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NO_x emissions in China: historical trends and future perspectives

B. Zhao[1], **S. X. Wang**[1,2], **H. Liu**[1,2], **J. Y. Xu**[1], **K. Fu**[1], **Z. Klimont**[3], **J. M. Hao**[1,2], **K. B. He**[1], **J. Cofala**[3], **and M. Amann**[3]

[1]School of Environment, and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China
[2]State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China
[3]International Institute for Applied System Analysis, Laxenburg, Austria

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

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Abstract. Nitrogen oxides (NO_x) are key pollutants for the improvement of ambient air quality. Within this study we estimated the historical NO_x emissions in China for the period 1995–2010, and calculated future NO_x emissions every five years until 2030 under six emission scenarios. Driven by the fast growth of energy consumption, we estimate the NO_x emissions in China increased rapidly from 11.0 Mt in 1995 to 26.1 Mt in 2010. Power plants, industry and transportation were major sources of NO_x emissions, accounting for 28.4 %, 34.0 %, and 25.4 % of the total NO_x emissions in 2010, respectively. Two energy scenarios, a business as usual scenario (BAU) and an alternative policy scenario (PC), were developed to project future energy consumption. In 2030, total energy consumption is projected to increase by 64 % and 27 % from 2010 level respectively. Three sets of end-of-pipe pollution control measures, including baseline, progressive, and stringent control case, were developed for each energy scenario, thereby constituting six emission scenarios. By 2030, the total NO_x emissions are projected to increase (compared to 2010) by 36 % in the baseline while policy cases result in reduction up to 61 % in the most ambitious case with stringent control measures. More than a third of the reduction achieved by 2030 between least and most ambitious scenario comes from power sector, and more than half is distributed equally between industry and transportation sectors. Selective catalytic reduction dominates the NO_x emission reductions in power plants, while life style changes, control measures for industrial boilers and cement production are major contributors to reductions in industry. Timely enforcement of legislation on heavy-duty vehicles would contribute significantly to NO_x emission reductions. About 30 % of the NO_x emission reduction in 2020 and 40 % of the NO_x emission reduction in 2030 could be treated as the ancillary benefit of energy conservation. Sensitivity analysis was conducted to explore the impact of key factors on future emissions.

1 Introduction

Nitrogen oxides (NO_x) play a crucial role in tropospheric chemistry. Production of ozone in the troposphere is controlled by the abundance of NO_x (e.g., Zhang et al., 2007). NO_x also contributes to the formation of secondary inorganic aerosols, resulting in adverse impacts on human health (Wang et al., 2011b; Mueller et al., 2004). Increasing nitrate / sulfate ratios in precipitation have been observed in monitored cities in China, attributable to increasing NO_x emissions (Zhao et al., 2009). In addition, NO_x may lead to climate forcing effects via ozone formation or via secondary aerosols (Solomon et al., 2007). Therefore, NO_x is a key pollutant for the overall improvement of ambient air quality under multi-objective environmental management policies.

With the rapid economic development and urbanization in China, air pollutant emissions have been increasing at an unprecedented rate over the last decade (Xing et al., 2011). NO_x emissions in China (or as part of regional/global inventories) have been estimated by a number of researchers (Kato and Akimoto, 1992; Akimoto and Narita, 1994; Olivier et al., 1998; van Aardenne et al., 1999; Xue et al., 1999; Shah et al., 2000; Streets and Waldhoff, 2000; Klimont et al., 2001; Streets et al., 2001, 2003a; Vallack et al., 2001; Hao et al., 2002; Zhang et al., 2007, 2009; Ohara et al., 2007; Wang et al., 2011a; Xing et al., 2011; Klimont et al., 2009; Zhao

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et al., 2013). The annual growth rate of NO_x emissions was as high as 6.3 % during 1995–2004 according to Zhang et al. (2007). Satellite-based observations of NO_2 columns have shown even faster growth in the same period (Richter et al., 2005). It is important to provide a reliable estimate of the historical trends in the past two decades with a consistent model structure and detailed Chinese data sources. In addition, nearly all the previous studies neglected the emissions from several "small industries", including the production of bricks, glass, lime, ceramics, and nitric acid, the emissions of which were quite uncertain but fairly important.

To mitigate the adverse effect of air pollution, the Chinese government aims to reduce NO_x emissions by 10 % (compared to 2010) during the 12th Five-Year Plan (2011–2015) (The State Council of the People's Republic of China, 2011a). It is of strategic importance to indicate the dimensions of the effort to achieve such an ambitious target, and to evaluate the impact of further control policies on the emission pathway beyond 2015. Some previous studies have presented NO_x emission projections (van Aardenne et al., 1999; Shah et al., 2000; Streets and Waldhoff, 2000; Klimont et al., 2001, 2009; Ohara et al., 2007; Amann et al., 2008; Xing et al., 2011). However, these projections were based on the emissions for the year 2005 or earlier, and underestimated China's economic growth experienced in the last decade, especially during the period from 2006 to 2010. In addition, none of the projections anticipated the aggressive NO_x emission control policies envisaged in the 12th Five-Year Plan, which may fundamentally change the future NO_x emission pathway. End-of-pipe control technologies were historically relied on for pollutant reductions while recent research has illustrated the importance of energy-saving policies for emission control in China (Yuan et al., 2011). The substantial reduction of NO_x emissions in the future calls for integrated control policies, which contribute to energy conservation and pollutant reductions simultaneously. Previous projections often adopted energy consumption projections directly from other sources. Therefore, it was difficult to quantify the impact of various energy-saving policies on emission reductions.

To reflect recent changes of NO_x emissions and quantify the effects of various control policies, we estimated China's NO_x emissions during 1995–2010 and developed future NO_x emission scenarios in five-year steps up to 2030 using a consistent model structure. These scenarios envisage not only end-of-pipe control measures, but also integrated energy-saving measures, such as life style changes, energy structure adjustment, and energy efficiency improvement. The impact of various control measures on NO_x emissions was evaluated, and the ancillary benefit of energy conservation on NO_x emission reductions was analyzed. Sensitivity analysis was then conducted to explore the impact of some key factors on future emissions.

2 Methodology and data sources

A consistent model structure was developed for the estimation of historical NO_x emissions, and the calculation of future energy consumption and NO_x emissions. The energy consumption and final NO_x emissions greatly depend on the energy technology mix, energy efficiencies of each technology, and end-of-pipe control technologies. Compared with previous studies, the technology-based model developed in this study has more detailed representation of energy technologies and end-of-pipe control technologies, which is critical for obtaining reliable emission estimates. A dynamic technology database was established to reflect the rapid renewal of energy technologies and control technologies, both in the past and future. While previous emission projections usually adopted the energy consumption projection developed with other models directly, this study assures the consistency of energy and emission projections by coupling the energy technologies and end-of-pipe control technologies. Each energy technology may be coupled with several types of control technologies. Based on the detailed, consistent, and dynamic representation of energy technologies and control technologies, we quantified the impact of various energy-saving measures and end-of-pipe control measures on NO_x emissions, as well as the ancillary benefit of energy conservation on NO_x emission reduction (see Sects. 3.2.2 and 3.2.3), which has significant policy implications but were not addressed in the previous studies.

For the past years (1995–2010), energy consumption data were collected from statistics, and the technology distribution was collected from a variety of local sources. To provide a robust baseline for the calculation of future data, the historical energy consumption was also calculated from energy service demand, technology distribution, and energy efficiencies, and the model was calibrated by adapting the technology-based energy calculation to energy statistics. For the future years (2010–2030), the driving forces (e.g., GDP, population) are assumed first, and then energy service demand is estimated based on driving forces. The future technology distribution and energy efficiencies are assumed, and the energy consumption is calculated. Both historical and future emissions are derived from energy consumption, emission factors and assumptions on the penetration of control technologies. The governing equations of the model are as follows:

$$E^{\wedge}_{k,i,j,l} = E_{k,i,j,l} D_{i,j} X_{i,j,l}, \tag{1}$$

$$E^{\wedge}_{k,i} = \sum_{j} \sum_{l \in W_j} E_{k,i,j,l} D_{i,j} X_{i,j,l}, \tag{2}$$

$$Q_i^m = \sum_j \sum_{l\in W_j} \sum_{p\in V_l} \left(\left(F^m_{i,j,l} D_{i,j} X_{i,j,l} + \sum_k f^m_{k,i,j,l} E^{\wedge}_{k,i,j,l} \right) Y_{i,j,l,p} \left(1-d^m_{i,j,l,p}\right) \right), \quad (3)$$

where i represents the economic sector in a specific province (e.g., power plants in Beijing); j represents energy service type; k represents fuel type; l represents energy technology type; p represents air pollutant control technology type; m represents air pollutant/greenhouse gas; W_j is all the energy technologies that supply energy service type j; V_l is all the control technologies coupled with energy technology l; D represents the energy service demand; X is proportion of energy service supplied by a specific energy technology; E is the energy efficiency (i.e., the energy consumption to supply per unit energy service with a specific energy technology); $\hat{E}$ is the total energy consumption; f is the energy-based uncontrolled emission factor (i.e., the uncontrolled air pollutant/greenhouse gas emission per unit energy consumption of a specific energy technology); F is the service-based uncontrolled emission factor (i.e., the uncontrolled air pollutant/greenhouse gas emission per unit energy service supplied with a specific energy technology); Y is the proportion of an energy technology equipped with a specific air pollutant control technology; d is the removal rate of a specific air pollutant control technology when coupled with a specific energy technology; Q is the total final air pollutant/greenhouse gas emissions. The sources and values of energy service demand, proportion of energy technologies, and energy efficiencies are documented in Sect. 2.1, while those of uncontrolled emission factors and proportion of control technologies are given in Sect. 2.2 and Sect. 2.3, respectively.

This study covers 31 provinces in mainland China. All data are at the provincial level. Unit-based methodology is applied to estimate the emissions from large point sources including coal-fired power plants, iron and steel plants, and cement plants (Zhao et al., 2008; Lei et al., 2011).

2.1 Data sources of energy consumption

2.1.1 Historical energy consumption

The historical energy consumption data were collected from a variety of sources, with a critical examination of the data reliability. Energy consumption data of the stationary combustion sectors (power plants, heat supply, industry, and domestic) were derived from China Energy Statistical Yearbooks (CESY) (National Bureau of Statistics, 1998, 2001, 2004a, b, 2005, 2006, 2007, 2008a, b, 2009, 2011a, b). While CESY provides both a national and provincial energy balances, they are inconsistent with each other. Following the method of Zhang et al. (2009), we adopted the energy consumption values from the provincial energy balances, except for diesel, which was taken from the national balance. The shares of technologies were collected from a wide range of statistics, peer-reviewed papers, a number of technical reports, and unpublished materials from industrial associations and research institutes.

The industry sector is classified into industrial boilers and industry process because of different combustion technologies. The amount of fuel consumed for the production of various industrial products was estimated from the yields and energy efficiencies, and the amount of fuel consumed in the boilers was obtained by extracting the fuels consumed for industrial products from the total fuel consumption of the industry sector. The provincial data on industrial production were collected from various governmental statistics, such as China Statistical Yearbook and China Statistical Yearbook for Regional Economy (National Bureau of Statistics, 1996–2011, 2000–2011). The brick production was estimated from the unpublished data of China Bricks and Tiles Industrial Association, as the governmental statistics includes only enterprises above a specific size, which accounts for only 10–20 % of the total production (Xu, 2008, 2010).

Fuel consumption of on-road vehicles was calculated from vehicle population, annual average vehicle mileage traveled, and fuel economy for each vehicle type, as documented in He et al. (2005) and Wang et al. (2006). Fuel consumption of off-road vehicles was also derived with a bottom-up method (Zhang, 2005; Zhang, 2008). The fuel consumption of transportation was subtracted from other sectors in the energy balance table to avoid double counting. The open burning of agricultural residue was calculated based on the residue production, the ratio of open burning, and the burning efficiency; the method and key parameters are described in Streets et al. (2003b) and Wang and Zhang (2008). Although biomass open burning is not the key source of emissions for NO_x, it should be noted that the estimate of burned agricultural residue has large uncertainty. Some remote sensing products have showed much lower activity than bottom-up estimate based on crop residue remaining on filed and the ratio of burning (van der Werf et al., 2010; Yevich and Logan, 2003). Soil and lightning NO_x might be important emission sources in China (Wang et al., 2011a). However, considering the difficulties to control them, we did not include soil or lightning NO_x emissions but rather focused on the energy-related NO_x emissions in this study.

2.1.2 Assumptions on future driving forces

1. GDP

The government aims to develop China into a medium developed country by 2050, which implies the GDP per capita should be over 20 000 USD (at 2005 exchange rate). We assume the annual average GDP growth rate is 8.0 % from 2011 to 2015, 7.5 % from 2016 to 2020, 6.5 % from 2021 to 2025, and 5.5 % from 2026 to 2030, respectively. Based on these assumptions and population development as discussed below, GDP per capita is estimated at about 9700 USD (at 2005 exchange rate), or about 11 400 USD (2007 exchange rate) in 2030. The provincial GDP was calculated with historical data from 1995 to 2010 using the logistic regression method. Minor adjustment was necessary to make the total of provincial GDP consistent with the national GDP. The share of primary, secondary, and tertiary industries in GDP, and the share of various industries in the secondary industry, were adopted from the Energy Research Institute (2009).

2. Population

Different projections of China's population agree fairly well with each other. In this study, we adopted the Research Report on National Population Development Strategy (National Population Development Strategy Research Group, 2007), and made minor revisions based on recent population growth rates. The national population is projected to increase from 1.34 billion in 2010 to 1.44 billion in 2020 and 1.47 billion in 2030. The provincial populations were calculated with historical data from 1995 to 2010 using the logistic regression method.

3. Urbanization and household size

Urbanization rate is assumed to increase from 49.95 % in 2010 to 58 % and 63 % in 2020 and 2030, respectively, representing a medium range in urbanization projections. Household sizes in urban and rural area are assumed to decrease from 2.88 and 3.95 in 2010 to 2.75 and 3.40 in 2030, respectively (Energy Research Institute, 2009).

