the total NO<sub>x</sub> emissions in this area. It can be seen that the  
26 growing trend of NO<sub>x</sub> emissions are well captured by both the observations of OMI and  
27 SCIAMACHY. The growth rates of NO<sub>2</sub> VCD from OMI, NO<sub>2</sub> VCD from SCIAMACHY, and  
28 NO<sub>x</sub> emissions are 27%, 34%, and 31%, respectively.

29 The trends in PM concentrations are not directly comparable with primary emissions, as  
30 secondary PM is formed through complex chemical reactions of primary pollutants. Our previous



1 study (Zhao et al., 2013a) simulated the concentrations of air pollutants in China in 2005 and  
2 2010 using Community Multi-scale Air Quality (CMAQ) model and the same emission inventory  
3 as presented in this paper. The trends of air pollutant emissions were evaluated by comparing the  
4 trends of simulated air quality with observations. From 2005 to 2010, the simulated PM<sub>10</sub>  
5 concentrations of 58 Chinese cities decreased by 7.3%, which agreed well with the rate of decline  
6 of the observations (7.6%, <http://datacenter.mep.gov.cn>). In addition, the simulated changes of  
7 Aerosol Optical Depth (AOD) during 2005-2010 can well reproduce the spatial pattern of the  
8 AOD changes observed by Moderate Resolution Imaging Spectroradiometer (MODIS). During  
9 2005-2010, AOD decreased in some areas such as the southeast coast of China, but increased in a  
10 large part of China, with especially pronounced increases in the Sichuan Basin and the southern  
11 part of the North China Plain (Zhao et al., 2013a).

12 As described above, both observation and simulation results indicate that annual average  
13 PM<sub>10</sub> concentrations in major cities of Eastern China decreased since 2005. However, based on  
14 our simulation results (Zhao et al., 2013a), the control policies had not been successful in  
15 reducing concentrations of fine particles over a large part of China. One of the important reasons  
16 for the increase of fine particles during 2005-2010 is that nitrate concentrations increased in most  
17 of China driven by the increase of NO<sub>x</sub> and NH<sub>3</sub> emissions. Although sulfate concentrations in  
18 East China decreased due to the decline of SO<sub>2</sub> emissions, the concentrations of secondary  
19 inorganic aerosol (SIA) increased in most of China, especially in the Sichuan Basin and eastern  
20 Hubei province. In addition, the increase in the emissions of NMVOC led to the increase of  
21 secondary organic aerosols. The increase in secondary PM<sub>2.5</sub> concentrations offset the decline of  
22 primary PM<sub>2.5</sub> concentrations and led to the increase of total PM<sub>2.5</sub> concentrations in a large part  
23 of China. Given above, although the emissions of primary PM and SO<sub>2</sub> decreased in most of  
24 China, the modeling results indicated that total PM<sub>2.5</sub> concentrations still increased in a large part  
25 of China (Zhao et al., 2013a).

## 26 **5 Conclusions and policy implications**

27 In this study we reviewed the application status of air pollution control measures in East Asia in  
28 the last decade, evaluated the impact of control policies on the emission trends during 2005-2010,

1 and projected future emissions of SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, and NMVOC up to 2030 under six  
2 emission scenarios based on a range of energy-saving and end-of-pipe emission control measures.

3 During 2005-2010, the emissions of SO<sub>2</sub> and PM<sub>2.5</sub> in East Asia decreased by 15% and 12%,  
4 respectively, mainly attributable to the large scale deployment of FGD in China's power plants,  
5 and the deployment of more efficient PM removal technologies in China's power and cement  
6 plants. During this period, the emissions of NO<sub>x</sub> and NMVOC increased by 25% and 15%,  
7 respectively, driven by the rapid increase in the emissions from China due to inadequate control  
8 strategies. In contrast, the NO<sub>x</sub> and NMVOC emissions in East Asia other than China decreased  
9 by 13-17% mainly due to the implementation of stringent vehicle emission standards in Japan  
10 and South Korea.

11 Under current regulations and implementation status (the BAU[0] scenario), NO<sub>x</sub>, SO<sub>2</sub>, and  
12 NMVOC emissions in East Asia are estimated to increase by about one quarter by 2030 from the  
13 2010 levels, while PM<sub>2.5</sub> emissions are expected to decrease by 7%. Assuming enforcement of  
14 new energy-saving policies, emissions of NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, and NMVOC in East Asia are  
15 expected to decrease by 28%, 36%, 28%, and 15%, respectively, compared with the baseline case.  
16 The implementation of progressive end-of-pipe control measures is expected to lead to another  
17 one-third reduction of the baseline emissions of NO<sub>x</sub>, and about one-quarter reduction of SO<sub>2</sub>,  
18 PM<sub>2.5</sub>, and NMVOC. Exploring the potential of currently known best-available technologies,  
19 their full implementation could reduce the emissions of NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> in East Asia to only  
20 about one quarter, and NMVOC to one third, of the levels of the baseline projection.

