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RESEARCH ARTICLE

Emissions inventory and scenario analyses of air pollutants in Guangdong Province, China

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Abstract Air pollution, causing significantly adverse health impacts and severe environmental problems, has raised great concerns in China in the past few decades. Guangdong Province faces major challenges to address the regional air pollution problem due to the lack of an emissions inventory. To fill this gap, an emissions inventory of primary fine particles ($PM_{2.5}$) is compiled for the year 2012, and the key precursors (sulfur dioxide, nitrogen oxides) are identified. Furthermore, policy packages are simulated during the period of 2012–2030 to investigate the potential mitigation effect. The results show that in 2012, SO_2, NO_x, and $PM_{2.5}$ emissions in Guangdong Province were as high as (951.7, 1363.6, and 294.9) kt, respectively. Industrial production processes are the largest source of SO_2 and $PM_{2.5}$ emissions, and transport is the top contributor of NO_x emissions. Both the baseline scenario and policy scenario are constructed based on projected energy growth and policy designs. Under the baseline scenario, SO_2, NO_x, and $PM_{2.5}$ emissions will almost double in 2030 without proper emissions control policies. The suggested policies are categorized into end-of-pipe control in power plants (ECP), end-of-pipe control in industrial processes (ECI), fuel improvement (FI), energy efficiency improvement (EEI), substitution-pattern development (SPD), and energy saving options (ESO). With the implementation of all these policies, SO_2, NO_x, and $PM_{2.5}$ emissions are projected to drop to (303.1, 585.4, and 102.4) kt, respectively, in 2030. This inventory and simulated results will provide deeper insights for policy makers to understand the present situation and the evolution of key emissions in Guangdong Province.

Keywords Guangdong Province, emissions inventory, SO_2, NO_x, $PM_{2.5}$, scenario analyses

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1 Introduction

Driven by rapid economic development and urbanization as well as growing energy consumption, air pollutants, especially particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$), have attracted wide-ranging attention in China during recent years. Due to the severe environmental problems and significant health effects caused by $PM_{2.5}$ (Pope and Dockery, 2006; Huang et al., 2014; Pui et al., 2014; Zhao et al., 2014), much effort has been devoted to thoroughly understanding $PM_{2.5}$ aerosols. Mo et al. (2015) collected samples to investigate the characterization of summer $PM_{2.5}$ aerosols from four forest areas in Sichuan, Southwest China. Meng et al. (2015) employed a supply-chain approach to study the role of final demand purchase in initiating production processes that lead to primary $PM_{2.5}$ emissions in China. Pui et al. (2014) reviewed the measurement, source apportionment, visibility, and health effects of $PM_{2.5}$, and identified the major $PM_{2.5}$ sources in China as coal combustion, motor vehicle emissions, and industrial sources. In addition, both sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions contribute to the formation of secondary $PM_{2.5}$ and the corresponding city haze in the atmospheric environment (Zhang et al., 2015).

Based on existing studies, a series of emissions control policies have been implemented in China. It was found that measures such as pollution levying (Wang and Wheeler, 2005), reform of fossil-fuel subsidies (Liu and Li, 2011), command-and-control for sulfur dioxide (Schreifels et al., 2012), and measures directed at specific industries (e.g., energy-efficient scheduling, installing desulfurization units, demand-side management) (Zhang et al., 2015) had significant effects on pollution control. However, considering China's current inferior environmental performances (Chang et al., 2009; Deng et al., 2012; Xue et al., 2014), there is still a great challenge in improving air quality.

A comprehensive understanding of pollution sources is the basis of pollution abatement as well as investigating the related health and environmental impacts. A series of efforts have been made to identify emissions from various sources at a global scale (Huang et al., 2014), intercontinental scale (Ohara et al., 2007), national scale (Winther, 2008), regional scale (Zheng et al., 2009), and urban scale (Majumdar and Gajghate, 2011). In the case of Guangdong Province, only its core region, the Pearl River Delta, has been studied regarding the air pollutants SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, and VOC, and only for the years of 1997, 2001, 2003, and 2006 (HG-JWGSDEP, 2005, 2008; Zheng et al., 2009). For the whole province, only a few emissions sources, such as vehicular emissions (Cai and Xie, 2007), and the burning of rice, wheat, and corn straws residues (Zhang et al., 2008a) have been investigated. Therefore, there is still a significant gap in establishing a comprehensive pollution emissions inventory in Guangdong Province, not to mention a long-term evaluation of possible emissions trends.

A long-term evolution of emissions depends on energy consumption forecasting and the modeling of policy implementation. Currently, a series of energy consumption forecasting methods have prevailed in previous studies, such as peak oil models (Feng et al., 2008), leap models (Huang et al., 2011; Liang et al., 2014), and the energy elasticity coefficient method (Wang and Li, 2008). The effects of policy implementation can be studied with a comparison between the baseline scenario and the policy scenarios. Various policy scenarios should be set corresponding to varied research purposes, such as the influence of new energy policies (Shabbir and Ahmad, 2010; Tao et al., 2011; Chen et al., 2013), energy consumption under emissions caps (Jiang et al., 2008), optimal technology options on energy supply and demand (Kikuchi et al., 2014), the assessment of the potential of flexible demand (Kwon and Østergaard, 2014), and the reduction effect of chief atmospheric pollutants (Pan et al., 2013).

The interaction between air pollution abatement and environmental policies has been widely studied. A series of environmental policies, involving efficiency improvements, fuel switching, and end-of-pipe control options without affecting the emission-producing activity, were employed to survey their effects on air pollutants reduction based on the computable general equilibrium model WorldScan (Bollen and Brink, 2014). Some suggested measures (e.g., technology improvement, process control, waste reutilization) were executed for a ceramic tile plant to achieve cleaner production with fewer air pollutants (Huang et al., 2013). Kanada et al. (2013) depicted the long-term impact of SO_2 control policies in Kawasaki City, Japan, indicating that pollutant treatment devices and facilities, emission limit enforcement, and the establishment of monitoring systems have been important contributors to SO_2 reduction during the past few decades. Numerous policies, including promotion of low-sulfur coal, substitution of natural gas consumption for coal consumption, switching from heat-only boilers to combined heat and power schemes, the China V standard for vehicles, improvement of energy efficiency, installation of end-of-pipe pollutants treatment devices, and others, were integrated into the GAINS-City model to evaluate their emissions reduction potential in Beijing (Liu et al., 2013). As indicated by Wang et al. (2011), technological improvement linked to the vehicle emissions standard would lead to a substantial decrease in emissions from cars by 2020 in China. The People's Government of Guangdong Province has issued multiple government documents introducing a series of qualitative policies (e.g., end-of-pipe control in power plants, oil quality improvement, energy efficiency improvement) in the context of energy saving and emissions control in recent years (PGGP, 2009, 2014a, b), but their quantitative influences integrated into policy scenarios need to be evaluated urgently.

Therefore, the main objective of this paper is to develop a comprehensive emissions inventory of primary $PM_{2.5}$ emissions and its key precursors (SO_2, NO_x) for the year 2012 in Guangdong Province in addition to quantifying the potential influence of several key policies. We first present the data sources and methods used in this study, wherein the methods of compiling emissions inventory and policy simulation are explored (Section 2). In Section 3, we focus on different emissions sources, the development trend of emissions under the baseline scenario, and the quantitative results of emissions abatement under the policy scenario. Findings and recommendations are discussed in Section 4.

2 Data and methodology

2.1 Study area

Guangdong Province lies in Southern China (109º04′E and 117º20′E, 20º09′N and 25º31′N), adjacent to Hong Kong and Macao. Its land area amounts to 179,800 km^2 (1.87% of the land area in China), of which 0.89% is island. In China, Guangdong Province has the longest coastline, with a length of 3368.1 km.

Since 1989, Guangdong Province has led China in economic growth and ranked first in terms of economic performance. In 2012, its GDP reached 5706.79 billion CNY, contributing 11.0% of the total GDP in China. The population of permanent residents was 105,500,000 in 2012, with a per capita GDP of 54,095 CNY, close to that in middle developed countries.

As shown in Table 1, energy production in Guangdong Province amounted to 10.1 Mtce (10^6 tons of standard coal equivalent) in 1990, of which coal was the dominant source. In the mid-1990s, coal contributed approximately one-third of energy production. Afterwards, the ratio of coal declined steadily, while natural gas and electricity use increased. In 2006, the last coal mine in Guangdong was

Table 1 Time series of energy production in Guangdong Province

Item	1990	1995	2000	2005	2010	2011	2012
Energy production/Mtce	10.1	26.2	37.1	47.6	52.7	48.5	50.9
Raw coal/%	63.1	29.1	8.0	7.2	0.0	0.0	0.0
Crude oil/%	7.0	35.5	53.6	44.1	37.9	34.0	34.0
Natural gas/%	0.0	0.5	11.3	12.5	21.5	22.9	21.8
Primary electricity/%	29.9	34.9	27.1	36.2	40.7	43.2	44.2

Source: Guangdong Statistical Yearbook (GSY, 2013).

closed, and there has been no local coal exploitation since then.

Final energy consumption in Guangdong Province witnessed a significant growth in recent years and in 2012 was 283.8 Mtce, which was 7.2 times as large as that in 1990 (Table 2). Guangdong Province relied on energy inflows to meet its energy demand, attributed to the closure of local coal mining and relatively small energy resource potential. The dilemma facing Guangdong Province is to decouple economic growth and energy consumption as well as showing awareness of energy consumption's negative impacts on the environment.