2.1.3 Assumptions on future energy consumption

We developed two energy scenarios: a business as usual scenario (BAU) and an alternative policy scenario (PC). The BAU scenario is based on current legislation and implementation status (until the end of 2010), in particular on the assumption that CO_2 intensity would be 40–45 % lower in 2020 than that of 2005 (The State Council of the People's Republic of China, 2009). In the PC scenario, we assume the introduction and strict enforcement of new energy-saving policies, including life style changes, structural adjustment, and energy efficiency improvement. Life style changes imply slower growth of energy service demand, including energy-intensive industrial products, building area and domestic service demand, vehicle population, electricity production, and heat supply, due to more conservative life styles. Structural adjustment includes promotion of clean and renewable fuels and energy-efficient technologies, such as renewable energy power and combined heat and power generation (CHP) for power plants and heat supply sector respectively, arc furnace and large precalcined kilns for industrial sector, biogas stoves and heat pumps for domestic sector, electric vehicles and biofuel vehicles for transportation sector, and so on. Assumed energy efficiency improvement includes the improvement of the energy efficiencies of single technologies in each sector. The definition and key parameters of the energy scenarios are summarized in Table 1 and Table 2, respectively. The energy consumption was calculated with a 5 yr resolution, though the parameters for selected years only are presented in the tables. Detailed assumptions of the energy scenarios are documented below.

1. Power plants

Future electricity production is calculated based on the demand of final consumption sectors. The method to estimate the demand of final consumption sectors is described in the next few sections. The total electricity production is projected to be 6690/5998 TWh and 8506/7457 TWh in BAU/PC scenario in 2020 and 2030, respectively.

The penetration of clean energy power is expected to increase rapidly in the future. The BAU scenario is designed based on the plan of the National Development and Reform Commission (2005, 2007b), with revisions according to recent development. The PC scenario considers an aggressive development plan proposed by China Electricity Council (2011) and a series of other analyses and projections. The installed capacities of hydropower, nuclear power, wind power, solar power, and biomass power are expected to be 300/320 GW, 40/70 GW, 40/60 GW, 1.8/8 GW, and 20/30 GW respectively in BAU/PC scenario in 2020. The corresponding capacities are projected to be 350/380 GW, 70/130 GW, 60/120 GW, 9/30 GW, 30/55 GW in 2030. Natural gas power is not expected to develop at a large scale due to its high cost, whereas it may be constructed in some metropolitan areas for the relief of air pollution (Zhao et al., 2011), or constructed at small scale for peak shaving in the power grid. The proportion of electricity production from coal-fired power plants is expected to decrease to 73 % and 57 % in 2030 under BAU and PC scenarios, respectively. Newly built coal-fired power plants are dominated by large units (300 MW or larger); smaller units (below 100–200 MW) will be phased out in the near future. Before 2005, sub-critical units were the dominant technology. Super-critical units have been widely applied since 2005. Ultra-supercritical units are expected to be widely promoted in the next five years. Integrated gasification-combined cycle (IGCC) units are promising to be applied at large scale in 5–10 yr. The structure adjustment of power plants is shown in Fig. 1.

2. Heat supply

Future heat supply is also estimated based on the demand of final consumption sectors. The total heat supply is projected at 258/243 Mtce and 345/325 Mtce in BAU/PC scenario in 2020 and 2030, respectively.

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 legislation and implementation status (until the end of 2010), especially that CO_2 intensity would be 40–45 % lower in 2020 than that of 2005.	BAU[0]	The BAU[0] scenario assumes the same energy-saving policies as BAU scenario. For end-of-pipe pollution control measures, it assumes that all current legislation (until the end of 2010) and the current implementation status will be followed during 2011–2030.
		BAU[1]	The BAU[1] scenario assumes the same energy-saving policies as BAU scenario. For end-of-pipe pollution control measures, it assumes that new pollution control policies would be released and implemented, representing progressive approach towards future environmental policies.
		BAU[2]	The BAU[2] scenario assumes the same energy-saving policies as BAU scenario. For end-of-pipe pollution control measures, it assumes that even more ambitious policies will be released and implemented; such a scenario could be realized only if the government takes quick and substantially aggressive action.
Alternative policy (abbr. PC)	The PC scenario assumes that new energy-saving policies will be released and enforced more stringently, including life style changes, structural adjustment and energy efficiency improvement.	PC[0]	The PC[0] scenario assumes the same energy-saving policies as PC scenario, and the same end-of-pipe pollution control measures as BAU[0] scenario.
		PC[1]	The PC[1] scenario assumes the same energy-saving policies as PC scenario, and the same end-of-pipe pollution control measures as BAU[1] scenario.
		PC[2]	The PC[2] scenario assumes the same energy-saving policies as PC scenario, and the same end-of-pipe pollution control measures as BAU[2] scenario.

Technologies for heat supply include CHP, coal-fired boilers, oil-fired boilers, and gas-fired boilers. The share of CHP is assumed to increase from 61 % in 2010 to 65 %/72 % in 2030 under BAU/PC scenario, attributable to the promotion of the government, and the increasing need of district heating from CHP in domestic sector. The penetration of gas-fired boiler is assumed to increase to 10 % and 15 % in BAU and PC scenarios respectively in 2030.

3. Industry sector

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

$$Y_{t1} = Y_{t0}\left(\frac{\mathrm{dv}_{t1}}{\mathrm{dv}_{t0}}\right)^{\delta}, \qquad (4)$$

where $t0$ and $t1$ are time periods (e.g., $t0 = 2010$, and $t1 = 2030$); Y is the yield of a specific industrial product; dv is the driving force, namely sectoral value added or population; δ is the product-specific elasticity coefficient. The values of δ are determined through (1) the historical trend during 1995–2010; (2) the experience of developed countries; (3) the projections of some industry associations. Most energy-intensive products for infrastructure construction are

Table 2. Key parameters of the energy scenarios.

		BAU		PC	
	2010	2020	2030	2020	2030
GDP (2005 price)/10^9 CHY[a]	31 165	65 741	117 718	65 741	117 718
Population/billion	1.340	1.440	1.474	1.440	1.474
Urbanization rate/%	49.7	58.0	63.0	58.0	63.0
Power generation/TWh	4205	6690	8506	5598	7457
Share of coal-fired power generation/%	75	74	73	64	57
Thermal efficiency of coal-fired power/%	35.7	38.0	40.0	38.8	41.7
Crude steel production/Mt	627	710	680	610	570
Cement production/Mt	1880	2001	2050	1751	1751
Urban residential building area per capita m^{-2}	23.0	29.0	33.0	27.0	29.0
Rural residential building area per capita m^{-2}	34.1	39.0	42.0	37.0	39.0
Vehicle population per 1000 persons	58.2	191.2	380.2	178.5	325.2
Share of new and renewable energy/%[b]	7.5	8.3	8.9	11.9	15.8
CO_2 emission per GDP/(t/10^6 CHY)[c]	267	182	120	148	84

[a] CHY, Chinese yuan.

[b] Including hydropower, solar energy, wind energy, ocean energy, and nuclear energy; excluding biomass.

[c] The CO_2 emission per GDP was 322 t/10^6 CHY in 2005, which was adopted as a benchmark value for the national target that the CO_2 emission per GDP should decrease by 40–45 % from 2005 to 2020.

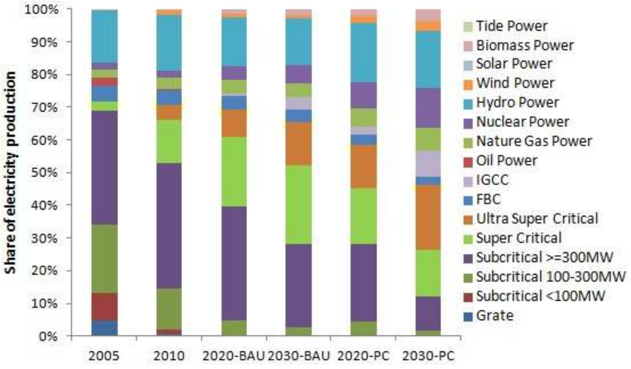


Fig. 1. Structure adjustment of power plants.

expected to increase until 2020, and stabilize or even decline after 2020, whereas the products closely related to everyday life are expected to increase until 2030, though at a declining rate. Future yields in PC scenario are less than those in BAU scenario because of a more conservative life style.

The National Development and Reform Commission released the Special Plan for Medium and Long Term Energy Conservation in 2004 (National Development and Reform Commission, 2004), which set the aim that the comprehensive energy efficiencies of most energy-intensive products would reach or approach the average level of developed countries by 2020. In BAU scenario, we assume the plan will be realized by 2020, whereas the energy efficiencies will not increase markedly beyond 2020. Under PC scenario, the best available technologies (BATs) are assumed to be adopted in some industries by 2020, and are expected to be widely used in 2030, which implies China's energy efficiencies would be among the highest in the world.

The improvement of comprehensive energy efficiency is achieved through structural adjustment and energy efficiency improvement of specific technology. The shares of less energy-intensive technologies are assumed to be higher in PC scenario than BAU scenario, as summarized in Table 3. For example, the share of precalcined kilns in cement production is projected to approach 100 % in 2030 in PC scenario, and 85 % of them have a capacity larger than or equal to 4000 t d^{-1}. However, energy-intensive shaft kilns are still expected to account for 15 % of cement production in 2030 under BAU scenario. The energy efficiencies of single technologies are also expected to improve in the future. For example, the energy consumption per unit product of blast furnaces, brick production, precalcined kilns for clinker production, machine coke ovens, and petroleum refineries is assumed to be 4 %, 18 %, 9 %, 33 %, and 21 % lower respectively in 2030 under BAU scenario compared with 2010. The corresponding reduction rates in the PC scenario are assumed to be 13 %, 27 %, 15 %, 44 %, and 31 % respectively.

4. Domestic sector

The domestic energy consumption is divided into urban residential consumption, rural residential consumption, and commercial consumption. Building area is a key factor of domestic energy consumption. In this study, future building area is estimated by referring to the governmental plan and comparing with the experience of developed countries. Average urban residential building area per capita is projected

Table 3. Technology evolution of selected industry sectors (%).

Process	Technology	2005	2010	2020 BAU	2030 BAU	2020 PC	2030 PC
Crude steel production	Arc furnace	11.8	11.2	14.0	18.0	25.0	40.0
	Basic oxygen furnace	88.1	88.8	86.0	82.0	75.0	60.0
Cement production	Shaft kiln	50.0	24.0	19.0	15.0	2.0	0.0
	Other rotary kiln	5.0	1.0	0.0	0.0	0.0	0.0
	Precalcined kiln <2000 $t\,d^{-1}$	10.8	8.6	7.3	6.0	6.9	3.0
	Precalcined kiln 2000–4000 $t\,d^{-1}$	19.4	21.4	20.3	17.9	19.6	12.0
	Precalcined kiln >4000 $t\,d^{-1}$	14.9	45.0	53.5	61.2	71.5	85.0
Glass production	Float process	80.0	85.0	95.0	100.0	100.0	100.0
	Vertical process	20.0	15.0	5.0	0.0	0.0	0.0
Coke production	Machine coke oven	81.9	87.0	96.0	100.0	100.0	100.0
	Indigenous coke oven	18.1	13.0	4.0	0.0	0.0	0.0
Ammonia synthesis	Ammonia synthesis from oil & natural gas	37.0	23.0	23.0	23.0	23.0	23.0
	Ammonia synthesis from coal	63.0	77.0	77.0	77.0	77.0	77.0
Caustic soda production	Ion-exchange membrane process	34.0	57.0	67.0	75.0	80.0	98.0
	Diaphragm process	66.0	43.0	33.0	25.0	20.0	2.0
Soda production	Combined-soda process	39.5	42.0	45.0	48.0	49.0	56.0
	Ammonia-soda process	60.5	58.0	55.0	52.0	51.0	44.0
Nitric acid production	Dual-pressure process	38.0	54.0	67.0	80.0	75.0	95.0
	Other process	62.0	46.0	33.0	20.0	25.0	5.0
Industrial boiler	Grate boiler	90.0	89.0	85.0	82.0	81.0	75.0
	Circulating fluidized bed boiler	10.0	11.0	15.0	18.0	19.0	25.0

at 33 m^2 in 2030 under BAU scenario, comparable to that of Japan and the target set by the Ministry of Construction of China. Rural residential building area per capita is projected at 42 m^2 since it is less populous, also comparable to the target of the Ministry of Construction. In PC scenario, the building area per capita is 3–4 m^2 lower than that of BAU scenario in both urban and rural area.

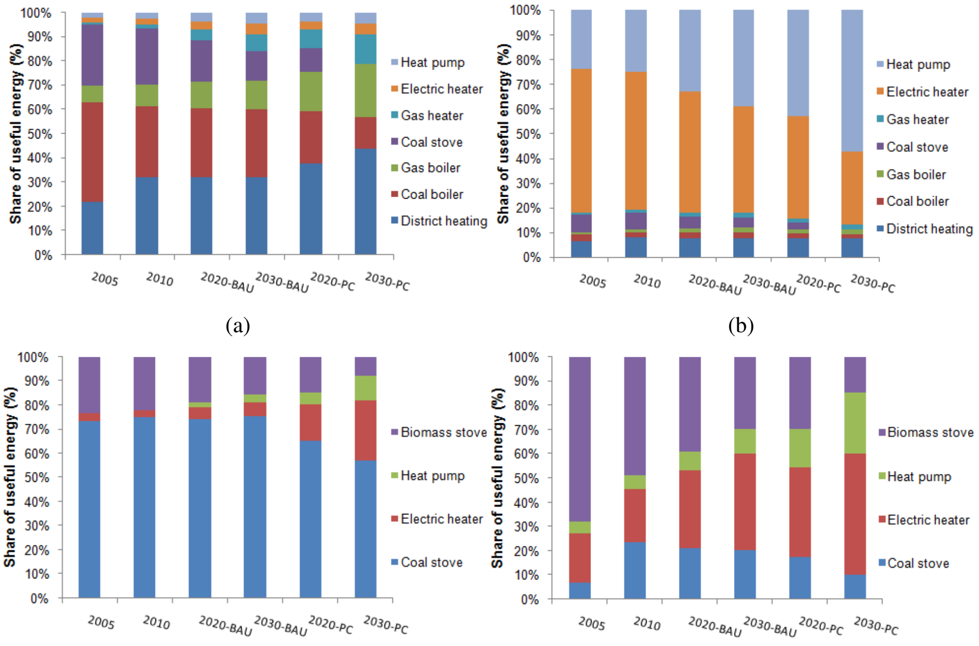
Energy service demand in the domestic sector is derived from building area/population and energy service intensity, which is defined as the energy service demand per building area/capita. Heating intensity is influenced by climate, the proportion of heating area, heating service quality, thermal insulation of the building envelope, and heating duration. As an integral effect, the heating intensity of urban area in north China is expected to decrease, while that of rural area and transition region (between north and south China) is expected to increase. The heating intensity is somewhat lower in our PC scenario than in the BAU scenario. The cooking and hot water intensity is projected to increase by a factor of 1.25–1.45 from 2010 to 2030, depending on rural or urban area, BAU or PC scenario. As for electric appliance, urban ownership in 2030 is projected to account for 70–100 % of that of Japan in 2005, while the rural ownership is lower.