21 Comparison with emission projections in the literature indicates that this study: (1) estimates  
22 similar recent emission trends until 2010; (2) projects larger reductions in NO<sub>x</sub> and SO<sub>2</sub>  
23 emissions by assuming aggressive governmental plans and standards scheduled to be  
24 implemented in the next decade; (3) accounts for the significant effects of detailed progressive  
25 control measures on NMVOC emissions up to 2030; and (4) quantifies technologically feasible  
26 reduction potentials. The results of this study provide future emission projections for the  
27 modeling community of the MICS-Asia program, allowing modelers to assess the impact of  
28 emission changes on future air quality. In addition, the emission projections at various stringency  
29 levels from a business-as-usual case to maximum feasible reduction case provide a basis for

1 further studies on cost-effective emission control strategies, which can balance control measures  
2 over all pollutants and control levels.

3 The results of this study have important policy implications. First, this study indicates that the  
4 successful implementation of the control policies set in China's 12<sup>th</sup> Five Year Plan, the recently  
5 released emission standards for various industrial sources, and slowly strengthened control  
6 measures after 2015 (as assumed in the "progressive" end-of-pipe control strategy) could reduce  
7 China's emissions of NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub> significantly. The resulting NO<sub>x</sub>, SO<sub>2</sub>, and PM<sub>2.5</sub>  
8 emissions would be 16-26% lower than the 2010 levels by 2020, and even lower by 2030,  
9 demonstrating a high mitigation potential when this legislation and associated regulations are  
10 enforced efficiently. Therefore we believe it is essential to support and monitor the progress of  
11 implementation of these measures. Second, the contributions of advanced energy-saving  
12 measures to the reduction of SO<sub>2</sub> and PM<sub>2.5</sub> emissions exceeds those of progressive end-of-pipe  
13 control measures by 2030. Since end-of-pipe control technologies (e.g., FGD facilities and high-  
14 efficiency dedusters) have already been widely applied in typical sources in the base year, their  
15 reduction potential will diminish in the future. The energy-saving measures would play an  
16 irreplaceable role for further reduction of air pollutant emissions. Third, control policies for  
17 NMVOC emissions are unfortunately lacking in China and South Korea at present; this study  
18 indicates that the simultaneous enforcement of energy-saving measures and progressive end-of-  
19 pipe control measures (mainly assuming enforcement of European standards) could reduce 38%  
20 of the total NMVOC emissions from the levels of baseline projection. Nevertheless, large  
21 reduction potential still remains, and additional policies to reduce NMVOC emissions efficiently  
22 and effectively warrant careful consideration .

23  
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## 1 Tables and figures

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

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

3

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

Energy technology	Control technology	Base year						BAU[0]/PC[0]						BAU[1]/PC[1]						BAU[2]/PC[2]		
		2005			2010			2020			2030			2020			2030			2030		
	Country	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea	China	Japan	South Korea
Grate boilers	CYC (PM)	12	-	-	12	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-
	WET (PM)	88	-	-	88	-	-	100	-	-	100	-	-	100	-	-	100	-	-	0	-	-
	HED (PM)	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	100	-	-
Pulverized coal combustion	WET (PM)	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ESP (PM)	92	3	72	93	2	67	90	0	64	80	0	61	65	0	64	50	0	61	0	0	0
	HED (PM)	0	97	28	7	98	33	10	100	36	20	100	39	35	100	36	50	100	39	100	100	100
	FGD (SO <sub>2</sub> )	12	97	95	88	98	97	93	100	98	96	100	98	100	100	98	100	100	98	100	100	100
	LNB (NO <sub>x</sub> )	53	10	23	75	0	13	82	0	13	84	0	13	8	0	13	0	0	13	0	0	0
	LNB+SNCR (NO <sub>x</sub> )	0	0	5	1	0	5	1	0	5	1	0	5	6	0	5	7	0	5	0	0	0
	LNB+SCR (NO <sub>x</sub> )	1	90	56	12	100	68	12	100	72	12	100	76	86	100	72	94	100	76	100	100	100
Fluidized bed combustion	WET (PM)	8	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-	-
	ESP (PM)	92	-	-	100	-	-	90	-	-	80	-	-	65	-	-	50	-	-	0	-	-
	HED (PM)	0	-	-	0	-	-	10	-	-	20	-	-	35	-	-	50	-	-	100	-	-
	CFB-FGD (SO <sub>2</sub> )	17	-	-	53	-	-	66	-	-	80	-	-	100	-	-	100	-	-	100	-	-
	SNCR (NO <sub>x</sub> )	0	-	-	0	-	-	0	-	-	0	-	-	30	-	-	80	-	-	70	-	-
SCR (NO <sub>x</sub> )	0	-	-	0	-	-	0	-	-	0	-	-	5	-	-	20	-	-	30	-	-	
Natural gas power	LNB (NO <sub>x</sub> )	30	80	20	74	61	15	87	52	15	91	50	15	50	52	15	10	50	15	0	0	0
	LNB+SNCR (NO <sub>x</sub> )	0	0	0	1	0	0	1	0	0	1	0	0	5	0	0	9	0	0	10	0	0
	LNB+SCR (NO <sub>x</sub> )	0	20	30	5	39	46	5	48	50	5	50	54	45	48	50	81	50	54	90	100	100

