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Quantitative analysis of economic impacts of health damages caused by air pollution in China

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Abbreviation

AAQS	Ambient Air Quality Standards
ALRI	Acute lower respiratory infection
CV	Contingent valuation
COPD	Chronic obstructive pulmonary disease
COI	Cost of illness
CGE	Computable general equilibrium
CNAAQS	Chinese National Ambient Air Quality Standard
CNY	Chinese Yuan
DBP	Diastolic blood pressure
EDV	Emergency department visits
ERF	Exposure-response function
GHG	Greenhouse gas
GDP	Gross domestic product
Gt	1000 million ton
HR	Hazard ratios
HC	Human capital
HA	Hospital admissions
IHD	Ischemic heart disease
LC	Lung cancer
Mt	Million ton
NH_3	Ammonia
NOx	Nitrogen oxides
OR	Odds ratio
PRD	Pearl River Delta
PM	Particulate matter
SSP	Shared socioeconomic pathways

SO_2	Sulphur dioxide
ug/m^3	Micrograms per cubic meter
solar PV	Solar photovoltaics
TSP	Total suspended particulates
USEPA	United States Environmental Protection Agency
USD	United States dollar
VOC	Volatile organic compound
VSL	Value of a statistical life
WoPol	Without air pollution control policy
WPol	With air pollution control policy
WHO	World Health Organization
WDL	Work day loss
WRF-Chem	Weather Research and Forecasting-Chemistry

Abstract

In the first chapter, the background and purpose of this dissertation are explained. China experiences rapid economic development in the past 30 years. Meanwhile, it encounters severe unprecedented environmental problems, especially ambient air pollution. It is recognized that exposure to high outdoor air pollution contributes acute and chronic health effects. These kinds of health problems also lead to work day loss, school absence and reduction of labor's productivity, which also have negative impacts on the economy. This study aims to quantify the health and economic impact of air pollution in China using the different four kinds of models.

In the second chapter, methodology of this dissertation is introduced. This study combines the Greenhouse Gas and Air Pollution Interactions and Synergies(GAINS)-China model, the Goddard Earth Observing System (GEOS)-Chem model, Asia-Pacific Integrated Assessment (AIM)/CGE-China model, and health assessment model. AIM/CGE-China model provides energy consumption data to GAINS-China model. The GAINS-China model calculates the air pollutants primary emissions. GEOS-Chem model simulates $PM_{2.5}$ and ozone concentration. Health assessment model quantifies the health impacts of $PM_{2.5}$ pollution and ozone. AIM/CGE-China model evaluates the macroeconomic impacts of $PM_{2.5}$ and ozone pollution in 2030.

In the third chapter, health and economic impacts of $PM_{2.5}$ pollution are quantified. $PM_{2.5}$ pollution leads to 9.2 and 2.3 million people premature death in WoPol and WPol scenario in 2030 in China. China experiences a 2.0% GDP loss and 210 billion Chinese yuan (CNY) in health expenditure from $PM_{2.5}$ pollution in 2030 using the consistent price in 2002. In contrast, with control policy in the WPol scenario, the annual control investment of 830 billion CNY (0.79% of GDP) and a gain of 1.2% of GDP in China from improving $PM_{2.5}$ pollution is projected in 2030 in China. Developed regions have higher benefit from air pollution control policy.

In the fourth chapter, health and economic impacts of ozone pollution are quantified. The impact of ozone pollution is much lower than $PM_{2.5}$ in China. Mortality due to ozone pollution is about 580 thousand people in WoPol and 490 thousand people in WPol scenario in 2030 in China. Sichuan, Gansu Shaanxi and Hunan encounter most of the mortality, which accounts for 61% of the national total mortality. The total health expenditure on ozone exposure related morbidity is estimated to be 310 and 260 billion CNY in WoPol and WPol scenario in 2030 in China, equivalent to a per capita expenditure of 230 and 190 CNY.

In the fifth chapter, comparison of $PM_{2.5}$ and ozone pollution and conclusion are explained. Air pollution in China has negative impact on human health and the economy. Air pollution control policy can improve air quality and reduce economic impact in China. The benefit of air pollution control policy is higher than the cost in 2030 in China. Developed regions in the southeast of China get more benefit from air pollution control policy.

1 Introduction

China experiences rapid economic development in the past 30 years. Meanwhile, it encounters severe unprecedented environmental problems, especially ambient air pollution. The government and residents put more and more attention on air pollution issue. It is recognized that exposure to high outdoor air pollution contributes acute and chronic health effects. These kinds of health problems also lead to work day loss, school absence and reduction of labor's productivity, which also have negative impacts on the economy. The Chinese government has made great efforts to control air pollution, which will generate benefits for both the public health and the economy.

1.1 Situation of air pollution

Over its 3-decade-long trajectory of fast growth and development, China surpassed the U.S. to become the world largest carbon emitter in 2007 (Dong et al., 2015). In 2010, China overtook Japan and became the country with second largest gross domestic product (GDP) in the world. China's energy consumption and carbon emissions have been accelerating under the influence of urbanization and industrialization. In 2011, China became the largest consumer of fossil fuels and China's total CO_2 emissions are about 9 billion million ton (Mt), which accounted for 23% of the total emissions in the world. In 2012, carbon emissions from fossil fuel combustion and cement production reached 8.50Gt CO_2. While in 1950, China's carbon emissions were only 5.46 Mt CO_2. During last 60 years, the total CO_2 emissions increased more than 100 times. *Figure 1-1* shows the CO_2 emissions from different sectors. CO_2 emissions from fossil fuel combustion, which account for about 85% of total national CO_2 emissions, originated in 2013 for 83% from coal, 14% from oil products and 3% from natural gas.

Accompanying with a large amount of fossil fuels combustion, China is also the largest air pollutants emissions country all over the world. Fossil fuels play a dominant role in China. With the rapid economic development and urbanization, China is faced with quite severe air pollution. *Figure 1-2* shows the air pollutants emissions from 2000 to 2010 in China.

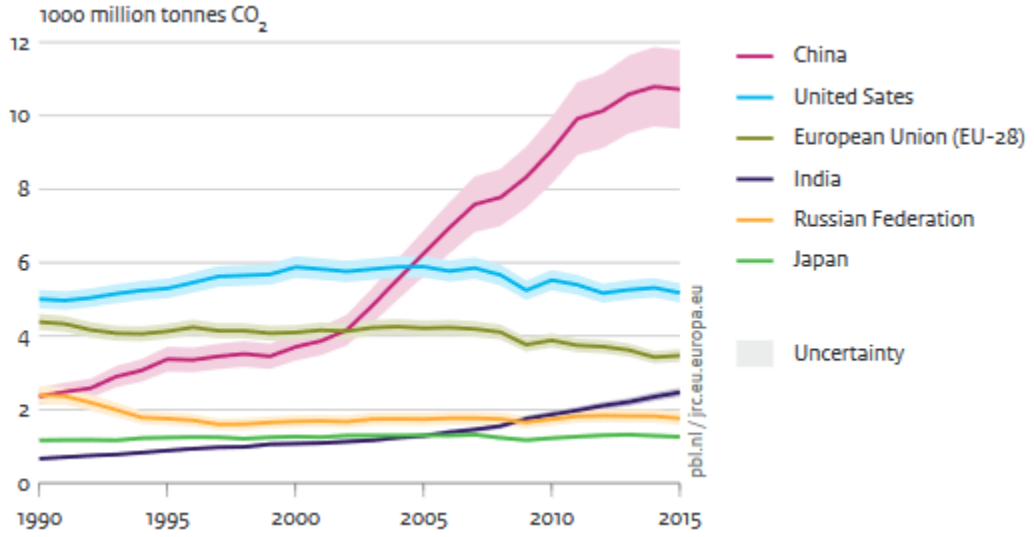


Figure 1-1 CO_2 emissions from fossil-fuel use and cement production in the top 5 emitting countries and the European Union.

Source:(Olivier et al., 2016)

TSP and SO_2 increased before 2005 and decreased after it. NO_x is increasing all the time. The State Environmental Protection Administration tried to reduce national SO_2 emission level in 2000. However, due to increasing in fossil fuel consumption, the SO_2 emission in China changed dramatically after 10th Five-Year Plan. SO_2 emissions increased from 2000 to 2005. After 2005, SO_2 emission decreased slightly (Wang and Hao, 2012). In the 11th Five-Year plan, the government tried to reduce the national energy consumption per unit GDP output and SO_2 emission of 20% and 10% in 2010, compared to 2005 levels. NO_x emissions have been increasing dramatically during past decade in China. With the increasing of on-road vehicles, NO_x emissions still are increasing trend in the future. Intensive studies were conducted on NO_x emission in China in response to their fast growth (Streets et al., 2003; Wang et al., 2007; Zhao and Wang, 2009). Between 2005 and 2010, China increased its thermal power generation by 63%, iron and cement production by 74% and 76%, respectively, and vehicle production by 220% (Qiang Zhang, 2012).

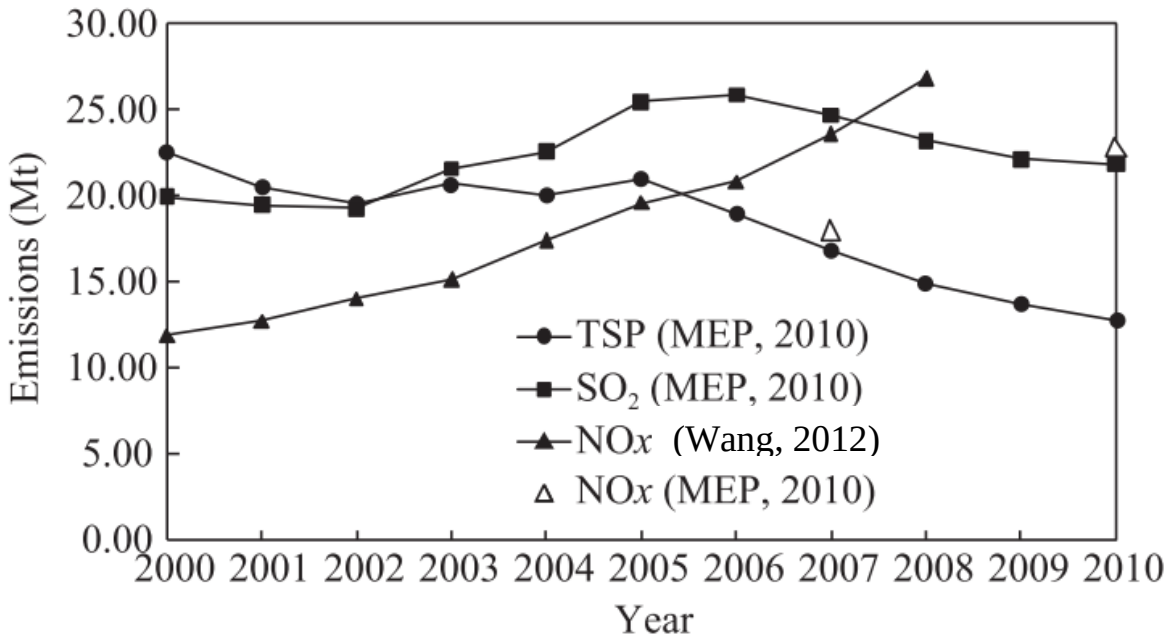


Figure 1-2 Emission of SO2, NOx and TSP in China.

Source: (Wang and Hao, 2012)

Table 1-1 shows the emission inventory of major air pollutants in 2008 and 2010 from different sectors. Power plant and industry are the dominant sectors of air pollutants emissions. In 2012, China's air pollutant emission was SO_2 (29.68 Mt), NO_x (29.38 Mt), $PM_{2.5}$ (11.98 Mt). Yang et.al (2013) used positive matrix factorization to identify the types of $PM_{2.5}$ sources and corresponding mass contributions to $PM_{2.5}$ mass concentrations using $PM_{2.5}$ measurements obtained from Dec. 2007 to Oct. 2008 in Jinan. They found that the reconstructed mass concentrations from six sources matched the observations, and the resolved sources constituted 98.91% of the $PM_{2.5}$ mass concentrations. Secondary sources, the major source contributor, accounted for 55.15% of $PM_{2.5}$ mass concentration, while several other sources, including coal burning (20.98%), soil dust (9.30%), motor vehicles (6.06%), biomass burning (4.55%), and industry (2.87%), contributed a total of 43.76%. Lin et.al (2014) found that in 2006, 36% of anthropogenic sulfur dioxide, 27% of nitrogen oxides, 22% of carbon monoxide, and 17% of black carbon emitted in China were associated with the production of goods for export.

Table 1-1 Air pollutant emission inventory by sector in China in 2010(unit: million ton).

sector	CO2	NO_x	$PM_{2.5}$	PM_{10}	SO2	CO	NH_3	VOC	BC	OC
total	9800.51	28.53	12.15	16.53	28.48	170.08	9.76	22.97	1.75	3.38
Agriculture	NA	NA	NA	NA	NA	NA	9.01	NA	NA	NA
Transportation	644.10	7.01	0.49	0.51	0.22	20.35	0.07	2.36	0.27	0.10
Residential	1253.46	1.12	4.73	5.24	3.48	76.55	0.44	6.19	0.91	2.75
Industry	4854.87	11.07	6.03	9.40	16.69	71.16	0.24	14.16	0.57	0.53
PowerPlant	3048.08	9.33	0.89	1.39	8.08	2.02	NA	0.25	0.00	0.00

Source: http://www.meicmodel.org/ (accessed on Feb.14, 2017)

China has 31 provinces and is a country with significant regional differences, such as economic development, technology, and energy mix (Feng et al., 2013). Carbon emissions and air pollutants emissions are also quite different from province to province. State of regional air pollutant emissions in China is very important for air pollution control. Shandong province contributed most to national emissions, followed by Hebei, Jiangsu, Henan and Liaoning province (*Figure 1-3*). Air pollutants emissions also have the same trend as carbon emissions. Taking SO_2 as an example (*Figure 1-4*), Shandong, Hebei, Henan, Jiangsu, Guangdong and InnerMong provinces shared most of the SO_2 emission. Air quality in these regions is extremely severe in China (Xie et al., 2016). Significant differences exist among provinces in terms of air pollutants emissions. More air pollutants emissions inventories are listed in the Appendix A2.

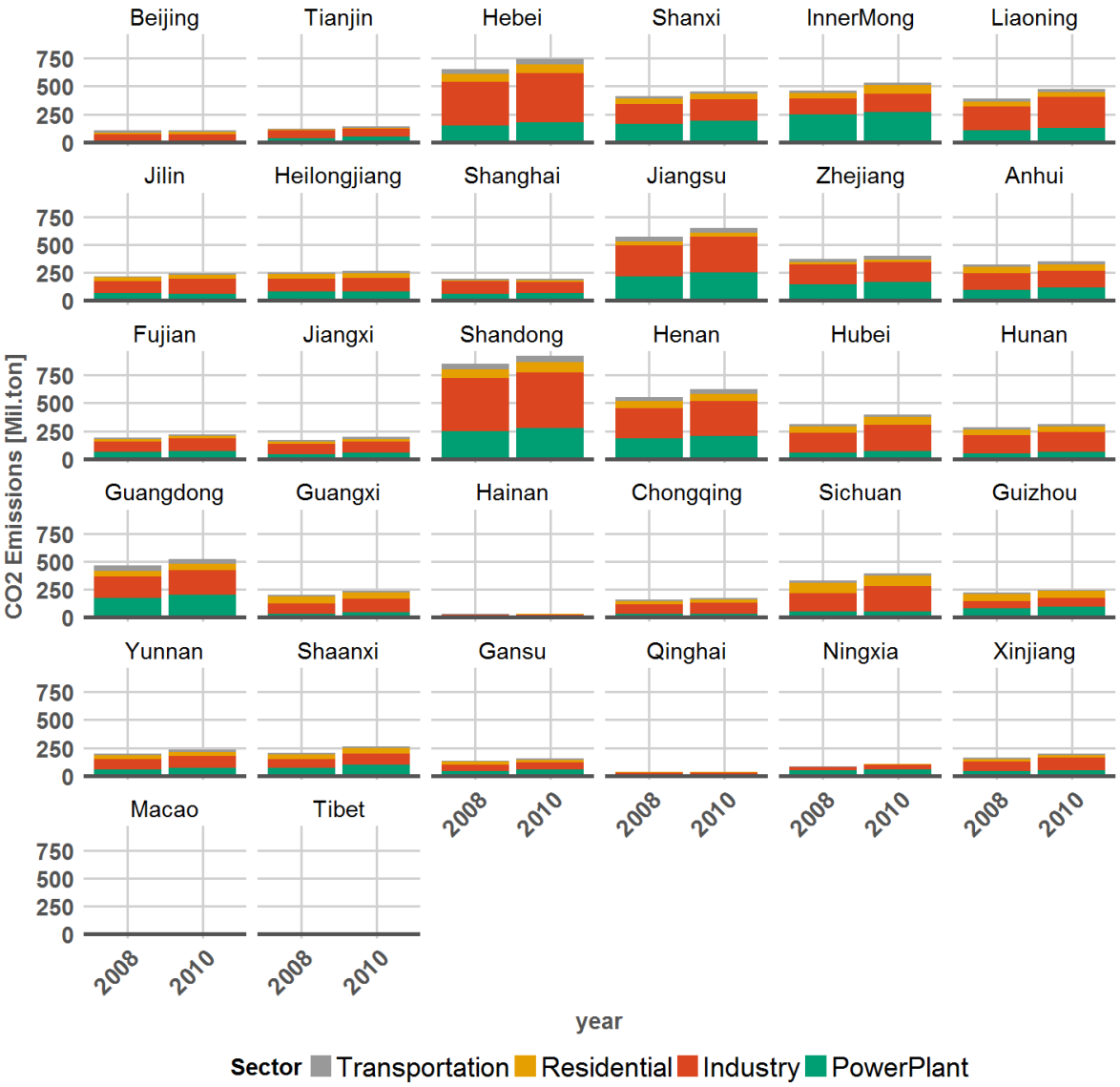


Figure 1-3 Emission of CO_2 in 30 provinces in China.

Source: http://www.meicmodel.org/ (accessed on Feb.14, 2017)

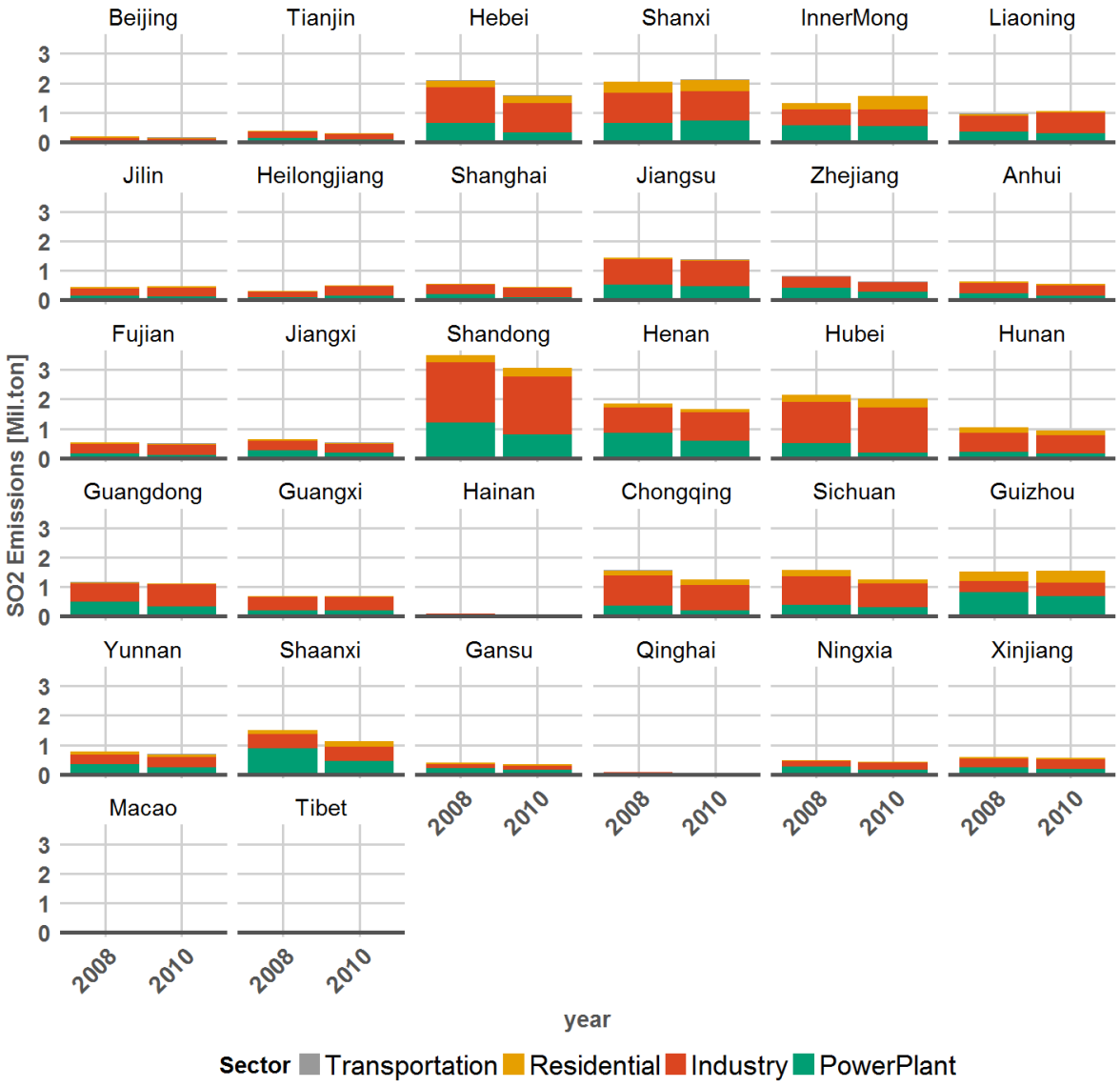


Figure 1-4 Emission of SO_2 in 30 provinces in China.

Source: http://www.meicmodel.org/ (accessed on Feb.14, 2017)

1.2 Air pollution standard in China

With the huge amount of air pollutants emissions, China encounters worst air quality ever before. The public puts more attention to air pollution issue after 2010, followed by being aware of $PM_{2.5}$. China encountered two most serious air pollution attack in winter of 2010 and 2013. During 2013, air pollution in China became a major economic and social issue across the country. In January of 2013, thick smog blanketed Beijing and northern China, covering 2.7 million square kilometers and affecting more than 600 million people (Sheehan et al., 2014). To limit air pollution, China has made tremendous efforts, such as requiring coal-fired power plants to install flue-gas desulphurization systems, strengthening vehicle-emissions standards and air quality monitor system and new air quality standard.

Table 1-2 Air quality standard from China and WHO.