People tend to use cleaner fuels for heating and cooking as incomes rise. Natural gas utilization as a domestic fuel enjoys the highest priority according to the "National Natural Gas Utilization Policy" (National Development and Reform Commission, 2007a). The development of biogas and solar water heaters has also been considered in the governmental plan (National Development and Reform Commission, 2007b). The heating structure adjustment is presented in Fig. 2, and that of cooking and hot water is presented in Fig. 3. Generally, in urban areas, coal is expected to be replaced by natural gas, electricity, heat pumps, and solar water heaters, except that district heating from CHP is expected to be promoted. In rural areas, coal and traditional biomass are expected to be replaced by electricity, biogas, heat pumps, and solar water heaters, with faster progress in the PC scenario. The technology mix for heating differs greatly depending on provinces. In urban areas, heating demand is mainly supplied by district heating, coal-fired boilers and coal-fired stoves in north China, while electric heaters and heat pumps dominate the heating technologies in the transition regions. In the future, we assume coal-fired boilers and coal-fired stoves would be gradually replaced by district heating, gas-fired boilers and gas heaters in north China, while heat pumps constitute the major technology to be promoted in the transition regions. The progress is faster in the PC scenario.

5. Transportation sector

Future on-road vehicle population is estimated using the Gompertz curve:

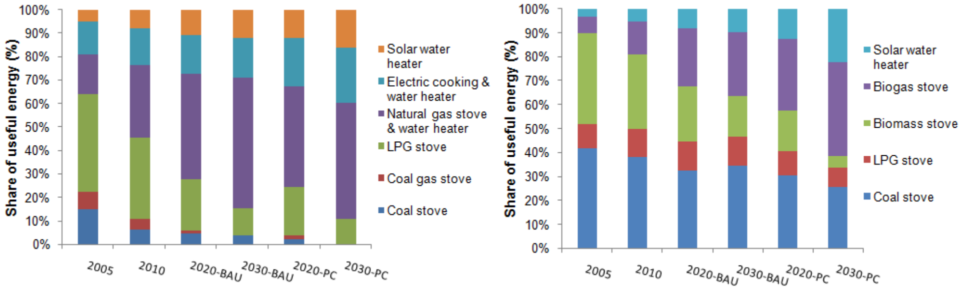
$$\mathrm{VPper}_i = \mathrm{VPper}_\mathrm{S} \times e^{\alpha e^{\beta \cdot \mathrm{GDPper}_i}}, \qquad (5)$$



(a) (b)

(c) (d)

Fig. 2. Structure adjustment of heating: **(a)** urban area in north region; **(b)** urban area in transition region; **(c)** rural area in north region; **(d)** rural area in transition region.



(a) (b)

Fig. 3. Structure adjustment of cooking and hot water: **(a)** urban area; **(b)** rural area.

where VPper$_i$ is on-road vehicle population per 1000 persons in year i; VPpers$_S$ is on-road vehicle population per 1000 persons, saturation level; GDPper$_i$ represents GDP per capita in year i; α and β are parameters. The saturation levels are assumed to be 500 and 400 units per 1000 persons in BAU and PC scenarios, similar to those of Japan and South Korea, respectively. The population of tractors, agricultural conveyers, the power of agriculture and construction machines, as well as the passenger and freight traffic volume of trains and inland waterway ships, are also related to total or sectoral GDP growth.

Passenger car ownership is assumed to maintain its exploding growth. The market share of passenger cars is projected to increase from 52 % in 2010 to 82 % in 2030. China has set up several initiatives to promote electric vehicles. In the BAU scenario, it is assumed that the market share of HEV (hybrid electric vehicle) in passenger cars will increase slowly in the first few years, speed up gradually and eventually reach 20 % in 2030. The PC scenario is designed by referring to several scenarios designed for the American market, and making adjustment according to China's conditions. The market shares of HEV, PHEV (plug-in hybrid electric vehicle) and EV (electric vehicle) in passenger cars are estimated to be 25 %, 28 % and 2 % in 2030, respectively. Electric buses and light-duty electric trucks are also expected to be promoted. The annual consumption of biogasoline and biodiesel is expected to reach 10 Mt and 2 Mt, respectively in 2020 under the BAU scenario, consistent with the governmental plan (National Development and Reform Commission, 2007b). In the PC scenario, the annual consumption of biogasoline is projected to increase to 20 Mt and 50 Mt in 2020 and 2030, respectively.

Several fuel efficiency standards have been released in China, including "Limits of Fuel Consumption for Passenger Cars" in 2004, "Limits of Fuel Consumption for Light Duty Commercial Vehicles" in 2007, "Low-speed Goods Vehicles – Limits and Measurement Methods for Fuel Consumption" and "Tri-wheel Vehicles – Limits and Measurement Methods For Fuel Consumption" in 2008. In 2010, the fuel efficiencies of new gasoline passenger cars and new heavy-duty diesel vehicles are about 13.5 km L^{-1} and 3.6 km L^{-1}, respectively. In BAU scenario, only the policies released in the year 2010 or before are considered. In PC scenario, for light-duty vehicles, a new standard entitled, "Fuel Consumption Evaluation Methods and Targets for Passenger Cars" issued in 2011 is assumed to be implemented during 2012–2015. Potential improvements of fuel economy corresponding to Path Three of NAS (US National Academy of Sciences) are assumed to be implemented during 2015–2025. Path Three, the most aggressive pathway designed by NAS, necessitates the introduction of emerging technologies that have the potential for substantial market penetration within 10–15 yr (US National Research Council, 2002). For heavy-duty vehicles, the Japanese fuel consumption limits of new heavy-duty vehicles are assumed to be implemented between 2015 and 2025, and the fuel economy requirements are assumed to be 20 % more stringent than the Japanese limit after 2025. Considering the policies discussed above, the resulting fuel economy of new passenger cars and light-duty buses is 33 % better in 2030 in the PC scenario than in 2010, while the corresponding improvement for new heavy-duty vehicles is 57 %. The historical and future fuel economies of electric vehicles are determined based on Lin (2010) and Huo et al. (2010). Fuel economy of motorcycle, agricultural tractors and conveyers, agriculture and construction machines, trains, and inland waterway ships is projected to increase by 23 %/29 %, 13 %/19 %, 14 %/23 %, 10 %/12 %, and 18 %/24 %, respectively, in BAU/PC scenario in 2030, compared to 2010.

6. Open burning of agricultural residue

Since 1997, the government has enacted a series of regulations and laws to prohibit field burning (Yan et al., 2006). A formal regulation to prohibit field burning and promote environmentally friendly utilization of agricultural residues was published in 1999 (State Environmental Protection Administration, 1999). Farmers are encouraged to return crop residue to agricultural soils as fertilizer. In addition, China's Ministry of Environmental Protection (MEP) released a notice to strengthen the prohibition of open burning before the harvest season almost every year (http://www.zhb.gov.cn/). Moreover, since 2004, MEP has been monitoring agricultural field burning with satellites, and a report of the numbers and locations of fire points has been published every day (http://hjj.mep.gov.cn/stjc/). Once the field burning was confirmed by satellite observations, local officials would take quick actions to forbid such behavior. Considering the government's continuous efforts to prohibit open burning, we assume the crop residue burned in the field will decline by 10 % every five years in both BAU and PC scenarios.

2.2 Data sources of uncontrolled emission factors

The uncontrolled emission factors were obtained through a thorough survey of literature reporting field measurements from Chinese sources. The uncontrolled NO_x emission factors for stationary sources are summarized in Table 4. Here, we include a brief discussion of the "small industries", including the production of glass, bricks, lime, ceramics, and nitric acid, which were often neglected in previous studies. Information on emission factors for these industries is limited but has been increasing in the past few years. The Chinese Research Academy of Environmental Sciences and Bengbu Glass Industry Design & Research Institute (2010) investigated the NO_x concentration in the flue gas of 14 glass plants, and estimated that the NO_x emission factor was within a range of 1.7–7.4 kg (t glass)$^{-1}$, and 5.2 kg (t glass)$^{-1}$ on average. The NO_x concentrations in the flue gas of brick kilns were within a range of 31.5–232.7 mg m^{-3} (78.6 mg m^{-3} on average, with annular kilns larger than tunnel kilns) for 8 brick plants investigated by Chinese Research Academy of Environmental Sciences (2009). However, the brick plants under investigation were mostly advanced tunnel kilns, and the production capacities were larger than 10 million units per year. In contrast, the traditional annular kilns account for more than 90 % of total brick production, and the plants with production capacity less than 10 million units per year account for over 60 %. Zhang et al. (2007) used 0.21 kg (t brick)$^{-1}$ (about 106 mg m^{-3}) based on the measurements of Tang et al. (1995). The Manual of Emission Factors for the Pollution Source Census recommended 0.27 kg (t brick)$^{-1}$ (about 140 mg m^{-3}) to represent the average emission rate of brick plants in China (Data Codification Committee of the First National Pollution Source Census, 2011), which was also adopted by Chinese Research Academy of Environmental Sciences (2009) for the estimation of total emissions. In this study, we used an emission factor of 0.27 kg (t brick)$^{-1}$. The emission factor for ceramics production, 4.35 kg t^{-1} ceramics, was based on the measurements of 22 plants by Hunan Research Academy of Environmental Sciences (2008). Qingdao University of Science & Technology (2008) collected the NO_x emission rates of 60 nitric acid plants. The NO_x concentrations in the flue gas of dual-pressure processes are usually less than 600 mg m^{-3}, while those of other processes are significantly higher. We estimated the uncontrolled NO_x emission factors to be 1.8 and 13.6 kg t^{-1} nitric acid, for dual-pressure process and other processes, respectively.

Table 4. Uncontrolled NO_x factors for stationary sources.

Technology	Unit	emission factors in this study	emission factors in other references
Coal-fired power plants < 100 MW (tangentially fired)	kg t^{-1} coal	6.81[a] (6.17 for bituminous, 9.36 for anthracite)	8.85[b] (average factor for coal-fired power plants) 5.55–10.5[c](vary with size and control measures, the average uncontrolled factor is estimated to be 9.10) 6.27[d] (uncontrolled factor for coal-fired power plants burning hard coal)
Coal-fired power plants < 100 MW (swirl burner)	kg t^{-1} coal	7.67[a] (6.93 for bituminous, 10.65 for anthracite)	
Coal-fired power plants ≥ 100 MW (tangentially fired)	kg t^{-1} coal	7.29[a] (6.60 for bituminous, 10.07 for anthracite)	
Coal-fired power plants ≥ 100 MW (swirl burner)	kg t^{-1} coal	8.21[a] (7.40 for bituminous, 11.46 for anthracite)	
Diesel-fired power plants	kg t^{-1} diesel	7.21[e]	10.06[b]; 6.56[f]
Heavy fuel (HF) fired power plants	kg t^{-1} HF	5.10[e]	
Gas-fired power plants	g m^{-3} gas	4.10[b]	9.82[f]; 1.95[e]
Coal-fired industrial grate boiler	kg t^{-1} coal	5.60[g]	7.25[b]; 3.8–4.0[c]; 5.25[e]; 6.1[f]
Coal-fired industrial CFB boiler	kg t^{-1} coal	1.20[g]	
Gas-fired industrial boiler	g m^{-3} gas	2.10[b]	2.61[e]
Sintering production	kg t^{-1} sinter	0.64[h]	0.14[g]; 0.50[d]
Cement – shaft kiln	kg t^{-1} coal	1.7[i]	0.4[g]
Cement – other rotary kiln	kg t^{-1} coal	18.5[i]	14.7[g]
Cement – precalcined kiln	kg t^{-1} coal	15.3[i]	9.6[g]
Brick production	kg (t brick)$^{-1}$	0.27[j]	0.06–0.45[k]; 0.21[c]
Lime production	kg t^{-1} lime	1.60[g]	1.75[d]
Glass production	kg (t glass)$^{-1}$	5.20[l]	8.20[d]
Ceramics production	kg t^{-1} ceramics	4.35[m]	
Refinery	kg t^{-1} crude oil input	0.30[d]	
Nitric acid – dual pressure process	kg t^{-1} nitric acid	1.8[n]	1.38[g] (dual-pressure process); 43.8[g] (other process); 7.14[d] (all process)
Nitric acid – other process	kg t^{-1} nitric acid	13.6[n]	
Domestic coal stove	kg t^{-1} coal	1.88[b]	
Domestic biomass stove – agricultural residue	kg t^{-1}ce	2.19[o]	2.74[b] (agricultural residue); 1.23[b] (firewood); 1.90[g] (all biomass)
Domestic biomass stove – firewood	kg t^{-1}ce	2.52[o]	
Biomass open burning	kg t^{-1} biomass	3.80[p]	3.37[q]

[a] Zhao et al. (2010); [b] Tian (2003); [c] Zhang et al. (2007); [d] IIASA GAINS-Asia: http://gains.iiasa.ac.at/index.php/gains-asia; [e] Wang et al. (2011a); [f] Yu (2009); [g] Zhang (2008); [h] Lei (2008); [i] Lei et al. (2011); [j] Data Codification Committee of the First National Pollution Source Census (2011); [k] Chinese Research Academy of Environmental Sciences (2009); [l] Chinese Research Academy of Environmental Sciences and Bengbu Glass Industry Design & Research Institute (2010); [m] Hunan Research Academy of Environmental Sciences (2008); [n] Qingdao University of Science & Technology (2008); [o] Wang et al. (2009); [p] Li et al. (2007); [q] Wang and Zhang (2008).

For on-road vehicles, there have been a fairly large number of measurements in the last decade. Our emission factors are compiled mainly based on some systematic measurement studies (e.g., Huo et al. (2012a) and the literature therein for light-duty gasoline vehicles and Huo et al. (2012b) and the literature therein for diesel vehicles). Considering the complex real-life driving conditions and the detailed classification of vehicle types in the our model structure, we also referred to some studies of vehicle emission estimation using transportation emission models, including Cai et al. (2007), Xie et al. (2006), Li et al. (2003), and Greenhouse Gas and Air Pollution Interactions and Synergies (Gains)-Asia project

Table 5. NO_x emission factors of mobile sources.