2 Notes: CYC, cyclone dust collector; WET, wet scrubber; ESP, electrostatic precipitator; HED, high efficiency deduster; FGD, flue gas desulfurization; CFB-FGD, flue gas  
3 desulfurization for circulated fluidized bed; LNB, low-NO<sub>x</sub> combustion technology; SCR, selective catalytic reduction; SNCR, selective non-catalytic reduction. The table  
4 gives the national average penetrations of major control technologies. Note, however, that the penetrations vary with provinces and the penetration in “key regions” as defined  
5 by the Chinese government, is usually larger than that of other regions.

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

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

3 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  
4 combustion condition, catalytic stove); STV\_PELL, biomass pellet stove.

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

2 (a) SO<sub>2</sub>

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	FGD	0	10	20	40	95	100	100
Coke oven	FGD for coal-charging process	0	0	0	0	10	10	0
	FGD for coke oven gas	0	0	0	0	10	10	0
	Combination of the technologies above	0	0	0	0	30	50	100
Glass production (float process)	FGD	0	0	0	0	50	90	100
Sulfuric acid production	Ammonia acid desulfurization method	0	0	0	0	40	80	100

3

4 (b) NO<sub>x</sub>

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
Precalciner cement kiln	LNB	30	35	35	35	30	25	0
	LNB+SNCR	0	0	0	0	30	45	0
	LNB+SCR	0	0	0	0	20	30	100
Glass production (float process)	OXFL	0	0	0	0	80	88	70
	SCR	0	0	0	0	10	12	30
Nitric acid (dual pressure process)	ABSP	10	12	12	12	18	18	18
	SCR	15	18	18	18	72	82	82
	ABSP+SCR	0	0	0	0	0	0	0
Nitric acid (other process)	ABSP	60	63	66	66	5	5	0
	SCR	30	32	34	34	15	15	0
	ABSP+SCR	0	0	0	0	80	80	100

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

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2 (c) 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
Precalciner cement kiln	WET	1	0	0	0	0	0	0
	ESP	52	40	35	30	20	5	0
	HED	47	60	65	70	80	95	100
Glass production	CYC	5	0	0	0	0	0	0
	WET	25	20	20	20	0	0	0
	ESP	68	75	75	75	85	75	0
	HED	3	5	5	5	15	25	100
Brick production	CYC	40	30	30	30	20	0	0
	WET	8	20	20	20	40	50	0
	ESP	0	20	20	20	40	50	0
	HED	0	0	0	0	0	0	100

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

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## 2 (d) NMVOC

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

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

3 (a) China

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

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

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2 (b) Japan

Vehicle	Standard	BAU[0]/					Vehicle	Standard	BAU[0]/				
		Base year		BAU[1]/	BAU[2]/	PC[0]/			PC[2]	Base year		BAU[1]/	BAU[2]/
		2005	2010	PC[1]	PC[2]					2005	2010	PC[0]/	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%

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

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1 (c) South Korea

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

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

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2 Table 6. Penetrations of major control technologies for NMVOC emissions from selected  
3 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
	Substitution 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