Number	Pollutant	Averaging Time	concentration threshold		WHO	unit
			1	2		
1	SO2	Annual	20	60	20	ug/m3
		24 hours	50	150	NA	ug/m3
		1hours	150	500	500	ug/m3
2	NOx	Annual	40	40	40	ug/m3
		24 hours	80	80	NA	ug/m3
		1hours	200	200	200	ug/m3
3	CO	24 hours	4	4	NA	mg/m3
		1hours	10	10	NA	mg/m3
4	O3	daily-8-hours-maximun	100	160	100	ug/m3
		1hours	160	200	NA	ug/m3
5	PM_{10}	Annual	40	70	20	ug/m3
		24 hours	50	150	50	ug/m3
6	$PM_{2.5}$	Annual	15	35	10	ug/m3
		24 hours	35	75	25	ug/m3

http://www.cnemc.cn/publish/106/news/news_25941.html (accessed time Feb. 14, 2017)

http://www.who.int/mediacentre/factsheets/fs313/zh/ (accessed time Feb. 14, 2017)

Ambient Air Quality Standards (AAQS) in China were originally formulated in 1982, and the first amendment of AAQS was implemented in 1996. The second amendment was formulated in 2000, which made a little bit change about NO_x. Chinese Ministry of Environmental Protection formulated the third ambient air quality standard in 2012, and it was implemented in 2016. Air pollutants include SO_2, NO_x, CO, O_3, PM_{10} and $PM_{2.5}$. *Table 1-2* shows AAQS from the Chinese government and World Health Organization (WHO). For SO_2, NO_x, CO and O_3, WHO standard is as same as Chinese grade one. However, for PM, the Chinese standard is much higher than WHO standard. For PM_{10}, Chinese grade one is annual average under 40 ug/m^3, and WHO standard is 20 ug/m^3. In 24 hours, PM_{10} is 50 ug/m^3 from Chinese grade one and WHO standard. For $PM_{2.5}$, Chinese standard is 15 ug/m^3 for annual average and 35 ug/m^3 for 24-hour average. WHO standard is 10 ug/m^3 for annual average and 25 ug/m^3 for 24-hours average.

USEPA has given more detailed air quality standards. USEPA has set National Ambient Air Quality Standards for six principal pollutants, which may be reviewed or revised periodically. The current standards are listed below (*Table 1-3*), which is more detailed standard for ambient air quality standard. In this standard, pollutants are divided into primary emission and secondary emission. It shows the exceeded time for each pollutant. Especially, $PM_{2.5}$ has three kinds of standards. For the primary emission, annual average concentration is 12 ug/m^3 over three years. For secondary emission, annual average concentration is 15 ug/m^3 over three years. For both primary and secondary emission, the 98th percentile in 24 hours is 35 ug/m^3 over three years.

PM2.5 is the most important air pollutant in urban area. Besides air quality for six principal pollutants, USEPA also has sent up air quality guide for particle pollution (*Table 1-4*). From this guide, when the air quality index is under 50, $PM_{2.5}$ concentration is lower than 38 ug/m^3, there no cautionary statement for human. If the air quality is moderate, sensitive people should consider reducing prolonged or heavy exertion. This guide only focuses on $PM_{2.5}$ pollution, so it is very important for the urban area, where $PM_{2.5}$ is the dominated pollutant.

This air quality guide is also very practical to provide advice for outdoor exercise (Li et al., 2015). If the index is under 50, everybody can be active outside. If the index is 51-150, unusually sensitive people should consider reducing prolonged or heavy exertion. If the index is 101-150, the sensitive group should take more breaks and do less intense activities when they active outside. For those people who have asthma, they should follow their asthma action plan and keep quick

relief medicine handy. If the index is 151-200, everyone should pay more attention to the active outside. The sensitive groups should avoid prolonged or heavy exertion and keep active indoors. If the index is 201-300, air is very unhealthy. Everyone should avoid all physical activity outdoors. The highest is 300-500, it is hazardous. Everyone must avoid all physical activity outdoors.

Table 1-3 Air quality standard from USEPA.

Pollutant	Primary/Secondary	Averaging Time	Level
CO	primary	8 hours	9 ppm
		1 hour	35 ppm
Pb	primary and secondary	Rolling 3-month average	0.15 μg/m3
NO_2	primary	1 hour	100 ppb
	primary and secondary	1 year	53 ppb
O_3	primary and secondary	8 hours	0.070 ppm
$PM_{2.5}$	primary	1 year	12.0 μg/m3
	secondary	1 year	15.0 μg/m3
	primary and secondary	24 hours	35 μg/m3
PM_{10}	primary and secondary	24 hours	150 μg/m3
SO_2	primary	1 hour	75 ppb
	secondary	3 hours	0.5 ppm

Source: https://www.epa.gov/criteria-air-pollutants/naaqs-table (accessed time Feb. 14, 2017)

Table 1-4 Air quality guide for particle pollution.

Adjective	Air quality Index	$PM_{2.5}$ concentration(μg/m3)
Good	0-50	0-38
Moderate	51-100	39-88
Unhealthy for sensitive groups	101-150	89-138
Unhealthy	151-200	139-351
Very Unhealthy Alert	201-300	351-526
Hazardous	301+	526+

Source: https://airnow.gov/index.cfm?action=pubs.aqguidepart (accessed time Feb. 14, 2017)

Table 1-5 Annual average $PM_{2.5}$ concentration in 31 provinces in China.

Ranking	Province	Concentration(ug/m3)
1.	Henan	80.7
2.	Beijing	80.4
3.	Hebei	77.3
4.	Tianjin	71.5
5.	Shandong	66.4
6.	Hubei	65.9
7.	Jiangsu	56.6
8.	Shanxi	56.4
9.	Anhui	55.1
10.	Chongqing	55.0
11.	Liaoning	55.0
12.	Jilin	54.4
13.	Shanghai	53.9
14.	Xinjiang	53.7
15.	Hunan	52.5
16.	Shaanxi	52.0
17.	Zhejiang	47.7
18.	Sichuang	46.7
19.	Ningxia	45.8
20.	Jiangxi	42.8
21.	Qinghai	42.6
22.	Gansu	41.2
23.	Innermogolia	41.0
24.	Guangxi	40.2
25.	Heilongjiang	39.4
26.	Guangdong	34.0
27.	Guizhou	31.7
28.	Fujian	28.7
29.	Yunnan	28.0
30.	Tibet	25.4
31.	Hainan	19.3

Source: http://www.jiemian.com/article/332418.html(accessed time: Feb.14, 2017).

Air quality in China far exceeds the standards listed before. *Table 1-5* shows the annual average $PM_{2.5}$ concentration in 31 provinces in 2015 in China. $PM_{2.5}$ concentration is higher in the north of China, and lower in the south of China. $PM_{2.5}$ concentration is highest in Henan, Beijing, Hebei and Tianjin, about 80.7 ug/m^3, 80.4 ug/m^3, 77.3 ug/m^3 and 71.5 ug/m^3, respectively. The lowest concentrations are 19.3 ug/m^3 in Hannan, 25.4 ug/m^3 in Tibet, 28.0 ug/m^3 in Yunnan, 28.7 ug/m^3 in Fujian, 31.7 ug/m^3 in Guizhou and 34.0 ug/m^3 in Guangdong. Only these six provinces in China meet the Chinese second grade standard 35 ug/m^3. No province meets the first-grade standard.

1.3 Health impact of air pollution

People experience a wide range of health effects from being exposed to air pollution. Effects can be broken down into short-term effects and long-term effects. *Table 1-6* shows the acute and chronic impacts of air pollution on the respiratory system and cardiovascular system. Short-term effects, which are temporary, include illnesses such as pneumonia or bronchitis, symptoms such as upper or lower respiratory symptoms, exacerbations of existing diseases. They also include discomforts such as irritation to the nose, throat, eyes, or skin. Air pollution can also cause headaches, dizziness, and nausea. Bad smells made by factories, garbage, or sewer systems are considered air pollution. Acute exposure to high-level air pollutant can also lead to hospitalization and school or work absences.

Long-term effects of air pollution can last for years or an entire lifetime. They can even lead to a person's premature death. Long-term health effects from air pollution include chronic heart disease, lung cancer, and respiratory diseases such as emphysema, chronic bronchitis, asthma. Air pollution can also cause long-term damage to people's nerves, brain, kidneys, liver, and other organs. Some scientists suspect air pollutants cause birth defects. Nearly 2.5 million people die worldwide each year from the effects of outdoor or indoor air pollution (WHO, 2014). Lelieveld et al. (2013) calculated a global respiratory mortality per year of about 773 thousand, 186 thousand by lung cancer and 2.0 million by cardiovascular disease. The global mean per capita mortality caused by air pollution is about 0.1 % per year. The highest premature mortality rates are found in the Southeast Asia and Western Pacific regions, about 25 % and 46% of the global rate, respectively.

Table 1-6 Respiratory and cardiovascular health effect of air pollution.

	Respiratory system	Cardiovascular system
Acute	Lung	Heart/vasculature
	Forced expiratory volume and flow	Heart rate, blood pressure
	Inflammatory mediators	Blood coagulation factor, vascular reactivity, inflammation
	Air way remodeling	Vessel structure
	Upper/lower respiratory symptoms,	Thrombosis, myocardial infarction, stroke,
	Exacerbations, hospitalization	Hospitalization
	School/work absences	Death
	Hospitalization	
Chronic	Reduced lung growth	Reduced life expectancy (premature cardiovascular death)
	Reduced small airway function,	Atherosclerosis
	Chronic bronchitis	
	Asthma	
	Lung cancer	
	Reduced life expectancy	

Source:ExternE 2005; KampaM., 2008.

People react differently to different types of air pollutants. Young children and older adults, whose immune systems tend to be weaker, are more sensitive to air pollution. Conditions such as asthma, heart disease, and lung disease can be made worse by exposure to air pollution. The health effects are related to the length of exposure time and amount and type of pollutants (Q. He et al., 2010). One study in Shanghai conducted a time series analysis to examine the modifying effect of season, sex, age and education on the association between outdoor air pollutants and daily mortality. They found that ambient air pollution was associated with mortality from all causes and from cardio-respiratory diseases in Shanghai. An increasing of 10 ug/m^3 in a 2-day average concentration of PM_{10}, SO_2, NO_2, and ozone corresponds to increases in all-cause mortality of

0.25% (0.14-0.37), 0.95% (0.62-1.28), 0.97% (0.66-1.27), and 0.31% (0.04-0.58), respectively. The effects of air pollutants were more evident in the cool season than in the warm season, and females and the elderly were more vulnerable to outdoor air pollution. Effects of air pollution were generally greater in residents with low educational attainment (illiterate or primary school) compared with those with high educational attainment (middle school or above) (Kan et al., 2008).

1.3.1 Respiratory system

Numerous studies describe that all types of air pollution can affect the airways. Similar effects are also observed with long-term exposure to lower pollutant concentrations. In patients with lung lesions or lung diseases, pollutant-initiated inflammation will worsen their condition. Finally, chronic exposure to ozone and certain heavy metals reduces lung function, while the later are also responsible for asthma, emphysema, and even lung cancer (Carracedo-Martínez et al., 2010; Chen et al., 2015; Chung et al., 2011; Fan et al., 2016; Guarnieri and Balmes, 2014; Guo et al., 2016; Kelly and Fussell, 2011; Kim et al., 2013; Loomis et al., 2014; Meng et al., 2013).

1.3.2 Cardiovascular system

Air pollution is also associated with cardiovascular disease, increasing emergency visit and hospital admissions (*Table 1-8*). Apart from lung inflammation, systemic inflammatory changes are induced by particulate matter, affecting equally blood coagulation (Lipsett et al., 2011; Luo et al., 2015; Riediker et al., 2004). Air pollution that induces lung irritation and changes in blood clotting can obstruct (cardiac) blood vessels, leading to angina or even to the myocardial infraction (X. Cai et al., 2016; Vermylen et al., 2005).

1.3.3 Nervous system

The nervous system is affected by heavy metal and dioxins Neurotoxicity is leading to neuropathies (Ratnaike, 2003). Strock accounts for five million deaths each year and is a major cause of disability. Gaseous and particulate air pollutants have a marked and close temporal association with admissions to hospital for stroke or mortality from stroke. Public and environmental health policies to reduce air pollution could reduce the burden of stroke (Shah et al., 2015)

Table 1-7 Association between air pollution and respiratory disease.

outcome	Author*	published year	pollutant	OR/RR (95% CI)
asthma	Fan J	2016	$PM_{2.5}$	EDV RR:1.015(1.012,1.017)
	Lim H	2016	$PM_{2.5}$	EDV RR:1.027(1.011,1.044); HA RR1.048(1.029, 1.067)
	Ding L	2015	$PM_{2.5}$	HA OR: 1.035(1.010, 1.060)
			PM_{10}	HA OR: 1.018(1.010, 1.025)
	Zheng XY	2015	$PM_{2.5}$	EDV RR:1.017(1.006,1.029); HA RR1.028(1.017, 1.040)
			PM_{10}	EDV RR:1.027(1.006,1.014); HA RR1.011(1.008, 1.015)
	Gasana J	2012	$PM_{2.5}$	Incidence OR: 1.40(0.77, 2.56)
			PM_{10}	Incidence OR: 1.39(0.71, 2.69)
CODP	Bloemsma LD	2016	PM_{10}	FEV 1 : -3.38 ml (-6.39, -0.37) PEF: -0.61 L/min (-1.20, -0.01)
	DeVries R	2016	$PM_{2.5}$	EDV RR: 1.023 (1.002, 1.043) HA RR: 1.019 (0.998, 1.041) Mortality RR: 1.048 (1.019, 1.078)
	Li MH	2016	$PM_{2.5}$	HA OR: 1.031 (1.016, 1.046) Mortality OR: 1.025 (1.015, 1.035)
	Zhu R	2013	PM_{10}	HA OR: 1.027 (1.019, 1.036) Mortality OR: 1.011 (1.008, 1.014)
lung cancer	Chen G	2015	$PM_{2.5}$	Incidence OR: 1.11 (1.00, 1.22)
	Cui P	2014	$PM_{2.5}$	Incidence RR: 1.03 (0.48, 1.58) Mortality RR: 1.09 (1.06, 1.11)
			PM_{10}	Incidence RR: 1.45 (0.87, 2.03) Mortality RR: 1.05 (1.03, 1.07)
	Hamra GB	2014	$PM_{2.5}$	Incidence RR: 1.09 (1.04, 1.14)
			PM_{10}	Incidence RR: 1.08 (1.00, 1.17)

** First author. Abbreviations: COPD, chronic obstructive pulmonary disease; EDV, emergency department visits; FEV1, forced expiratory volume in 1 s; CI: Confidence interval.*

Table 1-8 Association between air pollution and cardiovascular disease.

outcome	Author*	published year	pollutant	OR/RR (95% CI)
Myocardial infarction	Cai X	2016	$PM_{2.5}$	HA RR: 1.024 (1.007, 1.041) Mortality RR: 1.012 (1.010, 1.015)
			PM_{10}	HA RR: 1.011 (1.006, 1.016) Mortality RR: 1.008 (1.004, 1.012)
	Thurston GD	2016	$PM_{2.5}$	IHD:HR 1.05 (1.02, 1.08)
	Luo C	2015	$PM_{2.5}$	Incidence OR: 1.022 (1.015, 1.030)
			PM_{10}	Incidence OR: 1.005 (1.001, 1.008)
Heart failure	Mustafic H	2012	$PM_{2.5}$	Incidence RR: 1.025 (1.015, 1.036)
			PM_{10}	Incidence RR: 1.006 (1.002, 1.009)
	Shah AS	2013	$PM_{2.5}$	HA/Mortality RR: 1.021 (1.014, 1.028)
			PM_{10}	HA/Mortality RR: 1.016 (1.012, 1.021)
Hypertension	Cai Y	2016	$PM_{2.5}$	(Short-term) OR: 1.069 (1.003, 1.141); (Long-term) OR: 1.065(0.985, 1.152)
			PM_{10}	(Short-term) OR: 1.024 (1.017, 1.030) (Long-term) OR: 1.054 (1.036, 1.072)
	Liang R	2014	$PM_{2.5}$	Elevation of blood pressure: SBP: 1.393 mmHg (0.874, 1.912) DBP: 0.895 mmHg (0.490, 1.299)
	Pedersen M	2014	$PM_{2.5}$	PIHD OR: 1.57 (1.26, 1.96)
			PM_{10}	PIHD OR: 1.13 (1.02, 1.26)

Abbreviations: DBP, diastolic blood pressure; HA, hospital admissions; OR, odds ratio; PIHD, pregnancy-induced; hypertensive disorders; RR, relative risk; SBP, systolic blood pressure.

Table 1-9 Association between air pollution and nervous disease.

outcome	Author*	published year	pollutant	OR/RR (95% CI)
Autism	Flores-Pajot MC	2016	$PM_{2.5}$	(Exposure during pregnancy) RR: 1.34 (0.83, 2.17); (Exposure after birth) RR: 2.43 (1.61, 3.68)
			PM_{10}	(Exposure during pregnancy) RR: 1.03 (0.77, 1.37); (Exposure after birth) RR: 1.33 (0.86, 2.05)
	Lam J	2016	$PM_{2.5}$	Incidence OR: 2.32 (2.15, 2.51)
			PM_{10}	Incidence OR: 1.07 (1.06, 1.08)
	Shah AS	2015	$PM_{2.5}$	HA RR: 1.011 (1.010, 1.012) Mortality RR: 1.012 (1.011, 1.012)
			PM_{10}	HA RR: 1.002 (1.000, 1.003) Mortality RR: 1.003 (1.002, 1.004)
	Wang Y	2014	$PM_{2.5}$	HA RR: 1.003 (0.995, 1.012) Mortality RR: 1.014 (1.009, 1.019)
			PM_{10}	HA RR: 1.003 (0.999, 1.008) Mortality RR: 1.005 (1.003, 1.007)
Stroke	Li XY	2012	$PM_{2.5}$	(Time-series) daily attack OR: 1.006 (1.002, 1.010) (case-crossover) daily attack OR: 1.016 (0.937, 1.097)
			PM_{10}	(Time-series) daily attack OR: 1.002 (0.999, 1.005); (case-crossover) daily attack OR: 1.028 (1.001, 1.057)
	kioumourtzoglou M-A	2016	$PM_{2.5}$	Hazard ration: 1.08 (1.05, 1.11) for dementia 1.15 (1.11, 1.19) for Alzheimer disease 1.08 (1.04, 1.12) for Parkinson admissions

Abbreviations: HA, hospital admissions; OR, odds ratio; RR, relative risk.

1.3.4 Reproductive system

Studies show that air pollution has the negative impact on preterm birth (*Table 1-10*). Air pollutants can also affect the developing fetus. Maternal exposure to heavy metals, especially to lead and increases the risks of spontaneous abortion and reduced fetal growth (Fleischer et al., 2014; Lamichhane et al., 2015; Sun et al., 2015).

Table 1-10 Association between $PM_{2.5}$ pollution and reproductive system disease.

outcome	Author	published year	OR/RR (95% CI)
Preterm birth	Lamichhane DK	2015	1.14(1.06,1.22)
	Sun X	2015	1.13(1.03,1.24)
	Zhu X	2015	1.10(1.03,1.18)
	Sapkota A	2012	1.15(1.14,1.16)
	Stieb DM	2012	1.16(1.07,1.26)
Low birth weigh	Sun X	2016	-15.9g(-26.8g,-5.0g)
	Lamichhane DK	2015	-13.88g(-15.70g,-12.06g)
	Zhu X	2015	-14.58g(-19.31g,-9.86g)
	Stieb DM	2012	-23.44g(-45.50g,-1.38g)
	Fleischer NL	2014	low birth weigh OR 1.22(1.07,1.39)
			China preterm birth OR 2.54(1.42,4.55)
			China low birth weigh OR 1.99(1.06,3.72)

1.3.5 Mortality

Numerous studies have found that air pollution increases the all-cause mortality and disease-specific mortality (Chapman et al., 2006; Zhang et al., 2002, 2009). *Table 1-11* shows that the association between $PM_{2.5}$, PM_{10} and mortality in China and other countries. One study in the US developed a novel $PM_{2.5}$ exposure model based on remote sensing data to assess both short-term and long-term human exposures. Their results show for short-term exposure, for every 10-ug/m^3 increase in $PM_{2.5}$ exposure, there was a 2.8% (2.0-3.5) increase in PM-related mortality. For the long-term exposure, they found an odds ratio (OR) for every 10-ug/m^3 increase in long-term $PM_{2.5}$

exposure of 1.6 (1.5-1.8) for particle-related diseases. Local $PM_{2.5}$ had an OR of 1.4 (1.3-1.5) (Kloog, Ridgway, et al., 2013).

Apte et.al (2015) used high-resolution (10 km, global-coverage) concentration data and cause-specific integrated exposure-response (IER) functions developed for the Global Burden of Disease 2010 to assess how regional and global improvements in ambient air quality could reduce attributable mortality from $PM_{2.5}$. They found that aggressive global program of $PM_{2.5}$ mitigation in line with WHO interim guidelines could avoid 750000 (23%) of the 3.2 million deaths per year currently (2010) attributable to ambient $PM_{2.5}$. Major improvements in air quality would be required to substantially reduce mortality from $PM_{2.5}$ in more polluted regions, such as China and India (Lim et al., 2013). Cao et al.(2011) found significant associations between air pollution levels and mortality from cardiopulmonary diseases and from lung cancer. Each 10-ug/m^3 elevation of TSP, SO_2 and NOx was associated with a 0.9% (0.3%, 1.5%), 3.2% (2.3%, 4.0%), and 2.3% (0.6%, 4.1%) increased risk of cardiovascular mortality. Huang et.al (2015) found that $PM_{2.5}$ reduction to 2008 Olympic levels in Beijing would reduce stroke deaths by 2.7%, coronary heart disease(CHD) deaths by 7.2% over 2015-2030.

Table 1-11 Association between air pollution and mortality.