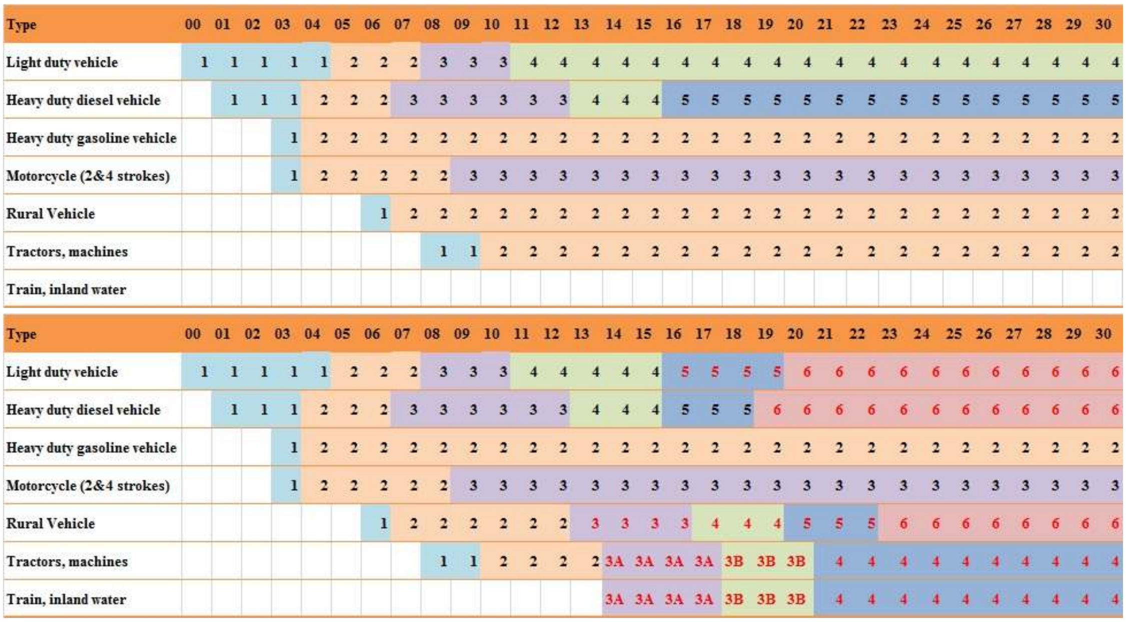
Technology	Fuel	Emission factors (kg t^{-1}ce)						
		Uncontrolled	Euro-I	Euro-II	Euro-III	Euro-IV	Euro-V	Euro-VI
Heavy-duty truck	Diesel	62.90	43.41	46.54	40.25	23.27	13.84	2.52
Medium-duty truck	Diesel	45.13	31.14	33.40	28.89	16.71	9.92	1.81
	Gasoline	11.53	2.08	1.14	0.82			
Light-duty truck	Diesel	21.43	21.43	21.43	21.43	16.07	8.37	3.63
	Gasoline	18.56	5.39	2.40	1.49	0.73	0.56	0.38
Mini truck	Gasoline	27.60	8.02	3.60	2.20	1.11	0.82	0.56
Heavy-duty bus	Diesel	56.55	39.02	41.83	36.18	20.93	12.44	2.25
	Gasoline	15.69	2.84	1.58	1.11			
Medium-duty bus	Diesel	36.18	24.97	26.78	23.15	13.38	7.96	1.43
	Gasoline	16.01	2.87	1.61	1.11			
Light-duty bus	Diesel	15.25	15.25	15.25	15.25	11.42	5.94	2.61
	Gasoline	19.73	5.74	2.58	1.58	0.79	0.59	0.38
Mini bus	Diesel	12.09	12.09	12.09	12.09	9.07	4.71	2.05
	Gasoline	18.91	5.47	2.46	1.52	0.76	0.56	0.38
Motorcycle	Gasoline	4.77	4.77	4.77	3.54			
Tractor	Diesel	37.11	24.50	18.56	11.12	11.12	7.05	1.49
Agricultural conveyer	Diesel	37.11	24.50	18.56	11.12	11.12	7.05	1.49
Train	Diesel	24.88	16.42	14.93	11.21	7.46	4.74	1.00
Inland waterway ship	Diesel/heavy fuel oil	32.87	21.69	19.73	14.78	9.86	6.23	1.32
Agriculture machine	Diesel	13.43	8.87	6.73	4.04	4.04	2.55	0.53
Construction machine	Diesel	13.43	8.87	6.73	4.04	4.04	2.55	0.53

(available online at http://gains.iiasa.ac.at/models/). The final emission factors, including uncontrolled factors, and controlled factors under Euro-I, Euro-II and Euro-III, were derived using field measurements as a starting point, which were subsequently adjusted based on the results of transportation emission models to reflect the complicated driving conditions in China. The emission factors of non-road vehicles are quite uncertain, as there are only a limited number of studies where emission performance of non-road vehicles has been analyzed. We rely on Tian (2003) for trains and agricultural tractors and conveyers, Wang et al. (2007) and Tian (2003) for agricultural and construction machinery, and Ding et al. (2000) and Song (2007) for inland waterway ships. It is valuable to do more measurements of the emission characteristics of non-road vehicles in the future. The emission factors of transportation sector are summarized in Table 5.

2.3 Data sources for NO_x emission control measures

2.3.1 Historical NO_x emission control measures

Low NO_x combustion technology (mainly Low NO_x Burner, LNB) was the only NO_x control technology widely used in China's power plants before 2005. Flue gas denitrification, including selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), began to be installed from 2005 onwards. The installed capacity of power plants equipped with SCR/SNCR increased from 4.2 GW in 2005 to 80.7 GW in 2010 (Ministry of Environmental Protection of China, 2011a). Fifty-seven percent of the total SCR/SNCR capacities in 2010 were located in the three "key regions", including the Greater Beijing region (including Beijing, Tianjin, Hebei), the Yangtze River delta (YRD, including Shanghai, Jiangsu, Zhejiang), and the Pearl River delta (PRD, mainly Guangdong province). The LNB penetration was estimated based on the following assumptions due to the lack of official statistics: (1) no boilers were equipped with LNB before 31 December 1996; (2) large units ($\geq$ 300 MW) built



(a)

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

(b)

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

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

after 1 January 1997 were equipped with LNB, according to the emission standard released in 1996 (State Environmental Protection Administration, 1996b); (3) smaller units (< 300 MW) were not equipped with LNB until 31 December 2003, but LNBs were installed with new boilers after 1 January 2004, based on the emission standard released in 2003 (State Environmental Protection Administration, 2003). The penetration of LNB (including LNB+SCR and LNB+SNCR) in coal-fired power plants was estimated to be 22.3 % in 2000, 50.5 % in 2005, and 87.9 % in 2010 based on the assumptions above. The data for 2005 are between the estimates of Zhang (2008) (46 % in 2005) and Zhao et al. (2008) (60 % in 2005).

NO_x control technologies were rarely adopted in the industry sector. Low NO_x combustion technologies were installed in some new precalcined cement kilns, while end-of-pipe control technologies like SCR/SNCR were seldom installed in the cement industry by 2010. The flue gas of dual-pressure nitric acid processes can be exhausted untreated according to the current emission standard (State Environmental Protection Administration, 1996a), though some plants are equipped with end-of-pipe control technologies. In contrast, other nitric acid processes were usually equipped with SCR or absorption methods in order to achieve the standard (Tang, 2006; Wang and Zeng, 2008).

Since 2000, China has released a series of emission standards for new vehicles, which are basically consistent with the corresponding European standards, though released several years later. The implementation timeline of these standards is summarized in Fig. 4. Megacities including Beijing and Shanghai are subject to greater pressure for regulating vehicle emissions, and are therefore 2–3 yr ahead of the national legislation. Recently, Beijing Environmental Protection Bureau began promoting regulations for new emission standards, i.e., Euro V in 2012 and Euro VI in 2016 (Wang and Hao, 2012).

2.3.2 Assumptions on future NO_x emission control measures

We developed three sets of end-of-pipe pollution control measures for each energy scenario, including baseline (abbr. [0]), progressive (abbr. [1]), and stringent control measures (abbr. [2]), thereby constituting six emission scenarios (BAU[0], BAU[1], BAU[2], PC[0], PC[1], and PC[2]). The baseline control measures (BAU[0]/PC[0] scenario) assume that all current pollution control legislation (until the end of 2010) and the current implementation status would be followed during 2011–2030. The progressive control measures (BAU[1]/PC[1] scenario) assume that new pollution control policies would be released and implemented, representing progressive approach towards future environmental policies. The stringent control measures (BAU[2]/PC[2] scenario) assume that even more ambitious policies would be released and implemented; such a scenario could be realized only if the government takes quick and substantially aggressive action. The definitions of the emission scenarios are summarized in Table 1, and the penetration of major control

Table 6. Removal rates and penetrations of air pollution control technologies (%).

Sector	Technology	Removal rate		Penetrations							
				2005	2010	2020 BAU[0]/PC[0]	2030 BAU[0]/PC[0]	2020 BAU[1]/PC[1]	2030 BAU[1]/PC[1]	2020 BAU[2]/PC[2]	2030 BAU[2]/PC[2]
Power plants	Coal-fired power plants < 100 MW (excl. CFB)	NOC	0	46	11	5	3	0	0	0	0
		LNB	30	54	89	95	97	100	100	100	100
		LNB+SNCR	58	0	0	0	0	0	0	0	0
		LNB+SCR	86	0	0	0	0	0	0	0	0
	Coal-fired power plants ≥ 100 MW (excl. CFB)	NOC	0	46	11	5	3	0	0	0	0
		LNB	30	53	75	82	84	8	0	0	0
		LNB+SNCR	58	0	1	1	1	6	7	4	5
		LNB+SCR	86	1	12	12	12	86	94	96	95
	CFB	NOC	0	100	100	100	100	65	0	20	0
		LNB	30	0	0	0	0	0	0	0	0
		LNB+SNCR	58	0	0	0	0	30	80	70	70
		LNB+SCR	86	0	0	0	0	5	20	10	30
	NGCC	NOC	0	70	21	8	4	0	0	0	0
		LNB	30	30	74	87	91	50	10	0	0
		LNB+SNCR	58	0	1	1	1	5	9	10	10
		LNB+SCR	86	0	5	5	5	45	81	90	90
Industrial sector	Coal-fired industrial grate boiler	NOC	0	100	100	100	100	9	0	10	0
		LNB	30	0	0	0	0	91	100	17	0
		LNB+SNCR	58	0	0	0	0	0	0	73	100
	Precalcined cement kiln <2000 t d^{-1}	NOC	0	70	70	70	70	20	0	0	0
		LNB	30	30	30	30	30	30	25	0	0
		LNB+SNCR	58	0	0	0	0	30	45	20	20
		LNB+SCR	86	0	0	0	0	20	30	80	80
	Precalcined cement kiln 2000–4000 t d^{-1}	NOC	0	70	65	65	65	20	0	0	0
		LNB	30	30	35	35	35	30	25	0	0
		LNB+SNCR	58	0	0	0	0	30	45	20	20
		LNB+SCR	86	0	0	0	0	20	30	80	80
	Precalcined cement kiln ≥4000 t d^{-1}	NOC	0	70	60	60	60	0	0	0	0
		LNB	30	30	40	40	40	0	0	0	0
		LNB+SNCR	58	0	0	0	0	60	60	20	20
		LNB+SCR	86	0	0	0	0	40	40	80	80
	Glass production – float process	NOC	0	100	100	100	100	10	0	0	0
		OXFL	75	0	0	0	0	80	88	70	70
		SCR	80	0	0	0	0	10	12	30	30
	Sintering	NOC	0	100	100	100	100	40	10	0	0
		SNCR	40	0	0	0	0	36	54	20	20
		SCR	80	0	0	0	0	24	36	80	80
	Nitric acid – dual pressure process	NOC	0	75	70	70	70	10	0	0	0
		ABSP	75	10	12	12	12	18	18	18	18
		SCR	80	15	18	18	18	72	82	82	82
		ABSP+SCR	94	0	0	0	0	0	0	0	0
	Nitric acid – other process	NOC	0	10	5	0	0	0	0	0	0
		ABSP	75	60	63	66	66	5	5	5	0
		SCR	80	30	32	34	34	15	15	15	0
		ABSP+SCR	94	0	0	0	0	80	80	80	100

Notes: NOC – no control; LNB – low NO$_x$ burner; SCR – selective catalytic reduction; SNCR – selective non-catalytic reduction; LNB+SCR – combination of LNB and SCR; LNB+SNCR – combination of LNB and SNCR; ABSP – absorption method; OXFL – Oxy-fuel combustion technology.
The table gives the national average penetration of NO$_x$ control technologies. However, the penetrations vary with provinces. The penetration of the "key region" is usually larger than that of other regions.

technologies under each emission scenario is summarized in Table 6. The future emissions are calculated with a 5 yr resolution, though the parameters are presented for selected years only.

1. Power plants

The "Twelfth Five-Year Plan for Environmental Protection" (the "Plan") requires that all newly built thermal power plants be equipped with low NO$_x$ combustion technologies and flue gas denitrification (SCR/SNCR) during 2011–2015. Existing thermal power plants should be upgraded with low NO$_x$ combustion technologies, and flue gas denitrification is required for large units (≥ 300 MW). In the "key regions" (see Sect. 2.3.1), nearly all coal-fired power plants are requested to be equipped with flue gas denitrification (The State Council of the People's Republic of China, 2010, 2011c). A new emission standard for thermal power plants (the "New standard") was issued in July 2011, which is more stringent than the "Plan". The "New standard" requires that nearly all thermal power plants be equipped with SCR, except for some circulating fluidized bed (CFB) boilers and some boilers burning coal with very high volatile matter content.

Table 7. Capacities of control technologies expected to be installed for the power sector during every five-year period in BAU[0], BAU[1], and BAU[2] scenarios (GW).