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

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

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

	Base year		BAU[0]		BAU[1]		BAU[2]	PC[0]		PC[1]		PC[2]
	2005	2010	2020	2030	2020	2030	2030	2020	2030	2020	2030	2030
<b>NO<sub>x</sub></b>												
China, mainland	19.48	26.05	31.69	35.35	19.18	15.82	9.85	26.32	25.16	15.95	11.47	7.18
Japan	2.050	1.616	1.033	0.860	1.033	0.860	0.461	0.954	0.727	0.954	0.727	0.392
South Korea	1.112	1.055	0.809	0.697	0.809	0.697	0.245	0.778	0.575	0.778	0.575	0.210
North Korea	0.276	0.284	0.345	0.481	0.345	0.481	0.086	0.342	0.375	0.342	0.375	0.067
Mongolia	0.064	0.058	0.055	0.057	0.055	0.057	0.041	0.052	0.047	0.052	0.047	0.034
Hong Kong & Macao, China	0.199	0.230	0.229	0.260	0.229	0.260	0.039	0.208	0.218	0.208	0.218	0.033
Taiwan, China	0.551	0.440	0.348	0.342	0.348	0.342	0.091	0.316	0.287	0.316	0.287	0.076
Total	23.73	29.74	34.51	38.05	21.99	18.51	10.81	28.97	27.39	18.60	13.70	8.00
Total except mainland China	4.252	3.682	2.819	2.697	2.819	2.697	0.963	2.649	2.229	2.649	2.229	0.813
<b>SO<sub>2</sub></b>												
China, mainland	28.70	24.42	29.07	30.68	20.59	18.23	13.32	22.24	19.49	15.69	11.55	8.34
Japan	0.705	0.562	0.520	0.518	0.520	0.518	0.294	0.507	0.470	0.507	0.470	0.268
South Korea	0.410	0.400	0.408	0.358	0.408	0.358	0.162	0.384	0.301	0.384	0.301	0.141
North Korea	0.268	0.297	0.368	0.471	0.368	0.471	0.099	0.363	0.333	0.363	0.333	0.070
Mongolia	0.087	0.073	0.065	0.073	0.065	0.073	0.011	0.054	0.036	0.054	0.036	0.005
Hong Kong & Macao, China	0.022	0.016	0.019	0.021	0.019	0.021	0.007	0.017	0.016	0.017	0.016	0.006
Taiwan, China	0.244	0.139	0.115	0.119	0.115	0.119	0.026	0.104	0.122	0.104	0.122	0.026
Total	30.44	25.91	30.57	32.24	22.08	19.78	13.92	23.67	20.77	17.12	12.83	8.85
Total except mainland China	1.735	1.486	1.496	1.559	1.496	1.559	0.599	1.431	1.278	1.431	1.278	0.516
<b>PM<sub>10</sub></b>												
China, mainland	18.61	15.81	16.24	15.26	13.24	10.53	5.55	13.13	11.15	10.76	7.52	4.17
Japan	0.206	0.167	0.137	0.125	0.137	0.125	0.087	0.131	0.111	0.131	0.111	0.078