Author	published year	pollutant	OR/RR (95% CI)
Mills IC	2016	$PM_{2.5}$	All-cause: 0.74 (0.34, 1.14)
		PM_{10}	All-cause: 0.51 (0.29, 0.74)
Chang X	2015	$PM_{2.5}$	Respiratory: 0.50 (0.30, 0.70)
		PM_{10}	Respiratory: 0.50 (0.00, 0.90)
Lu F	2015	$PM_{2.5}$	Non-accidental: 0.40 (0.22, 0.59)
			Respiratory: 0.75 (0.39, 1.11)
			Cardiovascular: 0.63 (0.35, 0.91)
		PM_{10}	Non-accidental: 0.36 (0.26, 0.46)
			Respiratory: 0.42 (0.28, 0.55)
			Cardiovascular: 0.36 (0.24, 0.49)
Atkinson RW	2014	$PM_{2.5}$	All-cause: 1.04 (0.52, 1.56)
			Respiratory: 1.51 (1.01, 2.01)
			Cardiovascular: 0.84 (0.41, 1.28)
Bell ML	2013	PM_{10}	All-cause (men): 0.50 (0.34, 0.65)
			All-cause (women): 0.55 (0.41, 0.70)
			All-cause (younger): 0.34 (0.25, 0.42)
			All-cause (older): 0.64 (0.50, 0.78)
Lai HK	2013	PM_{10}	All-cause: 0.31 (0.22, 0.41)
			Respiratory: 0.57 (0.40, 0.75)
			Cardiovascular: 0.49 (0.34, 0.63)
Park HY	2013	PM_{10}	Non-accidental: 0.47 (0.33, 0.62)
Kloog Itai	2013	$PM_{2.5}$	short-term effect: 0.028(0.02,0.035)
			long-term effect: 1.6(1.5-1.8)

1.3.6 Health impact of $PM_{2.5}$

The air quality in China is still much lower than the WHO recommendation (Ma et al., 2014; Sheehan et al., 2014), which poses significant threats to human health (Ebi and McGregor, 2008; Kampa and Castanas, 2008; Watts et al., 2015; Zelm et al., 2016). Outdoor suspended particulate matter (PM) is considered to be the most serious pollutant in metropolitan areas, in view of its adverse health effects as a cause of cardiovascular disease, respiratory irritation, and pulmonary

dysfunction (Delfino et al., 2005; Zhu et al., 2011). $PM_{2.5}$ penetrates more deeply into the lung and may reach the alveolar region and poses greater health risks than PM_{10}, because its higher surface area per unit mass increases the potential for the adsorption and condensation of toxic air pollutants such as oxidant gasses, organic compounds, and transition metals (G. Yang et al., 2013). Many studies have shown associations between exposure to high $PM_{2.5}$ concentration and higher rates of outpatient visits and hospital admissions for respiratory diseases, cardiovascular diseases and cerebrovascular disease (Aunan and Pan, 2004; Chen et al., 2004; Z. Chen et al., 2013; Guo et al., 2009, 2010; W. Huang et al., 2012; Kan et al., 2008; Krzyzanowski et al., 2005; Zhang et al., 2014). Acute exposure to severe air pollutant or long-term exposure to air pollutant can increase mortality (R. Chen, Kan, et al., 2012; Hoek et al., 2013; Lu et al., 2015; Shang et al., 2013).

Punger et al.(2013) quantified the mortality in the USA attributable to ozone and $PM_{2.5}$ at coarse resolution differ from those at a finer resolution. Using the finest modeled concentrations 12 km, they estimate that 66000 (39300-84500) all-cause and 21400(5600-34200) respiratory deaths per year are attributable to $PM_{2.5}$ and ozone concentrations. Using model results at 36 km resolution gives mortality burdens that are 11 % higher for $PM_{2.5}$ and 12 % higher for ozone than the 12 km estimates. Coarse grid resolutions produce mortality estimates that are substantially biased low for $PM_{2.5}$ (30-40% lower than the 12 km estimated at >250 km resolution), but less than 6 % higher for ozone at any resolution. Kheirbek et al.(2013) found that the neighborhood-level analysis demonstrated increasing impacts with greater neighborhood poverty levels, particularly for $PM_{2.5}$-attributable asthma emergency department visits, which were 4.5 times greater in high compared to low-poverty neighborhoods. $PM_{2.5}$-attributable health impacts were similar using seasonal and annual average incidence rates.

Anenberg et al.(2012) examined the air quality and health benefits of 14 specific emission control measures targeting BC and methane. They estimated that, for $PM_{2.5}$ and ozone, respectively, fully implementing these measures could reduce global population-weighted average surface concentrations by 23-34% and 7-17% and avoid 0.6-4.4 and 0.04-0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia. Kunzli et al.(2000) estimated the impact of outdoor and traffic-related air pollution on public health in Austria, France, and Switzerland. They found that air pollution caused 6% of total mortality or more than 40000 attributable cases per year. About half of all mortality caused by air pollution was attributed to motorized traffic, accounting more than 25000 new cases of chronic bronchitis

(adults); more than 290000 episodes of bronchitis (children); more than 0.5 million asthma attacks; and more than 16 million person-days of restricted activities.

Pope III et al.(2009) found that a decrease of 10 ug/m^3 in the concentration of $PM_{2.5}$ was associated with an estimated increase in mean life expectancy of 0.61(0.41, 0.81) year (P=0.004). Reductions in air pollution accounted for as much as 15% of the overall increase in life expectancy in the study areas. Likhvar et al.(2015) used consistent climate-air-quality-health modeling framework across three geographical scales (World, Europe and Ile-de-France) to assess future (2030-2050) health impacts of ozone and $PM_{2.5}$ under two emissions scenarios (Current Legislation Emissions, CLE, and Maximum Feasible Reductions, MFR). They found more reductions in deaths under MFR scenario compared to CLE. 1.5 (0.4, 2.4) million CV deaths could be delayed each year in 2030 compared to 2010 under MFR scenario, 84% of which would occur in Asia, especially in China. In Europe, the benefits under MFR scenario (219 000 deaths) are noticeably larger than those under CLE (109 000 deaths). In Ile-de-France, under MFR more than 2830 annual deaths associated with $PM_{2.5}$ changes could be delayed in 2050 compared to 2010.

The leading cause of death in China in 2010 was stroke, ischaemic heart disease(IHD), and chronic obstructive pulmonary disease (COPD), and ambient particulate matter pollution is the fourth leading risk factor in China (Feigin et al., 2014). Numerous studies show the severe health impacts of air pollution in China. Huai River policy, which provided free winter heating via the provision of coal for boilers in cities north of the Huai River but denied heat to the south, increases ambient concentrations of TSPs about 184 ug/m^3 (61, 307) or 55% higher in the north. These TSPs causes the 500 million residents of Northern China to lose more than 2.5 billion life years of life expectancy. Their results indicate that life expectancies are about 5.5 y (0.8, 10.2) lower in the north owing to an increased incidence of cardiorespiratory mortality. They also found that long-term exposure to an additional 100 ug/m^3 of TSPs is associated with a reduction in life expectancy at birth of about 3.0 y (0.4, 5.6) (Chen et al., 2013). The leading causes of death in China in 2010 were stroke, ischaemic heart disease(IHD), and chronic obstructive pulmonary disease, and ambient particulate matter pollution is the fourth leading risk factor in China. Residents of Asian cities are likely to have higher exposures to air pollution than those in Western industrial nations because they spend more time outdoors and less time in air conditioning (Wong et al., 2008).

Xie et al.(2011) found that if the PM_{10} and $PM_{2.5}$ concentrations were reduced to below WHO guideline value, about 2700 (2200-3400) premature deaths would be avoided from PM_{10} exposure annually for short-term exposure. The annual avoidable deaths would be 42000 (28000-55000) and 40000 (23000-54000) for PM_{10} and $PM_{2.5}$, respectively. And the average lifespan of residents would prolong 2.57 years for PM_{10} and 2.38 years for $PM_{2.5}$ if reducing the PM annual concentrations. The authors examined seasonal variation of mortality risk in association with $PM_{2.5}$ and chemical species in Xi'an, China. Increases of 2.29% (0.83, 3.76) for all-cause mortality and 3.08% (0.94, 5.26) for cardiovascular mortality were associated with an interquartile range increase of 103.0 ug/m^3 in lagged 1-2 day $PM_{2.5}$ exposure. Stronger effects were observed in the elderly (>65 years), males, and cardiovascular diseases groups. Secondary components, combustion species and transition metals appeared most responsible for increased risk, particularly in the cold months (W. Huang et al., 2012).

Gao et al.(2015) used Weather Research and Forecasting-Chemistry (WRF-Chem) model to simulate $PM_{2.5}$ concentrations during the 2013 severe haze event in Beijing. Health impacts assessments show that the $PM_{2.5}$ concentrations in January might cause 690 (490, 890) premature deaths, 45350 (21640, 57860) acute bronchitis and 23720 (17090, 29710) asthma cases in Beijing area. Song et al.(2017) estimated the health burden attributable to $PM_{2.5}$ in China. They found that $PM_{2.5}$ in 2015 contributed as much as 40.3% to total stroke deaths, 33.1% to acute lower respiratory infection (ALRI, <5yr) deaths, 26.8% to ischemic heart disease (IHD) deaths, 23.9% to lung cancer (LC) deaths, 18.7% to chronic obstructive pulmonary disease (COPD) deaths, 30.2% to total deaths combining IHD, stroke, COPD, and LC, 15.5% to all-cause deaths.

1.3.7 Health impact of ozone

Ozone is the common air pollutant all over the world, not only developing countries, but also developed countries. Ozone and other photochemical oxidants pollutants are not directly emitted by primary sources, but generate from nitrogen oxides (NO_x) and volatile organic compounds(VOCs). They encompass a group of chemical species formed through a series of complex reactions in the atmosphere driven by the energy transferred to nitrogen dioxide (NO_2) molecules when they absorb the light from solar radiation. Climate change, as well as changes in anthropogenic emissions of ozone precursors, is likely to have an effect on ground-level ozone concentration in the future (Doherty et al., 2013; Jacob and Winner, 2009). As the largest

developing country, China is under rapid urbanization. With the fast increasing of fossil fuels, China is faced with worst air pollution problem and accompanying with the severe health problems.

Many studies have reported associations between outdoor ozone concentrations and morbidity and mortality (Atkinson et al., 2016; Cakmak et al., 2016; Jerrett et al., 2009; Liu et al., 2013; Silva et al., 2013). Ozone pollution is associated with series of health endpoints, such as respiratory-related hospital admissions, cardiovascular disease, lost school days, restricted activity days, asthma-related emergency department visits, and premature mortality (Hubbell et al., 2005; Orru et al., 2013; Rosenthal et al., 2013; World Health Organization, 2013). Ozone exposure is also related to respiratory symptoms and the use of asthma medication for asthmatic school children using maintenance medication (Gent et al., 2003). McDonnell et al.(1999) also found long-term exposure to ozone has been tentatively associated with the development of asthma in adult male.

Berman et al., (2012) evaluated health benefits from large-scale ozone reduction in the U.S. It can avoid a large number of premature deaths, reduce acute respiratory symptom and school-loss day if the current 75-ppb standard had been attained. Substantially greater health benefits, such as would have resulted if the ozone range of standards (70-60 ppb) had been met. Cakmak et al.(2016) found that a 10 ppb increase in ozone long-term exposure was associated with increases in hazard ratios (HRs) that ranged from 1.007 (0.99, 1.015) to 1.03 (1.02, 1.041) for cardiovascular disease, 1.013 (0.996,1.03) to 1.058 (1.034, 1.082) for cerebrovascular disease, and 1.02 (1.006, 1.034) for ischemic heart disease in Canada. Chang and others estimated an increase of 0.43 ppb (0.14, 0.75) in average ozone concentration during the 2040s compared to 2000 due to climate change alone. Fann et al.(2012) estimated 4700 ozone-related deaths to result from 2005 air quality levels and 36000 life years lost from ozone exposure in the United States.

Fann and Risley (2013) estimated that reductions in monitored $PM_{2.5}$ and ozone from 2000 to 2007 are associated with 22000-60000 $PM_{2.5}$ and 880-4100 ozone net avoided premature mortalities in the United States. Heal et al. (2013) found including population changes in 2030, both the current legislation and maximum feasible reduction scenarios yield greater O3-attributable health burdens than the high emission scenario: +28%, +22%, and +16%, respectively, above 2003 baseline deaths brought forward (11500) and respiratory hospital admissions (30700), using ozone exposure over the full year and no threshold for health effects. Jerrett et al. (2009)

found that relative risk of death from respiratory causes that was associated with an increment in ozone concentration of 10 ppb was 1.040 (1.010-1.067) in U.S.. Shindell et al.(2012) considered ~400 emission control measures to reduce these pollutants by using current technology and experience. These control measures can reduce projected global mean warming ~0.5 degree by 2050. This strategy avoids 0.7 to 4.7 million annual premature deaths from outdoor air pollution.

Kheirbek et al.(2013) assessed the sensitivity of estimated citywide morbidity and mortality attributable to $PM_{2.5}$ and ozone to the geographic and temporal resolution of health incidence data. They found citywide ozone-attributable asthma morbidity was estimated to be 15 % lower when calculated from seasonal, compared to annual average incidence rates, as asthma morbidity rates are lower during the summer ozone season than the annual average rate. Within the ozone season, 57 % of estimated ozone-attributable emergency department for asthma in children occurred in the April-June period when average baseline incidence rates are higher than in the July-September period when ozone concentrations are higher. Nawahda et al. (2012) found that the effect of $PM_{2.5}$ on human health is greater than the effect of ozone for the age group of 30 years and above. Results show the premature mortality due to both ozone and $PM_{2.5}$ in East Asia for the years 2000 and 2005 to be around 316 and 520 thousand cases, respectively. For future scenarios of the year 2020, the estimated annual premature mortality rates are 451, 649, and 1035 thousand in policy succeed scenario, reference scenario, and policy failed scenario, respectively.

There are several studies about ozone and nitrogen dioxide-related health impacts in China (R. Chen, Samoli, et al., 2012). Madaniyazi et al. (2016) used a global chemical transport model (MIROC-ESM-CHEM) and regional chemical transport modelling system (including the Weather Research and Forecasting model and the Community Multiscale Air Quality model) to estimate daily ozone concentrations in 2005 and 2030 in East China in current legislation (CLE) and maximum technically feasible reduction (MFR) scenarios. The annual mean ozone concentration increases between 2005 and 2030 in CLE scenario, while decreases in MFR scenario. Under the CLE scenario, O3-attributable health burden could increase by at least 40000 premature deaths. In MFR scenario, the health burden could decrease by up to 260000 premature deaths as a result of the reduction in ozone concentration. The premature death is under static population. If considering the population growth, ozone-related premature deaths will increase 46000 in East China.

Yang et al.(2012) found that maximum-8-hour-average and 1-hour-maximum concentrations seem to be more strongly associated with increased mortality rate compared to 24-hour average concentrations in Suzhou. Using maximum 8-hour average, an inter-quartile range increase of 2-day average ozone corresponds to 2.15% (0.36 to 3.93), 4.47% (1.43 to 7.51), -1.85% (-6.91 to 3.22) increase in all-cause, cardiovascular, and respiratory mortality, respectively. The associations between ozone and daily mortality appeared to be more evident in the cool season than in the warm season. Tao et al. (2012) found consistent positive associations between ambient oxidants and daily mortality across the PRD cities. Overall, 10-ug/m^3 increases in average O_3 and NO_2 concentrations over the previous 2-days were associated with 0.81% (0.63%, 1.00%) and 1.95% (1.62%, 2.29%) increases in total mortality, respectively, with stronger estimated effects for cardiovascular and respiratory mortality.

1.4 Economic impacts of air pollution

Air pollution also has the negative impacts on the economy. To quantify health-related economic impact, both market and non-market are used to evaluate the economic impact of health outcome. Because health and life have no market price, indirect approaches are used to assess the value of health. These approaches, which are widely used, are contingent valuation(CV) approach, human capital(HC) and cost of illness(COI) approach.

1.4.1 Contingent valuation (CV) method

Contingent valuation method is a simple and nonmarket valuation method which is widely used in environmental impact assessment and cost benefit analysis (Bell et al., 2011; Venkatachalam, 2004). The CV method was originally proposed by Ciriacy-Wantrup. It is a possible way of estimating individuals' willingness to pay for these extra market benefit through a survey method (Portney, 1994). It also can measure the money that individuals would like to pay to improve their own health or avoid premature death. *Table 1-12* and *Table 1-13* show the money people are willing to pay for avoiding mortality and morbidity in Europe and China. It can be found that the value is different in different countries. Because this data is from survey, it is related to a lot of factors, such as income, GDP, education, age, gender and so on. During all kinds of health endpoint, mortality has the highest value in all the countries. The chronic illness, such as

chronic bronchitis, chronic respiratory illness, asthma, have a higher value than slight illness, because people suffer more when they have chronic diseases.

Table 1-12 Willingness to pay for health endpoint in Europe.

Health endpoint	Willingness to pay	Matus(2012) 1997 cost	ExternE2005 2000 cost
Value of life lost (VSL)	USD/case	250000	8.15-31.1 million
Hospital admission	USD/admission	284	2000
Emergency room visits for respiratory illness	USD/visit	23	670
General practitioner visits asthma	USD/consultation	4	53
General practitioner visits lower respiratory symptoms	USD/consultation	13	75
Respiratory symptoms in asthmatics: Adults	USD/event	0.6	130
Respiratory symptoms in asthmatics: Children	USD/event	0	280
Respiratory medication use-adults and Children	USD/day	0	1
Restricted activity day	USD/day	2.32	130
Cough day	USD/day	0.6	38
Symptom day	USD/day	0.6	38
Work loss day	USD/day	1.43	82
Minor restricted activity day	USD/day	0.6	38
Chronic bronchitis	USD/day	8000	190000
Mortality from acute exposure	USD/case	662	NA
New case asthma	USD/case	NA	60000

Table 1-13 Willingness to pay for health endpoint in China (Unit: USD).

Receptor	Impact category	Value
All age	Asthma attacks	1711
	Respiratory feelings	3~6
	Chronic respiratory illness	500~1000
Children	Chronic bronchitis	8000
	Respiratory symptoms	13
	Bronchodilator usage	1711
	Lower respiratory symptoms	13
Adults	Minor restricted activity day	0.6
	Work loss day	0.6
	Respiratory symptom days	0.6
	Chronic bronchitis	8000
	Lower respiratory symptoms	13

Source: Guo et al.（2006）; Hammitt and Zhou（2006）; Xie (2011)

Table 1-14 below shows the VSL from studies in China. There are several studies about the VSL in China. The value is from 4000 USD to 800000 USD.

Table 1-14 Value of statistical life in China.

Year	Unit	Value	Source
2006	USD	4000-17000	Hammitt and Zhou
2006	USD	34458	Wang and Mullahy
2009	USD	15000~800000	Wang et al.
2006	USD	24000	Guo et al.
1997	USD	60000	The World Bank
2010	USD	430000	Hoffmann et al.
2011	USD	250000	Xie

1.4.2 Human capital (HC) method

In human capital approach, labors are considered as the unit of human capital who providing products and services. When the labor cannot attend to work to provide products or services, it will lead to wage loss or labor loss. In this approach, the value of the life of individuals with different incomes is different. And this approach neglects people who are not labor, such as children and old people.

1.4.3 Cost of illness (COI) method

COI method just estimates the health expenditure including pharmaceutical, diagnostic treatment and hospitalization cost on the health outcomes, which is the minimum value of health damage. In the various regions with different levels of economic and social development, the COI for each disease is different.

1.4.4 Economic impact of air pollution in other countries

These health problems can pose heavy economic burdens by further increasing health expenditure, increasing work day loss, and decreasing the labor supply (Kamp and Bachmann, 2015; Kjellstr et al., 2009). Some studies indicated that reduced pollution boosts labor productivity and magnifies benefit (Williams, 2002; Zivin and Neidell, 2012). In the USA, health-related loss of productive time costs employers UDS225.5 billion per year (Stewart et al., 2003). A study in Mexico City showed that a 19.7% decline in air pollution led to a 1.3 hour (or 3.5%) increase in work hours per week (Hanna and Oliva, 2015). These findings underscore the need to evaluate not only the health impacts from air pollution, but also the economic impact. Thompson et al.(2014) evaluated the air quality co-benefit of U.S. carbon policies by reducing $PM_{2.5}$ and ozone. They found that co-benefits to key policy-relevant sources of uncertainty and variability. They found that monetized human health benefits associated with air quality improvements can offset 26-1050% of the cost of US carbon policies.

Fann et al.(2015) adopt a 2030 emissions inventory in U.S. that accounts for fully implementing anthropogenic emissions controls required by federal, state or local policies, which is projected to strongly influence future ozone levels. They quantified a comprehensive suite of ozone-related mortality and morbidity impacts including emergency department visits, hospital

admissions, acute respiratory symptoms, and lost school days, and estimate the economic value of these impacts. Their results estimated tens to thousands of additional ozone-related premature deaths and illnesses per year and calculated an economic burden of these health outcomes of hundreds of millions to tens of billions of USD (2010 price). Patankar and Trivedi (2011) estimated that the total monetary burden of air pollution-related impacts, including personal burden, government expenditure and societal cost, is estimated at 4522.96 million Indian Rupees (INR) or USD113.1 million for a 50-ug/m^3 increase in PM_{10}, and INR 8723.6 million or USD 218.1 million for a similar increase in NO_2.

A set of air quality improvement policy proposed in 2005 would bring a welfare gain of 37 to 49 billion Euros in 2020 for the whole of Europe (Nam et al., 2010). Reduction of greenhouse gas emissions can reduce co-emitted air pollutants, bringing co-benefit for air quality and human health. West and others found that global GHG mitigation avoids 0.5 (0.3, 0.7), 1.3 (0.8, 1.8) and 2.2 (1.4, 3.0) million premature deaths in 2030, 2050 and 2100. Global average marginal co-benefits of avoided mortality are USD 50-380 per ton of CO2, which exceed previous estimates, exceed marginal abatement costs in 2030 and 2050. East Asian co-benefits are much higher than the global average in 2030 (West et al., 2013). Shindell et al.(2016) examined the impacts of clean energy and vehicles. They found that clean energy policies could prevent ~175000 premature deaths, with ~22000 (11000-96000) fewer annually thereafter, whereas clean transportation could prevent ~120000 premature deaths and ~14000 (9000-52000) annually thereafter by 2030. Near-term national benefits are valued at ~USD 250 billion (140-1050 billion) per year, which is likely to exceed implementation costs. Driscoll et al.(2015) found that the US power plant carbon standards could change fine particulate matter and ozone concentrations in ambient air, and the resulting public health co-benefits.

1.4.5 Economic impact of air pollution in China

Air pollution not only increases health effect on human health, but also has negative impact on the economy. There are many studies try to quantify the economic impact of air pollution-related health problem (*Table 1-15*). For example, Matus et al.(2012) found that by improving ozone and PM pollution, China's GDP would have increased by USD 22 billion in 1975 and USD 112 billion (about 5% of GDP) in 2005. Xia et al.(2016) developed I-O model to capture both direct economic costs and indirect cascading effects throughout inter-regional production supply

chains and the indirect effects greatly outnumber the direct effects in most Chinese provinces. They found that the total economic losses of 346.26 billion CNY (approximately 1.1% of the national GDP) based on the number of affected the Chinese employees whose work time in years was reduced due to mortality, hospital admissions and outpatient visits related $PM_{2.5}$ pollution in 2007. Studies showed an economic loss of 29.21 billion CNY, equivalent to 1.35% of the regional GDP, was incurred from the impact of PM_{10} in the Pearl River Delta (PRD) in 2006. Moreover, the economic loss incurred from $PM_{2.5}$ pollution in Beijing-Tianjin-Hebei area of China was estimated at 172.9 billion CNY, about 4.68% of the regional GDP (D. Huang et al., 2012; Huang and Zhang, 2013).