With the rapid economic development in the past thirty years, air pollution has demonstrated a new feature in China. Haze days induced by atmospheric $PM_{2.5}$ have increased significantly, leading to a revision of a national ambient air quality standard in 2012 in which $PM_{2.5}$ was forced to be monitored for the first time. To protect and improve the atmospheric environment in Guangdong Province, the People's Government of Guangdong Province (PGGP) released a series of measures, paying special attention to $PM_{2.5}$. To control air pollution in the Pearl River Delta, PGGP issued a law pledging to control the total amount of key emissions (PGGP, 2009). Afterwards, PGGP aimed to reduce SO_2 and NO_x emissions to 0.72 and 1.10 Mt in 2015 (PGGP, 2014a). In light of the adverse impacts of $PM_{2.5}$ emissions, the concentration of $PM_{2.5}$ in the Pearl River Delta in 2017 should be 15% lower than that in 2012, while the concentration in the other regions of Guangdong Province should be less than 35 $\mu g/m^3$ (PGGP, 2014b).

2.2 Data collection and methodology

Mass balance and emission factor methods adopted in this study are typical for regional emissions quantification. Emissions sources are categorized into power plants, agriculture, industrial processes, transport, residential use, and others, referring to previous studies (Zheng et al., 2009; Tang et al., 2012). It should be noted that emissions from industrial processes arise from energy and non-energy activities.

Multiple data sources are used covering various sectors, fuels, and non-energy sources. Fossil fuel consumption for power plants, industrial processes, and residential use are collected from the China Energy Statistical Yearbook (CESY, 2013). Agricultural products are derived from the China Agriculture Statistical Yearbook (CASY, 2013). Industrial products and possession of vehicles are cited from GSY (2013).

2.2.1 The estimation of emissions

The general equation for emissions estimation can be expressed in Eq. (1), which is consistent with the method used by the United States Environmental Protection Agency (EPA, 2009).

$$E = A \times EF_{un} \times (1-\eta), \tag{1}$$

where E is the total emission; A is a specified activity data; EF_{un} is an emission factor without end-of-pipe emissions control, i.e., the unabated emission factor; and η is the removal efficiency of emissions. An emission factor means

Table 2 Time series of final energy consumption in Guangdong Province

Year	Energy consumption/Mtce	Composition/%			
		Raw coal	Oil products	Electricity	Others
1990	39.4	33.6	22.4	33.0	11.0
1995	70.6	27.0	20.9	39.7	12.4
2000	90.8	17.1	22.6	45.4	14.9
2005	172.6	10.9	23.6	50.7	14.8
2010	263.4	11.4	18.9	47.0	22.7
2011	277.8	12.3	17.3	48.6	21.8
2012	283.8	11.6	17.2	49.2	22.0

Source: Guangdong Statistical Yearbook (GSY, 2013).

the average amount of a specific pollutant or material discharged into the atmosphere by a specific process, fuel, equipment, or source (EPA, 2009). In a Chinese national standard (the manual of pollutants-producing and discharging coefficients from industrial sources), unabated emissions factors are termed pollutants-producing coefficients of emissions, and abated emissions factors are termed discharging coefficients of emissions (MEP, 2010), wherein abated emissions factors are the product of unabated emissions factors and the remaining ratio of emissions after the end-of-pipe control. In this paper, abated and unabated emissions factors are distinguished and used for different purposes.

2.2.1.1 Power plants, industrial processes, and residential use

For SO_2 emission, the annual emissions are calculated using the mass balance method, as presented in Eq. (2).

$$E=\sum_{i,k}M_{i,k}\times S_{i,k}\times 2\times\beta_{i,k}\times(1-\eta_{i,k}),\tag{2}$$

where i represents fuel type; k indicates different fuel usage for power plants, industrial sources, or residential use; E is the total emission of SO_2; M is annual fuel consumption; S is the sulfur content of fuel; β is the transformation ratio of sulfur from fuel; and η is the removal efficiency. Notably, for coal in power plants, industrial sources, or residential use, there is a variance of removal efficiencies. The coal consumed by power plants in Guangdong Province has a low sulfur content, taken to be 0.8% by weight, and the average desulphurization efficiency is approximately 80%, as estimated by Guangdong Electric Power Design Institute (GEDI, 2013). As a result, the unabated SO_2 emission factor of coal for power plants is calculated as 14.4 kg/t, and the corresponding abated SO_2 emission factor is 2.9 kg/t, with an average transformation ratio of sulfur from coal being 90%. In addition, compared with power plants, there is a lower average desulphurization efficiency in industrial processes, which is assumed to be 60%. For residential use, emissions are released into the atmosphere directly, and hence, its desulphurization efficiency is set to be zero.

For NO_x emission, the emission inventory is compiled with Eq. (3).

$$E=\sum_{i}M_i\times PPC_i\times(1-\eta_i),\tag{3}$$

where i represents fuel type; E is the total emission of NO_x; M is annual fuel consumption; PPC is the average pollutants-producing coefficient or unabated emission factor; and η is the removal efficiency. For coal for power plants, industrial sources, or residential use, it is worthwhile to note that these removal efficiencies are different. The unabated NO_x emission factors of power plants and industrial processes are drawn from Zheng et al. (2009). The denitration efficiency of power plants in 2012 is estimated to be 50% because it will be just 75% in 2015 (GEDI, 2013). Moreover, the denitration efficiency of industrial processes and residential use are assumed to be 40% and zero, respectively. The corresponding calculated results are listed in Table 3.

Secondary particulate matter is formed from precursors (SO_2 and NO_x) released into the atmosphere (Ying and Kleeman, 2006), and these amounts are not calculated directly in this paper due to the unclear formation mechanism (Wang and Wang, 2014). As a result, we calculate SO_2 and NO_x instead. Primary $PM_{2.5}$ emissions from coal combustion of power plants or industrial sources are estimated as follows:

$$E=\sum_{i,j,k}M_{i,j,k}\times Aar_{i,j,k}\times\sigma_{i,j,k}\times\omega_{i,j,k}\times(1-\eta_{i,j,k}),\tag{4}$$

where i represents fuel type; j indicates the j^{th} boiler; k indicates different fuel usage for power plants or industrial sources; E is the total emission of $PM_{2.5}$; M is annual fuel consumption; Aar is the ash content of coal; σ is the ratio of fly ash; ω is the mass fraction of $PM_{2.5}$ in fly ash; and η is the dust collection efficiency of the exhaust control system.

As suggested by MEP (2014), for power plants, the ash content of coal is 20%, the ratio of fly ash for a pulverized coal boiler and a fluidize-bed boiler are 85.00% and 60.00%, respectively, and the mass fraction of $PM_{2.5}$ in the fly ash of a pulverized coal boiler and a fluidize-bed boiler are 6.00% and 5.00%, respectively. Dust collection efficiency depends on the choice of exhaust control system, while a value of 92.6% from electrostatic precipitator is used. Similarly, $PM_{2.5}$ emission factors from industrial sources and residential use can be calculated with Eq. (4), and their dust collection efficiencies are 80% and zero, respectively. The final calculated results are shown in Table 3.

In addition, a fraction of emissions can be traced back to

Table 3 Abated emissions factors of SO_2, NO_x and $PM_{2.5}$ from energy sources

Emissions source	Fuel type	Emissions factor		
		$PM_{2.5}$	SO_2	NO_x
Power plants	Coal/($kg\cdot t^{-1}$)	0.7	2.9	3.9
	Oil/($kg\cdot t^{-1}$)	0.0	2.0	7.0
	Natural gas/($kg\cdot 10^{-6}\cdot m^{-3}$)	15.3	180.0	1660.0
Industrial use	Coal/($kg\cdot t^{-1}$)	0.4	5.4	3.2
	Oil/($kg\cdot t^{-1}$)	0.1	4.0	4.8
	Natural gas/($kg\cdot 10^{-6}\cdot m^{-3}$)	60.0	180.0	96.5
Residential use	Coal/($kg\cdot t^{-1}$)	7.4	20.8	1.9
	Oil/($kg\cdot t^{-1}$)	0.6	10.0	1.1
	Natural gas/($kg\cdot 10^{-6}\cdot m^{-3}$)	300.0	180.0	21.0

the non-energy industrial manufacturing process, as shown in Eq. (5).

$$E=\sum_{i} InP_i \times PPC_i \times (1-\eta_i), \tag{5}$$

where i represents industrial product type; E is the total emissions of SO_2, NO_x, and $PM_{2.5}$ from industrial manufacturing processes; InP is the amount of industrial products; PPC is the average pollutants-producing coefficient; and η is the removal efficiency.

Table 4 presents the unabated emissions factors of industrial products collected from previous studies and national standards in which chemical fertilizer, cement, pig iron, steel, coke, paper, glass, ceramic, sulfuric acid, copper, lead, and zinc are included. Average dust collection efficiency, desulphurization efficiency, and denitration efficiency of industrial products are the same as those of industrial energy sources.

2.2.1.2 Transport

Regarding the contribution of SO_2, NO_x, and $PM_{2.5}$ emissions, vehicles are classified as passenger vehicles, freight vehicles, and others. Passenger vehicles consist of large, medium, small vehicles, and minibuses, while freight vehicles include heavy, medium, light vehicles, and mini trucks. As illustrated in Eq. (6), emissions of vehicles are estimated from vehicle population annual vehicle kilometers traveled (AVKT) categorized by vehicle types (He et al., 2005; Tang et al., 2012).

$$E=\sum_{i} V_i \times EF_i \times AVKT_i, \tag{6}$$

where i represents vehicle type; E is the total emissions of SO_2, NO_x, and $PM_{2.5}$ from vehicles; V is the vehicle population; EF is the emission factor of vehicles in each category; and $AVKT$ represents annual vehicle kilometers traveled.

Table 5 shows the emissions factors and AVKT of on-road vehicles, derived from Zhao and Ma (2008). Due to the lack of statistical data on fuel consumption for each vehicle type, this relatively simple estimation method of transport emissions is used in this study, although more complicated models (e.g., MOBILE 5b and COPERT IV models) can be employed when more comprehensive and abundant data are available (Zheng et al., 2009; Qiu et al., 2014).