South Korea	0.093	0.116	0.115	0.117	0.115	0.117	0.062	0.112	0.111	0.112	0.111	0.059
North Korea	0.596	0.558	0.557	0.599	0.557	0.599	0.134	0.477	0.444	0.477	0.444	0.099
Mongolia	0.053	0.040	0.034	0.035	0.034	0.035	0.008	0.029	0.019	0.029	0.019	0.004
Hong Kong & Macao, China	0.039	0.043	0.049	0.046	0.049	0.046	0.012	0.043	0.033	0.043	0.033	0.009
Taiwan, China	0.095	0.085	0.078	0.081	0.078	0.081	0.035	0.072	0.066	0.072	0.066	0.029
Total	19.69	16.81	17.21	16.26	14.21	11.53	5.88	13.99	11.94	11.62	8.31	4.45
Total except mainland China	1.082	1.007	0.970	1.002	0.970	1.002	0.338	0.864	0.784	0.864	0.784	0.277
<b>PM<sub>2,5</sub></b>												
China, mainland	13.34	11.79	11.74	10.87	9.61	7.29	3.41	9.43	7.73	7.71	5.03	2.50
Japan	0.142	0.102	0.084	0.077	0.084	0.077	0.051	0.077	0.064	0.077	0.064	0.044
South Korea	0.071	0.085	0.082	0.083	0.082	0.083	0.051	0.080	0.079	0.080	0.079	0.048
North Korea	0.407	0.383	0.401	0.426	0.401	0.426	0.101	0.349	0.329	0.349	0.329	0.078
Mongolia	0.025	0.019	0.016	0.016	0.016	0.016	0.004	0.014	0.010	0.014	0.010	0.002
Hong Kong & Macao, China	0.023	0.024	0.026	0.027	0.026	0.027	0.006	0.023	0.022	0.023	0.022	0.005
Taiwan, China	0.057	0.049	0.045	0.047	0.045	0.047	0.019	0.041	0.038	0.041	0.038	0.016
Total	14.07	12.45	12.39	11.55	10.27	7.97	3.64	10.01	8.27	8.29	5.57	2.69
Total except mainland China	0.724	0.662	0.653	0.676	0.653	0.676	0.231	0.584	0.542	0.584	0.542	0.193
<b>NM VOC</b>												
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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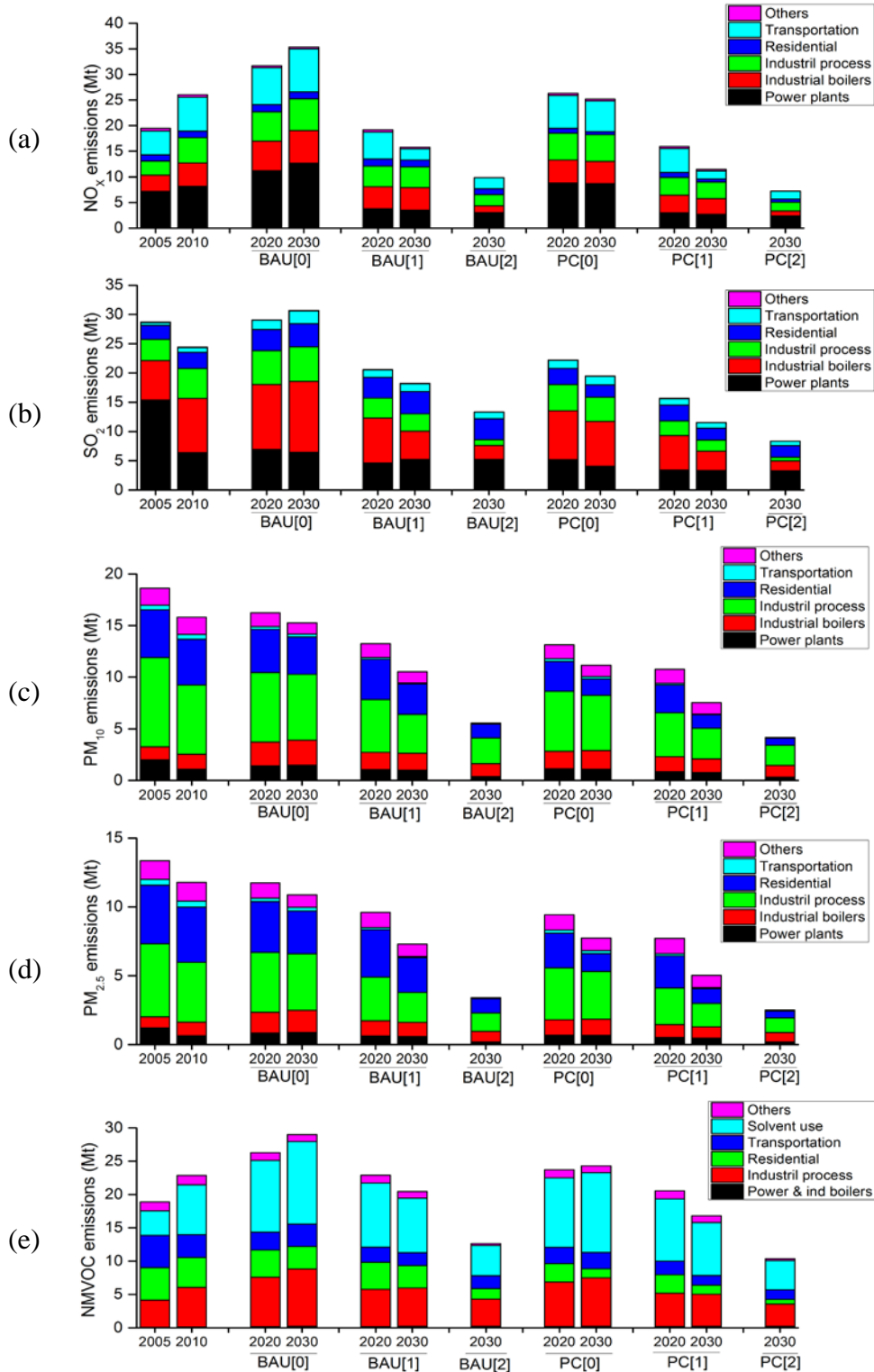
Type	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Light duty vehicle	1	1	1	1	1	2	2	2	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Heavy duty diesel vehicle	1	1	1	2	2	2	3	3	3	3	3	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Heavy duty gasoline vehicle				1	2	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	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	2
Train, inland water																															