Table 1-15 Economic impacts in other studies in China.

Study	Method	Economic impacts
K. Matus et al. (2012)	Willingness To Pay and CGE	63.9 (8.7% of GDP), 77.0 (6.9% of GDP), 103.9 (5.9% of GDP) billion USD in 1995, 2000 in 2005, respectively.
World Bank (1997)	Willingness To Pay	33.9 billion USD in 1995 (4.6% of GDP)
World Bank and SEPA (2007)	Willingness To Pay	54.6 billion USD in 2003 (3.8% of GDP)
Huang et al. (2012)	Willingness To Pay, Cost of Illness	29.21 billion CNY in 2006 (1.35% of GDP in PRD)
Huang et al (2013)	Willingness To Pay, Cost of Illness	172.9 billion CNY in 2009 (4.68% of GDP in Beijing)
Kan et al. (2004)	Willingness To Pay, Cost of Illness	625.4 million CNY in 2001 (1.03% of GDP in Shanghai)
Zhang et al. (2010)	Cost of Illness, Value of a statistical life and Adjusted human capital	2.4-4.9% of GDP in 2000 in Taiyuan city, 1-2% of GDP in 2015 in Taiyuan city

Kan and Chen (2004) estimated a total economic cost of USD 625.40 million from the PM pollution in Shanghai in 2001, or the equivalent of 1.03% of the city's GDP. In Taiyuan, economic costs of PM pollution amounts to 2.4-4.9% and 1-2% of the city's GDP in 2000 and 2015, respectively (Zhang et al., 2010). Wang and Mauzerall (2006) found that total health damages due

to anthropogenic emissions from Zaozhuang in 2000 were equivalent to 10% of Zaozhuang's GDP. With no new air pollution controls implemented between 2000 and 2020 but with projected increases in energy use, they estimated health damages of air pollution exposure to be equivalent to 16% of Zaozhuang's projected 2020 GDP. Under best available emission control technology scenario and advanced coal gasification technologies scenario could reduce the potential health damage from air pollution in 2020 to 13% and 8% of projected GDP, respectively. Gao et al.(2015) estimated that the haze in January 2013 might lead to 253.8 (170.2, 331.2) million USD losses, accounting for 0.08% (0.05%, 0.1%) of the total 2013 annual GDP of Beijing.

1.5 Air pollution control policy in China

Air pollution has been reduced in North America and Europe. Improvements have been forced by regulations and related public policies and enabled by the development of improved emission control technologies, such as scrubbers on power plants and catalytic converters on motor vehicles, or by changes in energy sources and use (West et al., 2016). The Chinese government and population increase their concern on the air pollution issue, because they are growing realization of the health threat from high level of fine particles and a lot of impacts of air pollution on human life, such as health expenditure on air pollution-related health problem, schools and factories were closed, warning for the children and elderly to stay indoors, flights cancelling (Jacobson, 2010). The Chinese government has launched series air pollution control policy to improve air quality (K He et al., 2010; Li et al., 2011). Henschel et al. (2012) found that air pollution interventions have succeeded in improving air quality. Most of these interventions have been associated with health benefits, mainly by way of reduced cardiovascular and respiratory mortality and morbidity. In the 12th-five-year plan, the Chinese government sent up the target of $PM_{2.5}$ pollution prevention and control in the key regions, including Beijing-Tianjin-Hebei area, Yangtze River Delta area, Pearl River Delta area and other regions. The plan targets improvement in air quality to 2017, focusing on the three regions that account for 40% of China's GDP. These three big areas have a large population and high population density, where also are the most developed region in China. The air quality target is also quite strict there.

Beijing-Tianjin-Hebei area is the most polluted region in China, annual average $PM_{2.5}$ concentration target is 106 ug/m^3 in 2013, it will be reduced to 64 ug/m^3 in 2020 and 35ug/m^3 in

2030. Annual average $PM_{2.5}$ concentration target in Yangtze River Delta area is lower than Beijing-Tianjin-Hebei area, which is 67 ug/m^3 in 2013, 48 ug/m^3 in 2020 and 34 ug/m^3 in 2030. Pearl River Delta area is in the south of China, and air quality is much better than the other regions in China, annual average $PM_{2.5}$ concentration target is 47 ug/m^3 in 2013, 35 ug/m^3 in 2020 and 27 ug/m^3 in 2030. From this $PM_{2.5}$ pollution prevention target, all the regions in China $PM_{2.5}$ concentration will not exceed the national standard 35 ug/m^3 in 2030. Jiang and others evaluated the air quality improvement after the Air Pollution Prevention and Control Action Plan in 2013 and associated health benefits achievable under the Action Plan in the Pearl River Delta (PRD) area from 2012 to 2017. Measure-by-measure quantification results show that the Action Plan would promise effective emissions reductions of 34% of SO_2, 28% of NO_x, 26% of $PM_{2.5}$, and 10% of VOCs. These emissions abatements would lower the $PM_{2.5}$ concentration by 17%, surpassing the 15% target established in the Action Plan. Results show that this action can reduce more than 2900 deaths and 4300 hospital admissions annually (Jiang et al., 2015).

Table 1-16 Target of $PM_{2.5}$ pollution prevention and control in the key regions.

Region	2013	2020	2030
Beijing-Tianjin-Hebei	106	64	35
Yangtze River Delta	67	48	34
Pearl River Delta	47	35	27
Other regions	69	50	35

Source: 12th Five-Year-Plan for air pollution prevention and control

To achieve these air quality targets (*Table 1-16*), the Action Plan defines ten measures, such as intensifying integrated control efforts and reducing multiple pollutants emissions; optimizing industrial structure and promoting upgrade; accelerating technological transformation; adjusting energy structure and developing clean energy; strengthening energy saving and environmental-friendly access; improving environmental economic policies; improving environmental protection law; establishing regional coordination mechanism; establishing monitoring and warning emergency response system; clarifying responsibilities of government, enterprise and society (Zhang et al., 2016). According to these measures, the government sent up a ban in these regions

on new coal power plants and sharp cutbacks in coal consumption in and steel production for the first time.

The Chinese government removed heavily polluting vehicles from these regions by 2015 and nationally by 2017. They introduced Euro V equivalent fuel standards in these regions in 2015 and nationally by 2017. For reducing fossil fuel combustion, non-fossil energy resources such as natural gas, solar PV will rise from 9.4% of total energy consumption in 2012 to 13% by 2017. Wang and Zou (2014) found that with the structure adjustment policy, the proportion of coal in primary fossil fuels in 2030 will decrease from 53% to 48% and CO_2 emissions will decrease by 11.3%-22.8% compared to the baseline scenario. With the energy intensity reduction policy, CO_2 emissions will decrease by 33.3% in 2030 and 47.8% in 2050 than baseline scenario. Other pollutants will also be controlled as synergetic effects, but the GDP will decrease by 2.96%-8.23% under different scenarios.

For developing clean energy, China is increasing natural gas infrastructure in China and imports from neighboring countries. *Figure 1-5* shows the natural gas infrastructure in China. Beside the natural gas, the Chinese government also sent up ambitions on the development of renewable energy and other clean energy. The natural gas will increase from 5.2% in 2012 to 10% in 2020 and 15% in 2030. Renewable energy will rise from 9.4% in 2012 to 15% in 2020 and 25% in 2030 (Sheehan et al., 2014).

H. Dai et al.(2016) assessed the economic impacts and environmental co-benefits of large-scale development of renewable energy (RE) in China toward 2050. The results show that large-scale RE development would not incur a significant macroeconomic cost. It would have significant green growth effects that benefit the growth of upstream industries, reshape the energy structure, and bring substantial environmental co-benefits. If the share of RE reaches 56% in the total primary energy in 2050, then non-fossil power sectors will become a mainstay industry with value added accounting for 3.4% of the GDP. In RE max scenario, the large scale-RE development will stimulate the output worth of $1.18 trillion from other RE related upstream industries and create 4.12 million jobs in 2050. It could substantially reduce the emissions of CO_2 and air pollutants such as NO_x, SO_2.

Figure 1-5 Natural gas infrastructure in China.

Source: (Sheehan et al., 2014).

China also established an air quality monitor network, which covers 31 provinces step by step. Cities in China began to monitor $PM_{2.5}$ and ozone from 2012. Firstly, only Beijing, Shanghai, Guangzhou and 31 capital cities have monitors. By 2015, all the country level cities started monitoring $PM_{2.5}$ (Yuan et al., 2012). Most of the cities in China have the real-time data for air quality (*Figure 1-6*). There are also many studies to use the model to simulate air pollutants concentration. Ma and others estimated ground-level $PM_{2.5}$ from satellite-derived aerosol optical depth using a spatial statistical model. Their predicted annual $PM_{2.5}$ concentrations indicated that over 96% of the Chinese population lives in areas that exceed the Chinese National Ambient Air Quality Standard (CNAAQS) Level 2 standard. Their results also confirmed satellite-derived aerosol optical depth in conjunction with meteorological fields and land use information can be

successfully applied to extend the ground $PM_{2.5}$ monitoring network in China. Their satellite-driven model can provide reliable historical $PM_{2.5}$ estimates in China, which is resolution comparable to the concentration used for the health effect assessment in epidemiologic studies (Ma et al., 2014, 2016).

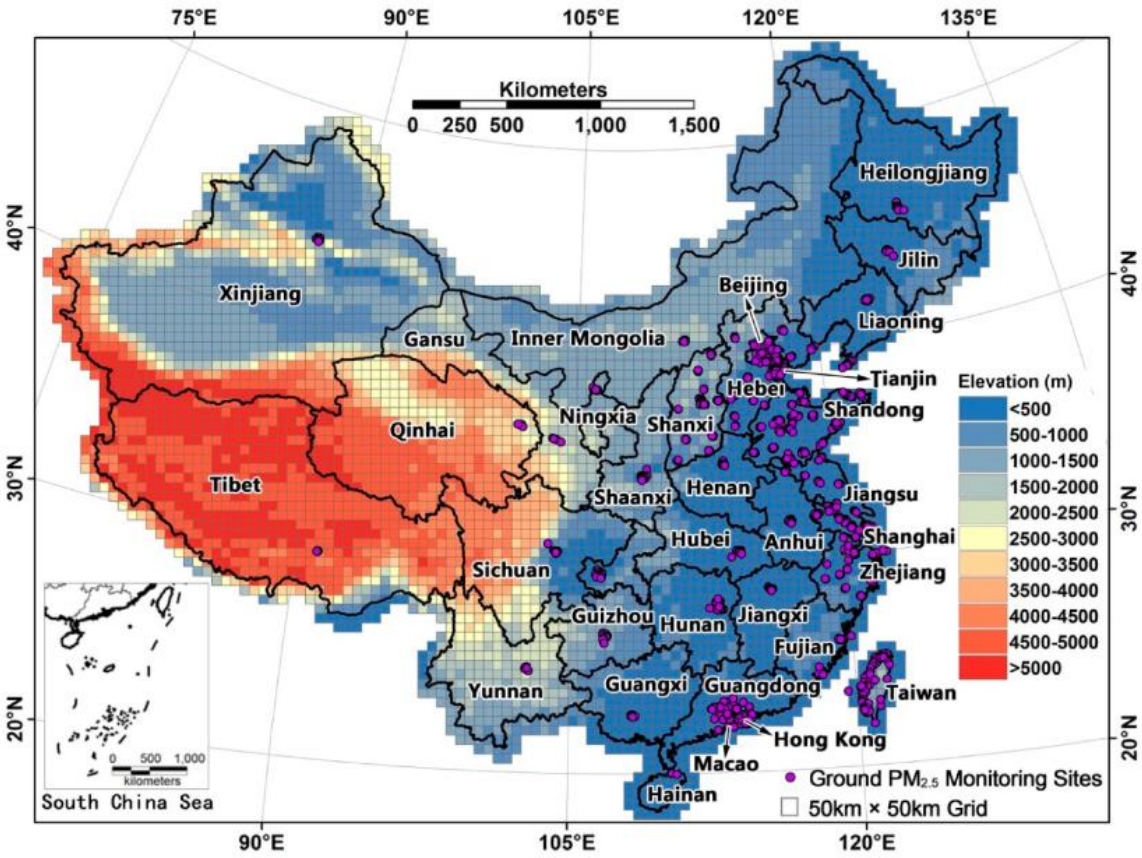


Figure 1-6 Spatial distribution of $PM_{2.5}$ monitoring in China.

Source:(Ma et al., 2014)

1.6 Research objectives and innovation of this study

1.6.1 Research objectives

China experiences fast development and urbanization. At the same time, air pollution is becoming the most serious environmental issues in China after 2010, especially for $PM_{2.5}$ and

ozone pollution in the urban area. Over 90% of the population in China live in the air polluted regions. Air pollution leads to hundreds of thousand premature deaths and millions of sickness in China every year (Han et al., 2014; Wen and Gu, 2012). It also results in the economic impact on the national economy. This study tries to quantify the health effects on the population and evaluate the economic impacts of air pollution-related health problem in 30 provinces of China. This study aims to answer the following questions:

If air pollution is not improved, how many premature death and diseases will be caused by air pollution in 2030?

How much will additional health expenditure be spent on the air pollution-related health problems in 2030 in China? What are the economic impacts?

Furthermore, what will be the benefits from air pollution control policy for each of the aspects above? This study tries to reveal cost-effective air pollution control option for each province in China.

1.6.2 Innovation of this study

Although there are many studies try to evaluate the health and economic impact in China. Most of existing studies use the willingness to pay method, focused on historic years and one region or national level. This study tries to assess the health and economic impact of air pollution in 30 provinces in China in 2030 and find a cost-effective air pollution control options for each province. For the above purposes, this study incorporated health-related environmental damages into a computable general equilibrium (CGE) model in combination with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-China model that provides primary emissions data for an air quality (GEOS-Chem) model that calculates $PM_{2.5}$ and ozone concentration. Integrated assessment method explicitly describes labor supply changes and dissimilar economic impacts in China's 30 provinces. This study can draw a picture of how changes in $PM_{2.5}$ and ozone pollution will affect health expenditure, labor supply, and overall economy about the market impacts in China's 30 provinces. More specifically, this study is innovative regarding the following aspects.

1.6.2.1 Air pollutant

The first distinguishing feature of this study is that this study tries to evaluate the evolution of air pollution in 2030 and compare the health and economic impacts of $PM_{2.5}$ and ozone in the future. Most existing studies in China evaluated health and economic impact of PM_{10} pollution. However, after 2010, PM_{10} concentration has been decreasing in most of urban areas in China, while $PM_{2.5}$ has been becoming the main air pollutant. Furthermore, in the developed countries such as USA and Japan, ozone pollution is a more serious air pollutant. Similarly, it is believed that after the $PM_{2.5}$ pollution is improved, ozone pollution will be the main air pollution issue in China in the longer future, because ozone pollution is more difficult to control. Therefore, it is meaningful to investigate the evolution of the air pollution over time in a developing country.

1.6.2.2 Regional disparity

This study analyzes the health and economic impacts in 30 provinces of China (except Tibet, Hong Kong, Macau and Taiwan due to data availability). Most previous studies only focused on the country level, one city or province, or just several limited provinces in China (Zhang et al., 2006). However, China has 31 provinces, in which geographical feature, climate condition, development stage and population are quite different from province to province. With this regard, this study provides analysis taking into account the specific conditions in each province of China. Such provincial analysis of air pollution impact is specific and suitable for policy makers not only in the central government but also at the provincial levels.

1.6.2.3 Integrated approach

This study develops an integrated approach to explore the health and economic impacts of air pollution by combining the state-of-the-art models in different disciplines. Most studies try to quantify the economic impacts of ozone pollution simply using the willingness to pay (WTP) and cost of illness (COI) methods. By contrast, this study combines an energy model, an air pollutant emission model, an air quality model, a health model and an economic model. These models cover the closed circle of energy-related air pollution problem: from economic activity to energy consumption, to air pollutant emissions and air quality, to health impacts and finally, back to the impacts on the economy. The models are soft-linked with each other to provide comprehensive

information for each other, such as energy consumption, carbon emissions and air pollutant emissions, $PM_{2.5}$ and ozone concentration, health impacts related to $PM_{2.5}$ and ozone exposure, work day loss due to mortality and morbidity and GDP loss and welfare loss.

1.6.2.4 Cost-benefit analysis

This study can not only evaluate the benefit of air pollution control policies, for example, avoided mortality and morbidity, GDP gain and health expenditure saving, but also assess the costs of investment and maintenance fee of the control costs in 30 provinces. Therefore, it can provide a comprehensive cost-benefit analysis of air pollution control in each province.

1.6.2.5 Time point

This study quantifies the health and economic impacts in China until 2030. Most studies in China focused on the historic years. On the contrary, this study will calculate energy consumption projection in different policy scenarios in the future considering China's air pollution control policy and climate change mitigation policy.

1.6.3 Possible contributions

Three contributions are expected from this study.

Firstly, this study improves understanding of impacts of regional air pollution on health and economy in 30 provinces. According to China's energy policy and economic development target, AIM/CGE-China model can predict energy consumption in the future. Air quality model can simulate air pollution concentration and show how the air quality will be in the future. This study can also quantify the health impact of air pollution, such as mortality, morbidity and work time loss.

Secondly, this study quantifies the economic impacts of air pollution through labor supply change and additional health expenditure on air pollution-related health problem for 30 provinces, for example, GDP loss, welfare loss.

Thirdly, this study could analyze the cost of air pollution control policy in 30 provinces in China, which are science-based and fit to the regional context and priorities. By systematic analysis of the cost of air pollution control technology and the benefit from air quality improvement, this

study can provide the cost-effective air pollution control options for the specific province, which is more practical for the local government.

1.7 Structure of this thesis

The thesis is structured as follows. Chapter 2 introduces methodology with four kinds of models (AIM/CGE-China, Health assessment, GAINS-China and GEOS-Chem model), energy consumption by province and by sector, population projection by the five-year-age group and four scenarios under different air pollution control policy. Chapter 3 presents the simulation results of health and economic impact of $PM_{2.5}$ pollution in 30 provinces in China, including $PM_{2.5}$ concentration, mortality, morbidity, additional health expenditure, GDP loss and welfare loss. Chapter 3 also presents the policy implication of this study in Beijing-Tianjin-Hebei region and shows the importance of collaboration with neighboring regions. Chapter 4 shows the health and economic impact of ozone pollution in 30 provinces in China. In this chapter, the natural and human activity source of ozone emission is separated by province. Chapter 4 also discusses the policy implication upon the dominated ozone emission source in 30 provinces. Chapter 5 summarizes the conclusion of health and economic impacts of $PM_{2.5}$ and ozone pollution in 30 provinces in China and compares the different impact from $PM_{2.5}$ pollution and ozone pollution in China. This study discusses the limitation in Chapter 5.

2 Methodology framework

This study is about quantitative analysis of economic impacts on health damages caused by air pollution in China in the future. To achieve this purpose, several models are needed for energy consumption, air pollutants primary emissions, $PM_{2.5}$ and ozone concentration, health impact and economic assessment. Firstly, AIM/CGE-China model predicts energy consumption. GAINS-China model is used to calculate air pollutants emission. GAINS-China and GEOS-Chem are used for air quality simulation. Health impacts are quantified by health assessment model. Finally, AIM/CGE-China model evaluates the economic impact.

2.1 Overview of methodology

This study combines the Greenhouse Gas and Air Pollution Interactions and Synergies(GAINS)-China model, the Goddard Earth Observing System (GEOS)-Chem model, Asia-Pacific Integrated Assessment (AIM)/CGE-China model, and health assessment model. AIM/CGE- China model provides energy consumption data to GAINS-China model. The GAINS-China model calculates the air pollutants primary emissions and simulates annual average $PM_{2.5}$ concentration data for 30 provinces in China. GEOS-Chem model simulates annual and seasonal $PM_{2.5}$ and ozone concentration in China on the grid scale. Health assessment model is developed to quantify the health impacts of $PM_{2.5}$ pollution and ozone. Health impacts as a result of mortality and morbidity are converted to annual total medical expenditure and per capita work loss caused by $PM_{2.5}$ and ozone pollution, which are then used as a change in the household expenditure pattern and labor participation rate by the CGE model to determine the macroeconomic impacts.

The health assessment model is extended to quantify the health impacts of $PM_{2.5}$ (Xie et al., 2016) and ozone pollution and monetize the value of such health impacts in China. Exposure to incremental $PM_{2.5}$ and ozone leads to health problem called health endpoints, which are categorized into morbidity and mortality.

Figure 2-1 shows the research framework of this study. There are three parts, air quality assessment, health impact assessment and economic assessment. In the first step, AIM/CGE-China model, GAINS-China model and air quality model are used to obtain the air pollutants concentration. In the second step with the input data concentration, health assessment model can

quantify the health impacts of air pollution, including mortality, morbidity, work time loss and additional health expenditure. Finally, economic impacts are assessed by AIM/CGE-China model.

In AIM/CGE-China model, economic driving forces include labor, expenditure pattern, technology, resource and policy. The change of these five factors will lead to output change of AIM/CGE-China model. Air pollution leads to labor supply reduction because of mortality and morbidity, and increases health expenditure on air pollution-related health endpoints. Both of labor reduction and health expenditure have impacts on labor and expenditure pattern. The changes of economic driving forces in CGE model will result in impact on economy, energy and environment. By using AIM/CGE-China model, the impact of air pollution on the economy can be quantified.

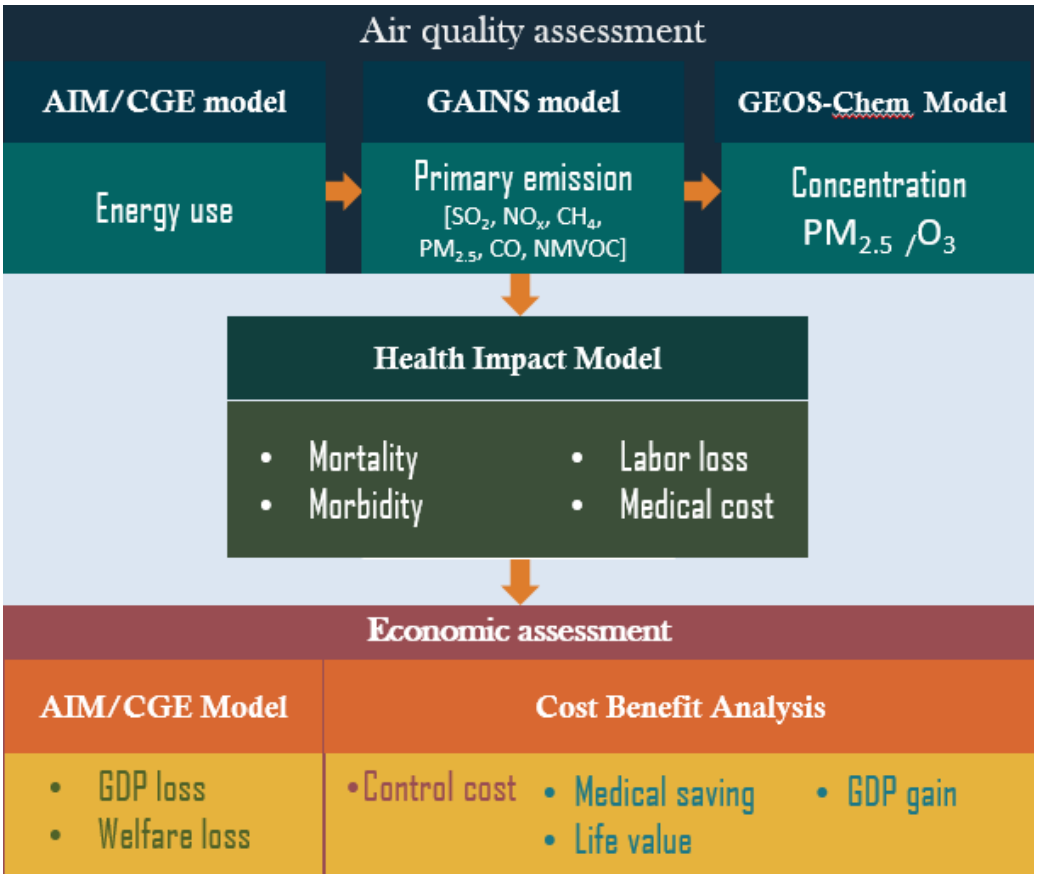


Figure 2-1 Research Framework.