2.2.1.3 Agriculture

Biomass burning leads to considerable emissions in the atmosphere, especially particulate matter emissions (Tang et al., 2012), because large amounts of crop residues are produced from rural cultivation, and a considerable percentage are disposed of via direct combustion. Emissions from burning crop residue are estimated in Eq. (7), and the details of this method are revealed elsewhere (Streets et al., 2003).

$$E=\sum_{i} P_i \times N_i \times B_i \times \eta_i \times EF_i, \tag{7}$$

where i represents crop type; E is the total emission of biomass burning; P indicates crop yield; N indicates a crop-specific production-to-residue ratio; B is the percentage of burned residues; η represents the burn efficiency of residues; and EF is the emission factor of crop dry matter residues.

In this paper, the crop-specific production-to-residue ratios of rice, wheat, soybean, tubers, fiber crops, and oil-bearing crops are 1.00, 1.00, 2.00, 1.50, 1.00, 0.50, and

Table 4 Unabated emissions factors from non-energy industrial products

Industrial products	Unabated emissions factor		
	$PM_{2.5}$	SO_2	NO_x
Chemical fertilizer/($kg \cdot t^{-1}$)	8.60 (Klimont et al., 2002)	—	—
Cement/($kg \cdot t^{-1}$)	3.30 (Lei et al., 2011b)	0.30 (Garg et al., 2001)	1.58 (MEP, 2010)
Pig iron/($kg \cdot t^{-1}$)	3.06 (Lei et al., 2011a)	0.11 (MEP, 2010)	0.50 (MEP, 2010)
Steel/($kg \cdot t^{-1}$)	10.50 (Klimont et al., 2002)	—	1.16 (MEP, 2011)
Coke/($kg \cdot t^{-1}$)	10.13 (Lei et al., 2011a)	1.11 (MEP, 2011)	0.39 (MEP, 2011)
Paper/($kg \cdot t^{-1}$)	—	—	1.50 (MEP, 2010)
Glass/($kg \cdot t^{-1}$)	7.01 (Lei et al., 2011a)	0.84 (MEP, 2011)	4.37 (MEP, 2011)
Ceramic/($g \cdot m^{-2}$)	—	33.6 (MEP, 2011)	48.35 (MEP, 2010)
Sulfuric acid/($kg \cdot t^{-1}$)	—	12.00 (Garg et al., 2001)	—
Copper/($kg \cdot t^{-1}$)	—	330.00 (Garg et al., 2001)	—
Lead/($kg \cdot t^{-1}$)	—	502.40 (MEP, 2010)	—
Zinc/($kg \cdot t^{-1}$)	—	3.34 (MEP, 2010)	—

Table 5 Emissions factors and AVKT of on-road vehicles

Vehicle type		Emissions factor/($g \cdot km^{-1}$)			Annual vehicle kilometers traveled (AVKT)/(10^4 $km \cdot yr^{-1}$)
		$PM_{2.5}$	SO_2	NO_x	
Passenger vehicles	Large	0.11	1.20	18.06	3.00
	Medium	0.11	0.80	3.96	2.80
	Small	0.01	0.40	1.12	2.00
	Minibuses	0.01	0.10	0.71	1.50
Freight vehicles	Heavy	4.61	1.00	17.20	3.00
	Medium	0.11	0.70	3.96	2.80
	Light	0.04	0.60	2.37	2.00
	Mini trucks	0.01	0.10	0.71	1.50
Others		0.01	0.10	0.72	1.00

2.00, respectively (Zhao and Ma, 2008). The percentage of burned residues and the burning efficiency of crops are estimated to be 20% and 80%, respectively, in contrast with the estimates by other researchers of approximately 22% and 90% (Zhang et al., 2008b; Tang et al., 2012).

2.2.2 Policy scenarios and simulations

Future energy consumption is mainly estimated according to energy consumption in the base year (2012) and forecasted sectoral energy growth rates. Energy growth rate projections are collected from the Energy Development Strategy of Guangdong Province (GDRC, 2013), whereas a few pieces of the data are adjusted in accordance with the projection of electricity consumption by Southern Power Grid. GDRC (2013) employed the sector-analysis method to estimate the long-term energy growth rates in Guangdong Province, wherein three energy-growth scenarios (i.e., a recommended scenario, a high-growth scenario, and a low-growth scenario) are introduced, and the recommended scenario is applied in this manuscript (Table 6). The supply and demand of electricity are balanced, which means the sum of indigenous electricity consumption and exported electricity are equal to the sum of indigenous production of thermal power, hydropower, nuclear power, wind power, and imported electricity. The baseline scenario is constructed using projected energy growth rates, in which no emissions control policies are strengthened.

Six types of policies are proposed to evaluate their impacts on emissions reduction under the policy scenario, as listed in Table 7. As a whole, the policies are categorized as end-of-pipe control in power plants (ECP), end-of-pipe control in industrial processes (ECI), fuel improvement (FI), energy efficiency improvement (EEI), substitution-pattern development (SPD), and energy saving options (ESO). Each policy has its own special meaning and can be precisely implemented and adjusted by establishing quantitative indicators. Taking ECP for example, desulfurization efficiency, denitration efficiency, and dust removal efficiency can be set to simulate their impacts on the emissions trend from power plants with appropriate volumes.

3 Results and discussion

3.1 Emissions inventory

The total emissions of SO_2, NO_x, and primary $PM_{2.5}$ of Guangdong Province in 2012 amounts to (951.7, 1363.6, and 294.9) kt, respectively. As listed in the official statistics

Table 6 Projected energy growth rates by sector in Guangdong Province

Sector	Energy growth rate/%			
	2011–2015	2016–2020	2021–2025	2026–2030
Agriculture	2.10	1.70	1.80	1.50
Industry	5.60	3.40	1.10	0.40
Construction	4.00	3.20	2.80	2.10
Transport and storage	5.20	4.20	3.80	2.80
Wholesale and catering	6.30	5.60	5.30	4.90
Other service activities	7.70	6.50	6.50	6.20
Residential use	5.30	5.20	4.00	5.70

Source: Energy Development Strategy of Guangdong Province (GDRC, 2013).

Table 7 List of policies by category

Policy	Content	Indicator
End-of-pipe control in power plants (ECP)	Improving desulfurization efficiency, denitration efficiency, and dust removal efficiency in power plants	Desulfurization efficiency in power plants
		Denitration efficiency in power plants
		Dust removal efficiency in power plants
End-of-pipe control in industrial processes (ECI)	Improving desulfurization efficiency, denitration efficiency, and dust removal efficiency in industrial processes	Desulfurization efficiency in industrial combustion
		Denitration efficiency in industrial combustion
		Dust removal efficiency in industrial combustion
Fuel improvement (FI)	Promotion for low-sulfur coal, oil quality improvement, and biomass burning reduction to decrease emissions	
Promotion for low-sulfur coal	Lowering sulfur content of coal in power plants, industrial processes, and residential use	Sulfur content of coal in power plants
		Sulfur content of coal in industrial processes
		Sulfur content of coal in residential use
Oil quality improvement	Lifting oil standards for oil quality improvement	Descent rate of SO_2 for vehicles
		Descent rate of NO_x for vehicles
		Descent rate of $PM_{2.5}$ for vehicles
Biomass burning reduction	Lowering the amount of biomass burning	Descent rate of biomass burning
Energy efficiency improvement (EEI)	Improving energy efficiency of thermal power and employing CHP	
Thermal power energy efficiency improvement	Lowering coal or natural gas inputs per unit of electricity generation	Coal equivalent input per unit of electricity generation
CHP	Coal-fired industrial boilers are substituted by CHP to decrease fossil fuel consumption for heat supply	Descent rate of coal for heat supply
		Descent rate of natural gas for heat supply
Substitution-pattern development (SPD)	Power supply mix optimization, substitution of natural gas for coal, substitution of electricity for oil, acceleration of natural gas usage	
Power supply mix optimization	Accelerating the supply of hydropower, nuclear power, wind power to reduce coal consumption	Descent rate of coal consumption
Substitution of natural gas for coal	Switching substitution of natural gas for coal in power plants to that in industrial processes	The proportion of natural gas in place of coal in power plants
		The proportion of natural gas in place of coal in industrial processes
		The proportion of natural gas in place of coal in residential use
Substitution of electricity for oil	Promoting electric vehicles to lower oil consumption of traditional vehicles	The amount of electricity usage in vehicles
Acceleration of natural gas usage	More natural gas is utilized	The amount of natural gas usage
Energy saving options (ESP)	Energy saving is achieved by technical progress, management progress, etc.	Energy saving efficiency

(GSY, 2013), industrial and residential SO_2 emissions are 771.5 kt and 27.2 kt, respectively; industrial, residential, and transport NO_x emissions are (809.1, 11.3, and 482.3) kt, respectively. The total SO_2 emissions in this study is higher than that in the official statistics, and it is likely that some emissions sources (e.g., transport, agriculture) are not included in the official statistics. To some extent, the estimated pollution emissions in this study and those in the official statistics are inconsistent. It should be noted that “others” represent remaining industries in Guangdong Province, excluding agriculture, power plants, industrial processes, transport, and residential use.

3.1.1 Sulfur dioxide

Figure 1 shows the contributions of SO_2 emissions from different sources in Guangdong Province. Industrial processes contribute the largest portion of the emissions (41.0%), followed by power plants (29.0%), others (9.7%), and transport (9.0%). Power plants consume more fossil fuels, but they release less SO_2 than industrial sectors. This is due to the lack of SO_2 emissions treatment devices in some industries or the usage of low-efficiency equipment. To alleviate the negative impacts of the overall SO_2 emission, technological and capital investments in SO_2 emissions reduction should be focused on industrial sectors, as well.