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	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	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	4
Train, inland water														3A	3A	3A	3A	3B	3B	3B	4	4	4	4	4	4	4	4	4	4	4

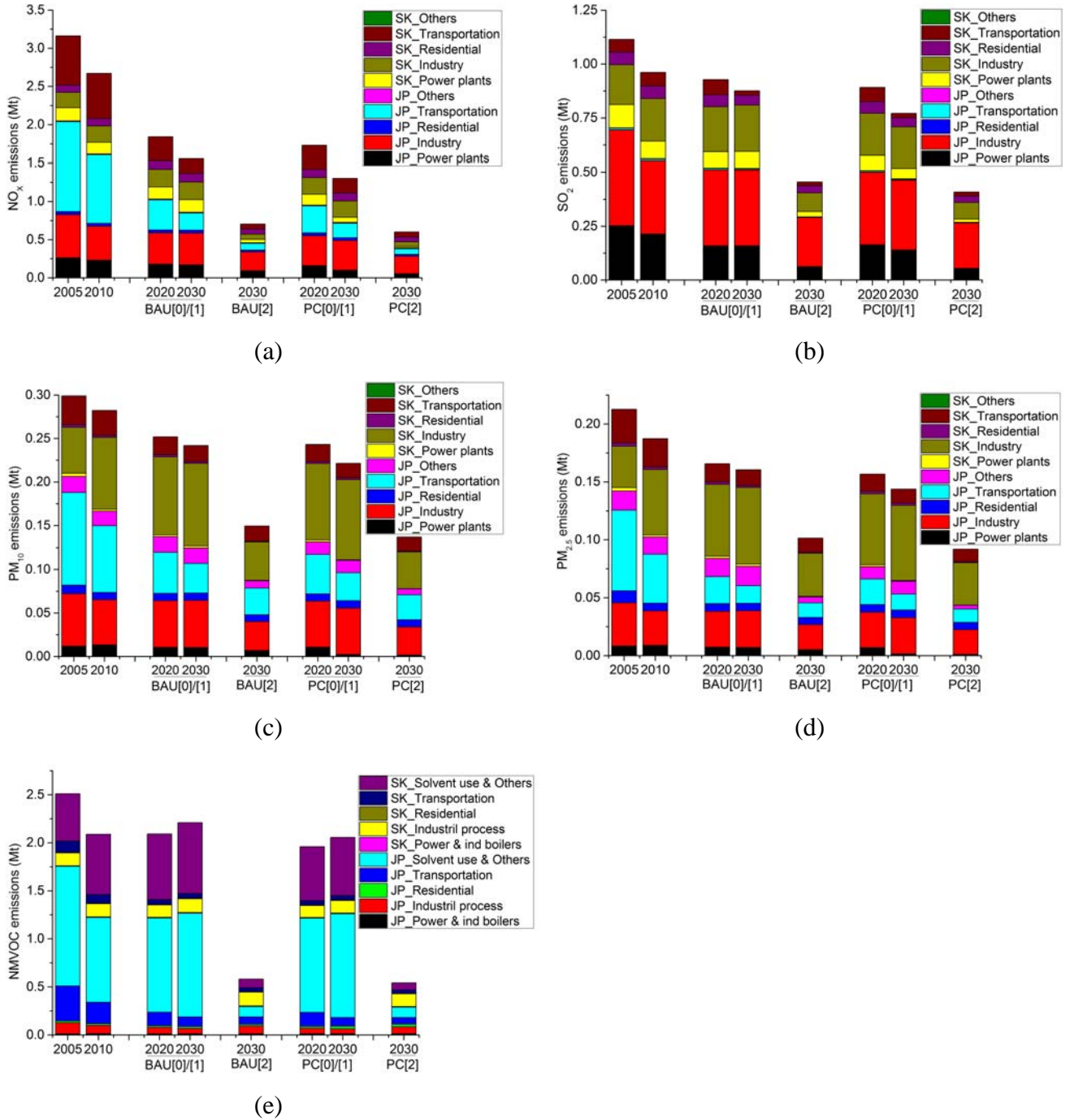
2 Figure 1. The implementation time of the vehicle emission standards in China: (a) the BAU[0]  
 3 and PC[0] scenarios; (b) the BAU[1], PC[1], BAU[2], and PC[2] scenarios. The Arabic  
 4 numbers 1-6 represent Euro I to Euro VI vehicle emission standards. Numbers in black  
 5 represent standards released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