		BAU[0]				BAU[1]				BAU[2]			
		2011 to 2015	2016 to 2020	2021 to 2025	2026 to 2030	2011 to 2015	2016 to 2020	2021 to 2025	2026 to 2030	2011 to 2015	2016 to 2020	2021 to 2025	2026 to 2030
Coal-fired units (excl. CFB)	LNB – new units*	289.4	247.8	189.7	179.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SCR – new units	41.1	35.1	26.9	25.5	311.7	266.8	204.3	193.8	318.6	272.7	208.6	197.7
	SCR – existing units*	0.0	0.0	0.0	0.0	255.0	67.4	38.6	24.5	408.9	14.0	0.0	0.0
	SNCR – new units	2.8	2.4	1.9	1.8	21.7	18.5	14.2	13.5	14.8	12.7	10.0	9.6
	SNCR – existing units	0.0	0.0	0.0	0.0	17.6	4.7	2.7	1.7	17.4	0.8	0.0	0.0
CFB	SCR – new units	0.0	0.0	0.0	0.0	0.0	3.0	2.4	3.0	0.0	2.2	3.1	10.7
	SCR – existing units	0.0	0.0	0.0	0.0	0.0	0.0	1.8	6.1	0.0	3.7	5.3	0.0
	SNCR – new units	0.0	0.0	0.0	0.0	7.3	11.6	12.9	12.1	14.9	15.5	12.2	4.4
	SNCR – existing units	0.0	0.0	0.0	0.0	0.0	0.0	8.7	15.3	14.1	1.1	5.3	0.0
NGCC	LNB – new units	17.6	16.6	13.6	13.6	6.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0
	SCR – new units	0.8	0.8	0.6	0.6	11.2	15.2	12.9	12.9	16.7	15.7	12.9	12.9
	SCR – existing units	0.0	0.0	0.0	0.0	0.0	0.0	5.6	9.8	19.4	3.6	0.0	0.0
	SNCR – new units	0.1	0.1	0.1	0.1	1.2	1.7	1.4	1.4	1.9	1.7	1.4	1.4
	SNCR – existing units	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.1	2.2	0.4	0.0	0.0

* "new units" indicates that the control technologies are installed when the power plants are newly built; "existing units" indicates that the old power plants are retrofitted with certain control technologies during the five-year period.

Only existing emission standards are considered in BAU[0]/PC[0] scenario. In contrast, BAU[1]/PC[1] scenario is designed based on the "Plan" during 2011–2015, and the assumption that SCR/SNCR will continue to spread gradually after 2015. In BAU[2]/PC[2] scenario, the "New standard" is assumed to be implemented stringently during the 12th Five-Year Plan. Table 6 gives the national average penetration of NO_x control technologies. Note that the penetrations in the "key regions" are usually larger than those of other regions. To illustrate the required effort, Table 7 shows the additional capacities of each control technology that need to be installed during every five-year period in BAU[0], BAU[1], and BAU[2] scenarios. With the implementation of the governmental plan for environmental protection, about 578 GW SCR devices are expected to be installed during 2011–2015 under BAU[1] scenario.

2. Industrial sector

There was no national NO_x emission limit for coal-fired industrial boilers in China. However, several provinces including Beijing and Guangdong have issued local standards recently. No control measures are assumed for BAU[0]/PC[0] scenario. The BAU[1]/PC[1] scenario is based on the "Plan", where newly built industrial boilers are required to be equipped with LNB, and existing boilers in the "key regions" are beginning to be retrofitted with LNB during 2011–2015. The vast majority of existing boilers are expected to be equipped with LNB by 2020. In BAU[2]/PC[2] scenario, newly built industrial boilers are assumed to be equipped with LNB+SNCR, and existing boilers in the "key region" are beginning to be reconstructed with LNB+SNCR during 2011–2015. The penetrations of LNB+SNCR are expected to increase to 73 %, 90 %, and 100 % in 2020, 2025, and 2030 respectively.

As for "industry process", only the emission thresholds for cement production and nitric acid production were formally regulated before 2010. However, new emission standards for ceramics industry, nitric acid industry, glass industry, steel industry (sintering), and brick industry have been released or drafted recently.

The standard for cement released in 2004 can be met by all shaft kilns and most precalcined kilns without additional control measures. Other rotary kilns, which may exceed the standard, are assumed to be phased out in the near future. Thus, we assume the control technology mix of 2010 would be kept in the BAU[0]/PC[0] scenario. The BAU[1]/PC[1] scenario is designed based on the "Plan". Newly built precalcined kilns (mostly $\geq 4000\,\mathrm{t\,d^{-1}}$) are required to be equipped with flue gas denitrification (SCR/SNCR), and existing precalcined kilns should be reconstructed with LNB during 2011–2015. SCR/SNCR is assumed to continue to spread gradually after 2015. In the BAU[2]/PC[2] scenario, the penetration of flue gas denitrification is assumed to grow much faster. The shares of major control technologies are given in Table 6.

Glass production was almost completely uncontrolled before 2010. However, to attain the new flue gas concentration standard of $700\,\mathrm{mg\,m^{-3}}$ as specified in "Glass industry air pollutants emission standards (GB26453-2011)", add-on control technologies should be used, typically oxy-fuel combustion technology or SCR. No control measures are assumed for the BAU[0]/PC[0] scenario. In the BAU[1]/PC[1] scenario, the new standard is assumed to be released but nevertheless enforced leniently because of the difficulty in implementation. In BAU[2]/PC[2] scenario, the new standard is assumed to be enforced stringently. The draft of new standards for brick industry and ceramic industry

(GB25464-2010) can be reached without additional end-of-pipe control technologies, though these standards are comparable with the most stringent standards in the world. Thus, no control measures are assumed for brick and ceramic production. The draft of new standards of sintering in 2007 can also be attained without additional control technologies. However, the "Plan" requests newly built sintering plants to be equipped with flue gas denitrification (SCR/SNCR). The BAU[0]/PC[0] scenario assumes no control measures, while BAU[1]/PC[1] scenario is developed on the basis of the "Plan". Even more aggressive promotion of SCR/SNCR is assumed for BAU[2]/PC[2] scenario. To attain the new emission standard for the nitric acid industry (GB26131-2010), the dual-pressure process should be equipped with absorption method (ABSP) or SCR, while other processes need to adopt both ABSP and SCR. The BAU[0]/PC[0], BAU[1]/PC[1], and BAU[2]/PC[2] scenarios assume the technology mix of 2010, lenient enforcement of the new standard, and stringent enforcement of the new standard, respectively.

3. Transportation sector

In BAU[0]/PC[0] scenario, only existing standards (released before the end of 2010) are considered. In BAU[1]/PC[1] scenario, all the current standards in Europe are assumed to be implemented in China gradually, and the time intervals between the releases of two stage standards would be a little shorter than those of Europe. As described in Sect. 2.3.1, megacities including Beijing and Shanghai have been 2–3 yr ahead of the national legislation. Such a trend is assumed to continue in the future. The BAU[2]/PC[2] scenario shares the same assumptions as BAU[1]/PC[1] scenario. It should be noted that the application of Euro IV and after probably varies by region, which might have considerable impact on future emissions. We have not included such detailed assumptions in the current scenarios, but it is of importance to address this issue in the future studies. The removal efficiencies of the future emission standards are from the GAINS-Asia model of International Institute for Applied System Analysis (IIASA) (Amann et al., 2008, 2011). The emission factors are listed in Table 5, and the implementation timeline of the emission standards is given in Fig. 4.

4. Heat supply, domestic sector, and open burning of agricultural residue

The control technology mix of CHP is assumed to be the same as ordinary thermal power plants, while that of other heating boilers is consistent with the corresponding industrial boilers. No end-of-pipe control technology is assumed for domestic sector, and for open burning of agricultural residue we assume decline in activity as discussed in Sect. 2.1.3 (6).

5. Plausibility of the emission scenarios

Emission scenarios developed here represent different futures, which vary with respect to stringency and enforcement of NO_x emission policies. While their feasibility assessment is beyond the scope of this study, we discuss below implications of assumptions behind these scenarios, including enforcement mechanisms, necessary pace of implementation and associated costs.

In recent years, Chinese authorities have implemented continuous emission monitoring systems (CEMSs), which have been widely used to monitor SO_2 emissions from power plants. The 12th Five-Year Plan calls for installation of CEMSs for high emitting plants (e.g., power plants, iron and steel plants, and large cement plants) for the online monitoring of NO_x emissions before 2015 (The State Council of the People's Republic of China, 2011b). The CEMSs data are transmitted in real time to administrative departments. Similarly, a stringent "environmental label" system is implemented for road vehicles. Environmental labels are necessary for new vehicles to come into markets. High emitting vehicles with "yellow labels" registered before 2005 will be forbidden by 2015 (The State Council of the People's Republic of China, 2012). Finally, field inspections will be strengthened to ensure the operation of control technologies. The SO_2 scrubbers and CEMSs have been inspected once or twice a month in the past few years, and harsh penalties were imposed in case of non-compliance (Xu et al., 2011). Similar inspections will be performed for NO_x control technologies. The continuity of compliance with emissions standards for new vehicles will be assured via frequent inspections of manufacturers (The State Council of the People's Republic of China, 2012). The number of inspectors has increased from 50 040 in 2005 to 62 468 in 2010 (Ministry of Environmental Protection of China, 2006, 2012).

Scenario BAU[1] and BAU[2] set ambitious goals with respect to reductions and consequently require large capacities to be equipped with control measures within a relatively short period of time. For example, as described above, 578 GW of SCR capacity are expected to be installed for power plants during 2011–2015 under BAU[1] scenario. Such a policy will be associated with significant costs. Based on Liu (2013), the investment cost for the implementation of control technologies in power sector is estimated at about 65 billion CHY during this period. For comparison, the government has committed 816 billion CHY for the installation of control technologies for air and water pollutants in the same period (The State Council of the People's Republic of China, 2012), accounting for about 0.4 % of China's GDP (40.1 trillion CHY in 2010, i.e., about 200 trillion CHY for five years). In addition, economic policies including denitrification compensation price and pollutant discharge fee have been released. The electricity generation unit equipped with flue gas denitrification is supported by a price subsidy of 0.008 CHY kWh^{-1}. Although it is not enough to

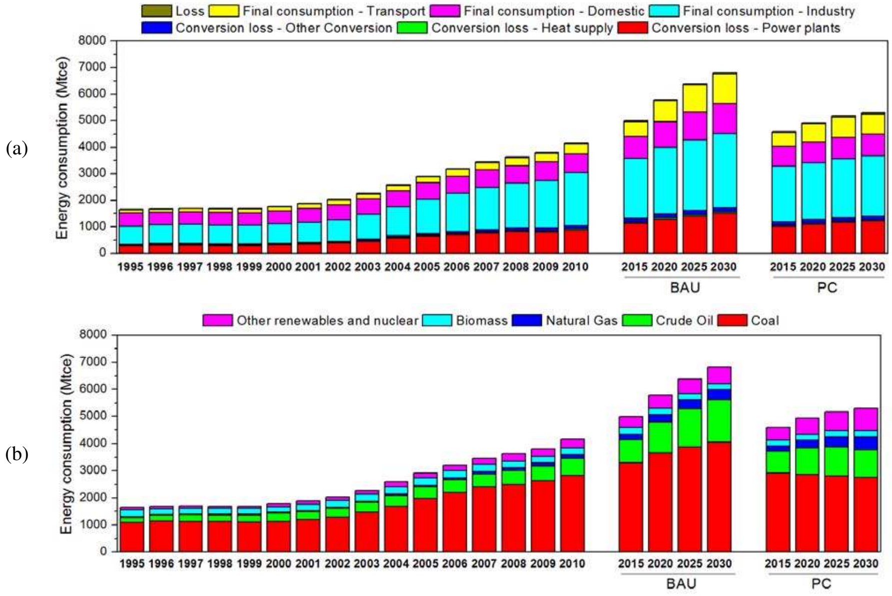


Fig. 5. Temporal evolution of energy consumption from 1995 to 2030: **(a)** energy consumption by sector; **(b)** energy consumption by fuel.

compensate for the denitrification cost, the price subsidy and the pollutant discharge fee (0.63 CHY kg^{-1} NO_x, approximately 0.002 CHY kWh^{-1}) together will be a little higher than the denitrification cost of 0.0083 CHY kWh^{-1} (Liu, 2013). Therefore, it is a rational decision for the power plant managers to run the flue gas denitrification properly, considering the economic benefits.

3 Results and discussion

3.1 Historical and future energy consumption

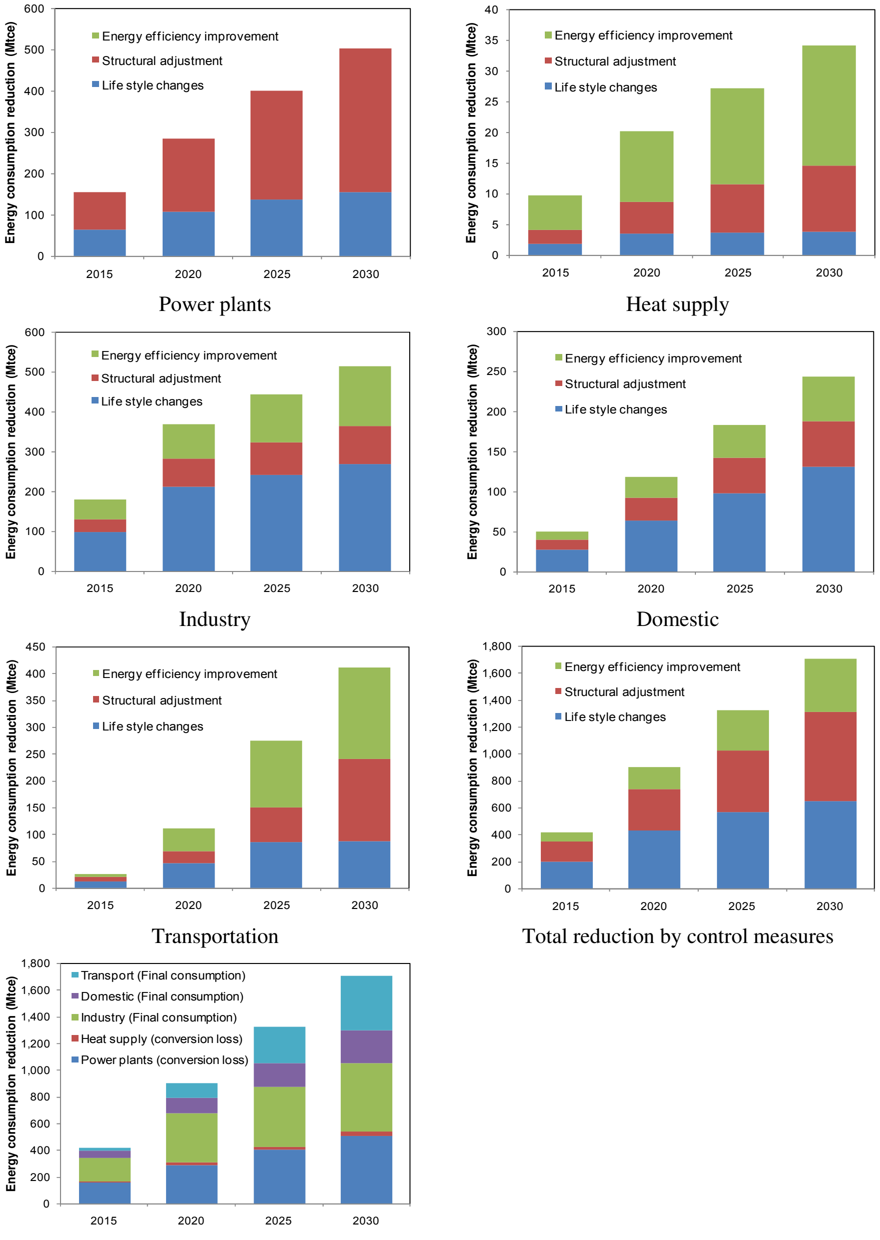
3.1.1 Trends and sectoral distribution of energy consumption

Figure 5 shows the evolution of energy consumption by sector and fuel in the period from 1995 to 2030. Total energy consumption in China increased from 1651.6 Mtce in 1995 to 4159.1 Mtce in 2010, with an annual average growth rate of 6.4 %. Energy consumption grew slowly from 1995 to 2000 (1.3 % annual average growth rate), largely due to the Asian economic crisis, and subsequently increased rapidly from 2000 to 2010 (8.9 % annual average growth rate) because of rapid economic growth. Industry was the largest energy consumer during 1995–2010; its share varied between 40.5 % and 47.8 %. The energy consumption of domestic and transportation sectors increased by 1.4 and 3.5 times, respectively, while their shares changed from 30.3 % and 6.6 % in 1995 to 17.1 % and 9.0 % in 2010, respectively. As for power plants, only the energy conversion loss (energy input minus electricity output) was included in the total energy consumption to avoid double counting. The share of power plants varied between 17.8 % and 22.4 % during the studied period. Coal was the dominant fuel type. Its share decreased from 67.8 % in 1996 to 63.3 % in 2001, and increased to 69.6 % in 2007, and decreased again to 68.1 % in 2010. The share of biomass decreased from 15.8 % to 5.9 %, while that of other renewable energy and nuclear energy increased from 5.3 % to 7.5 % during 1995–2010.