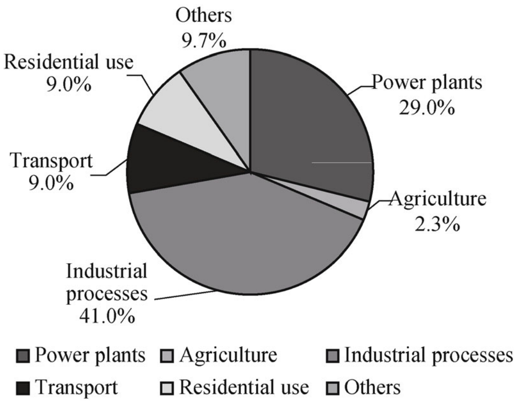

Fig. 1 Contributions of SO_2 emissions from different sources in Guangdong Province.

3.1.2 Nitrogen oxides

As demonstrated in Fig. 2, transport accounts for the largest share (35.4%) of NO_x emissions from different sources in Guangdong Province, while power plants and industrial processes are responsible for 33.2% and 25.8% of the total NO_x emission, respectively. As the most important contributor to NO_x emission, transport should be given priority for the achievement of NO_x emissions cap.

NO_x formation is a complicated process, where nitrogen from the combustion of air or fuel is converted to NO, NO_2, N_2O, NH_3, etc., relying on combustion temperature and fuel/oxygen ratio (Hill and Douglas Smoot, 2000). In general, the unabated emission factor of NO_x emissions for power plants is higher than that for industrial use according to combustion condition, as proven in Zheng et al. (2009). However, NO_x emissions control technologies, such as the low nitrogen boiler (LNB) and selective catalytic reduction (SCR), have been improved for power plants in Guangdong Province, leading to a lower abated NO_x emission factor than that from industrial processes.

Table 8 shows the emissions of on-road vehicles, of which passenger vehicles contribute 74.4% of SO_2 emissions, 60.0% of NO_x emissions, and 9.2% of $PM_{2.5}$ emissions, respectively. It is worth noting that heavy freight vehicles contribute the largest faction of $PM_{2.5}$ emissions because of the relatively high emission factor in Table 5. Heavy freight vehicles should be given priority for emissions control of on-road vehicles.

3.1.3 Particulate matter

As illustrated in Fig. 3, among the different $PM_{2.5}$ emissions sources in Guangdong Province, the major contributors are industrial processes, power plants, and agriculture, accounting for 35.0%, 28.3%, and 17.1%, respectively. In contrast to SO_2 and NO_x emissions, agriculture contributes a non-ignorable share for $PM_{2.5}$ emissions from biomass burning. Given that rice is the staple grain in Guangdong Province, and 60.0% of the sown area is utilized for rice plantation (GSY, 2013), rice residue is an important source of emissions from biomass burning.

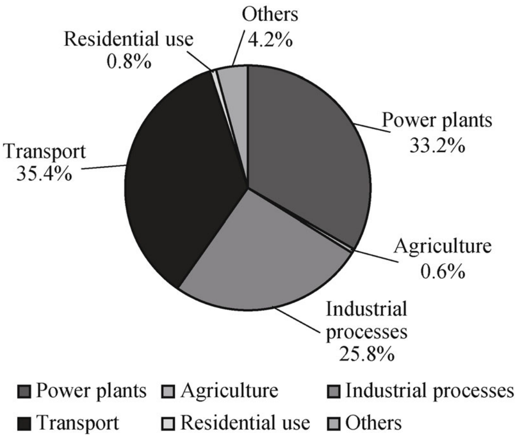

Fig. 2 Contributions of NO_x emissions from different sources in Guangdong Province.

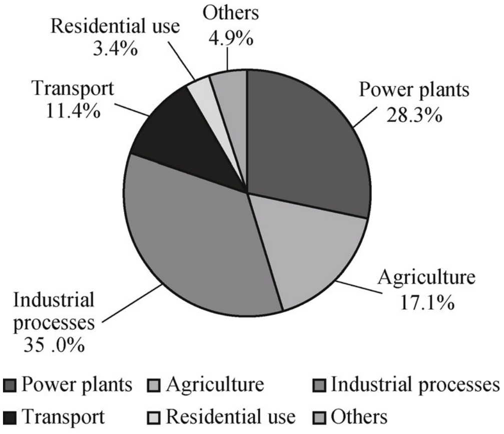

Fig. 3 Contributions of $PM_{2.5}$ emissions from different sources in Guangdong Province.

Table 8 Emissions of on-road vehicles

Vehicle type		Vehicle population	Emissions/t		
			SO_2	NO_x	$PM_{2.5}$
Passenger vehicles		8,616,036.0	75,363.4	290,713.8	3094.5
	Large	158,351.0	5700.6	85,794.6	536.8
	Medium	194,236.0	4350.9	21,561.9	598.3
	Small	8,142,154.0	65,137.2	182,058.6	1937.8
	Minibuses	121,295.0	174.7	1298.7	21.7
Freight vehicles		1,698,565.0	25,246.3	188,788.5	30,377.8
	Heavy	207,682.0	6230.5	107,163.9	28,722.4
	Medium	192,826.0	3779.4	21,405.4	593.9
	Light	1,265,840.0	15,190.1	59,874.2	1055.7
	Mini Trucks	32,217.0	46.4	345.0	5.8
Others		70,518.0	630.6	4762.2	78.2

In addition to primary $PM_{2.5}$ emissions released from fossil fuel combustion, biomass burning, and industrial production directly, secondary emissions formed from precursor gaseous species play an important role in the constitution of $PM_{2.5}$ emissions (Zhang et al., 2015). As a result, the SO_2, NO_x, and $PM_{2.5}$ emissions caps should all be set to control the formation of $PM_{2.5}$ aerosols.

3.1.4 Contributions of sub-category emissions sources

As indicated in Fig. 4, coal is responsible for 45.0% of energy consumption in Guangdong Province, followed by oil, primary electricity, natural gas, and others. According to official statistics (CESY, 2013), other energy sources consisted of heat, gangue, coke, coke oven gas, blast furnace gas, heat, and others. As an advanced economy, Guangdong Province has a large amount of oil consumption, implying that emissions control without oil reduction and oil quality improvement will be ineffective. The amount of primary electricity is estimated by the equivalent caloricity method rather than the equivalent heat value method, which is consistent with the official calculation (CESY, 2013).

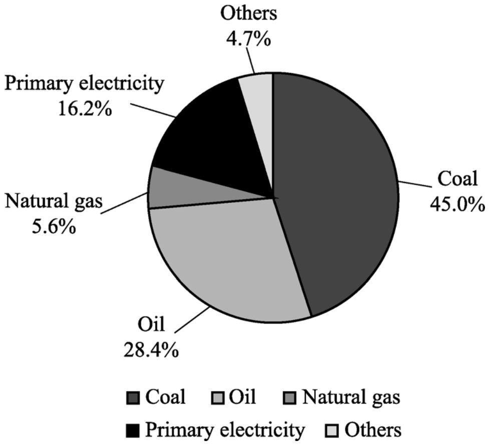

Fig. 4 Contributions of energy consumption by fuel types in Guangdong Province.

The source categories of SO_2, NO_x, and $PM_{2.5}$ emissions in Guangdong Province for the year 2012 are illustrated in Fig. 5. Because it accounts for the largest share of total energy consumption, coal categories are divided into coal for industrial sectors, coal for power plants, and coal for residential sectors to analyze the structural contributions of coal. Coal for power plants is responsible for the largest share of $PM_{2.5}$ emissions, approximately 28.3% of the total emissions in this region. At the same time, coal for power plants is the major source of SO_2 and NO_x emissions, accounting for 28.8% and 32.2%, respectively. Coal for industrial sectors contributes a considerable share of SO_2 emissions, while biomass burning and industrial products are important sources of $PM_{2.5}$ emissions. Oil accounts for 28.4% of total energy consumption, while its contribution to SO_2 and NO_x emissions both rank first, with shares of 30.3% and 44.0%, respectively. In addition, minor emissions can be attributed to coal for residential use and natural gas because of their low shares of energy consumption.

3.2 Energy and emission projections

As shown in Fig. 6, the total amount of energy consumption will increase sharply from 283.5 Mtce in 2012 to 507.9 Mtce in 2030 according to the energy and electricity consumption growth rates mentioned above. Primary electricity and natural gas will increase faster than other energy sources, with average annual growth rates of 5.5% and 6.5%, respectively, during 2012–2030.

Figure 7 presents a substantial transformation of the energy consumption mix from 2012 to 2030. In 2030, coal, oil, natural gas, primary electricity, and others will account

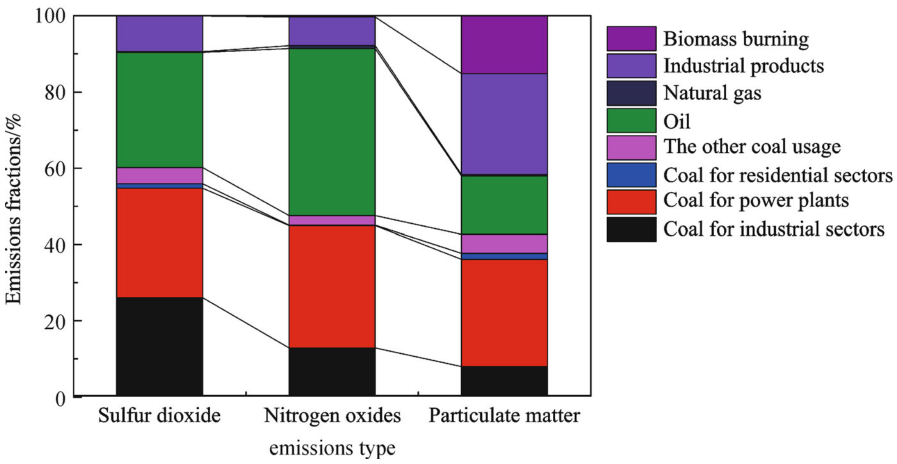

Fig. 5 Emissions contributions by sub-categories category in Guangdong Province.