7

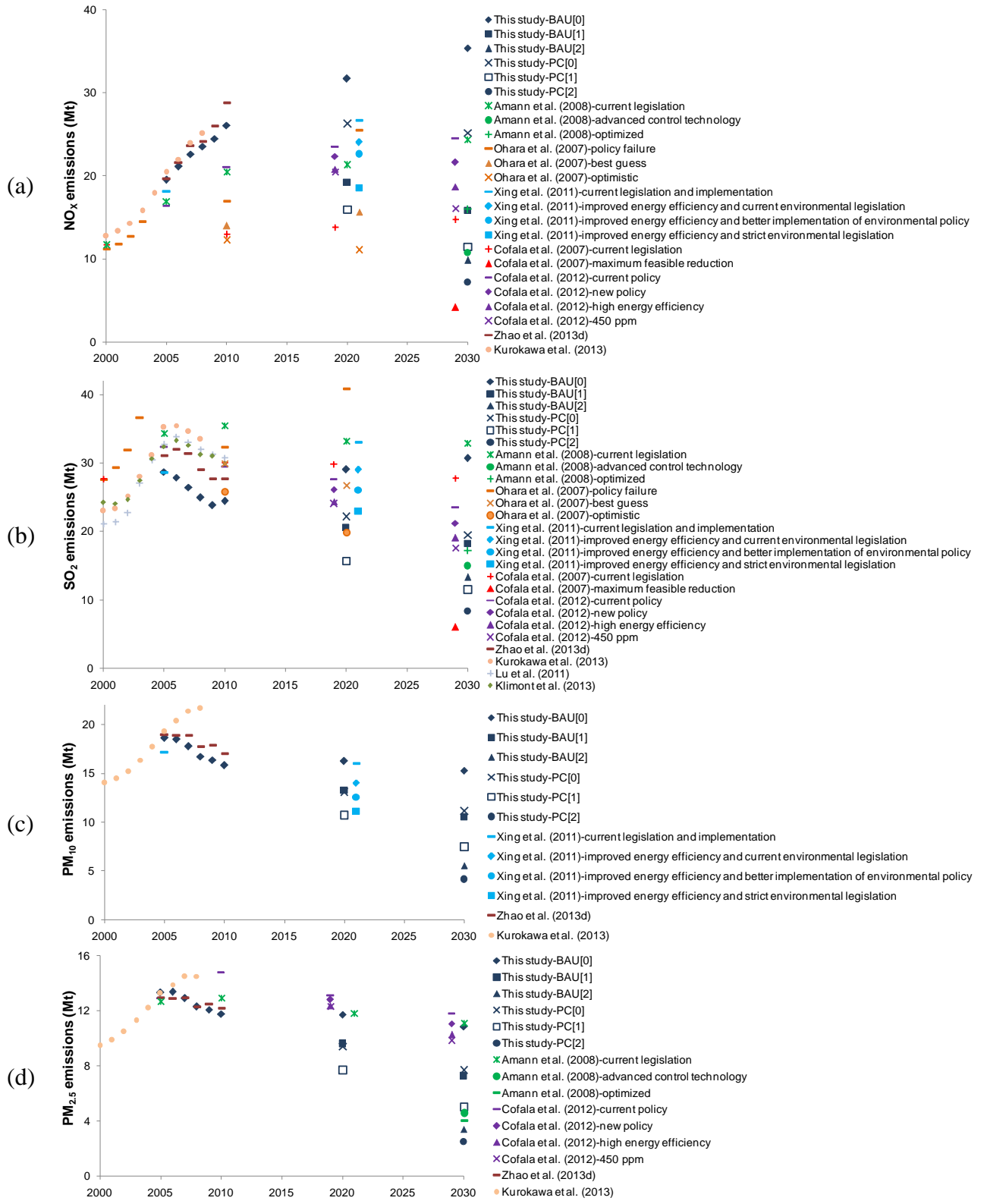


2 Figure 2. Emissions of major air pollutants in China and their sectoral distribution during  
 3 2005-2030: (a)  $\text{NO}_x$ ; (b)  $\text{SO}_2$ ; (c)  $\text{PM}_{10}$ ; (d)  $\text{PM}_{2.5}$ ; (e) NMVOC. The sector of “Others”  
 4 represents biomass open burning for  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{PM}_{10}$ , and  $\text{PM}_{2.5}$ ; for NMVOC, it includes  
 5 biomass open burning, waste treatment, cooking, and smoking, with biomass open burning  
 6 contributing over 80% of the total NMVOC emissions of this sector.