2.2 Computable general equilibrium model

2.2.1 Technical introduction of the AIM/CGE-China model

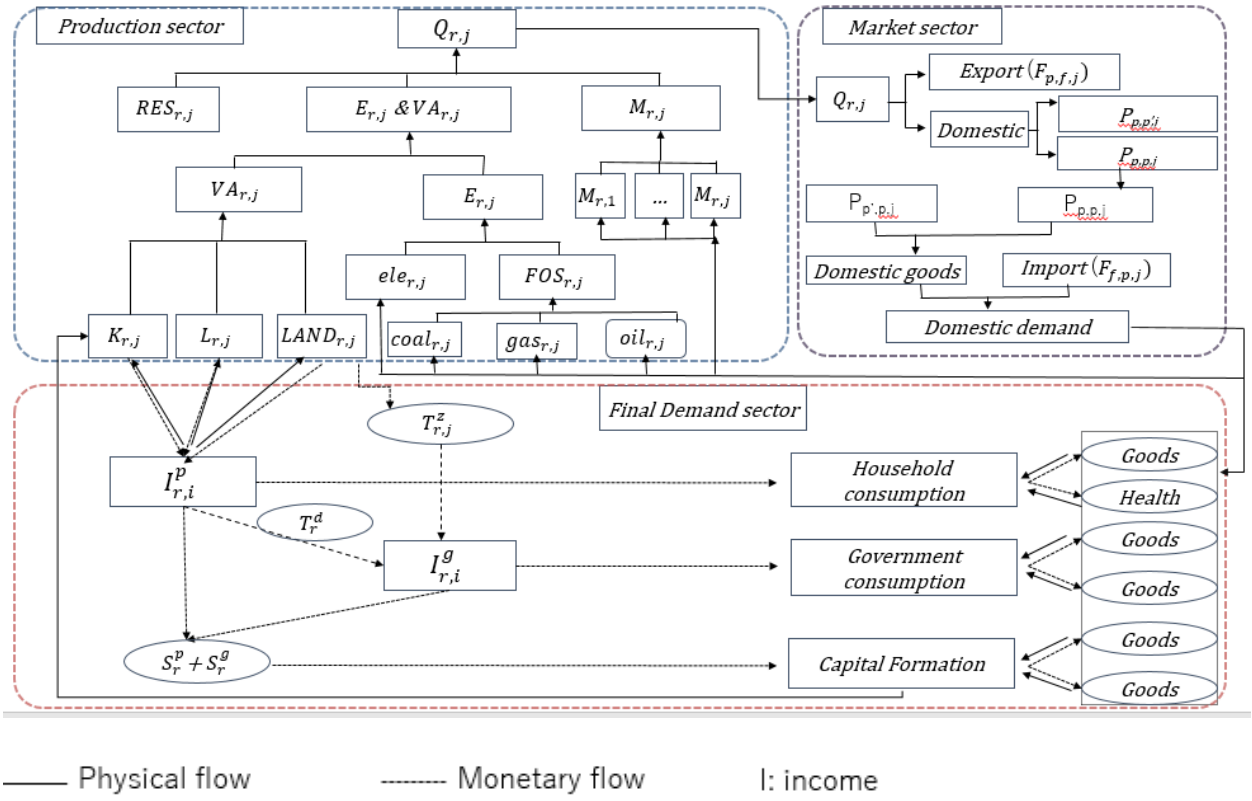
The Computable general equilibrium(CGE)-AIM/CGE-China model, applied in this study can be classified as a multi-sector, multi-region, recursive dynamic CGE model that covers 22 economic commodities and corresponding sectors, and eight power generation technologies as detailed in *Table 2-1* and *Figure 2-2.* It includes 30 provincial units of China (excluding Tibet, Hong Kong, Macau and Taiwan due to data availability) and one region of the rest of the world (*Table 2-2*). This CGE model is solved by Mathematical Programming System for General Equilibrium under General Algebraic Modeling System (GAMS/MPSGE) (Rutherford, 1999) at a one-year time step. The following paragraphs discuss the key technical features of this model to allow for a deeper understanding of associated modeling results.

Table 2-1 Classification of sectors in the model

Nr.	Code	Note	Nr.	Code	Note
1	Cagri	Agriculture	16	COthManuf	Other manufacturing
2	Coal	Coal	17	Celec	Power generation
3	Coil	Crude oil	18	CGas	Manufactured gas
4	Cmin	Other Mining	19	Cwater	Water production
5	CFdTbc	Food and Tabaco	20	CCnst	Construction
6	CTxt	Textile	21	CTrsp	Transport
7	Cpaper	Paper	22	Csvc	Service
8	Cpet	Petrol oil	i	CoalP	Coal power
9	Cchem	Chemicals	ii	CoilP	Crude oil power
10	CNonMPrd	NonMetal product	iii	Cngs	Natural gas power
11	CMetSmlt	Metal smelting and processing	iv	Hydro	Hydro power
12	CMetPrd	Metal product	v	Nuclear	Nuclear power
13	CMchn	Machinery	vi	Wind	Wind power
14	CTspEq	Transport equipment	vii	Solar	Solar power
15	CElcEq	Electronic equipment	viii	Biomass	Biomass power

Table 2-2 Model regions defined in the model

China regions				International regions
Beijing	Shanghai	Hubei	Yunnan	rest of the world
Tianjin	Jiangsu	Hunan	Shaanxi	
Hebei	Zhejiang	Guangdong	Gansu	
Shanxi	Anhui	Guangxi	Qinghai	
InnerMong	Fujian	Hainan	Ningxia	
Liaoning	Jiangxi	Chongqing	Xinjiang	
Jilin	Shandong	Sichuan		
Heilongjiang	Henan	Guizhou		



—— Physical flow -------- Monetary flow I: income

Figure 2-2 Structure of AIM/CGE-China model

2.2.2 Production

For each sector (j) in region (r), gross output $Q_{r,j}$ is produced using inputs of labor ($L_{r,j}$), capital ($K_{r,j}$), energy ($E_{r,j}$ $Coal_{r,j}$, $oil_{r,j}$, $gas_{r,j}$ and $ele_{r,j}$), and non-energy material ($M_{r,j}$). In some sectors (Cagri, Coal, Coil, Cmin), resource ($RES_{r,j}$) is also input. A five-level nested function is used to characterize the production technologies as showed in *Figure 2-3* and CGE Equation 2 below. The producer maximizes its profit by choosing its output level and inputs use, depending on their relative prices (CGE Equation 1) subject to its technology (CGE Equation 2).

CGE Equation (1):

$$\max \pi_{r,j} = p_{r,j} \cdot Q_{r,j} - \left(\sum_{i=1}^{N} p_{r,i} \cdot X_{r,i,j} + \sum_{v=1}^{V} \omega_{r,v} \cdot V_{r,v,j}\right) - T_{r,j}^{z}$$

Subject to the production technology:

CGE Equation (2):

$$Q_{r,j} = LEO_{1rj}\{M_{r,i,j}, RES_{r,j}, CES_{2vae}(CES_{3va}(K_{r,j}, L_{r,j}, CES_{3e}(ele_{r,j}, CES_{4fos}\langle coal_{r,j}, gas_{r,j}, oil_{r,j}, pet_{r,j}\rangle)))\}$$

Where

$\pi_{r,j}$ is the profit of j-th producers in region r;

$Q_{r,j}$ Output of j-th sector in region r;

$X_{r,i,j}$ Intermediate inputs of i-th goods in j-th sector in region r; As shown in *Figure 2-2*, $X_{r,i,j}$ includes $M_{r,i,j}$ (non-energy material), $ele_{r,j}$ (electricity), $coal_{r,j}$ (coal), $gas_{r,j}$ (natural gas or manufactured gas), $oil_{r,j}$ (crude oil), $pet_{r,j}$ (refined oil) and $RES_{r,j}$ (resource which is originated from the natural resource endowment);

$V_{r,v,j}$ v-th primary factor inputs in j-th sector in region r;

$p_{r,j}$ Price of the j-th composite commodity;

$\omega_{r,v}$ v-th factor price in region r;

$K_{r,j}$ is capital input in sector j;

$L_{r,j}$ is labor force in sector j;

$T_{r,j}^{z}$ is production tax in sector *j*; $T_{r,j}^{z} = p_{r,j} \cdot Q_{r,j} \cdot \tau_{r,j}$, *where* $\tau_{r,j}$ *is the production tax rate*;

CES_{krj} is the CES function at the k-th nesting level, the first level, LEO_{1rj}, is Leontief function, the second level (CES_{2vae}) is aggregation of value added and energy composite, the third level CES_{3va} is aggregation of value added, and CES_{3e} is aggregation of energy composite, the fourth level CES_{4fos} is aggregation of fossil energy inputs.

The following conditions apply in this regard:

Land inputs are considered only for agriculture sector (Cagr), other resources are considered for crude oil and natural gas extraction (Coil), coal mining (Coal) and other mining (Cmin) sectors; Within energy transformation sectors such as oil refining (Cpet), gas manufacturing (Cgas), primary energy commodities are considered as material inputs;

The power sector is modelled by three fossil-fired (coal, gas and oil) and five non-fossil (nuclear, hydro, wind, solar and biomass) technologies(*Figure 2-3b).* The energy bundle is not combined with capital for fossil-fired technologies, but linked directly to activity output. This means that electricity output is in a linear relationship with energy inputs.

Labor is assumed to be fully mobile across industries within a region but immobile across regions. The mobility feature of capital follows a putty-clay approach, which means that vintage capital is immobile across either regions or industries while new investment is fully mobile across industries within a region.

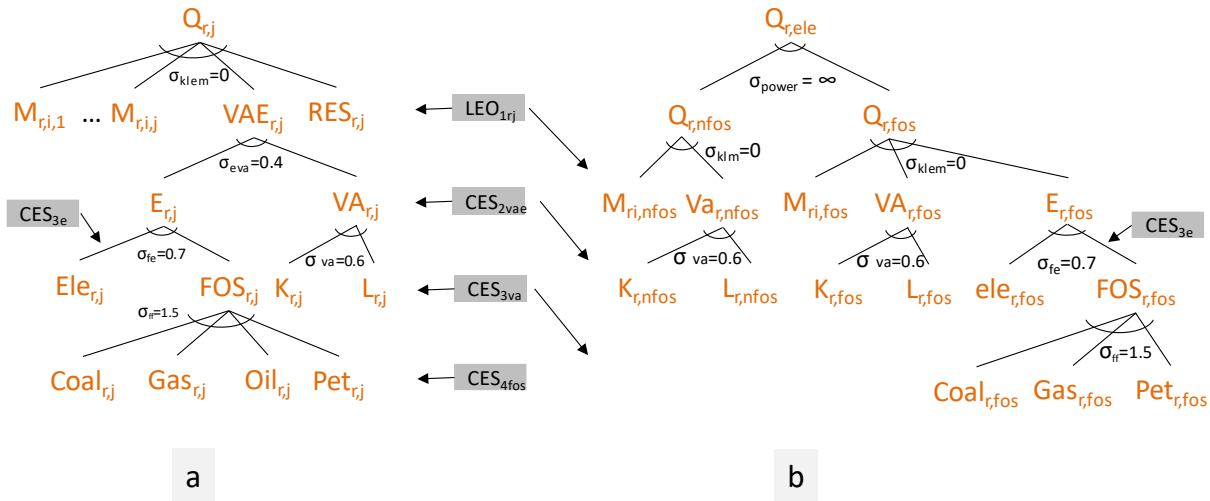


Figure 2-3 Nesting of production structure

a, except for electricity sector; b, electricity sector. σ is elasticity of substitution for inputs. $VAE_{r,j}$, $VA_{r,j}$, $E_{r,j}$, $FOS_{r,j}$ *are CES composites of value added & energy, value added, energy and fossil energy, respectively.*

2.2.3 Final demand

Household and government sectors are represented as two different final demand sectors. As CGE Equation 3 shows, the representative household receives income from the rental of primary factors ($\sum_{v=1}^{V}(\omega_{r,v} \cdot V_{r,v}) + \sum_j (pld_r \cdot QLAND_{r,j}) + \sum_{s,j}(p_r^{res} \cdot QRES_{r,j,s})$) and lump-sum transfer from the government. The income is used for either investment (or saving, T_r^p) or final consumption ($\sum_i \ p_{r,i}^q \cdot X_{r,i}^p$). Households maximize their utility by choosing the levels of final consumption of commodities, subject to the constraints of their income and commodity prices (see the income balance in CGE Equation 3). Total investment is assumed exogenously by CGE Equation 12. On the other hand, the government collects taxes ($T_r^d + \sum_j \ T_{r,j}^z + \sum_j \ T_{r,j}^m$) and spends the tax revenue in providing public services ($p_r^i \cdot x_{r,i}^g$) as explained in CGE Equation 4. The demands (DEM_r^d) of household consumption, investment goods and government are specified using Cobb-Douglas utility or demand functions (CGE Equation 5).

CGE Equation (3): income balance of the representative household

$$\sum_{v=1}^{V}(\omega_{r,v}\cdot V_{r,v})+\sum_{j}(pld_r\cdot QLAND_{r,j})+\sum_{s,j}(p_{r,s}^{res}\cdot QRES_{r,j,s})-T_r^d=\sum_{i}p_{r,i}^{q}\cdot X_{r,i}^{p}+S_r^p$$

CGE Equation (4): income balance of the government

$$T_r^d+\sum_{j}T_{r,j}^{z}+\sum_{j}T_{r,j}^{m}=\sum_{i}p_{r,i}\cdot X_{r,i}^{g}+S_r^g$$

CGE Equation (5): Cobb-Douglas representation of demand of household, investment and government

$$DEM_r^d=A_r^d\cdot\prod_{i=1}^{N}(X_{r,i}^{d})^{\alpha_{r,i}^{d}}$$

The first-order conditions for the optimality of the above problem imply the following demand functions for household, government and investment, respectively:

CGE Equation (6): demand function for household

$$X_{r,i}^{p}=\frac{\alpha_r^p}{p_{r,i}}\cdot(\sum_{v=1}^{V}(\omega_{r,v}\cdot V_{r,v})+\sum_{j}(pld_r\cdot QLAND_{r,j})+\sum_{s,j}(p_{r,s}^{res}\cdot QRES_{r,j,s})-T_r^d-S_r^p)$$

CGE Equation (7): demand function for government

$$X_{r,i}^{g}=\frac{\alpha_r^g}{p_{r,i}}\cdot(T_r^d+\sum_{j}T_{r,j}^{z}+\sum_{j}T_{r,j}^{m}-S_r^g)$$

CGE Equation (8): demand function for investment

$$X_{r,i}^{n}=\frac{\alpha_r^n}{p_{r,i}}\cdot(S_r^p+S_r^g+\varepsilon\cdot S_r^f)$$

Where

DEM_r^d is final demand of households - p, investment - n and government - g;
$\omega_{r,v}$ is price of the vth primary factor;
$V_{r,v}$ is vth primary factor endowment by household;

pld_r is land price;
$QLAND_{r,j}$ is land in sector *j*;
$p_{r,s}^{res}$ is price of resource *s*;
$QRES_{r,j,s}$ is quantity of resource *s* in sector *j*;
T_r^d is direct tax;
S_r^p is household savings;
$T_{r,j}^z$ is production tax in sector *j*;
$T_{r,j}^m$ is import tariff of commodity *j*;
S_r^g is government savings;
S_r^f is current account deficits in foreign currency terms (or alternatively foreign savings);
ε is foreign exchange rate;
$p_{r,i}$ is commodity price;
$X_{r,i}^d$ is final consumption of commodity *i* by agent *d* (*d* ∈ households - p, investment - n and government - g).
A_r^d is the scaling parameter in Cobb-Douglas function by agent *d* (*d* ∈ households - p, investment - n and government - g);
$\alpha_{r,i}^d$ is the share parameter in Cobb-Douglas function by agent *d* (*d* ∈ households - p, investment - n and government - g);

2.2.4 Commodity supply and inter-regional trade

Supply of commodity adopts Armington assumption (Armington, 1969), assuming that goods produced from other provinces and abroad are imperfectly substitutable for domestically and locally produced goods. This approach is shown in *Figure 2-4* and CGE Equation 9 and 10 below.

Supply to international region (f)

CGE Equation (9): Armington representation of domestically produced and imported commodity

$$X_{fi} = CES_{s1}\{D_{ffi}, CES_{s2}(P_{1fi}, \cdots, P_{pfi})\}$$

Where

D_{ffi} is commodity produced in the rest of world;

P_{pfi} is commodity produced in China's provinces and exported to the rest of world;

- Supply to China province (p)

CGE Equation (10): representation of commodity produced locally and produced in other provinces

$$X_{pi} = CES_{s1}\{F_{fpi}, CES_{s2}(D_{ppi}, CES_{s3}(P_{1pi}, \cdots, P_{p'pi}))\}$$

Where

F_{fpi} is commodity produced in the rest of world and imported by China's province;

D_{ppi} is commodity produced in the province and supplied to the same province;

$P_{p'pi}$ is commodity produced in the other provinces.

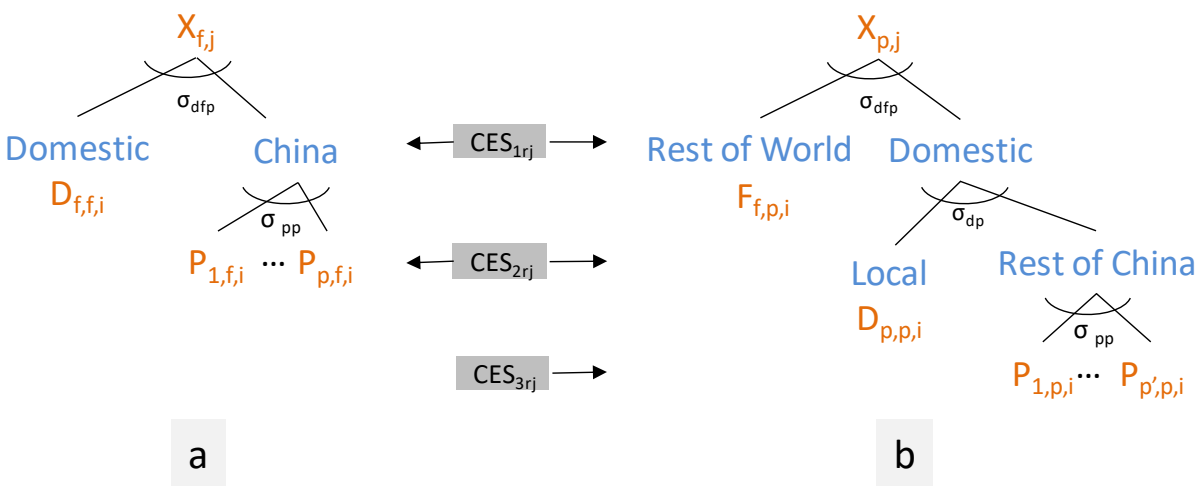


Figure 2-4 Aggregation of local, domestic and foreign varieties of good

a, international regions; b, China provinces. σ is elasticity of substitution for inputs

Two types of price variables are distinguished. One is prices in terms of the domestic currency p_i^e and p_i^m; the other is prices in terms of the foreign currency p_i^{We} and p_i^{Wm}. They are linked with each other as follows:

CGE Equation (11)

$$p_i^e = \varepsilon \cdot p_i^{We}$$

CGE Equation (12)

$$p_i^m = \varepsilon \cdot p_i^{Wm}$$

Furthermore, it is assumed that the economy faces balance of payments constraints, which is described with export and import prices in foreign currency terms:

CGE Equation (13)

$$\sum_i p_i^{We} \cdot E_{r,i} + S_r^f = \sum_i p_i^{Wm} \cdot M_i$$

Where

$E_{r,i}$ Export of i-th commodity in region r,

$M_{r,i}$ Import of i-th commodity in region r,

p_i^{We} Export price in terms of foreign currency,

p_i^e Export price in terms of domestic currency,

p_i^{Wm} Import price in terms of foreign currency,

p_i^m Import price in terms of domestic currency.

2.2.5 Market clearance

The market-clearing conditions hold for both commodity and factor markets.

For the commodity markets described in CGE Equation 14, output Q_{ri} in the corresponding sector j (i=j) is equal to the total demand of intermediate inputs, household, investment and government ($\sum_d X_{r,i}^d$), plus export to other international regions ($\sum_f F_{r,f,i}$) and provinces

($\sum_p P_{r,p,i}$), minus import from other international regions $\sum_f F_{f,r,i}$ and provinces ($\sum_p P_{p,r,i}$), and plus net stock change (STK_{ri}):

CGE Equation (14): market clearance of commodity and services

$$Q_{ri} = \sum_d X_{r,i}^d + \sum_f F_{r,f,i} + \sum_p P_{r,p,i} - \sum_f F_{f,r,i} - \sum_p P_{p,r,i} + STK_{r,i}$$

For the factor markets described in CGE Equation 15, supply of total factor ($V_{r,v}$) is equal to factor inputs in all sectors ($v_{r,v,j}$):

CGE Equation (15): market clearance of production factor

$$V_{r,v} = \sum_j v_{r,v,j}$$

2.2.6 Macro closure

In a CGE model, the issue of macro closure is the choice of exogenous variables, including macro closure of investment-saving balance and current account balance. In this CGE model, government savings (S_r^g), total investment and balanced of payment are fixed exogenously, and foreign exchange rate is an endogenous variable.