In 2030, the total energy consumption is projected to increase to 6816.5 Mtce under the BAU scenario and to 5295.1 Mtce under the PC scenario, 64 % and 27 % larger than that of 2010, respectively. As with the sectoral distribution, the share of industry is expected to decrease notably in both scenarios resulting from the economic structure adjustment, while the share of transportation is expected to experience a dramatic increase, especially under the BAU scenario. The relative contributions of other sectors change very slightly. Coal continues to dominate China's energy mix, but the proportion decreases from 68.1 % in 2010 to 59.5 % and 51.8 % in 2030 under the BAU and PC scenarios, respectively. In contrast, the shares of natural gas and "other renewable energy and nuclear energy" are estimated to increase from 3.4 % and 7.5 % in 2010 to 5.5 % and 8.9 % in 2030 under the BAU scenario, and 9.3 % and 15.8 % under the PC scenario, respectively.

3.1.2 Impact of various energy-saving measures

Energy conservation measures might play an important role in achieving ambitious NO_x reduction targets; therefore we present here a brief discussion of importance of particular measures included in our analysis. We use the BAU scenario



Power plants

Heat supply

Industry

Domestic

Transportation

Total reduction by control measures

Total reduction by sector

Fig. 6. Contribution of various control measures to the reductions of energy consumption under the PC scenario compared with the BAU scenario. Note: only the conversion loss (i.e., primary energy input minus secondary energy output) was included in the energy consumption to avoid double counting of the secondary energy output.

as our "benchmark"; the differences of energy consumption between BAU and PC scenarios represent the effects of various energy-saving measures. As documented in Sect. 2.1.3, energy-saving measures can be classified into three major categories, including life style changes, structural adjustment, and energy efficiency improvement. Figure 6 depicts the contribution of each control measure category to the reductions of energy consumption. Both life style changes and structural adjustment are critical for the energy conservation of power plants. Structural adjustment, namely the replacement of traditional coal power with advanced coal power and clean energy power, contributes 69 % of the total energy conservation in 2030. As for the industry sector, life style changes play the most important role, followed by energy efficiency improvement and structural adjustment. A more conservative life style implies relatively smaller living area, fewer passenger cars, and consequently reduced steel and cement production, thereby contributing to over half (52 %)

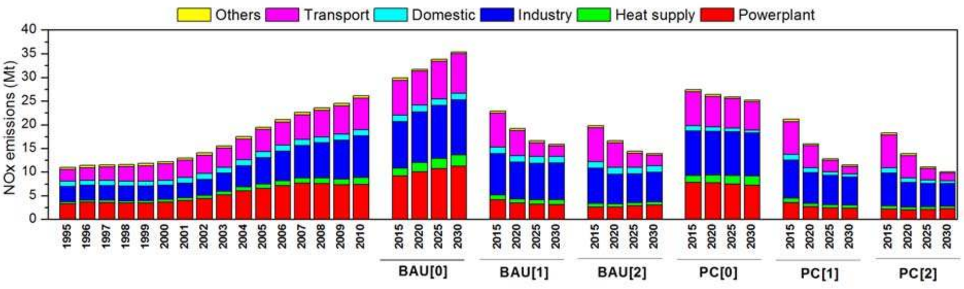


Fig. 7. Temporal evolution of NO_x emissions and their sectoral distribution during 1995–2030.

of the energy saving in 2030. Life style changes also dominate the energy saving (54 % in 2030) in the domestic sector. For the transportation sector, life style changes, structural adjustment and energy efficiency improvement account for 38 %, 39 %, and 23 % of the energy conservation in 2030, respectively, and their contribution to energy saving increases quickly with time. In terms of sectors, power plants and industry are expected to play the leading roles, accounting for 29 % and 30 % of the total energy saving in 2030, respectively.

3.2 Historical and future NO_x emissions

3.2.1 Trends and sectoral distribution of NO_x emissions

The trends in NO_x emissions and their sectoral distributions during 1995–2030 are presented in Fig. 7, and the provincial NO_x emissions are given in Table 8. As the high-efficient end-of-pipe control technologies were not widely used until 2010, the historical trends of NO_x emissions closely matched energy consumption, which experienced slow increases from 11.0 Mt in 1995 to 12.2 Mt in 2000 (2.0 % annual average growth rate), and faster growth from 12.2 Mt in 2000 to 26.1 Mt in 2010 (7.9 % annual average growth rate). The NO_x emissions during 2007–2010, which have not been documented in previous studies, increased rapidly with an annual growth rate of 5.4 % despite existing control measures (see Sect. 2.3.1). Power plants, industry and transportation accounted for 81.4–87.9 % of the total NO_x emissions during 1995–2010, of which the share of power plants varied between 28.4 % and 34.5 %. It is worth noting that the share of power plants in total NO_x emissions decreased remarkably after 2004, though the share in energy consumption remained stable. This could be attributed mainly to the nation-wide utilization of low NO_x combustion technologies, and the promotion of flue gas denitrification in designated areas (the "key regions"; see Sect. 2.3.1). Although the share of energy used in transportation increased in the 1995–2010 period, the share in NO_x emissions from transportation showed a decreasing trend after 2001 (from 28.4 % in 2001 to 25.4 % in 2010) owing to introduction of emission standards for new vehicles. The share of industry decreased slightly during 1995–2002, but rose quickly from 23.9 % in 2002 to 34.0 % in 2010, which could be attributed both to the rapid development of industry, and to the control measures taken in power plants and transportation sectors. The industry sector exceeded power plants, and became the largest source for NO_x emissions in 2009. Emissions from several "small industries", including the production of bricks, glass, lime, ceramics, and nitric acid, which were often neglected or approximated in previous published studies, were estimated to be 1143 kt, 1303 kt, and 1977 kt in 1995, 2005 and 2010, respectively. The corresponding contributions to total NO_x emissions are 10.4 %, 67 %, and 7.6 % respectively. Shandong, Henan, Jiangsu, Guangdong, and Hebei provinces were top five emitters of NO_x emissions, each of which had over 1500 kt NO_x emissions and contributed together over 35 % of total emissions.

A Monte Carlo uncertainty analysis was performed on the NO_x emission inventory, as described in Wei et al. (2011) and Bo et al. (2008). Results showed that the 90 % confidence interval of NO_x emissions was [−32 %, 49 %] on average in the period of 1995–2010. The coefficients of variation (CVs) were ±27–34 % during 1995–2010, and 30 % on average. The CVs of emissions from the power plants, heat supply, industry, domestic, transportation, and biomass open burning were ±34 %, ±49 %, ±50 %, ±54 %, ±92 %, and ±231 % on average during 1995–2010, respectively. The variation of CVs with emission sectors is attributed to different magnitude of uncertainties associated with activity levels and emission factors. Biomass open burning has the largest CV because both the activity level and the emission factors are quite uncertain. The CV of transportation sector is larger than power and industrial sources (though smaller than that of biomass open burning), as the fuel consumption of on-road vehicles is calculated from vehicle population, annual average vehicle mileage traveled, and fuel economy, rather than the energy statistics (see Sect. 2.1.1).

In 2030, the total anthropogenic NO_x emissions are projected to be 35.4 Mt, 15.8 Mt, 13.8 Mt, 25.2 Mt, 11.5 Mt, and 10.1 Mt under BAU[0], BAU[1], BAU[2], PC[0], PC[1], PC[2] scenarios, respectively. The corresponding change rates compared with 2010 are 36 %, −39 %, −47 %, −3 %,

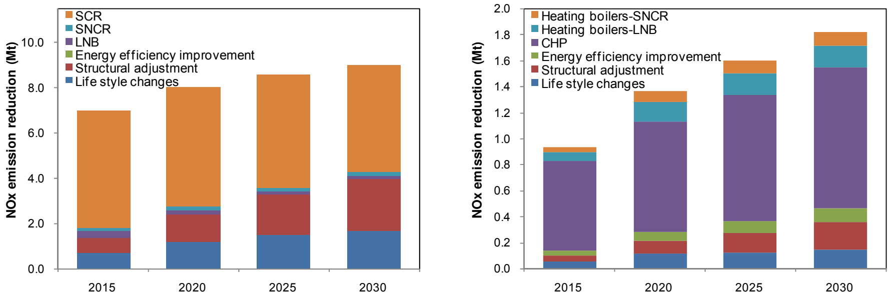
Table 8. Provincial NO_x emissions during 2005–2030 (Mt).

Province	2005	2010	BAU[0]		BAU[1]		BAU[2]		PC[0]		PC[1]		PC[2]	
			2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
Beijing	0.41	0.48	0.47	0.46	0.33	0.23	0.29	0.19	0.39	0.32	0.27	0.16	0.24	0.13
Tianjin	0.31	0.41	0.46	0.49	0.24	0.20	0.21	0.17	0.37	0.34	0.20	0.14	0.17	0.12
Hebei	1.35	1.62	2.11	2.30	1.27	1.04	1.11	0.88	1.77	1.67	1.07	0.76	0.94	0.64
Shanxi	0.84	1.05	1.35	1.50	0.76	0.63	0.64	0.56	1.09	1.04	0.62	0.45	0.52	0.40
Neimeng	0.70	1.16	1.52	1.70	0.75	0.62	0.60	0.54	1.22	1.17	0.61	0.44	0.49	0.39
Liaoning	0.90	1.15	1.40	1.56	0.88	0.74	0.74	0.64	1.16	1.11	0.72	0.53	0.61	0.46
Jilin	0.46	0.64	0.68	0.78	0.42	0.37	0.35	0.31	0.58	0.59	0.35	0.27	0.29	0.23
Heilongjiang	0.60	0.72	0.88	0.97	0.54	0.43	0.47	0.38	0.74	0.70	0.45	0.31	0.39	0.27
Shanghai	0.41	0.47	0.59	0.65	0.33	0.28	0.27	0.23	0.48	0.44	0.27	0.20	0.22	0.16
Jiangsu	1.49	1.75	2.07	2.22	1.15	0.93	1.01	0.79	1.71	1.57	0.97	0.69	0.85	0.59
Zhejiang	1.08	1.27	1.54	1.63	0.82	0.64	0.73	0.55	1.26	1.14	0.68	0.47	0.61	0.40
Anhui	0.68	0.99	1.21	1.40	0.69	0.56	0.59	0.51	1.03	1.04	0.59	0.43	0.51	0.40
Fujian	0.43	0.73	1.02	1.16	0.68	0.61	0.61	0.57	0.83	0.80	0.55	0.44	0.50	0.41
Jiangxi	0.36	0.50	0.62	0.74	0.41	0.35	0.37	0.32	0.53	0.54	0.35	0.26	0.31	0.24
Shandong	1.97	2.52	3.01	3.13	1.96	1.50	1.74	1.36	2.45	2.18	1.59	1.06	1.41	0.96
Henan	1.40	1.86	2.16	2.45	1.37	1.14	1.19	1.02	1.82	1.77	1.14	0.82	1.00	0.74
Hubei	0.65	0.96	1.09	1.24	0.68	0.56	0.57	0.48	0.91	0.89	0.57	0.41	0.48	0.35
Hunan	0.64	0.84	1.04	1.21	0.65	0.56	0.55	0.48	0.89	0.90	0.55	0.43	0.47	0.37
Guangdong	1.35	1.76	2.16	2.40	1.36	1.13	1.25	1.03	1.77	1.65	1.12	0.81	1.03	0.74
Guangxi	0.39	0.58	0.72	0.84	0.46	0.39	0.39	0.33	0.62	0.62	0.40	0.30	0.34	0.25
Hainan	0.06	0.09	0.12	0.14	0.07	0.06	0.06	0.05	0.10	0.10	0.06	0.04	0.05	0.04
Chongqing	0.27	0.46	0.52	0.61	0.34	0.29	0.29	0.24	0.44	0.44	0.29	0.22	0.25	0.18
Sichuan	0.60	0.98	1.10	1.27	0.75	0.61	0.66	0.54	0.93	0.91	0.63	0.43	0.55	0.38
Guizhou	0.42	0.52	0.69	0.81	0.39	0.34	0.32	0.28	0.56	0.55	0.32	0.24	0.26	0.20
Yunnan	0.36	0.52	0.63	0.75	0.40	0.34	0.33	0.28	0.53	0.55	0.34	0.26	0.28	0.21
Xizang	0.01	0.02	0.03	0.03	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.01
Shaanxi	0.46	0.68	0.86	1.02	0.49	0.42	0.42	0.38	0.72	0.73	0.41	0.30	0.35	0.27
Gansu	0.32	0.46	0.59	0.70	0.34	0.29	0.29	0.26	0.50	0.51	0.29	0.21	0.24	0.19
Qinghai	0.06	0.09	0.10	0.12	0.06	0.05	0.05	0.04	0.08	0.08	0.05	0.04	0.05	0.03
Ningxia	0.18	0.30	0.40	0.46	0.19	0.17	0.15	0.15	0.32	0.32	0.16	0.12	0.13	0.11
Xinjiang	0.34	0.49	0.56	0.63	0.37	0.32	0.31	0.26	0.47	0.46	0.30	0.22	0.26	0.19
Total	19.48	26.05	31.69	35.35	19.18	15.82	16.60	13.85	26.32	25.16	15.95	11.47	13.84	10.07

−56 %, −61 % respectively. The NO_x emissions are projected to be 22.9 Mt in 2015 under the BAU[1] scenario, 12.2 % lower than that of 2010. This implies that if the control policies in the related work plan of the Chinese government (i.e., "Twelfth Five-Year Plan for Environmental Protection") could be implemented successfully (as assumed in the BAU[1] scenario), the national target to reduce the NO_x emissions by 10 % during 2011–2015 would be achieved. However, many uncertainties exist, and some major ones are analyzed in Sect. 3.3.