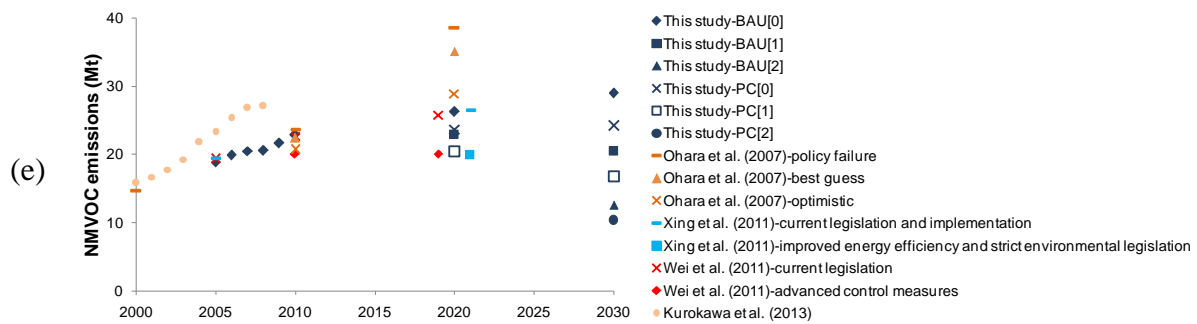
1



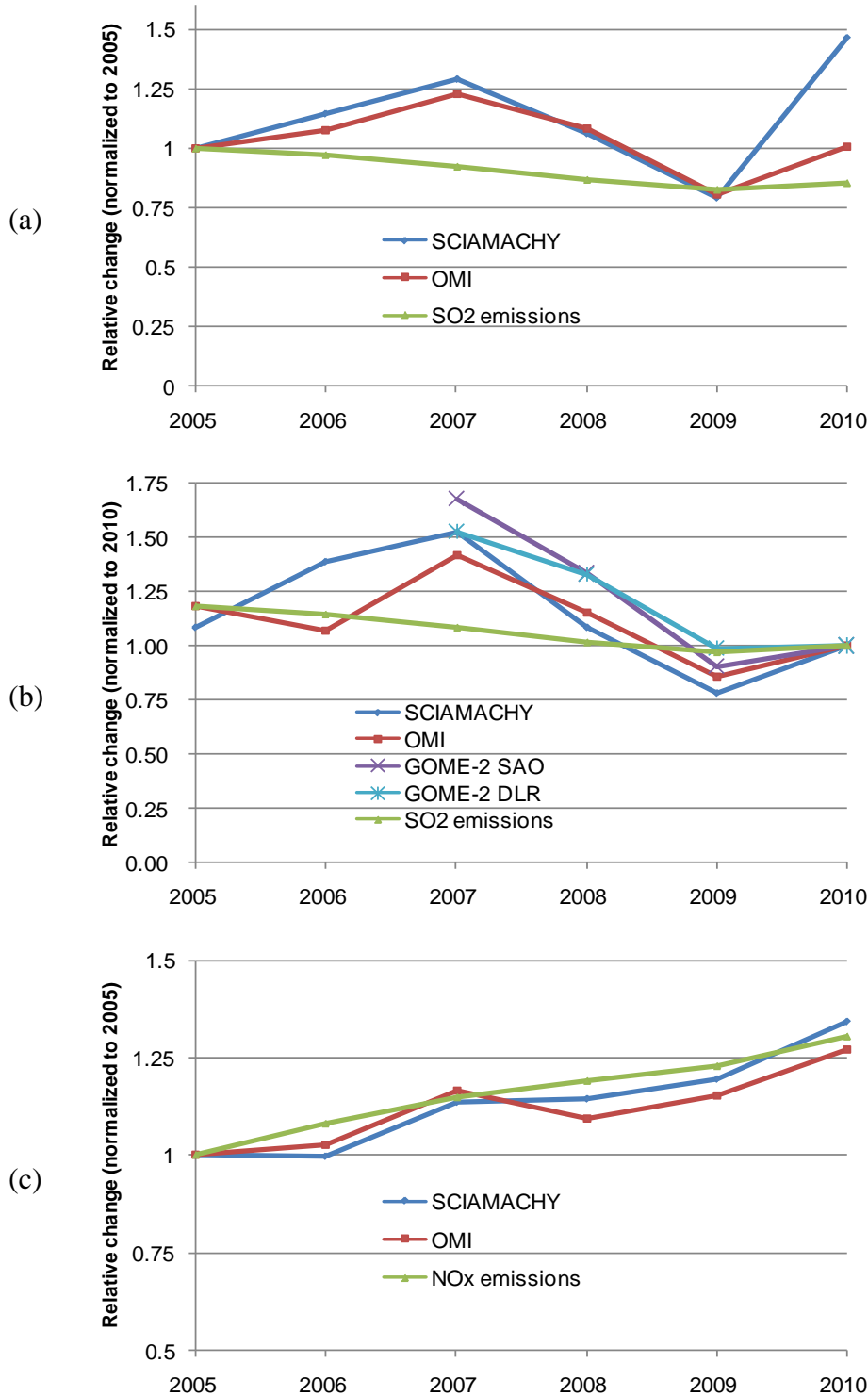
2 Figure 3. Emissions of major air pollutants in Japan and South Korea and their sectoral  
 3 distributions during 2005-2030: (a)  $\text{NO}_x$ ; (b)  $\text{SO}_2$ ; (c)  $\text{PM}_{10}$ ; (d)  $\text{PM}_{2.5}$ ; (e) NMVOC. JP and  
 4 SK in the legend represent Japan and South Korea, respectively. The sector of “Others” is  
 5 mainly biomass open burning.







1 Figure 4. Comparison of estimated emissions in this study with those of other studies: (a)  
 2 NO<sub>x</sub>; (b) SO<sub>2</sub>; (c) PM<sub>10</sub>; (d) PM<sub>2.5</sub>; (e) NMVOC. The scenarios from the same study are  
 3 shown with symbols of the same colour, and since their historical emissions duplicate each  
 4 other, we show just the historical values of one scenario. Some points for the years 2020 and  
 5 2030 are shifted a little left or right, in order to avoid overlapping representation. Note that the  
 6 current legislation scenario in Amann et al. (2008) is consistent with the baseline scenario in  
 7 Klimont et al. (2009), and the historical emission trends of Zhao et al. (2013a) is consistent  
 8 with this study. Therefore, Klimont et al. (2009) and Zhao et al. (2013a) are not shown in the  
 9 figures.  
 10



2 Figure 5. Inter-annual relative changes of SO<sub>2</sub> and NO<sub>2</sub> VCD from satellite observations and  
 3 estimated emissions in this study. (a) Average SO<sub>2</sub> VCD and total SO<sub>2</sub> emissions in Eastern  
 4 Central China (latitude <45°N, longitude >100°E). SO<sub>2</sub> VCD was derived by Lu et al. (2011).  
 5 All data are normalized to 2005. (b) Average SO<sub>2</sub> VCD and total SO<sub>2</sub> emissions over an area  
 6 of Eastern China (34°N–38°N, 112°E–118°E). SO<sub>2</sub> VCD was derived by Fioletov et al.  
 7 (2013), in which a filtering procedure was applied to remove local biases, in particular  
 8 volcanic signals. All data are normalized to 2010 because the data of GOME-2 are only  
 9 available since 2007. (c) Average NO<sub>2</sub> VCD and total NO<sub>x</sub> emissions in Eastern Central  
 10 China. NO<sub>2</sub> VCD was retrieved from OMI and SCIAMACHY in this study. All data are  
 11 normalized to 2005.