2.2.7 Dynamic process

The model is solved at one-year time step in a recursive dynamic manner, in which the parameters of capital stock (CGE Equation 16 and 17), labor force (CGE Equation 18), land, natural resource, efficiency (CGE Equation 19), and extraction cost of fossil fuels are updated based on the modelling of inter-temporal behavior and results of previous periods.

- Capital accumulation process:

CGE Equation (16): total investment demand

$$TI_{r,t+1} = \sum_j CAPSTK_{r,j,t} \cdot [(1 + g_{r,t+1})^T - (1 - d_r)^T]$$

CGE Equation (17): capital accumulation process

$$CAPSTK_{r,j,t} = (1 - d_r)^T \cdot CAPSTK_{r,j,t-1} + T \cdot I_{r,j,t-1}$$

Where total investment ($TI_{r,t}$) is given exogenously, investment in sector j in the previous period ($I_{r,j,t-1}$) is determined by the model depending on the rate of return to capital, capital stock accumulation ($CAPSTK_{r,j,t}$) follows CGE Equation 18, d_r is the depreciation rate (5% for all regions), and T is time step (1 year).

Supply of total labor, land and resource:

CGE Equation (18): factor growth pattern

$$V_{r,v}^{t} = V_{r,v}^{t-1} \cdot (1 + gr_{r,v}^{t})$$

Where $V_{r,v}^{t}$ is primary factor (v) of labor force, land and resource, and $gr_{r,v}^{t}$ is the corresponding exogenous growth rate.

Efficiency parameters:

The CGE model distinguishes technological efficiency improvement of new investments from that of existing capital stock.

For new investments, sectoral efficiencies of energy, land productivity and total factor productivity are given as exogenous scenarios, while for existing capital stock, efficiency of par (par efficiency of energy and capital) in time t ($EFF_{r,par,j}^{ext,t}$) is the average of capital stock ($EFF_{r,par,j}^{ext,t-1}$) and new investments ($EFF_{r,par,j}^{new,t-1}$) in the previous period, as per CGE Equation 19 here:

CGE Equation (19): updating of efficiency parameters

$$EFF_{r,par,j}^{ext,t} = \frac{(EFF_{r,par,j}^{ext,t-1} \cdot CAPSTK_{r,j,t-1} + EFF_{r,par,j}^{new,t-1} \cdot I_{r,j,t-1}) \cdot (1 - d_r)^T}{CAPSTK_{r,j,t}}$$

2.2.8 Data

Most of the global data in the CGE model are based on GTAP 6 (Dimaranan and V., 2006) and IEA (International Energy Agency, 2009). China-specific provincial data sources are the 2002

inter-regional input-output tables (IOT) (Li et al., 2010) and the 2002 energy balance tables (EBT) (National Bureau of Statistics of China (NBS), 2003). In addition, carbon emission factors; energy prices for coal, oil and gas (National Bureau of Statistics of China (NBS), 2013) and renewable energy technology costs (China National Renewable Energy Centre (CNREC), 2014) are also required. All the datasets are currently converted to the base year of 2002. Moreover, it is well known that IOT and EBT are inconsistent when it comes to energy consumption across sectors, and the energy data from EBT is regarded as more reliable than IOT. A novel characteristic of this CGE model is that the IOT of China is consistent with the sectoral energy consumption from China's EBT. To achieve this consistency, this study used the linear least square method, as described in CGE Equation 20 - 23 below.

Minimizing:

CGE Equation (20):

$$\varepsilon = \sum_{en,j} (Shr_{en,j}^{IOT} - Shr_{en,j}^{EBT})^2$$

Subject to:

CGE Equation (21):

$$Shr_{en,j}^{IOT} = \frac{EN_{en,j}^{IOT}}{TCON_{en}^{IOT}}$$

CGE Equation (22):

$$Shr_{en,j}^{EBT} = \frac{EN_{en,j}^{EBT})}{TCON_{en}^{EBT}}$$

CGE Equation (23):

$$\sum_{j} E\,N_{en,j}^{IOT} = \sum_{j} E\,N_{en,j}^{EBT} \cdot P_{en}$$

Where

ε: Error to be minimized

en: Energy commodities (coal, gas, oil, electricity)

j: Sector classification in *Table2-1*.

$Shr_{en,j}^{IOT}$: Share of energy consumption across sectors in IOT (%)

$Shr_{en,j}^{EBT}$: Share of energy consumption across sectors in EBT (%) according to (NBS, 2008)

$EN_{en,j}^{IOT}$: Energy consumption of *en* in sector *j* in IOT (USD)

$EN_{en,j}^{EBT}$: Energy consumption of *en* in sector *j* in EBT (PJ)

$TCON_{en}^{IOT}$: Total energy consumption of *en* in IOT (USD)

$TCON_{en}^{EBT}$: Total energy consumption of *en* in EBT (PJ)

P_{en}: Price of energy *en* (USD/PJ)

2.3 Health assessment model

Health assessment model can quantify the health endpoints from air pollutants exposure, calculate additional health expenditure and evaluate work time loss due to air pollution-related health outcome. Health impacts as a result of mortality and morbidity are converted to annual total medical expenditure and per capita work time loss caused by $PM_{2.5}$ and ozone pollution, which are then used as a change in the household expenditure pattern and labor participation rate by AIM/CGE-China model to assess the economic impact of air pollution. In this health assessment model, air pollutants only include $PM_{2.5}$ and ozone. Other health-related air pollutants will be extended into health assessment model in the future work.

2.3.1 Health endpoint

All results are region *r*, year *y*, scenario *s*, and uncertainty range *g* specific. For simplification, they are omitted in the following description. Exposure to incremental $PM_{2.5}$ pollutant leads to health problems called health endpoints, which are categorized into morbidity and mortality (*Table 2-7*). Most studies (R. Chen, Kan, et al., 2012; Hoek et al., 2013; Pope III et al., 2002) indicate that the Relative Risk (RR) for the endpoints is in a linear relationship with the concentration level. Recent studies (Apte et al., 2015; Burnett et al., 2015) argue that it is in a non-linear relationship, especially at high concentration level. This study follows the methodology that the relative risk for the endpoints is in both linear and nonlinear relationship with the concentration level of $PM_{2.5}$ and ozone (Silva et al., 2013; Cakmak et al., 2016; Kampa and Castanas,2008). When the concentration

is lower than the threshold value (10ug/m^3 for $PM_{2.5}$ and 70ug/m^3 for ozone) (Berman et al., 2012), air pollution causes no health impacts. Exposure-response functions for $PM_{2.5}$ and ozone are used as shown in the *Table 2-8* and *Table 2-9*.

Health impacts due to mortality and morbidity are converted to annual total medical expenditure and per capita work loss, which is then used as a change in the household expenditure pattern and labor participation rate by the CGE model to determine the market impacts (Schultz and Edington, 2007). Furthermore, this study also monetizes the non-market VSL based on the method (West et al., 2013), in which VSL in all provinces is calculated using their current GDP per capita values relative the national average per capita GDP in 2010 and an income elasticity of 0.5 (Viscusi and Aldy, 2003). The value of life ranges from 8.2 to 31.1 million USD in literature (Matus et al., 2012), here this study adopts the latest VSL about 250000 USD from empirical investigation using willingness to pay method in China (Xie, 2011).

As showed in Health Equation 1 and 2, this study adopted both linear and non-linear functions. When the concentration is lower than the threshold value of 10 ug/m^3, RR is 1, which causes no health impacts. Linear function assumes that the concentration-response function (CRF) is a constant. For mortality, this study also adopted China-specific linear function from (Cao et al., 2011) and cause-specific log-linear function based on the lookup table in (Apte et al., 2015). The number of health endpoints is estimated by multiplying RR with population and reported cause-specific mortality rate.

Health Equation (1):

$$RR_{p,r,s,y,m,e,v}(C) = \begin{cases} 1, & & \text{if } C_{p,r,s,y} \leq C0_p \\ 1 + CRF_{m,e,v} \times (C_{p,r,s,y} - C0_p), & \text{linear function,} & \text{if } C_{p,r,s,y} > C0_p \\ 1 + \alpha \times e^{(-\gamma \times (C_{p,r,s,y} - C0_p)^{\delta})}, & \text{nonlinear function,} & \text{if } C_{p,r,s,y} > C0_p \end{cases}$$

Health Equation (2):

$$EP_{p,r,s,y,m,e,v}(C) = \begin{cases} P_{r,y,m} \times (RR_{p,r,s,y,m,e,v}(C) - 1), & \text{for linear morbidity function} \\ P_{r,y,m} \times (RR_{p,r,s,y,m,e,v}(C) - 1) \times I_{r,\text{"all cause"}}, & \text{for linear mortality function} \\ P_{r,y,m} \times (RR_{p,r,s,y,m,e,v}(C) - 1) \times \hat{I}_{r,e}, & \text{for nonlinear mortality function} \end{cases}$$

where

RR(C): Relative risk for endpoint at concentration C [case/person/year or day/person/year]

EP: Health endpoint [case/year or day/year]

C: Concentration level of pollutant

C0: Threshold concentration that causes health impacts (10 ug/m^3 for $PM_{2.5}$; 70ug/m^3 for ozone)

CRF: Concentration-response function

P: Population, aged 15-65 for work day loss, age 25-65 for Ischemic heart disease and Stroke, and entire cohort for other endpoints

$\hat{I}$: cause-specific mortality rate

I: Reported average annual disease incidence (mortality) rate for endpoint

$I_{r,\text{"all cause"}}$: Reported average annual natural death rate

α, γ, δ: Parameters that determine the shape of the non-linear concentration-response relationship for mortality.

Suffix *p, r, s, y, m, e, v* represent pollutant ($PM_{2.5}$ and ozone), region, scenario, year, endpoint category (morbidity or mortality), endpoint, value range (medium, low and high), respectively.

2.3.2 Work time loss

Annual total work day loss (WDL) of a region is a summation of work day loss from morbidity and cumulative work day loss from mortality aged from 15 to 65 years old. Based on death rates for different age group and cause-specific mortality from China health statistics, this study assumes 4% of total mortality is aged between 15 and 65 years old. Note that different from $PM_{2.5}$ impact, in the literature there is no ERF for work day loss for ozone pollution. In this study, this study converted minor restricted activity day of ozone into work day loss based on the relationship of $PM_{2.5}$, e.g., minor restricted activity day is 2.78 times of work day loss. Annual per capita work loss rate (WLR) is obtained by dividing WLD with working population and annual working days (Health Equation 3). In the CGE model, WLR is used to calculate the actual labor force after subtracting the work loss (Health Equation 4).

Health Equation (3):

$$WLD_{p,r,s,y,v} = \sum_{m} (EP_{p,r,s,y,m,\text{"wld"},v}) + \sum_{e,y'<y} (EP_{p,r,s,y',\text{"mt"},e,v}) \times 0.04 \times DPY$$

Health Equation (4):

$$WLR_{p,r,s,y,v} = \frac{WLD_{p,r,s,y,v}}{DPY \times P_{r,y,\text{"15-65"}}}$$

Health Equation (5):

$$LAB_{p,r,s,y,v} = LAB0_{r,\text{"ref"},y} \times (1 - WLR_{p,r,s,y,v})$$

Where

WLD: Annual work day loss [day/year];

WLR: Annual per capita work loss rate;

"wld": Subset "Work loss day" of e;

"mt": Subset "mortality" of m;

LAB: Labor force after considering work loss;

LAB0: Labor force in the reference scenario;

DPY: Per capita annual working days (5 day/week * 52 week/year = 260 day/year).

2.3.3 Health expenditure

Average outpatient fee and hospital admission fee can be obtained from Chinese statistical yearbook from 2003 to 2012 in 30 provinces, except 2004 (*Table 2-3* and *Table 2-4*).

Based on the statistical data, this study did regression analysis about average hospital admission fee and outpatient fee with per capita GDP, and calculate the coefficient for hospital admission fee and outpatient fee for 30 provinces (*Table 2-5* and *Table 2-6*). From this coefficient, the average hospital admission fee and outpatient fee in the future can be predicted.

Additional health expenditure is obtained by multiplying outpatient and hospital admission price with total endpoints (Health Equation 6). The price is a function of per capita GDP of each province (Health Equation 7), and the parameters β, θ are estimated through regression analysis of statistical price by disease and GDP of each province from 2003 to 2012. Additional medical expenditure is regarded as household expenditure pattern change, which means as more money is spent on medical services, less is available on other commodities.

Health Equation (6):

$$HE_{p,r,s,y,m,e,v} = PR_{r,s,y,e,v} \times EP_{p,r,s,y,m,e,v}$$

Health Equation (7):

$$PR_{r,s,y,e,v} = \beta_{r,e} \times GDPPC_{r,s,y} + \theta_{r,e}$$

Where:

HE: Total additional health expenditure [billion CNY /year]

PR: Price of medical service in 30 provinces[CNY /case]

GDPPC: Per capita Gross Domestic Production(GDP) from CGE model

$\beta_{r,e}$, $\theta_{r,e}$: Parameters derived from regression analysis of medical service price for each health endpoint in 30 provinces.

Table 2-3 Average hospital admission fee in 30 provinces in China (Unit: CNY).

Province	2003	2005	2006	2007	2008	2009	2010	2011	2012
China	3910.7	4661.5	4668.9	4973.8	5463.8	5951.8	6193.9	6632.2	6980.4
Beijing	11578.1	12743.0	12551.7	12876.3	13730.4	15028.9	15211.8	16630.7	17401.6
Tianjin	6524.3	7602.4	7849.9	8575.0	9702.8	10559.5	11718.7	12428.9	12679.4
Hebei	2717.4	3498.0	3427.0	3976.8	4486.2	4824.9	5168.1	5661.5	6121.9
Shanxi	2721.1	3042.2	3934.4	4104.7	4577.4	5035.6	5608.2	6170.9	6858.2
InnerMong	2003.3	3626.8	3669.9	4026.6	4776.8	5205.5	5894.6	6532.4	7082.7
Liaoning	3404.4	4639.4	4623.5	5321.3	5971.2	6757.6	6657.2	7175.9	7409.3
Jilin	3215.8	3743.6	3758.3	4450.0	5031.4	5908.2	6166.6	6674.6	7237.1
Heilongjiang	3702.2	4522.4	4360.9	4801.1	5346.2	5766.0	6073.4	6760.9	7170.9
Shanghai	7539.4	8693.6	8974.9	9395.8	10287.2	11276.1	12249.9	12966.5	13642.8
Jiangsu	5436.1	6253.9	6298.9	6779.7	7642.7	8444.5	7961.1	8431.3	8810.2
Zhejiang	6212.7	7101.8	7111.0	7518.9	8188.6	8905.9	8933.7	8922.9	9422.7
Anhui	2801.0	3637.9	3933.5	4220.3	4634.6	5013.2	5231.1	5627.8	5971.5
Fujian	4172.5	4661.6	4487.0	5057.1	5654.8	6035.9	5964.2	6152.3	6334.2
Jiangxi	2503.0	3269.4	3174.2	3545.0	3955.1	4395.1	4707.3	5024.3	5560.1
Shandong	3206.1	3949.2	4052.7	4283.6	4993.8	5303.3	5702.5	6308.3	6698.2
Henan	2521.6	2885.1	2934.9	3320.6	3888.5	4423.3	4759.2	5221.3	5676.8
Hubei	3656.6	4157.6	4255.9	4599.0	4636.1	5114.4	5735.2	6243.2	6699.0
Hunan	3439.4	4212.7	4172.6	4568.9	5008.2	5318.4	5289.9	5675.8	6009.9
Guangdong	5675.3	6845.5	6440.4	6682.3	6591.9	7282.5	7533.9	7853.2	8066.2
Guangxi	2870.4	3514.7	3457.8	3757.6	4150.0	4589.8	5038.6	5614.0	6013.6
Hainan	3922.9	4580.5	4485.4	4738.5	5321.3	6046.3	6385.9	7049.7	7924.1
Chongqing	3522.8	4185.8	4158.5	4525.4	5147.3	5758.6	5781.6	6126.8	6681.9
Sichuan	3298.7	3635.4	3601.8	3607.8	4486.5	4962.2	5094.6	5617.9	5981.1
Guizhou	2924.1	3524.3	3655.4	3625.4	3795.8	4210.6	4139.6	4411.4	4639.4
Yunnan	3447.4	3524.2	3558.3	3825.3	4206.7	4523.8	4520.0	4766.6	5007.8
Shaanxi	3262.0	3765.6	3770.2	3862.9	4382.3	4842.3	4733.8	5182.7	5505.3
Gansu	2299.2	2484.9	2730.0	2928.9	3233.6	3464.6	4126.1	4458.2	4852.3
Qinghai	3224.5	3732.5	3292.4	4169.4	4704.2	5241.8	5541.4	5706.2	6657.4
Ningxia	3340.8	3978.6	3826.9	4039.6	4602.8	5024.2	4966.0	5489.7	5610.7
Xinjiang	2834.7	3482.7	3366.7	3547.8	3889.1	4390.4	4716.2	5159.5	5283.4

Source: National Bureau of Statistics of China (2003-2012)

Table 2-4 Average outpatient fee in 30 provinces in China (Unit: CNY*).*

Province	2003	2005	2006	2007	2008	2009	2010	2011	2012
China	108.20	126.87	128.70	136.10	146.50	159.50	166.80	179.80	192.50
Beijing	215.60	247.37	259.50	278.90	301.90	322.10	326.20	352.50	372.90
Tianjin	163.10	175.79	170.30	177.00	193.10	216.60	226.90	234.40	243.30
Hebei	90.90	114.38	116.90	122.10	137.20	147.00	151.40	164.10	180.30
Shanxi	84.80	105.61	127.70	129.40	132.40	141.90	148.70	170.00	190.00
InnerMong	66.60	101.19	103.60	108.90	122.90	137.00	160.00	172.20	191.00
Liaoning	101.50	134.55	133.00	144.70	164.60	182.40	183.90	203.10	216.70
Jilin	94.60	103.07	102.20	120.80	133.60	141.70	153.50	171.40	184.70
Heilongjiang	109.80	130.24	133.60	141.80	150.80	164.20	169.60	189.30	203.70
Shanghai	167.10	205.73	202.00	211.00	224.50	237.20	247.90	257.70	271.40
Jiangsu	131.60	139.28	136.20	145.20	157.60	171.40	175.90	190.50	199.90
Zhejiang	135.60	143.42	145.80	153.90	168.20	182.00	186.80	189.90	198.30
Anhui	84.60	105.04	115.90	118.80	129.80	139.50	141.50	155.10	168.50
Fujian	101.00	107.37	109.60	116.50	130.70	138.40	139.80	149.40	154.30
Jiangxi	77.10	94.37	97.50	109.50	117.40	133.00	131.90	145.10	161.80
Shandong	112.10	127.95	131.80	138.10	154.40	161.30	160.70	174.90	186.50
Henan	69.40	83.37	83.70	94.20	104.60	116.40	114.00	122.40	133.80
Hubei	110.10	120.85	121.60	126.60	133.30	145.80	153.80	167.00	178.00
Hunan	114.00	137.14	135.10	145.60	158.30	174.00	173.70	192.10	208.60
Guangdong	107.60	129.89	123.60	126.10	123.90	136.10	153.70	161.80	174.00
Guangxi	66.70	83.26	83.90	91.20	101.90	114.00	118.50	131.00	142.20
Hainan	108.50	117.95	115.90	122.40	134.90	153.10	145.80	161.00	176.70
Chongqing	99.60	120.44	121.60	130.80	150.30	169.10	177.90	192.20	207.00
Sichuan	76.10	90.91	91.90	101.20	112.80	126.80	136.60	152.70	165.70
Guizhou	87.90	112.80	120.40	130.00	140.30	156.80	153.00	164.60	183.40
Yunnan	76.40	82.01	89.40	96.90	106.70	116.10	114.20	126.80	140.10
Shaanxi	97.20	107.50	110.50	117.60	124.40	135.60	138.10	156.00	171.30
Gansu	47.60	54.23	64.20	69.40	80.20	89.70	106.20	120.30	128.80
Qinghai	56.30	67.17	79.30	83.10	88.80	93.90	104.80	117.20	142.50
Ningxia	93.90	112.45	108.10	107.60	126.60	136.40	130.40	139.70	143.00
Xinjiang	82.50	107.85	108.80	109.30	122.30	136.00	134.10	153.70	161.60

Source: National Bureau of Statistics of China (2003-2012)

Table 2-5 Coefficient of hospital admission regression in 30 provinces in China.

	θ			β			R^2
	coef	T	p	coef	T	p	
Beijing	8527.23	9.03	0.00	0.07	3.82	0.01	0.71
Tianjin	3389.19	5.65	0.00	0.13	8.51	0.00	0.92
Hebei	450.64	1.40	0.21	0.23	10.68	0.00	0.95
Shanxi	-1886.85	-4.24	0.01	0.51	13.45	0.00	0.97
InnerMong	1234.74	6.41	0.00	0.17	15.88	0.00	0.98
Liaoning	2352.63	4.17	0.01	0.12	4.83	0.00	0.80
Jilin	265.95	0.77	0.47	0.28	12.18	0.00	0.96
Heilongjiang	695.57	1.33	0.23	0.27	7.60	0.00	0.91
Shanghai	3134.18	6.11	0.00	0.11	11.69	0.00	0.96
Jiangsu	4733.95	7.15	0.00	0.06	2.42	0.05	0.49
Zhejiang	5676.94	9.78	0.00	0.04	2.12	0.08	0.43
Anhui	1577.31	7.78	0.00	0.26	11.93	0.00	0.96
Fujian	3578.76	7.70	0.00	0.05	2.27	0.06	0.46
Jiangxi	375.21	1.11	0.31	0.34	9.30	0.00	0.94
Shandong	1377.41	5.78	0.00	0.14	12.33	0.00	0.96
Henan	902.18	5.32	0.00	0.20	15.20	0.00	0.97
Hubei	1376.22	3.37	0.02	0.25	7.22	0.00	0.90
Hunan	2719.18	9.22	0.00	0.15	5.03	0.00	0.81
Guangdong	6043.68	9.64	0.00	0.00	-0.09	0.93	0.00
Guangxi	655.61	2.23	0.07	0.35	10.63	0.00	0.95
Hainan	989.30	2.57	0.04	0.30	10.05	0.00	0.94
Chongqing	1833.90	4.44	0.00	0.22	6.28	0.00	0.87
Sichuan	680.92	1.27	0.25	0.34	5.92	0.00	0.85
Guizhou	2844.46	9.66	0.00	0.09	1.69	0.14	0.32
Yunnan	2219.89	7.20	0.00	0.16	4.29	0.01	0.75
Shaanxi	2327.01	7.39	0.00	0.14	4.57	0.00	0.78
Gansu	-857.00	-3.67	0.01	0.50	16.31	0.00	0.98
Qinghai	-331.53	-0.43	0.68	0.42	5.69	0.00	0.84
Ningxia	2030.83	4.39	0.00	0.18	4.08	0.01	0.74
Xinjiang	456.02	0.87	0.42	0.24	5.83	0.00	0.85

Table 2-6 Coefficient of outpatient fee admission regression in 30 provinces in China.