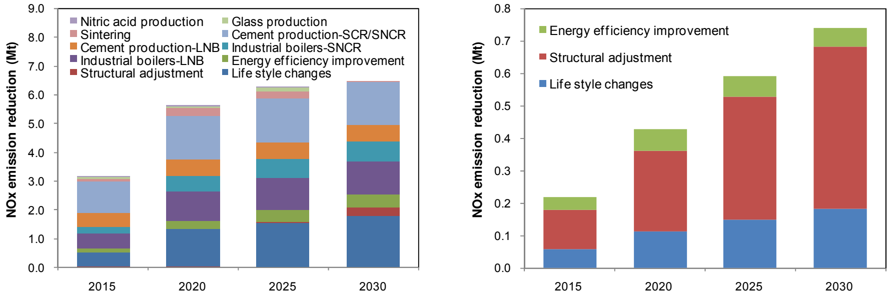
It is important to stress that early implementation of measures is important to the success of the BAU[1]/PC[1]/BAU[2]/PC[2] policies. This implies rapid installation of control measures. For example, according to our calculation, during the 12th Five-Year Plan nearly 600 GW flue gas denitrification capacity needs to be installed, accounting for about 65 % of the total thermal power generation capacity. Such an investment is consistent with the current requirements laid down in the 12th Five-Year Plan specifying SCR/SNCR installation requirements in the power sector (see Sect. 2.3.2). In addition, the government announced the Euro IV emission standard for heavy-duty diesel vehicles that would be implemented in July 2013 (Ministry of Environmental Protection of China, 2011b). This is expected to reduce the NO_x emissions of heavy-duty diesel trucks by about 40 % of the Euro III levels. Besides, as described in Sect. 2.3.2 further policies assuring enforcement of the control programs have been released in China.

The sectoral distribution is not expected to change significantly in the future under the BAU[0] and PC[0] scenarios. However, under BAU[1], BAU[2], PC[1], and PC[2] scenarios, the share of power plants in total NO_x emissions is expected to decrease strongly during 2011–2015, due to extensive SNCR/SCR installation. However, it is expected to reverse and increase after 2015, because the reduction potential of power plants will be exhausted. The share of transportation decreases all along during 2011–2030 as a result of the implementation of stringent vehicle emission standards. The proportion of industry increases despite the control measures, reflecting the lower ambition of explored policies with



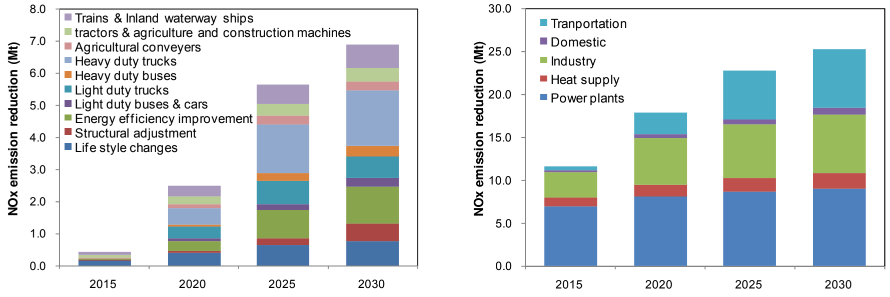
Power plants

Heat supply



Industry

Domestic



Transportation

Total reduction by sector

Fig. 8. Contribution of various control measures to the reductions of NO_x emissions under the PC[2] scenario compared with the BAU[0] scenario.

respect to control of industrial NO_x emissions. The provincial distribution pattern is not expected to change much, and Shangdong, Henan, Guangdong, Hebei, and Jiangsu continue to have the largest emissions under nearly all scenarios. However, the emissions of the "key regions" (see Sect. 2.3.1) decrease more rapidly than other regions under the BAU[1], BAU[2], PC[1], and PC[2] scenarios.

3.2.2 Impact of various energy-saving measures and end-of-pipe control measures

Both energy-saving measures and end-of-pipe control measures contribute to the reductions of NO_x emissions. As documented in Sect. 2.1 and 3.1.2, the energy-saving measures were categorized into life style changes, structural adjustment, and energy efficiency improvement. In contrast, the end-of-pipe control measures were categorized considering the characteristics of each specific sector. For example, all end-of-pipe control technologies of industry sector were classified into seven kinds, including low NO_x burners for industrial boilers, SNCR for industrial boilers, low NO_x burners for cement production, SNCR/SCR for cement production, control measures for sintering, control measures for glass production, and control measures for nitric acid production. The contributions of each control measure category to the reduction of NO_x emissions between BAU[0] and PC[2] scenarios are given in Fig. 8. SCR accounts for 74 % of the total NO_x emission reduction in power plants in 2015. However, its contribution decreases gradually to 52 % in 2030 as the installation potential of SCR is exhausted. Therefore, energy-saving measures such as life style changes and structural adjustment are expected to play a leading role for the further reductions of NO_x emissions in power plants after 2015. For industry sector, life style changes, control measures for industrial boilers, and control measures for cement production contribute 26 %, 27 %, and 31 % of the total NO_x emission reduction in 2030, respectively. For the transportation sector, the energy-saving measures, end-of-pipe control measures for on-road transportation, and end-of-pipe control measures for off-road transportation account for 36 %, 43 %, and 21 % of the total NO_x emission reduction in 2030, respectively. Within the end-of-pipe measures for on-road transportation, the control measures for heavy-duty vehicles account for as much as 69 % of the reduction. Adding up all the control measures, power plants, industry, and transportation contribute 60 %, 26 %, and 4 % of the total NO_x emission reduction in 2015. However, the relative importance of power plants is expected to decrease while that of transportation increases after 2015. The contributions of power plants, industry, and transportation to the total NO_x emission reduction in 2030 are estimated to be 36 %, 27 %, and 27 %, respectively.

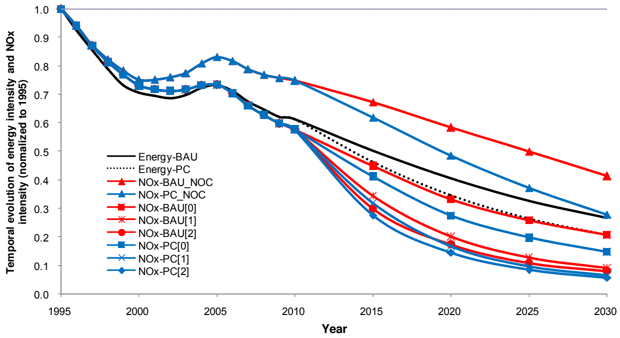


Fig. 9. Temporal evolution of energy intensity and NO_x intensity during 1995–2030 (normalized to 1995). Note that this study focused on the emission pathway every five years. The lines are only used to improve the readability. They do not necessarily indicate the trajectories of energy intensity or emission intensity year by year.

3.2.3 Ancillary benefit of energy conservation on NO_x emission reduction

The contribution of energy-saving measures to total NO_x emission reductions (between BAU[0] and PC[2]) is 21 %, 30 %, 35 %, and 40 % in 2015, 2020, 2025, and 2030, respectively. We further analyzed the increment of the NO_x emission reduction (between BAU[0] and PC[2]) for every five years. The integrated energy-saving measures account for only 21 % of the NO_x reduction increment during 2010–2015. However, during 2025–2030, 89 % of the NO_x reduction increment could be attributed to energy-saving measures. Therefore, the traditional end-of-pipe measures might dominate the NO_x emission reductions in the short term, but their reduction potential might nevertheless be exhausted in the near future. To achieve further reductions, it is strategically important to take advantage of the ancillary benefit of energy conservation on NO_x emission reductions.

Actually, the "latent" ancillary benefit of energy saving on NO_x emission reductions might be much larger than documented above. Figure 9 shows the temporal evolution of energy intensity (energy consumption per unit GDP) and NO_x intensity (NO_x emission per unit GDP) during 1995–2030 (normalized to 1995). The line of "BAU_NOC" in Fig. 9 defines what the NO_x intensity in BAU[0]/BAU[1]/BAU[2] scenario would be if no end-of-pipe NO_x control measures were applied, and, similarly, the line of "PC_NOC" defines that of PC[0]/PC[1]/PC[2] scenario. With no energy-saving measures, the NO_x intensity under BAU_NOC/PC_NOC would have remained roughly unchanged. In fact, the NO_x intensity decreases by 25 % under BAU_NOC/PC_NOC, during 1995–2010, attributable to the integrated energy-saving measures in these years. In other words, energy savings avoided 25 % of the NO_x emissions by 2010. From 2010 to 2030, the NO_x intensity decreases by 46 % and 63 % under BAU_NOC and PC_NOC, respectively. This implies that the integrated energy-saving measures assumed in BAU and PC scenarios could avoid 46 % and 63 % of the NO_x emissions by 2030, respectively. Thus, making full use of the ancillary benefit of energy saving on NO_x emission reductions would be of strategic importance in the pollution control policies.

3.3 Sensitivity analysis

The intrinsic uncertainties in the key drivers (including economic growth, energy-saving policies, pollution control policies, etc.) constitute the major sources of the uncertainties of future emissions, which, however, cannot be considered thoroughly in the scenarios. It is instructive to quantify the impacts of some key factors on the future emissions, which were not considered in the scenarios developed in this study (see Table 1).

3.3.1 Uncertainty in the GDP growth rate

The GDP growth rate in such a rapidly developing country as China is quite uncertain. The actual GDP growth rate was significantly higher than the governmental target in the past few decades. Therefore, we designed a higher GDP growth case (HGDP) for each of the scenarios developed in this study (see Table 1), where the GDP growth rate was one percent higher, i.e., 9.0 % from 2011 to 2015, 8.5 % from 2016 to 2020, 7.5 % from 2021 to 2025, and 6.5 % from 2026 to 2030, respectively. In 2030, the total NO_x emissions under the six sensitivity (HGDP) cases are projected to be 4.8–9.0 % higher than the corresponding scenarios. The NO_x emissions are estimated to be 23.8 Mt in 2015 under the HGDP-BAU[1] case, 8.6 % lower than that of 2010, implying that the national target to reduce the NO_x emissions by 10 % during 2011–2015 might not be achieved with 1 percent higher GDP growth.

3.3.2 Failure in the control of heavy diesel vehicles

The Euro I–Euro III standards for heavy diesels vehicles have already been implemented nationwide, and the Euro IV is expected to be implemented during the 12th Five-Year Plan. However, the effectiveness of the standards has been questioned in recent research. Wang et al. (2012) suggested that current emission standard implemented in Beijing (Euro I–Euro IV) and nationwide might have limited impacts on reducing NO_x emissions. Wu et al. (2012) found the NO_x emission factors for heavy-duty diesel buses did not improve in most cases as emission standards became more stringent, and that the average NO_x emission factors of Euro II, Euro III and Euro IV buses in Beijing under the same typical driving cycle were all around $12\,\mathrm{g\,km^{-1}}$. These findings are consistent with earlier work of Velders et al. (2011) for Europe as well as Huo et al. (2012b) for China, where similar noncompliance was identified. Therefore, we designed a heavy-duty diesel vehicle control failure case (HDF) for each of the scenarios developed in this study (see Table 1), where the NO_x removal rates of Euro IV, Euro V, and Euro VI were assumed to be 50 %, 50 %, and 75 %, respectively (or relative to Euro III, reductions of 22 %, 22 %, and 60 %, respectively). In 2030, the NO_x emissions of the transportation sector under the HDF cases are projected to be 1.5–2.8 times the corresponding scenarios. Consequently, the total NO_x emissions under the six HDF cases are projected to be 13–29 % higher than the corresponding scenarios. The NO_x emissions are estimated to be 23.3 Mt in 2015 under the HDF-BAU[1] case, 10.5 % lower than that of 2010, still meeting the national target to reduce the NO_x emissions by 10 % during 2011–2015.

3.3.3 Failure in the operation of flue gas denitrification for power plants

As described in Sect. 3.2.2, SCR accounts for 74 % and 52 % of the total NO_x emission reductions in power plants in 2015 and 2030, respectively. However, we must take into account that some of the installed SCRs might actually not be operating. In fact, the actual operation of the SO_2 scrubbers has been questioned before by the government and research community (Xu et al., 2009). A power plant control failure case (PPF) for each of the emission scenarios listed in Table 1 was developed, where we assumed 25 % of the installed flue gas denitrification technologies were not actually running. In 2030, the NO_x emissions of power plants under the PPF cases are projected to be 1.0–2.3 times the corresponding scenarios. Consequently, the total NO_x emissions under the six PPF cases are projected be 1.2–29 % higher than the corresponding scenarios. The NO_x emissions are estimated at 25.2 Mt in 2015 under the PPF-BAU[1] case, 3.2 % lower than that of 2010, implying failure to meet the national target to reduce the NO_x emissions by 10 % during 2011–2015.