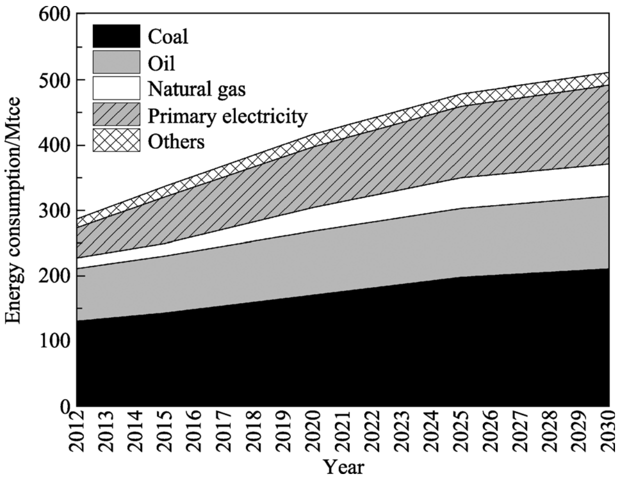

Fig. 6 Energy consumption under the baseline scenario during 2012–2030.

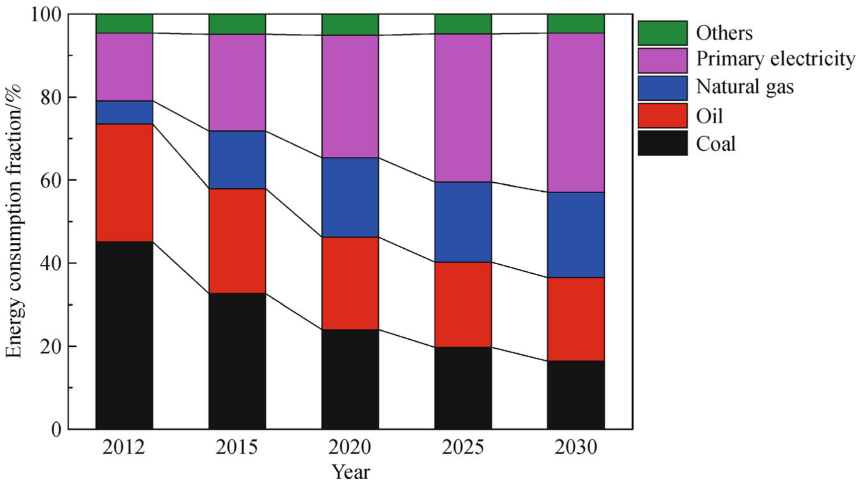

Fig. 7 Energy consumption mix under the baseline scenario during 2012–2030.

for 45.0%, 28.4%, 5.6%, 16.2%, and 4.7%, in contrast with the volumes of 41.0%, 21.8%, 9.7%, 23.7%, and 3.7% in 2012, respectively. Clearly, under the baseline scenario, coal and oil are partially displaced by natural gas and primary electricity.

As indicated in Fig. 8, future SO_2, NO_x, and $PM_{2.5}$ emissions will continue to rise rapidly without proper emissions control measures. NO_x emissions will reach 2331.8 kt in 2030, and SO_2 and $PM_{2.5}$ emissions will be 1505.2 kt and 416.8 kt. Faced with urgent pressures from rising emissions, policy makers should be engaged in formulating effective emissions reduction policies.

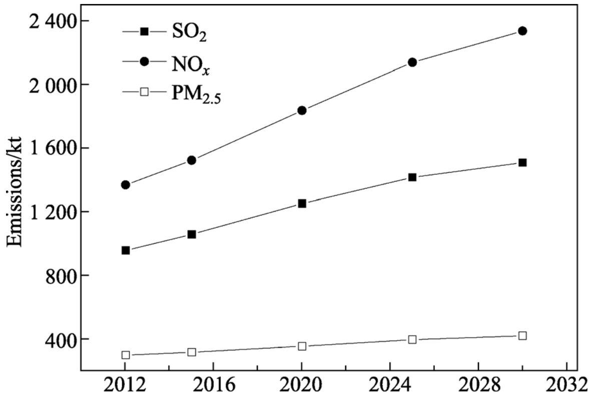

Fig. 8 Emissions under the baseline scenario during 2012–2030.

3.3 Policy simulations

The mix of policies implemented in Guangdong Province during the period 2012–2030 will contribute to emissions abatement. Table 9 shows the default values of various indicators under a policy scenario in 2030. Taking "the great progress in end-of-pipe control technologies towards emissions control" into account, future emissions removal efficiencies in both power plants and industrial processes will increase. Desulfurization efficiency of boilers can be improved with the application of matured desulfurization technologies such as limestone-gypsum technology, flue gas desulfurization, circulating fluidized bed, and others. NO_x emissions can be eliminated by the improvement of combustion condition or typical technologies involving selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and the combination of these two technologies. As suggested by GEDI (2013), most power plants adopt limestone-gypsum technology, whose desulfurization efficiency for boilers is designed to be 95% in China due to the unacceptable economic cost accompanied by an efficiency higher than 95%. However, it is difficult for all the power plants to achieve the best efficiency of 95% in Guangdong Province, and hence, the value in 2030 is set to be 92%. Similarly, because of technical limitations, denitration efficiency in 2030 is set to be 75%. Additionally, dust removal efficiency in power plants is assumed to be 98%, referring to an estimation by Zhang et al. (2015). Moreover, it should be noted that emissions removal efficiencies in industrial processes are not higher than those in power plants, whose corresponding desulfurization, denitration, and dust removal efficiencies are shown in Table 9.

The sulfur content of coal has a critical impact on SO_2 emissions, and the sulfur content of coal in power plants in Guangdong Province is appropriately 0.8% in 2012 (GEDI, 2013). With the popularization of washing coal or importing low-sulfur coal, the sulfur content of coal in power plants will be reduced to 0.7% in 2030. The sulfur content of coal in residential use is higher than that in power plants, which is set to be 0.8% in 2030. Due to a higher oil quality allowing for lower pollutant generation and the promotion of the China IV standard in Guangdong Province, emissions from oil combustion will be reduced substantially in 2030. With the appearance of the gasoline stage IV quality standard in 2014, the permissible sulfur content of gasoline was reduced by 66.7% compared with that of the stage III standard (Zhou et al., 2013). With respect to the diesel quality standard, it is estimated that the stage IV quality standard will greatly reduce the permissible sulfur content (Zhou et al., 2013). As a result, the descent rate of SO_2 for vehicles is estimated to be 40% in 2030. Grounded in the result of the emissions inventory, we find that biomass burning is an important source of $PM_{2.5}$, implying that actions to recycle biomass residues, e.g., biogas production, should be taken, as they could offer promising solutions to emissions reduction. The descent rate of biomass burning is assumed to be 50% in 2030.

Energy efficiency improvement is highly correlated with thermal power energy efficiency improvement or systematic progress with Combined Heat and Power (CHP). Once supercritical and ultra-supercritical technologies are promoted in power plants, thermal power energy efficiency will be remarkably improved. Ultra-supercritical technology can even decrease by 30 gce/kWh of fuel consumption, in contrast to supercritical technology with the same capacity. Currently, ultra-supercritical technology is very costly, but it will be popularized in the future as its price gradually declines. As suggested by GEDI (2013), coal equivalent input per unit of electricity generation will be 290 gce/kWh in 2030. Subject to heat demand and the length of heat-supply pipelines, CHP plants are commonly built upon industrial parks. Given that industrial production dominates heat consumption in Guangdong Province, descent rate of fossil fuels for heat supply is assumed to be 90%.

Substitution-pattern development receives wide acceptance in emissions reduction policies, and involves power supply mix optimization, substitution of natural gas for coal, substitution of electricity for oil, and acceleration of natural gas usage. An optimization of the energy supply mix refers to the substitution of renewable energy for fossil

Table 9 Values of indicators the under policy scenario

Policy	Indicator	Value in 2030
End-of-pipe control in power plants (ECP)	Desulfurization efficiency in power plants	92.0%
	Denitration efficiency in power plants	75.0%
	Dust removal efficiency in power plants	98.0%
End-of-pipe control in industrial processes (ECI)	Desulfurization efficiency in industrial combustion	80.0%
	Denitration efficiency in industrial combustion	75.0%
	Dust removal efficiency in industrial combustion	95.0%
Fuel improvement (FI)		
Promotion for low-sulfur coal	Sulfur content of coal in power plants	0.7%
	Sulfur content of coal in industrial processes	0.6%
	Sulfur content of coal in residential use	0.8%
Oil quality improvement	Descent rate of SO_2 for vehicles	40.0%
	Descent rate of NO_x for vehicles	60.0%
	Descent rate of $PM_{2.5}$ for vehicles	60.0%
Biomass burning reduction	Descent rate of biomass burning	50.0%
Energy efficiency improvement (EEI)		
Thermal power energy efficiency improvement	Coal equivalent input per unit of electricity generation (gce/kWh)	290
CHP	Descent rate of coal for heat supply	90.0%
	Descent rate of natural gas for heat supply	90.0%
Substitution-pattern development (SPD)		
Power supply mix optimization	Descent rate of coal consumption	10.0%
Substitution of natural gas for coal	The proportion of natural gas in place of coal in power plants	30.0%
	The proportion of natural gas in place of coal in industrial processes	68.1%
	The proportion of natural gas in place of coal in residential use	1.9%
Substitution of electricity for oil	The amount of electricity usage in vehicles/(10^8 kWh)	150
Acceleration of natural gas usage	The amount of natural gas usage/(10^8 m^3)	800
Energy saving options (ESP)	Energy saving efficiency	30.0%

fuels, and hence, fossil fuel use will decrease by 10% in 2030. A switch from coal boilers to natural gas boilers is an attractive alternative for air quality improvement, although natural gas has a higher price and a relatively scarce supply compared with coal. Consequently, natural gas is prone to displace coal use in industrial processes rather than in power plants, due to the higher emissions factors of coal use in industrial processes. In 2030, the proportion of natural gas in place of coal in industrial processes is assumed to be 68.1%, in contrast with 30% in power plants. The development of electric vehicles can accelerate the usage of electricity, and it is estimated its amount will achieve 15 billion kWh in 2030. Moreover, the amount of natural gas usage in the policy scenario nearly doubles the amount in the baseline scenario, replacing coal consumption to some extent.