	θ			β			
	coef	T	p	coef	T	p	R^2
Beijing	147.93	14.99	0.00	0.0021	11.06	0.00	0.95
Tianjin	119.47	8.57	0.00	0.0013	3.71	0.01	0.70
Hebei	50.45	6.68	0.00	0.0045	8.98	0.00	0.93
Shanxi	24.82	1.18	0.28	0.0081	4.49	0.00	0.77
InnerMong	38.84	5.31	0.00	0.0043	10.45	0.00	0.95
Liaoning	62.88	6.24	0.00	0.0034	7.90	0.00	0.91
Jilin	28.27	4.16	0.01	0.0058	12.94	0.00	0.97
Heilongjiang	40.75	3.75	0.01	0.0064	8.56	0.00	0.92
Shanghai	152.75	13.39	0.00	0.0007	3.61	0.01	0.69
Jiangsu	91.13	12.00	0.00	0.0017	6.11	0.00	0.86
Zhejiang	104.85	10.65	0.00	0.0012	3.87	0.01	0.71
Anhui	55.68	9.18	0.00	0.0061	9.31	0.00	0.94
Fujian	76.53	12.48	0.00	0.0014	5.35	0.00	0.83
Jiangxi	22.92	2.36	0.06	0.0086	8.27	0.00	0.92
Shandong	89.95	14.33	0.00	0.0019	6.24	0.00	0.87
Henan	54.97	9.35	0.00	0.0026	5.84	0.00	0.85
Hubei	63.95	7.16	0.00	0.0047	6.25	0.00	0.87
Hunan	65.86	5.93	0.00	0.0072	6.52	0.00	0.88
Guangdong	87.91	5.03	0.00	0.0011	1.72	0.14	0.33
Guangxi	21.57	3.66	0.01	0.0078	11.70	0.00	0.96
Hainan	66.55	5.98	0.00	0.004	4.61	0.00	0.78
Chongqing	29.24	3.07	0.02	0.0089	10.85	0.00	0.95
Sichuan	-2.04	-0.29	0.78	0.0111	14.66	0.00	0.97
Guizhou	52.20	4.85	0.00	0.013	6.42	0.00	0.87
Yunnan	26.30	2.91	0.03	0.0079	7.16	0.00	0.90
Shaanxi	56.03	7.80	0.00	0.0054	7.63	0.00	0.91
Gansu	-58.75	-11.12	0.00	0.0176	25.16	0.00	0.99
Qinghai	-15.47	-1.14	0.30	0.0092	7.10	0.00	0.89
Ningxia	84.43	5.44	0.00	0.002	1.31	0.24	0.22
Xinjiang	35.05	2.29	0.06	0.0057	4.76	0.00	0.79

Table 2-7 Health endpoints of air pollution

Category	Endpoint from $PM_{2.5}$	Endpoint from ozone
Work loss	Work loss day from morbidity	Work loss day from morbidity
	Work loss day from cumulative Mortality	Work loss day from cumulative mortality
Morbidity	Respiratory hospital admissions	Respiratory hospital admissions
	Cerebrovascular hospital admission	Lower respiratory symptoms
	Cardiovascular hospital admissions	Asthma
	Chronic bronchitis	Allergic rhinitis
	Asthma	Bronchodilator usage
	Respiratory symptoms days	
Mortality	All cause (international)	All cause (international)
	All cause (China-specific)	
	COPD	
	Lung cancer	
	Ischemic heart disease(25-65 y)	
	Stroke(25-65 y)	
	Upper respiratory infections	

Table 2-8 Exposure-response functions for $PM_{2.5}$

Health endpoint	Unit	ER function	C.I.95% low	C.I.95% high
Respiratory hospital admissions	case/person/ug-m3	1.17E-05	6.38E-06	1.72E-05
Cerebrovascular hospital admission	case/person/ug/m3	8.40E-06	6.47E-07	1.16E-05
Cardiovascular hospital admissions	case/person/ug/m3	7.23E-06	3.62E-06	1.09E-05
Chronic bronchitis	case/person/ug/m3	4.42E-05	-1.82E-06	9.02E-05
Asthma	case/person/ug/m3	1.22E-04	4.33E-05	2.08E-04
Restricted activity day	day/person/ug/m3	9.02E-02	7.92E-02	1.01E-01
Minor restricted activity day	day/person/ug/m3	5.77E-02	4.68E-02	6.68E-02
Mortality	case/person/ug/m3	4.00E-03	3.00E-04	8.00E-03
Work loss day	day/person/ug/m3	2.07E-02	1.76E-02	2.38E-02

Source: Bickel, Peter and Friedrich, Rainer, 2004; Apte et al., 2015; Berry et al., 1995; Cao et al., 2011; Pope et al., 2004.

Table 2-9 Exposure-response functions for ozone.

Health endpoint	Unit	ER function	C.I.95% low	C.I.95% high
Bronchodilator usage in adults	case/person/ug/m3	7.30E-02	-2.55E-02	1.57E-01
Lower respiratory symptoms in adults	case/person/ug/m3	1.60E-02	-4.30E-02	8.10E-02
Asthma in adults	case/person/ug/m3	4.29E-03	3.30E-04	8.25E-03
Minor restricted activity day in adults	case/person/ug/m3	1.15E-02	4.40E-03	1.86E-02
Resporatory hospital admissions 65+	case/person/ug/m3	1.25E-05	-5.00E-06	3.00E-05
Allergic rhintis in adults	case/person/ug/m3	1.60E-04	1.22E-04	2.03E-04
Allergic rhintis in children	case/person/ug/m3	3.03E-04	1.89E-04	4.29E-04
Cough in children	case/person/ug/m3	9.30E-02	-1.90E-02	2.22E-01
Lower respiratory symptoms in children	case/person/ug/m3	1.60E-02	-4.30E-02	8.10E-02
Acute mortality	case/person/ug/m3	2.60E-04	1.35E-04	3.85E-04
Mortality	case/person/ug/m3	2.00E-03	6.50E-04	3.35E-03
Work loss day in adults	day/person/ug/m3	4.13E-03	1.65E-03	6.63E-03

Source: Bickel, Peter and Friedrich, Rainer, 2004; Apte et al., 2015; Berry et al., 1995; Cao et al., 2011; Pope et al., 2004.

2.3.4 Willingness to pay for health endpoint

As showed in Health Equation 8, this study also quantified the value of health endpoint using the willingness to pay (WTP) approach following the method of (West et al., 2013). The willingness to pay for avoiding premature death and morbidity is shown in *Table 2-10*. Individuals make decisions every day that reflects how they value health and mortality risks. Because increases in health risk and undesirable, there must be some other aspect of activity that makes it attractive. Using evidence on market choices that involve implicit tradeoffs between risk and money, economists have developed estimates of the value of a statistical life(VSL) (W.KIP Viscusi, 2003). VSLs in all provinces are calculated using their current GDP per capita values relative the national average per capita GDP in 2010 and an income elasticity of 0.5 (Viscusi and Aldy, 2003).

Table 2-10 Value of health endpoint.

Health endpoint	Willingness to pay	China Matus(2012) 1997 cost	Europe ExternE2005 2000 cost
Value of life lost	USD/case	250000	8.15-31.1 million
Hospital admission	USD/admission	284	2000
Emergency room visits for respiratory illness	USD/visit	23	670
General practitioner visits asthma	USD/consultation	4	53
General practitioner visits lower respiratory symptoms	USD/consultation	13	75
Respiratory symptoms in asthmatics: Adults	USD/event	0.6	130
Respiratory symptoms in asthmatics: Children	USD/event	0	280
Respiratory medication use adults and Children	USD/day	0	1
Restricted activity day	USD/day	2.32	130
Cough day	USD/day	0.6	38
Symptom day	USD/day	0.6	38
Work loss day	USD/day	1.43	82
Minor restricted activity day	USD/day	0.6	38
Chronic bronchitis	USD/day	8000	190000
Mortality from acute exposure	USD/case	662	NA
New case asthma	USD/case	NA	60000

Health Equation (8):

$$VoE_{p,r,s,y,e} = WTP_{r,y,e} \times EP_{p,r,s,y,m,e,v} \times \left(\frac{GDP_{r,y}}{GDP_{\text{"China","2010"}}}\right)^{0.5}$$

Where:

$VoE_{p,r,s,y,e}$: Value of health endpoint;

$WTP_{r,y,e}$: Willingness to pay for avoiding premature death and morbidity.

2.4 GAINS model

The Greenhouse Gas and Air Pollution Interactions and Synergies(GAINS) model is an integrated assessment model dealing with costs and potentials for air pollution control and greenhouse gas mitigation, and assessing interactions between policies. GAINS model was developed by the International Institute for Applied Systems Analysis (IIASA) in Austria, originally as the Regional Air Pollution Information and Simulation (RAINS) model to estimate air pollutant emissions and design abatement strategies in Europe. It provides a consistent framework for estimating emissions, mitigation potentials, and costs for air pollutants (SO_2, NO_x, PM, NH_3, NMVOC) and GHG included in the Kyoto protocol (Amann et al., 2008, 2011, 2013). It helps in analysis of policy implications of controlling emissions or major air pollutants at the national and international scales. For example, GAINS is used for policy analyses under the Convention on Long-range Transboundary Air Pollution (CLRTAP), e.g., for the revision of the Gothenburg Protocol, and by the European Commission for the EU Thematic Strategy on Air Pollution and the air policy review. Scientists in many nations use GAINS as a tool to assess emission reduction potentials in their regions. For the negotiations under the United Nations Framework Convention on Climate Change (UNFCCC), a special version of GAINS has been developed to compare greenhouse gas mitigation efforts among countries. The model identifies air pollution impacts (acidification, eutrophication, ozone, human health).

GAINS model not only analyzes the potential for controlling these air pollutants and GHG emissions, but also evaluates costs of such emission reductions. Together with the existing modules dealing with the emissions of the precursor emissions of secondary aerosols such sulphur

dioxide(SO_2), nitrogen oxides(NO_x), ammonia(NH_3) and volatile organic compounds(VOC), this extension enables the comparison of the potentials and costs for controlling primary emissions of fine particles with those of secondary aerosols and to find cost-minimal approaches for reducing ambient levels of particulate matter. Fine particles are emitted from a large number of sources with large differences in their technical and economic properties. The methodology distinguishes 392 source categories for stationary energy combustion, industrial processes, mobile sources and agriculture. For each of these sectors, the study explores the applicable options for reducing PM emissions, their efficiency and their costs (Klimont et al., 2002). For the individual source sectors, emissions are estimated based on statistical information on economic activity and emission factors that reflect hypothetical emissions if no control measures were applied. Actual emissions are calculated taking into account the application of emission control measures to the country-specific conditions in a given sector, for which also costs are estimated.

GAINS estimates historic emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics, emission inventories and data supplied by countries themselves. It assesses emissions on a medium-term time horizon, with projections being specified in five-year intervals through the year 2050.

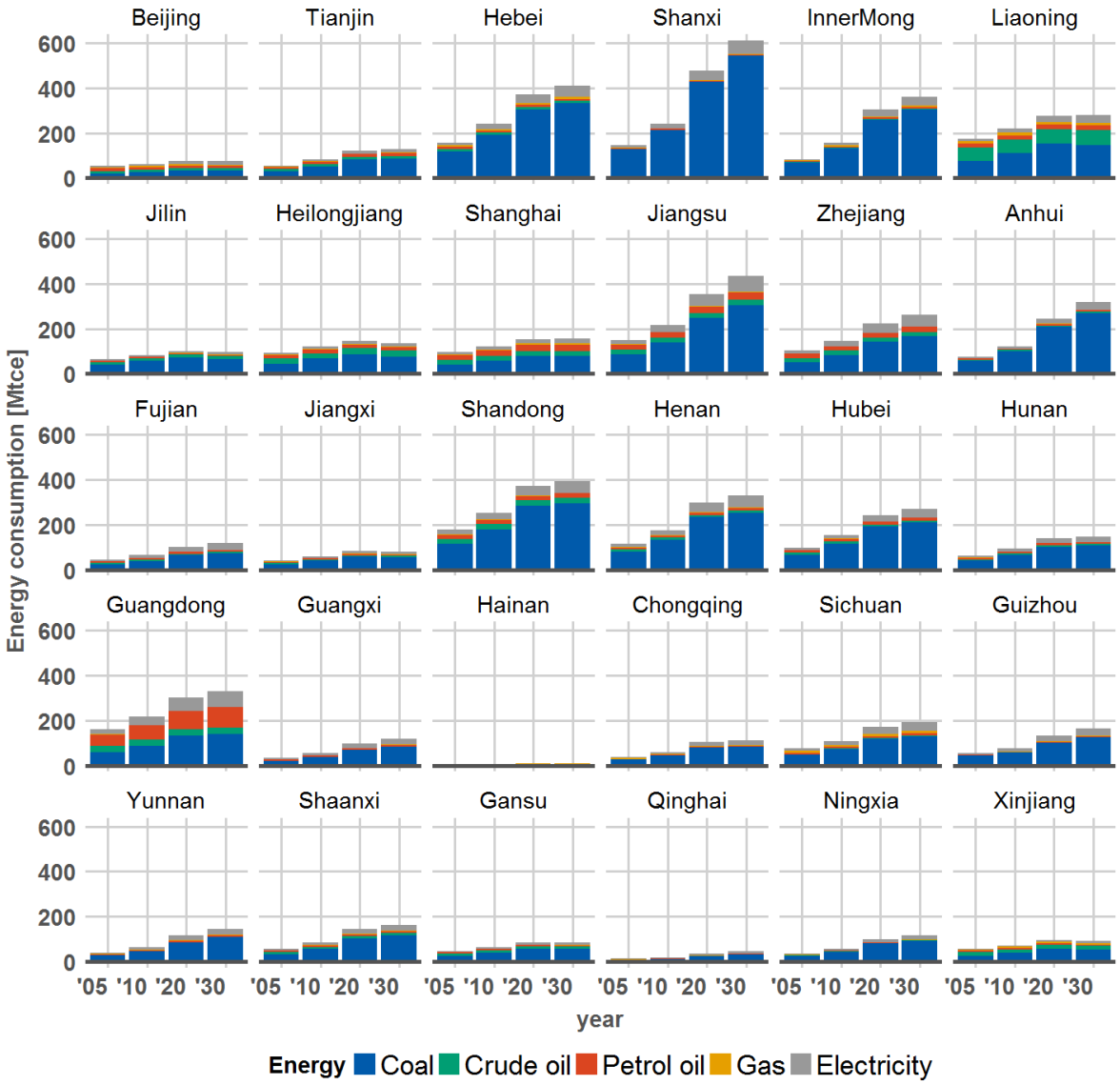


Figure 2-5 Energy consumption input data of GAINS-China model.

GAINS estimates for each country or region the potential emission reductions that are offered by about 2000 specific emission control measures and their costs.

The GAINS model allows estimation of air pollutant emissions by using the following equations.

GAINS Equation (1):

$$E_{i,p} = \sum_{k,m} (A_{i,k} \times ef_{i,k,m,p} \times (1 - \eta_{i,m}) \times x_{i,k,m,p})$$

Where

i, k, m, p represent region, activity type, abatement measure and pollutant, respectively;

$E_{i,p}$ denotes emissions of pollutant *p* in region *i*;

$A_{i,k}$ denotes activity of type k (e.g., coal consumption in power plants) in region *i*;

$ef_{i,k,m,p}$ denotes emission factor of pollutant *p* for activity *k* in country *i* without the application of control measures;

$\eta_{i,m}$ denotes removal efficiency of control measure *m* in region *i*;

$x_{i,k,m,p}$ denotes the technology penetration rate, which means the share of total activity of type *k* in country *i* to which a control measure m for pollutant *p* is applied.

As for the emission factors(*ef*) of different air pollutants, there are different equations. Taking SO_2 for example, the emission factor can be calculated by using the following GAINS Equation 2.

GAINS Equation (2):

$$ef_{i,k,p} = 2 \times \frac{sc_{i,k,p}}{hv_{i,k,p}} \times (1 - sr_{i,k,p})$$

Where

sc denotes fuel sulfur content;

hv denotes fuel low heat value;

sr denotes fuel sulfur retention rate.

GAINS is now implemented for the whole world, distinguishing 165 regions including 48 European countries and 46 provinces/states in China (31 provinces) and India (15 states). GAINS-China is an application of the GAINS model for East Asia. Documentation on the model and access to principal data, assumptions, and results are freely available online. Various air-pollutant-mitigation technologies were considered in GAINS-China model. However, energy and climate policies targeting carbon dioxide emissions were reflected implicitly through alternative

exogenous scenarios. The GAINS-China model provides annual average $PM_{2.5}$ concentration, air pollutant emissions and pollution control costs data for Shanghai.

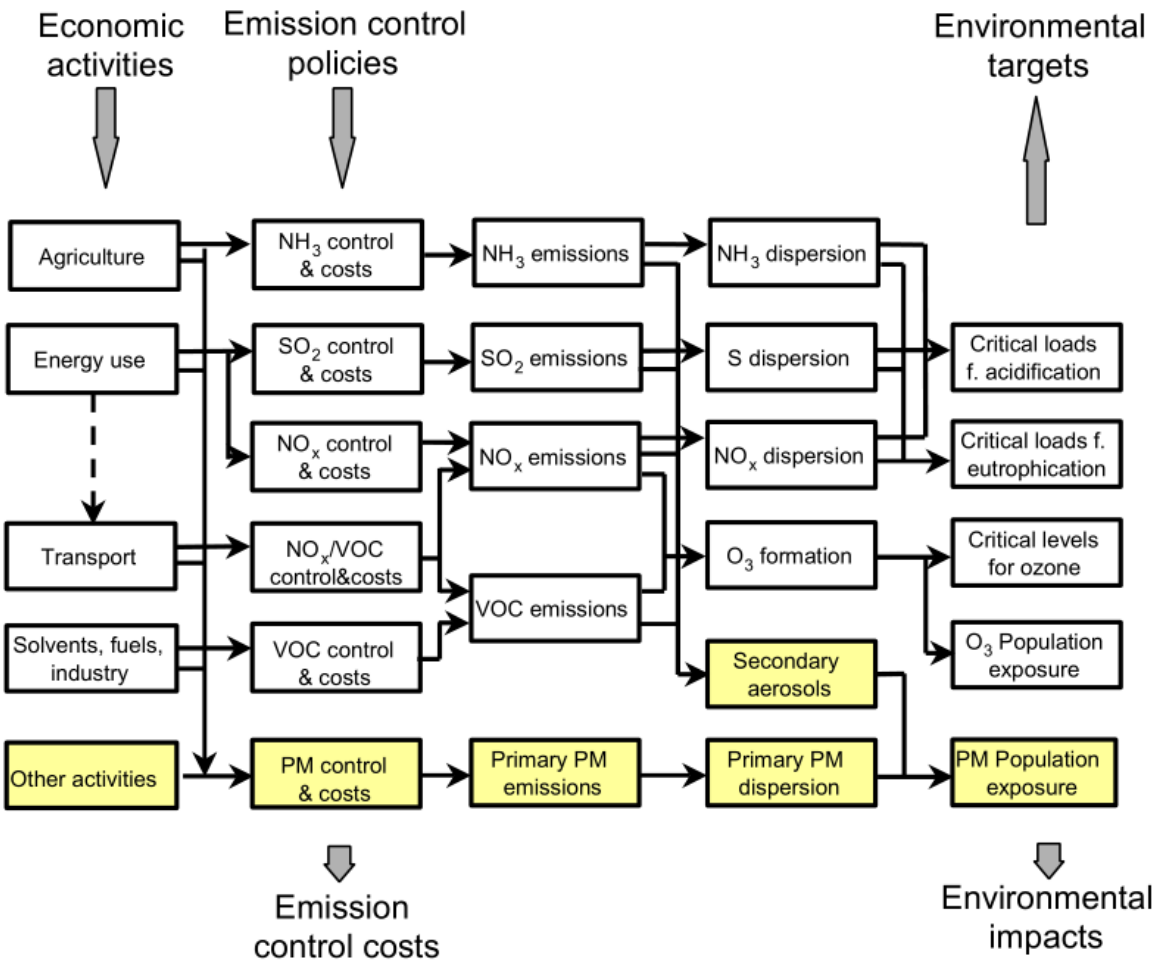


Figure 2-6 Flowchart of the GAINS model to address particulate matter.

Source:(Klimont et al., 2002)

The basic principles of calculating emissions and emission control costs in the model present in GAINS Equation 3 and 4. Components appearing on the right side of the Equation reorganized into three different data categories: activity pathways, emission vectors, and control strategies (*Figure 2-6*). Each emission scenario in GAINS is created through a combination of these three data categories. Emissions-generating economic Activities are organized into activity pathways

which are divided into five groups: Agriculture (AGR), Energy (ENE), Mobile (MOB), Process (PROC), and VOC sources (VOCP). This study mainly focuses on Energy and Mobile sources activity.

GAINS Equation (3):

$$Emissions = \sum_{i,t} A\,ctivity_i \times F_{t,i} \times (1 - R_{t,i}) \times C_{t,i}$$

GAINS Equation (4):

$$Costs = \sum_{i,t} A\,ctivity_i \times U_{t,i} \times C_{t,i}$$

Where

$F_{t,i}$: emission factors of activities,

$R_{t,i}$: removal efficiencies of control technology *t* in activity *i*,

$U_{t,i}$: unit cost of control technology *t* in activity *i*, together with all background information, form the so-called emission vectors.

$C_{t,i}$: control technology for each activity specified in control strategies.

2.4.1 Unit reduction cost calculation in GAINS model

Cost evaluation is to identify the values to society of air pollutants emissions reduction. GAINS model only estimates the cost at production level rather than prices to the consumers. The transfer of money with impacts on the distribution of income or on the competitiveness of market and taxes added to production cost are ignored in this assessment.

The expenditures on emission controls are differentiated into:

Investments

Fixed operation cost

Variable operating cost

GAINS calculates the annual costs per unit of activity level, which is related to ton of pollutant abated (PM_{10}, $PM_{2.5}$ or TSP). This cost also reflects country-specific cost by different

parameters in a given country and its operation regime. More information about air pollution control technology is in the Appendix A3.

The annual cost per unit of activity level is the sum of initial cost, fixed operating cost and variable operating cost.

(1) Initial costs (I): costs related to plant installation, construction and others.

GAINS Equation (5):

$$I = (ci^f + \frac{ci^v}{bs}) \times v \times (1 + r)$$

Where

ci is a coefficient based on investment functions;

bs represents the boiler size;

v represents flue gas volume;

r is the retrofitting cost factor.

The annual average of the initial costs (I^{an}), considering the technical lifetime of the plant (lt), is provided in GAINS Equation 6 by using the real interest rate q.