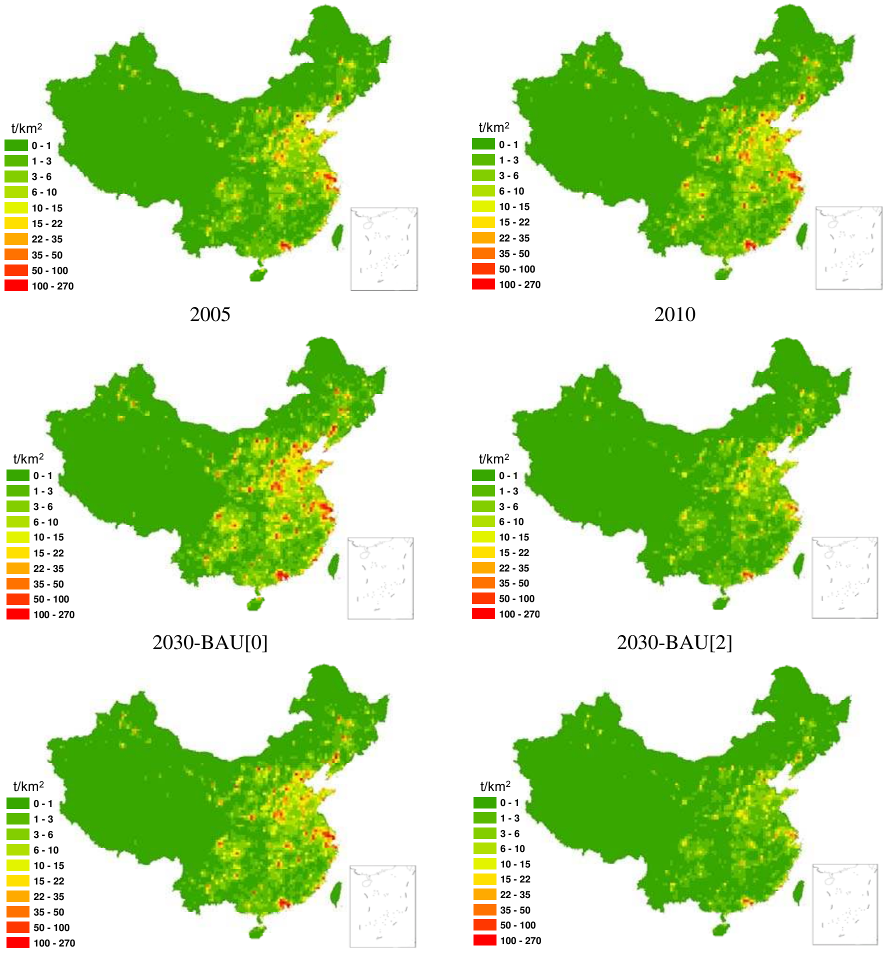
3.4 Gridded emissions

Figure 10 shows the spatial distribution of NO_x emissions in 2005, 2010, and 2030 for four scenarios. Most coal-fired power plants, iron and steel plants, and cement plants were identified as large point sources, and allocated based on their geographical coordinates. The historical geographical locations of these large point sources were updated year by year based on the annual reports of industrial associations. As for future development, we first calculated provincial emissions based on the assumed energy-saving policies and emission control policies. The locations of large point sources within a specific province were assumed to remain the same as 2010, and the NO_x emission of each point was calculated based on the growth rates of provincial emissions. The other sources were treated as area sources, the emissions of which were distributed into 36 km × 36 km grid cells using various spatial proxies at a grid resolution of 1 km × 1 km using the methodology described in Streets et al. (2003a) and Woo et al. (2003). The spatial proxies are assumed to remain unchanged from 2010 onwards. Figure 10 illustrates that the NO_x emission intensities were much higher in eastern China than in western China. Moreover, the vast North China Plain, the eastern coastal region, the southern coastal region, Liaoning Province and the Sichuan Basin were typical high emission regions. The YRD, the PRD, and the areas around Beijing stood out with highest emissions. This characteristic of spatial distribution is closely related with the unbalanced economic development in China. In considered scenarios, the spatial distribution in 2030 is similar to that of 2010. However, under the BAU[0] scenario, the emission intensity of high emission regions is increasing, and the area of such regions is increasing over the years. Under the PC[2] scenario, in which stringent energy-saving measures and end-of-pipe control measures are taken, the emission intensity decreases distinctly and the high emission areas are significantly reduced. However, high emission intensity still occurs in some metropolitan areas, such as the Pearl River delta and the Yangtze River delta.

3.5 Comparison with other studies and satellite observations

Figure 11 compares the emission estimates in this study with other studies.

Comparison of historical emissions shows that this study represents a medium estimation of NO_x emissions. Our estimate was quite close to those of Zhang et al. (2007) for 1995–2004, with relative errors within 6 %. The estimation of Ohara et al. (2007) was 7–15 % lower than this study during 1995–2003. The result of Klimont et al. (2001) was 12 % lower than ours in 1995, and that of Streets et al. (2003a) was 14 % lower in 2000. Estimates by Olivier et al. (2005) were 12 % higher in 1995 and 13 % higher in 2000, while that by Streets et al. (2001) was 9 % higher than this study



2005 2010

2030-BAU[0] 2030-BAU[2]

2030-PC[0] 2030-PC[2]

Fig. 10. Spatial distributions of NO_x emissions in 2005, 2010, and 2030 for four scenarios.

in 1997. NO_x emission estimates for year 2005 by Amann et al. (2008), Wang et al. (2011a), and Xing et al. (2011) were 13 %, 5 % and 7 % lower than this study, respectively. The estimates of Zhao et al. (2013), MEIC inventory, and Kurokawa et al. (2013) are 1–10 %, 9–10 %, and 4–7 % higher than this study during 2005–2010, respectively.

Previous projections (reported before 2005) about NO_x emissions of China (van Aardenne et al., 1999; Streets and Waldhoff, 2000; Klimont et al., 2001) were based on the emissions in 1995 or before, which substantially underestimated the rapid economic growth during 2000–2010. Therefore, they usually significantly underestimated the emissions in 2010.

Several recent projections have been reported since 2005. Ohara et al. (2007) projected NO_x emissions in China for 2020 by using the emissions for 2000 and three scenarios: a policy failure scenario, a "best guess" scenario, and an optimistic scenario. The projections of all the three scenarios for 2010 were much lower than our estimates, while the emissions of the policy failure scenario, best guess scenario, and optimistic scenario in 2020 were comparable to our PC[0], PC[1], and PC[2] scenarios, respectively. Amann et al. (2008) developed three scenarios until 2030 based on the emissions in 2005. The current legislation scenario assumed current legislation and current enforcement, while the advanced control technology scenario assumed across-the-board application of advanced control technologies – principally consistent with existing German legislation. The optimized scenario was a least-cost optimization scenario that would achieve the same health benefit as the advanced control technology scenario. The projections of these three scenarios for 2010 were also significantly lower than our estimation. The estimation of current legislation scenario, optimized scenario, and advanced control technology scenario for 2030 were similar to our PC[0], BAU[1], and PC[1], respectively. Xing et al. (2011) projected NO_x emissions for 2020 with four scenarios based on the emissions of 2005, including a scenario assuming current legislation and implementation status, a scenario assuming improvement of energy efficiencies and current environmental legislation, a

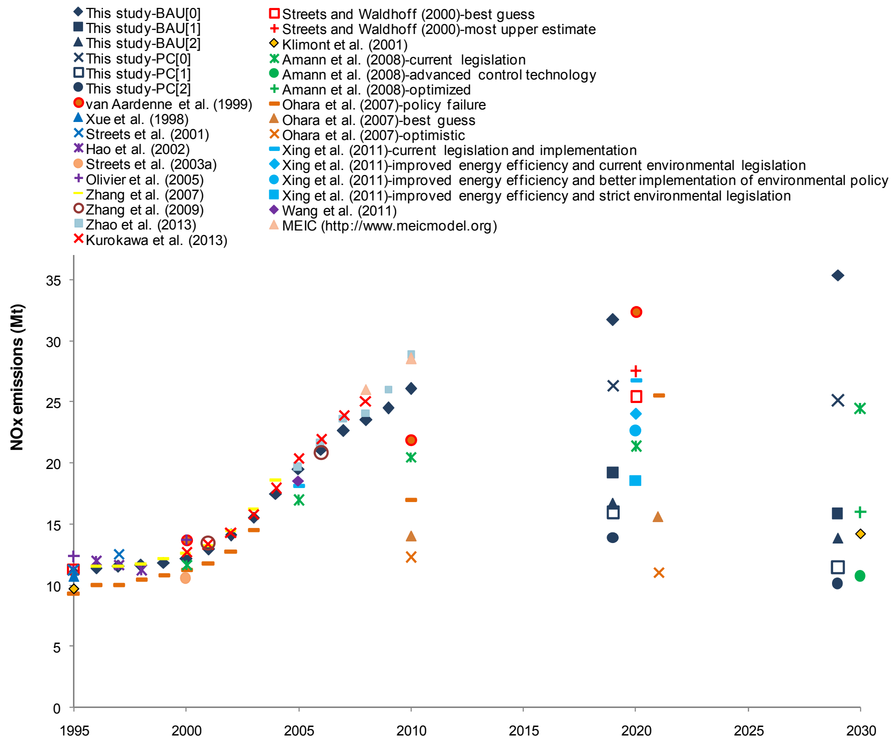


Fig. 11. Comparison of NO_x emission estimates in this study with other studies. Scenarios from the same study are shown with symbols of the same color, and only the historical emissions for the first scenario are shown. Some points for the years 2020 and 2030 are shifted a little left or right, in order to avoid overlapping. Note that the current legislation scenario in Amann et al. (2008) is consistent with the baseline scenario in Klimont et al. (2009); therefore, the latter is not shown in the figure.

scenario assuming improvement of energy efficiencies and better implementation of environmental legislation, and a scenario assuming improvement of energy efficiencies and strict environmental legislation. The results of the four scenarios were actually quite similar. The emissions of the most conservative scenario would be comparable to our PC[0] scenario in 2020, while those of the most optimistic scenario would be similar to our BAU[1] scenario. These projections underestimated the rapid economic growth experienced during 2006–2010, thereby underestimating the emissions for 2010. None of them foresaw the ambitious NO_x emission reduction policies scheduled for implementation in the 12th Five-Year Plan, which might significantly change the future NO_x emission pathway.

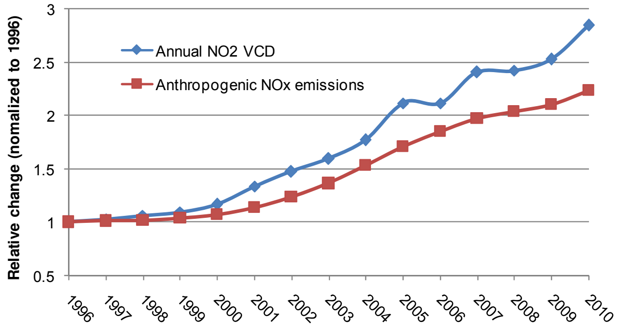


Fig. 12. Inter-annual relative changes in the NO_2 VCD and anthropogenic NO_x emissions. All data are normalized to the year 1996. Study region: 30–40° N, 110–123° E.

Figure 12 compares the relative changes of satellite NO_2 vertical column density (VCD) with those of the anthropogenic NO_x emissions. Zhang et al. (2012) retrieved and analyzed the satellite NO_2 VCD during 1996–2010, in which measurements of Global Ozone Monitoring Experiment (GOME) from April 1996 to the end of 2002, and the measurements of Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) from 2003 to 2010 were used. We adopted the satellite NO_2 VCD derived by Zhang et al. (2012) directly. We compared the changes of NO_x emissions and the satellite NO_2 VCD in east central China (ECC, 110–123° E, and 30–40° N). The bottom-up emission estimate indicates a 124 % increase of the anthropogenic NO_x emissions in ECC during 1996–2010, slightly lower than the 184 % increase in the NO_2 VCD. The difference between the two growth rates is acceptable, considering the uncertainties in emission estimates and satellite retrievals, and the inter-annual variations of the meteorological factors. In terms of five-year intervals, the growth rates based on bottom-up emission estimates are 7 %, 60 %, and 31 % during 1996–2000, 2000–2005, and 2005–2010, respectively. The satellite observations indicate the corresponding growth rates are 17 %, 82 %, and 34 %, respectively.

4 Conclusions

In this study we estimated the historical NO_x emissions of China from 1995 to 2010, calculated future NO_x emissions every five years until 2030 under six emission scenarios, and quantified the effects of various control policies on emissions.

With the rapid growth of energy consumption, NO_x emissions were estimated to more than double from 11.0 Mt in 1995 to 26.1 Mt in 2010, with an annual growth rate of 5.9 %. Power plants, industry and transportation were major sources of NO_x emissions, accounting for 28.4 %, 34.0 %, and 25.4 % of the total NO_x emissions in 2010, respectively. Although several control measures have been introduced for power plants and transportation, they were insufficient to constrain the strong increase of NO_x emissions.

Based on current legislation and current implementation status (BAU[0] scenario), NO_x emissions are estimated to increase by 36 % in 2030 from 2010 level. The implementation of new energy-saving policies and end-of-pipe control policies is expected to change the NO_x emission pathway significantly in the future. With the enforcement of new energy-saving policies, including life style changes, structural adjustments, and energy efficiency improvements, NO_x emissions are expected to decrease by nearly 30 % in 2030 compared with the baseline case (BAU[0] scenario). The implementation of the "progressive" and "more stringent" end-of-pipe control measures is expected to lead to about 55 % and 61 % reductions of the baseline NO_x emissions in 2030, respectively. If the energy-saving measures and stringent end-of-pipe measures are taken simultaneously, the NO_x emissions in 2030 could be reduced further, resulting in more than 70 % lower emissions than the baseline case (i.e., over 60 % less than the 2010 level).

Power plants, industry, and transportation contribute 36 %, 27 %, and 27 % of the total NO_x emission reduction respectively between the baseline and the most aggressive scenario in 2030. Industry is expected to account for 47.5 % of the total remaining NO_x emissions in 2030 under the most aggressive scenario. Research should be conducted on the reduction potential of the industry sector in order to achieve further NO_x emission reductions beyond the scenarios in this study.

About 30 % of the NO_x emission reduction in 2020, and 40 % of the NO_x emission reduction in 2030 could be treated as ancillary benefits of energy conservation, while the "latent" ancillary benefit of energy conservation could be much larger. The contribution of energy-saving measures is expected to become larger and larger in the long run, with the reduction potential of end-of-pipe measures being exhausted. Therefore, it is strategically important to adopt energy-saving measures besides the historically dominant end-of-pipe measures.

Some policy factors that were not considered in the energy and pollution control scenarios may also have significant impacts on NO_x emissions. Although the governmental target to reduce the NO_x emission by 10 % during the 12th Five-Year Plan (2011–2015) is estimated to be exceeded under the "progressive" control strategy, the target would not be met if the GDP growth rate were one percent higher, or if 25 % of the installed flue gas denitrification technologies for power plants were not actually in operation. Failure in the operation of flue gas denitrification for power plants is expected to increase the NO_x emissions dramatically in the next 5–10 yr, while failure to control heavy diesel vehicles is expected to pose more adverse effects in the long term.

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