There is a great potential in the improvement of energy end-use efficiency. Taking large public buildings as an example, nearly seventy percent of electricity consumption can be traced back to transportation and distribution of heating and cooling capability by fans and pumps, whose improvements can lead to a nearly thirty-percent electricity saving for the entire air-conditioning system. In consideration of other factors, such as industrial structure adjustment, stricter national energy-saving standards, and management progress, it is appropriately estimated that a thirty percent energy saving will be achieved in 2030.

With the combination of policies suggested by Table 7, the energy consumption mix will alter greatly. As shown in Fig. 9, in 2030 the proportions of primary electricity and natural gas will reach 38.2% and 20.6%, respectively, higher than the proportions in the baseline scenario. The current natural gas supply relies on imports from Australia under an inexpensive contract (Jiang et al., 2008), offshore gas exploited from the South China Sea, and the West-East Gas Pipeline project (GEDI, 2013). With a higher price and

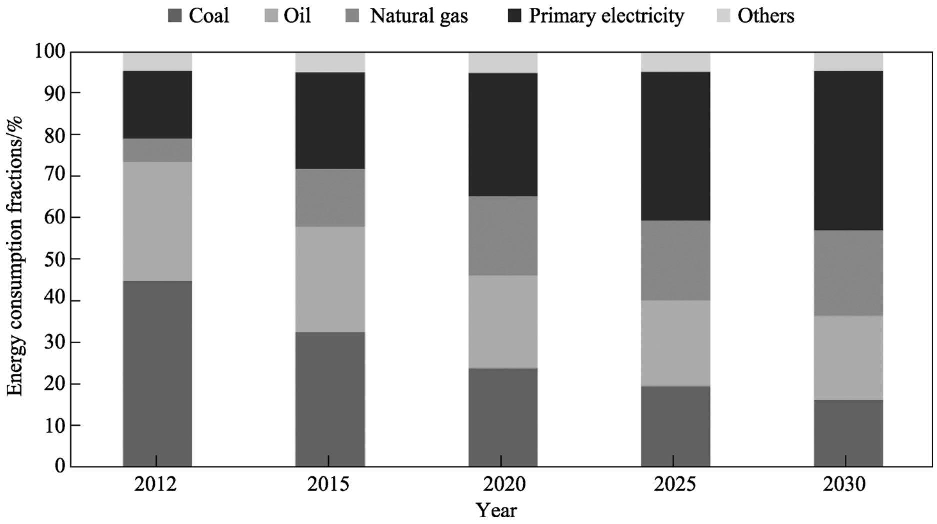

Fig. 9 Energy consumption mix under the policy scenario during 2012–2030.

limited supply, natural gas has been unable to compete with coal in recent years. However, in the long term, natural gas will be popularized for residential use, industrial production, and power generation with a stable supply. It is apparent that emissions reduction will benefit from the optimization of the energy consumption mix.

Figure 10 shows projections of SO_2, NO_x, and $PM_{2.5}$ emissions in the policy scenario from 2012 to 2030. In 2030, SO_2, NO_x, and $PM_{2.5}$ emissions will drop to (303.1, 585.4, and 102.4) kt, respectively, which means that SO_2, NO_x, and $PM_{2.5}$ emissions will be reduced by 68.2%, 57.1%, and 65.3% relative to their levels in 2012. The implementation of adequate policies makes emissions reduction possible in the future.

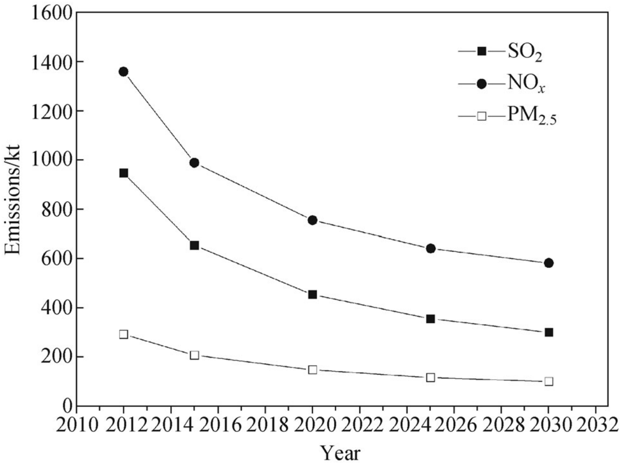

Fig. 10 Emissions under the policy scenario during 2012–2030.

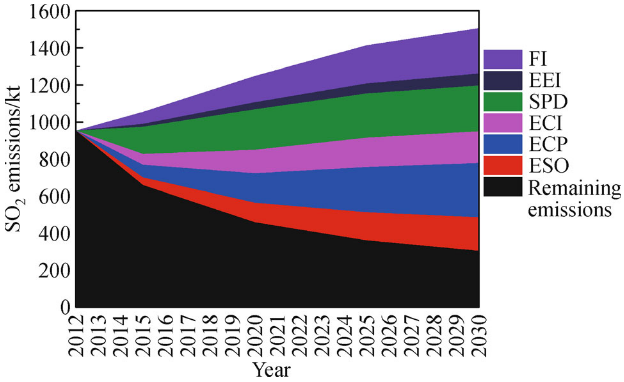

Fig. 11 SO_2 emissions under the policy scenario during 2012–2030.

As shown in Fig. 11, ECP contributes the largest portion of SO_2 emissions reduction, at 291.5 kt, followed by SPD (248.4 kt), FI (244.7 kt), ESO (181.1 kt), ECI (172.4 kt), and EEI (64.0 kt). Matured desulfurization technologies are more convenient to be employed in power plants with the concentrated usage of boilers, and thus end-of-pipe control of power plants is the largest contributor to SO_2 emissions reduction.

As presented in Fig. 12, FI, ECP, SPD, ECI, ESO, EEI rank first to six in terms of NO_x emissions reduction, accounting for (588.7, 379.9, 34.9, 184.5, 132.8, and 85.6) kt, respectively. NO_x emissions mainly stem from transport, power plants, and industrial processes, and hence, fuel improvement can lead to the largest NO_x emissions reductions. Substitution-pattern development will substantially reduce NO_x emissions in the long term as power supply mix optimization, substitution of natural gas for coal, substitution of electricity for oil, and acceleration of natural gas usage will account for (129.5, 11.3, 162.4, and 71.6) kt of emissions removal.

As indicated in Fig. 13, ECP, ECI, and FI take the top three places for $PM_{2.5}$ emissions reduction, followed by SPD, EEI, and ESO, whose reduced emissions amount to

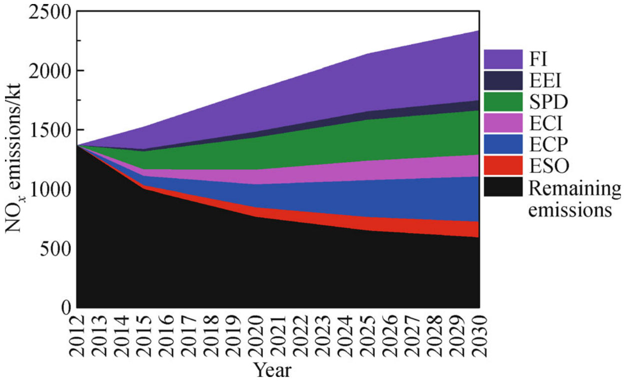

Fig. 12 NO_x emissions under the policy scenario during 2012–2030.

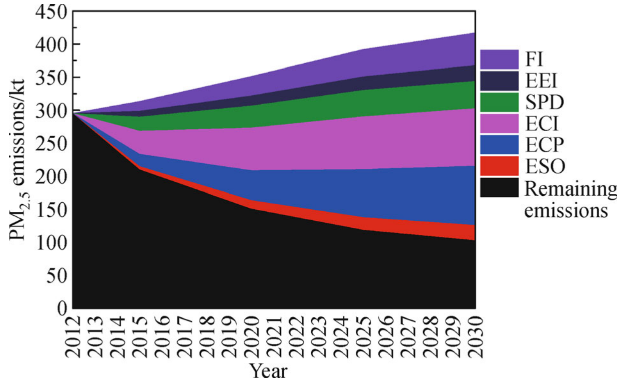

Fig. 13 $PM_{2.5}$ emissions under the policy scenario during 2012–2030.

(89.5, 87.5, 49.6, 41.3, 23.4, and 23.1) kt. End-of-pipe control in power plants and end-of-pipe control in industrial processes can remove $PM_{2.5}$ emissions with similar amounts. Song et al. (2011) found that secondary sulfate and secondary nitrate, which are important precursor gaseous species in Guangdong Province, caused 29.2% and 7.2% of $PM_{2.5}$ emissions, respectively; therefore, attention should be paid to the main sources of SO_2 and NO_x to restrain the formation of secondary $PM_{2.5}$.

Table 10 Energy consumption and emissions mix in 2030 under the policy scenario

Energy sources	Fraction of energy consumption/%	Fraction of emissions/%		
		SO_2	NO_x	$PM_{2.5}$
Coal	16.4	43.1	27.6	33.6
Industrial processes	0.7	2.1	0.8	0.3
Power plants	13.1	31.0	24.2	18.2
Residential use	0.1	2.5	0.4	4.2
Others	2.5	7.6	2.3	10.9
Oil	20.1	37.0	57.5	33.0
Natural gas	20.6	2.2	7.1	0.8
Primary electricity	38.2	—	—	—

Energy consumption and the emissions mix in the policy scenario are different from those in the baseline scenario. As shown in Table 10, it is worth noting that power plants are the dominant sources of coal consumption, while coal used in industrial processes and residential use is negligible in 2030. Coal is prone to being used for power generation under the policy scenario, due to greater emission removal efficiency in power plants. Electricity and natural gas can be substituted for the coal needs in industrial processes and for residential use. Coal in power plants and oil for transport will be the main contributors of emissions.

3.4 Uncertainly analysis

Uncertainties in an emissions inventory are mainly derived from the activities data of different emissions sources and their corresponding emissions factors. This study discusses the major uncertainties of emissions from fossil fuel combustion, road transportation, and biomass burning. First, due to the construction of on-line coal-consumption and pollution-monitoring systems in Guangdong Province, relatively high data quality is achieved regarding the amount of sulfur and ash content of fossil fuels, fossil fuel combustion, and emissions removal efficiencies. Therefore, power plants have the smallest emissions uncertainties, which is similar to the status quo of Yunnan Province (Tang et al., 2012). For residential use and small-size industrial use, an ample survey method is applied to collect the related data to publish official statistics, for which uncertainties can be reduced by a bottom-up method with larger sample sizes. Second, it is difficult to estimate emissions from road transportation because local traffic emissions factors relying on actual road conditions and the systematic survey of annual vehicle kilometers traveled (AVKT) are absent. In consideration of the rapid growth of vehicles from 2005 to 2012, Cai and Xie (2007) appropriately estimated that there were 52.0 kt SO_2 emissions in 2005 for Guangdong Province, which is comparable with that of 101.0 kt in 2012 with annual emission growth, and hence, the calculated results of traffic emissions in this study are credible to some extent. If a detailed transportation model is used and its parameters are adjusted to match Guangdong Province's situation, we believe the corresponding uncertainty can be further alleviated. Third, emissions from biomass burning are subject to the amount of crop residue burning, the percentage of burned residues, and the burning efficiency of crops, which are difficult estimate, resulting in a comparatively high uncertainty. Through a laboratory study of agricultural crop residue combustion consisting of rice, wheat, and corn, Zhang et al. (2008a) found that NO_x emissions from biomass burning amount to 8370 t, higher than the 5570.5 t in this study, which is mainly due to the application of a lower combustion efficiency and associated lower emissions factors in this study. If satellite data can serve as an effective tool for monitoring biomass burning, and emissions factors are obtained from outdoor experiments, the uncertainty for emissions from biomass burning will decrease.

Uncertainties also come from energy consumption projection data. As indicated by GDRC (2013), energy consumption in 2030 in the high-growth scenario will be 645 Mtce, and that in the low-growth scenario will be 445 Mtce, in comparison to the value of 507.9 Mtce in the recommended scenario. In actuality, there is an uncertainty between −12.4% and 27.0% for the energy consumption projection. The recommended scenario is adopted in this study because it is a near-real situation in the future, and we believe that the emissions projection based on the recommended energy-growth scenario will reduce intrinsic uncertainty as much as possible.

4 Conclusions

To address the air pollution problem, a comprehensive and detailed emissions inventory of primary $PM_{2.5}$, SO_2, and NO_x is built with the most available and appropriately used activity data and emissions factors. With mass balance and emissions factor methods, emissions factors of power plants, industrial sources, residential use, transport, and agriculture are calculated or collected based on previous studies. Emissions removal efficiencies for power plants, industrial sectors, and residential use are distinguished to reveal the internal structure of emissions. The results show that coal used by power plants and industrial sectors contributes a large amount of SO_2, NO_x, and $PM_{2.5}$ emissions. Oil combustion derived from the use of vehicles is mainly responsible for the largest shares of SO_2 and NO_x emissions. Biomass burning is non-negligible for $PM_{2.5}$ emissions.

As forecasted in the baseline scenario, emissions will rise greatly in 2030 without powerful emissions control measures. Several policies are integrated in the policy scenario to reveal their influences on emissions reduction. The results show that primary $PM_{2.5}$, SO_2, and NO_x emissions will drop to acceptable levels after the implementation of the combined policies. In the short term, end-of-pipe control measures have direct impacts on emissions reduction. Given the booming installation of emissions removal devices on power plants in recent years, policy makers should pay more attention to emissions from industrial sectors and the transport sector to further relieve environmental pressures; otherwise, the sole implementation of stricter emissions removal strategies towards power plants will be ineffective. In addition, removal efficiencies of end-of-pipe emissions will gradually move closer to their limit, and other policies of FI, EEI, SPD, and ESO should be promoted in the long term.

As an important component of the policy of SPD, primary electricity imports and local production will be encouraged to optimize the power supply mix to substitute for local fossil energy. In light of the “West Power to East” project, Guangdong Province can rely on electricity imports from Yunnan Province and Guizhou Province where hydropower is the main component, and thermal power only accounts for a minor portion. For thermal power imports from other provinces, emissions transferred from Guangdong to the other provinces seem to be caused from the perspective of input-output analysis (Chen et al., 2010; Chen and Chen, 2011, 2013; Zhang et al., 2013; Li et al., 2015). As a result, current electricity imports can avoid a large amount of local emissions caused by coal boilers, whereas its volume is subject to the uncertain availability of the external supply. Local primary electricity production, including hydropower, nuclear power, and wind power, plays an important role in emissions reduction. The development of hydroelectricity has reached the limit of hydropower in Guangdong Province, and hence, wind electricity and nuclear electricity should be boosted in the future. Moreover, natural gas is regarded as an alternative to replace coal, as fewer emissions are released from its combustion process compared to coal. Taking price and availability into account, natural gas should be used according to its higher marginal environmental benefit. Therefore, policy makers should substitute natural gas for coal in industrial processes and for residential use as much as possible.

With the combination of the suggested policies, the energy consumption mix in 2030 under the policy scenario will be different from that under the baseline scenario. Coal in industrial processes and residential use will be replaced by natural gas, primary electricity supply, and local thermal power, implying that coal for power generation rather than for industrial processes and residential use is an attractive alternative for emissions control.

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References

Bollen J, Brink C (2014). Air pollution policy in Europe: quantifying the interaction with greenhouse gases and climate change policies. Energy Econ, 46: 202–215

Cai H, Xie S D (2007). Estimation of vehicular emission inventories in China from 1980 to 2005. Atmos Environ, 41(39): 8963–8979

CASY (2013). China Agriculture Statistical Yearbook 2013. Beijing: China Statistical Publishing House (in Chinese)

CESY (2013). China Energy Statistical Yearbook 2013. Beijing: China Statistical Publishing House (in Chinese)

Chang D, Song Y, Liu B (2009). Visibility trends in six megacities in China 1973–2007. Atmos Res, 94(2): 161–167

Chen F F, Chou S C, Lu T K (2013). Scenario analysis of the new energy policy for Taiwan's electricity sector until 2025. Energy Policy, 61: 162–171

Chen Z M, Chen G Q (2011). An overview of energy consumption of the globalized world economy. Energy Policy, 39(10): 5920–5928

Chen Z M, Chen G Q (2013). Demand-driven energy requirement of world economy 2007: a multi-region input-output network simulation. Commun Nonlinear Sci Numer Simul, 18(7): 1757–1774

Chen Z M, Chen G Q, Zhou J B, Jiang M M, Chen B (2010). Ecological input-output modeling for embodied resources and emissions in Chinese economy 2005. Commun Nonlinear Sci Numer Simul, 15 (7): 1942–1965

Deng J J, Du K, Wang K, Yuan C S, Zhao J J (2012). Long-term atmospheric visibility trend in Southeast China, 1973–2010. Atmos Environ, 59: 11–21

EPA (2009). Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors. Also available at: http://www.epa.gov/ttn/chief/ap42/index.html

Feng L Y, Li J C, Pang X Q (2008). China's oil reserve forecast and analysis based on peak oil models. Energy Policy, 36(11): 4149–4153

Garg A, Shukla P R, Bhattacharya S, Dadhwal V K (2001). Sub-region (district) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility. Atmos Environ, 35(4): 703–713

GSY (2013). Guangdong Statistical Yearbook 2013. Beijing: China Statistical Publishing House (in Chinese)

Guangdong Electric Power Design Institute (GEDI) (2013). Guangdong power supply situation analysis and responsed solutions (in Chinese)

Guangdong Provincial Development and Reform Commission (GDRC) (2013). Energy development strategy of Guangdong Province (in Chinese)

He K B, Huo H, Zhang Q, He D Q, An F, Wang M, Walsh M P (2005). Oil consumption and CO_2 emissions in China's road transport: current status, future trends, and policy implications. Energy Policy, 33(12): 1499–1507

Hill S C, Douglas Smoot L (2000). Modeling of nitrogen oxides formation and destruction in combustion systems. Pror Energy Combust Sci, 26(4–6): 417–458

Hong Kong-Guangdong Joint Working Group on Sustainable Development and Environmental Protection (HG-JWGSDEP) (2005). Air Emission Inventory Handbook for Pearl River Delta Region. CH2M-IDC Hong Kong Ltd., Hong Kong

Hong Kong-Guangdong Joint Working Group on Sustainable Development and Environmental Protection (HG-JWGSDEP) (2008). Pearl River Delta Regional Air Quality Management Plan Mid-term Review Report. Also available at: http://www.legco.gov.hk/yr07-08/chinese/panels/ea/papers/ea0128cb1-666-4-ec.pdf

Huang K, Fu J S, Gao Y, Dong X Y, Zhuang G S, Lin Y (2014). Role of sectoral and multi-pollutant emission control strategies in improving atmospheric visibility in the Yangtze River Delta, China. Environ Pollut, 184: 426–434

Huang Y, Bor Y J, Peng C Y (2011). The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy, 39(11): 6790–6803

Huang Y, Luo J W, Xia B (2013). Application of cleaner production as an important sustainable strategy in the ceramic tile plant – A case study in Guangzhou, China. J Clean Prod, 43: 113–121

Jiang B B, Chen W Y, Yu Y F, Zeng L M, David V (2008). The future of natural gas consumption in Beijing, Guangdong and Shanghai: an assessment utilizing MARKAL. Energy Policy, 36(9): 3286–3299

Kanada M, Fujita T, Fujii M, Ohnishi S (2013). The long-term impacts of air pollution control policy: historical links between municipal actions and industrial energy efficiency in Kawasaki City, Japan. J Clean Prod, 58: 92–101

Kikuchi Y, Kimura S, Okamoto Y, Koyama M (2014). A scenario analysis of future energy systems based on an energy flow model represented as functionals of technology options. Appl Energy, 132: 586–601

Klimont Z, Cofala J, Bertok I, Amann M, Heyes C, Gyarfas F (2002). Modelling particulate emissions in Europe. A Framework to Estimate Reduction Potential and Control Costs IR-02-076, IIASA, Austria, In: http://www iiasa ac at/rains/reports html

Kwon P S, Østergaard P (2014). Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy, 134: 309–320

Lei Y, Zhang Q, He K B, Streets D G (2011a). Primary anthropogenic aerosol emission trends for China, 1990–2005. Atmos Chem Phys, 11(3): 931–954

Lei Y, Zhang Q, Nielsen C, He K (2011b). An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. Atmos Environ, 45(1): 147–154

Li J S, Chen G Q, Hayat T, Alsaedi A (2015). Mercury emissions by Beijing's fossil energy consumption: based on environmentally extended input–output analysis. Renew Sustain Energy Rev, 41: 1167–1175

Liang M C, Wang Y, Wang G H (2014). China's Low-carbon-city development with ets: forecast on the energy consumption and carbon emission of Chongqing. Energy Procedia, 61: 2596–2599

Liu F, Klimont Z, Zhang Q, Cofala J, Zhao L, Huo H, Nguyen B, Schöpp W, Sander R, Zheng B, Hong C P, He K, Amann M, Heyes C (2013). Integrating mitigation of air pollutants and greenhouse gases in Chinese cities: development of GAINS-City model for Beijing. J Clean Prod, 58: 25–33

Liu W, Li H (2011). Improving energy consumption structure: a comprehensive assessment of fossil energy subsidies reform in China. Energy Policy, 39(7): 4134–4143

Majumdar D, Gajghate D G (2011). Sectoral CO_2, CH_4, N_2O and SO_2 emissions from fossil fuel consumption in Nagpur City of Central India. Atmos Environ, 45(25): 4170–4179

Meng J, Liu J F, Xu Y, Tao S (2015). Tracing Primary $PM_{2.5}$ emissions via Chinese supply chains. Environ Res Lett, 10(5): 054005

Ministry of Environmental Protection (MEP) (2010). The manual of pollutants-producing and discharging coefficients from industrial sources. Also available at: http://www.cnemc.cn/publish/105/news/news_12893.html (in Chinese)

Ministry of Environmental Protection (MEP) (2011). Main pollutant total emission reduction accounting rules during the 12th Five-year plans. Also available at: http://www.zhb.gov.cn/gkml/hbb/bwj/201206/t20120605_230944.htm (in Chinese)

Ministry of Environmental Protection (MEP) (2014). The technical manual of emission inventories of atmospheric fine particulate matter ($PM_{2.5}$) (Exposure Draft). Available fromhttp://www.zhb.gov.cn/gkml/hbb/bgth/201401/W020140124409250653376.pdf (in Chinese)

Mo H Q, Li L, Lai W, Zhao M, Pu J G, Zhou Y, Deng S H (2015). Characterization of summer PM2.5 aerosols from four forest areas in Sichuan, SW China. Particuology, 20: 94–103

Ohara T, Akimoto H, Kurokawa J I, Horii N, Yamaji K, Yan X, Hayasaka T (2007). An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. Atmos Chem Phys, 7 (16): 4419–4444

Pan L J, Xie Y B, Li W (2013). An analysis of emission reduction of chief air pollutants and greenhouse gases in Beijing based on the LEAP Model. Procedia Environ Sci, 18: 347–352

PGGP (The people's Government of Guangdong Province) (2009). Measures on Prevention and Control of Air Pollution in Pearl River Delta of Guangdong Province. Also available at: http://www.gd.gov.cn/govpub/zfwj/zfxxgk/gz/200903/t20090330_88639.htm (in Chinese)

PGGP (The people's Government of Guangdong Province) (2014a). Action Plan on Low-Carbon Development for Energy Saving and Emissions Reduction in Guangdong Province (2014−2015). Also available at: http://zwgk.gd.gov.cn/006939748/201410/t20141022_551390.html (in Chinese)

PGGP (The people's Government of Guangdong Province) (2014b). Action Plan on Prevention and Control of Air Pollution in Guangdong Province (2014−2017). Also available at: http://zwgk.gd.gov.cn/006939748/201402/t20140214_467051.html (in Chinese)

Pope C A, Dockery D W (2006). Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc, 56(6): 709–742

Pui D Y H, Chen S C, Zuo Z (2014). PM2.5 in China: measurements, sources, visibility and health effects, and mitigation. Particuology, 13: 1–26

Qiu P P, Tian H Z, Zhu C Y, Liu K Y, Gao J J, Zhou J R (2014). An elaborate high resolution emission inventory of primary air pollutants for the Central Plain Urban Agglomeration of China. Atmos Environ, 86: 93–101

Schreifels J J, Fu Y, Wilson E J (2012). Sulfur dioxide control in China: policy evolution during the 10th and 11th Five-year Plans and lessons for the future. Energy Policy, 48: 779–789

Shabbir R, Ahmad S S (2010). Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using leap model. Energy, 35(5): 2323–2332

Song Y, Zhang Y, Dai W. (2011). PM2.5 sources and their effects on human health in China: case report. In: Nriagu J O, ed. Encyclopedia of Environmental Health. Burlington: Elsevier, 606–613

Streets D G, Yarber K F, Woo J H, Carmichael G R (2003). Biomass burning in Asia: annual and seasonal estimates and atmospheric emissions. Global Biogeochem Cycles, 17(4): doi: 10.1029/2003GB002040

Tang X L, Zhang Y, Yi H H, Ma J Y, Pu L (2012). Development a detailed inventory framework for estimating major pollutants emissions inventory for Yunnan Province, China. Atmos Environ, 57: 116–125

Tao Z, Zhao L, Changxin Z (2011). Research on the prospects of low-carbon economic development in China based on LEAP model. Energy Procedia, 5: 695–699

Wang H K, Fu L X, Bi J (2011). CO_2 and pollutant emissions from passenger cars in China. Energy Policy, 39(5): 3005–3011

Wang H, Wheeler D (2005). Financial incentives and endogenous enforcement in China's pollution levy system. Journal of Environmental Economics and Management, 49(1): 174–196

Wang Y S, Wang L L (2014). The sources, impact and regulation of atmospheric particulate matter. Sci Soc, 2: 9–18 (in Chinese)

Wang Y, Li J W (2008). China's present situation of coal consumption and future coal demand forecast. China Population. Chn Popu Res Envi, 18(3): 152–155

Winther M (2008). New national emission inventory for navigation in Denmark. Atmos Environ, 42(19): 4632–4655

Xue B, Mitchell B, Geng Y, Ren W X, Müller K, Ma Z X, Puppim de Oliveira J A, Fujita T, Tobias M (2014). A review on China's pollutant emissions reduction assessment. Ecol Indic, 38: 272–278

Ying Q, Kleeman M J (2006). Source contributions to the regional distribution of secondary particulate matter in California. Atmos Environ, 40(4): 736–752

Zhang B, Chen Z M, Xia X H, Xu X Y, Chen Y B (2013). The impact of domestic trade on China's regional energy uses: a multi-regional input–output modeling. Energy Policy, 63: 1169–1181

Zhang H F, Ye X N, Cheng T T, Chen J M, Yang X, Wang L, Zhang R Y (2008b). A laboratory study of agricultural crop residue combustion in China: emission factors and emission inventory. Atmos Environ, 42(36): 8432–8441

Zhang H, Ye X, Cheng T, Chen J, Yang X, Wang L, Zhang R (2008a). A laboratory study of agricultural crop residue combustion in China: emission factors and emission inventory. Atmos Environ, 42(36): 8432–8441

Zhang H, Zhang B, Bi J (2015). More efforts, more benefits: air pollutant control of coal-fired power plants in China. Energy, 80: 1–9

Zhao B, Ma J Z (2008). Development of an air pollutant emissions inventory for Tianjin Acta Scientiae Cirsumstantiae, 28(2): 368–375 (in Chinese)

Zhao Z Y, Chang R D, Zillante G (2014). Challenges for China's energy conservation and emission reduction. Energy Policy, 74: 709–713

Zheng J Y, Zhang L J, Che W W, Zheng Z Y, Yin S S (2009). A highly resolved temporal and spatial air pollutant emission inventory for the Pearl River Delta region, China and its uncertainty assessment. Atmos Environ, 43(32): 5112–5122

Zhou X S, Tong L, Han J H, Guo S (2013). The necessity of oil products standard promotion to improve the air quality. Petroleum Refinery Engineering, 43(07): 61–64 (in Chinese)