GAINS Equation (6):

$$I^{an} = I \times \frac{(1 + q)^{lt} \times q}{(1 + q)^{lt} - 1}$$

(2) Fixed operating costs: costs required for maintenance and operation.

The annual fixed operating costs (OM^{fix}) cover the costs for repair and maintenance and are calculated below by using a standard percentage of the total investments (f):

GAINS Equation (7):

$$OM^{fix} = I \times f$$

(3) Variable operating costs: costs incurred through actual use of the plant, and include labor demand, additional energy required to run the device, absorbent (such as lime stone), and byproduct/waste treatment.

The variable operating costs (OM^{var}) are calculated by GAINS Equation 8.

GAINS Equation (8):

$$OM^{var} = \frac{\lambda^l c^l}{pf} + \lambda^e c^e + ef \times \eta(\lambda^s c^s + \lambda^d c^d)$$

Where

λ^l is labor demand;

λ^e is additional energy demand;

λ^s is sorbent demand;

λ^d is byproduct/waste treatment demand;

c^l is labor cost;

c^e is electricity cost;

c^s is sorbent cost;

c^d is byproduct/waste treatment cost;

pf is plant annual operating hours;

ef and η represent the above mentioned emission factor and removal efficiency, respectively.

Finally, two types of unit reduction cost in terms of per unit of activity (C_{PJ}) and per unit of abated emission amount (C_{SO2}) could be calculated by GAINS Equations 9 and 10, respectively.

GAINS Equation (9):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var}$$

GAINS Equation (10):

$$c_{SO_2} = \frac{c_{PJ}}{ef \times \eta}$$

2.4.2 Mitigation technologies and application rate

There are more than thousands of emission air pollutant control options in GAINS model, but not all the technologies are selected and only a few mitigation technologies are selected in GAINS-

China model based on China's real situation. The mitigation technologies are listed in *Table A-1* As for the technology penetration rates, they are given according to sectors, fuel types, regions and air pollutants (SO_2, NO_x, PM). Hence, it is difficult to list all the penetration rates. Tables show the SO_2 mitigation technology penetration rate in different scenario years by taking Beijing as an example (*Table A-2*).

2.4.3 Conversion tables

Conversion tables are developed to make the database of the two models match each other. There are two types of conversion tables, namely conversion table for sector integration and fuel type integration. Each type of conversion tables is given in *Table* A-2 and *Table* A-2 by taking Beijing 2005 as an example.

In this study, GAINS-China model is used to calculate air pollutants emissions and provincial concentration. It can provide quick simulation for emissions and $PM_{2.5}$ concentration.

2.5 Models coupling

To calculate air pollutants emissions, this study combines AIM/CGE-China model and GAINS-China model. AIM/CGE-China model provides energy consumption data to GAINS-China model, then GAINS-China model calculates air pollutant primary emissions data. The structures of two models are little different. *Figure 2-7* shows the detailed information about two models. They cover 30 provinces of China. The period is from 2002 to 2030 in AIM/CGE-China model, and it has 22 sectors and five kinds of fuel. The period is from 2005 to 2030 in GAINS-China model, and it has five main sectors and 51 subsectors and 18 kinds of fuel. Energy consumption data by sector, fuel and region from AIM/CGE-China model is provided to GAINS-China model. GAINS-China model can calculate air pollutants emissions and mitigation cost.

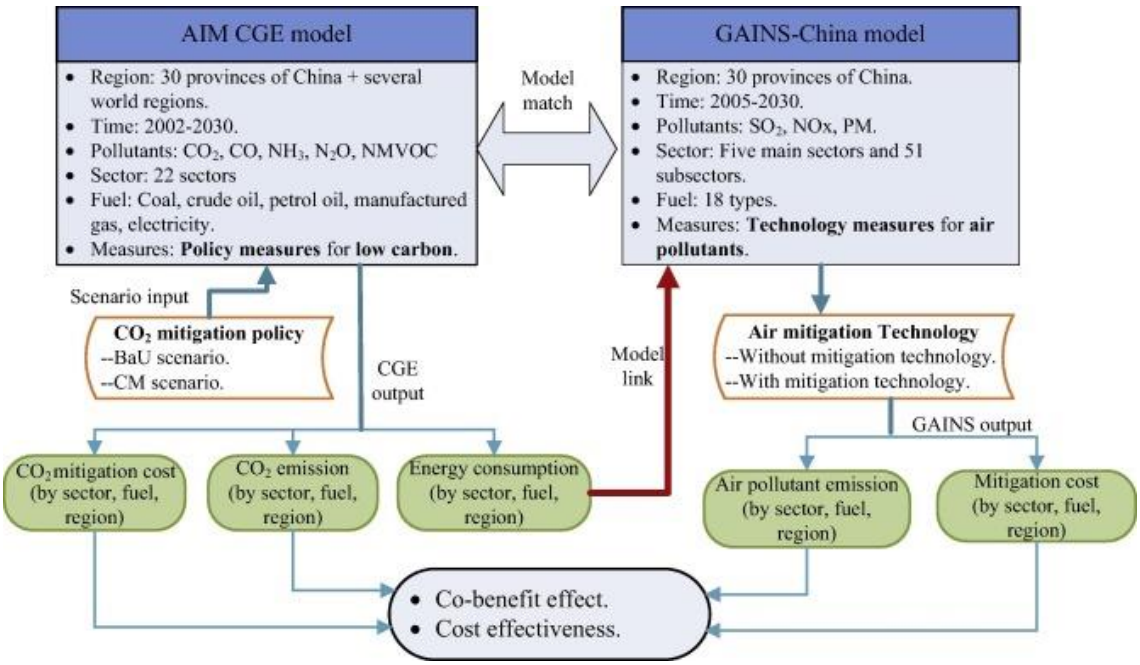


Figure 2-7 Models coupling of AIM/CGE-China and GAINS-China.

Source:(Dong et al., 2015)

2.6 GEOS-Chem model

2.6.1 General introduction

GEOS-Chem is a global 3-D chemical transport model (CTM) for atmospheric composition driven by meteorological input from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office(GMAO). It has wide applications, such as chemical transport, chemical budgets, flux inversions, climate forcing, air quality, ecosystem exchange, satellite retrievals and diagnostic studies. Its input data is GMAO meteorology data and detailed emission data, calculated by detailed time step models, for example, transport, convection, chemistry and photolysis.

The Chinese air quality is simulated in the global chemical transport model, GEOS-Chem (Atmospheric transport and chemistry model) (http://acmg.seas.harvard.edu/geos/). Simulations are performed at 1/2 degree latitude by 2/3 degree longitude horizontal resolution over China region embedded in a 4-degree latitude by 5-degree longitude global simulation. The global model

provides initial and boundary conditions for the China domain. The model is driven by the meteorological data from the Goddard Earth Observing System (version 5) of the NASA Global Modeling Assimilation Office. The model contains 47 vertical layers up to 0.01 hPa. GEOS-Chem uses the same advection algorithm with the GEOS general circulation model (http://gmao.gsfc.nasa.gov/GEOS/). Convective transport in GEOS-Chem is computed from the convective mass fluxes in the meteorological archive. Boundary layer mixing in GEOS-Chem is calculated by a non-local scheme. The wet deposition by rain is considered for both water-soluble aerosols and gasses, and the scavenging by snow and cold/mixed precipitation is also considered for aerosol. Dry deposition is calculated based on the resistance-in-series scheme for all the species with gravitational settling for dust and coarse sea salt.

2.6.2 Model chemistry

GEOS-Chem includes a detailed chemistry for 156 gas phase and aerosol phase species and 479 chemical reactions. The simulation contains a gas phase HO_x-NO_x-VOC-ozone-BrOx chemistry, which considers the production and loss of ozone through reacting with HO_x, NO_x, VOC and BrOx. GEOS-Chem also includes a detailed sulfate-nitrate-ammonium-carbonaceous-dust-seasalt aerosol chemistry, which is coupled to gas phase chemistry. GEOS-Chem considers the thermodynamics of inorganic aerosols and the incloud sulfate formation based on cloud water pH. Besides the directed emitted primary organic aerosol(POA), the formation of secondary organic aerosol(SOA) by reversible partitioning of semi-volatile products of VOC oxidation is also included in GEOS-Chem for the oxidation products of terpene, isoprene and aromatic hydrocarbons. GEOS-Chem also considers the formation of SOA from aerosol uptake of glyoxal and methylglyoxal. On top of the anthropogenic fraction of aerosol, GEOS-Chem simulates the dust and the sea salt aerosol in different size bins. Aerosols interact with gas-phase chemistry in GEOS-Chem through the effect of aerosol extinction on photolysis rates, heterogeneous chemistry, and gas-aerosol partitioning of semi-volatile compounds.

Because GAINS-China model can only provide provincial $PM_{2.5}$ concentration data, this study uses GEOS-Chem model to simulate gridded $PM_{2.5}$ and ozone concentration in 30 provinces of China. Air pollutant concentration is quite different even in the same province, and gridded concentration data can reflect the real situation as accurate as possible. AIM/CGE-China model provides energy consumption data to GAINS-China model. GAINS-China model calculates air

pollutants primary emissions, which is the input data to GEOS-Chem model. GEOS-Chem model simulates gridded $PM_{2.5}$ and ozone concentration for this study.

2.7 Scenarios

2.7.1 Air pollutants control scenarios

Three scenarios are constructed in this study, namely, Reference, WoPol and WPol scenarios, based on the air pollution control policy.

Reference scenario assumes that the health impacts air pollution are ignored, regardless of how serious the pollution is. There is no additional health service cost, premature death, or work day loss from $PM_{2.5}$ pollution. The scenario simulates an ideal situation that does not exist but can be used to evaluate the negative impacts of pollution and benefits by comparing with the other scenarios. In addition, this scenario provides assumptions of the future social-economic development, mainly including GDP and population, and data on $PM_{2.5}$ concentration.

WoPol: This scenario corresponds no-Tech scenario in Reference (Dong et al., 2015) which assumes penetration rate of mitigation technology remains the same as 2005 and additional emissions from energy combustion remain uncontrolled throughout the modeling period. It does not represent reality but is meant to show the impact of air quality policies.

WPol: This scenario corresponds no-Tech scenario in Reference (Dong et al., 2015) which reflects current air pollution policies in China, considering sectoral and provincial differences on emission limit values and time of their introduction. WPol assumes the existence of intensive air-pollution-control technologies. Various air-pollution-control technologies are used to reduce pollutant emissions and $PM_{2.5}$ concentration to levels much lower than those in reference and WoPol scenario. See *Table A-1* and *Table A-2* for more information about the technology penetration rate.

Also, this study also set up a scenario named WPol2 from GEOS-Chem simulation, in which more intensive air pollutant control technologies are adopted, and emissions of NOx, VOC, CO are further reduced by 50% and CH_4 is further reduced by 20% from the WPol scenario in 2030. This scenario is used for probing sensitivity of ozone pollution control. However, the ozone-related primary emissions reduction also have impact on $PM_{2.5}$ concentration.

$PM_{2.5}$ is the main air pollutant in urban area in China recently, especially in north and east of China, developed regions with high population density. In this section, $PM_{2.5}$ concentration is simulated by GAINS-China model and GEOS-Chem model. Health impacts are quantified by health assessment model. Economic impacts are assessed by AIM/CGE-China model.

2.7.2 Shared socioeconomic pathways2(SSP2)

The SSPs database is quantitative projections related Integrated Assessment scenarios (Riahi et al, 2016). The SSPs are used to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (van Vuuren et al., 2014; O'Neil et al., 2014). This study adopts the population, GDP and urbanization data from SSP2. The SSP2 narrative describes a middle-of-the-road development in the mitigation and adaptation challenges space. The SSP2 marker implementation reflects an extension of the historical experience, particularly regarding carbon and energy intensity improvements in its baseline, which leads to a steady emissions increase over the 21st century. The SSP2 can serve as a starting point to further explore integrated solutions for achieving multiple societal objectives in light of the climate adaptation and mitigation challenges that society could face over the 21st century (Fricko et al.,2016).

2.7.3 Energy consumption

AIM/CGE-China model provides energy consumption data to GAINS-China model to calculate carbon emissions and air pollutants emission. Chapter 3,4 and 5 share the same energy consumption data for $PM_{2.5}$ and ozone impacts assessment. *Figure 2-8* shows the energy consumption from 2005 to 2030 in 30 provinces in China. In 2030, energy consumption is about 31000 Mtce. Coal is the main energy and takes first place in 30 provinces in China; second is crude oil, third is petrol oil. Gas and electricity are quite low in China. From this result, higher energy consumption provinces are Hebei (410 Mtce), Shanxi (610 Mtce), Jiangsu (430 Mtce), Shandong (390 Mtce), Henan (330 Mtce), Guangdong (330 Mtce), Zhejiang (260 Mtce) and Anhui (320 Mtce) province. Energy consumption is much lower in Hainan (9.5 Mtce), Qinghai (46 Mtce), Xinjiang (91 Mtce), Ningxia (89 Mtce) in 2030.

In Beijing, energy consumption is very low and total energy consumption is about 76Mtce. The energy is 32Mtce (43%)from coal, 9.9(13%) from crude oil, 10 (13%) from petrol oil, 18 Mtce (23%) from electricity and 6.0 Mtce (7.9%) from gas. In Shanghai, total energy consumption is

about 160 Mtce. The energy is 79 Mtce (50 %)from coal, 20 Mtce (13 %) from crude oil, 31 Mtce (20%) from petrol oil, 23 Mtce (15%) from electricity and 5.2 Mtce (3.3%) from gas. Guangdong consumes more petrol oil than other provinces, about 140 Mtce (42 %)from coal, 28Mtce (8.4 %) from crude oil, 92 Mtce (28%) from petrol oil, 71 Mtce (21%) from electricity and 0.6 Mtce (0.2%) from gas. In Beijing-Tianjin-Hebei region, energy consumption in Hebei is 410 Mtce, which is 5.4 times in Beijing and 3.2 times in Tianjin.

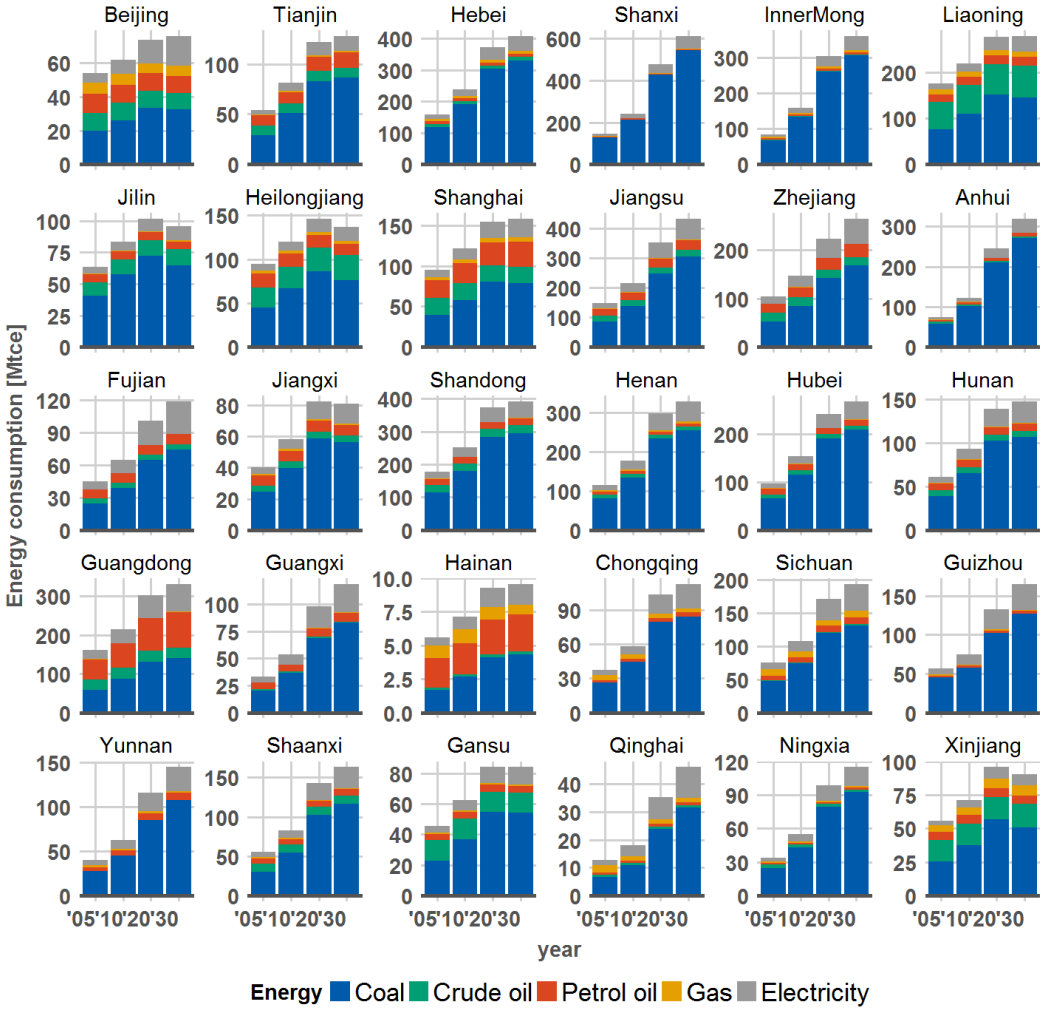


Figure 2-8 Energy consumption from 2005 to 2030 in 30 provinces in China.

2.7.4 Air pollutants emissions

Based on the energy consumption data (*Figure 2-8*), GAINS-China model calculates the carbon emissions and air pollutant emissions. The primary emissions of air pollutant are the same as used in (Xie et al., 2016) and (Dong et al., 2015). It could be seen that emissions (*Figure 2-9*) in the WPol scenario are much lower than WoPol scenario in the whole periods. Using these emission pathways as inputs for the GAINS model and GEOS-Chem model to calculate the $PM_{2.5}$ and ozone concentration.

For the national primary emissions, air pollutants include SO_2, NO_x, VOC, PM_{10}, CO, CH_4 and $PM_{2.5}$. All the air pollutants emissions increase from 2005 to 2030 in WoPol scenario. The total SO_2 emission in 2030 will be 93 Mt, which is 2.6 times that of 2005 level in WoPol scenario. While in the in WPol scenario, the total SO_2 emission will be 43 Mt, which is 1.5 times that of the 2005 level. In WoPol scenario, NO_x, VOC, CO, CH_4 and $PM_{2.5}$ emissions in 2030 will reach 30 Mt and 150 Mt, respectively. However, with air pollution control policy measures, NO_x, VOC, CO, CH_4 and $PM_{2.5}$ emissions will be 15 Mt and 38 Mt in WoPol scenario in 2030, respectively. In the WPol2 scenario, ozone-related primary air pollutant, including NO_x, VOC, CO, CH_4 was further reduced than WPol scenario. NO_x, VOC, CO emissions are the 50% of emission and CH_4 is the 80% in WPol scenario.

Power generation sector and industrial sector are main sources of SO_2 emissions, accounting for about 58% and 38% of the total emissions, respectively. While for NO_x, transport sector is another important emission source besides power generation sector and industrial sector. For $PM_{2.5}$, power generation sector is the main source of $PM_{2.5}$ emissions, followed by industrial process sector and industrial sector.

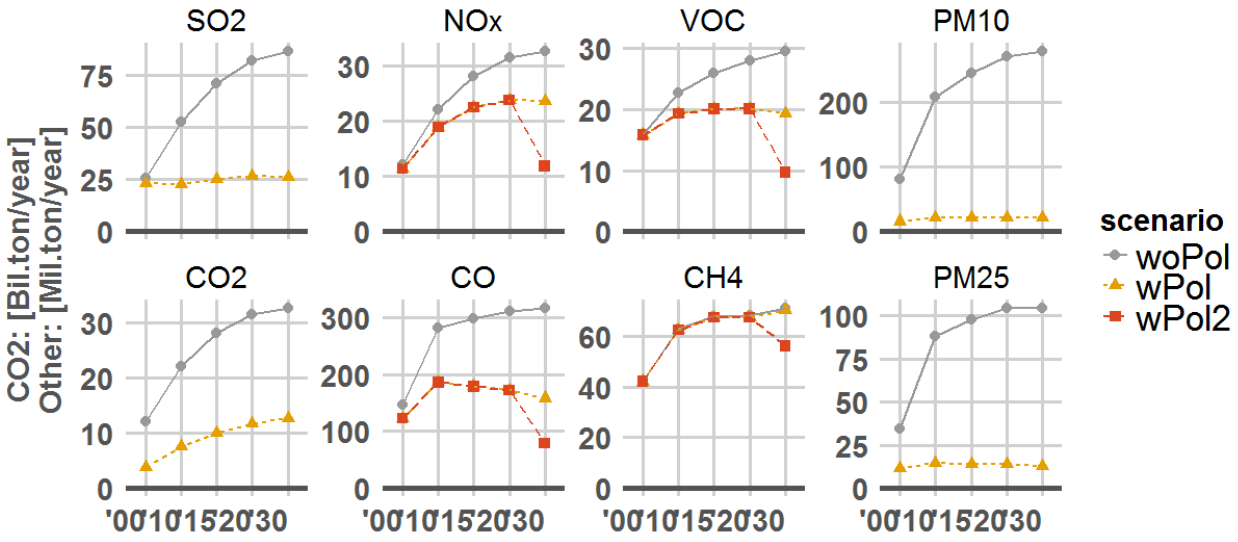


Figure 2-9 Primary air pollutants emission in China in different scenarios.

2.7.5 Exposure population

Population distribution and their spatio-temporal variation are a direct representation of urbanization in China. In the past 3-dacades, China encounters fast urbanization and the population density in urban area is increasing. *Figure 2-10* shows the population density in 2010 in China. Most of the population distributes in the east part of China. Beijing, Shanghai and Guangdong have higher population density. Hebei, Jiangsu, Shandong, Henan, Guangdong and Sichuan provinces have large population. The population exposed to air pollution will also change a lot in the future. One study in China shows that population projection in the future is one of most important factor to evaluate the health impact of air pollution, the other one is the emissions projection (Madaniyazi et al., 2015).

Population projection in the future is related to base year population, births rate, deaths rate and net migrants. Shared Socio-economic Pathways (SSP2) characterized by moderate economic growth, fairly rapid growing population and lessened inequalities between industrialized, emerging and developing world regions (Kriegler et al., 2014). Following this storyline, the future GDP growth rates of emerging and developing countries will be higher than those for

industrialized countries (H. Dai, Mischke, et al., 2016). This study adopts population projection from SSP2. In this study, labor population is the people age between 15 to 65 years old. Health impact on this group not only increases health expenditure, but also increases the work day loss due to morbidity and mortality.

In this study, two kinds of population data are used to calculate the exposure population province population data and grid population data. For the health and economic impact of $PM_{2.5}$ pollution, provincial average concentration data and provincial population data are used. For the health and economic impact of ozone pollution, grid concentration and grid population data are used.

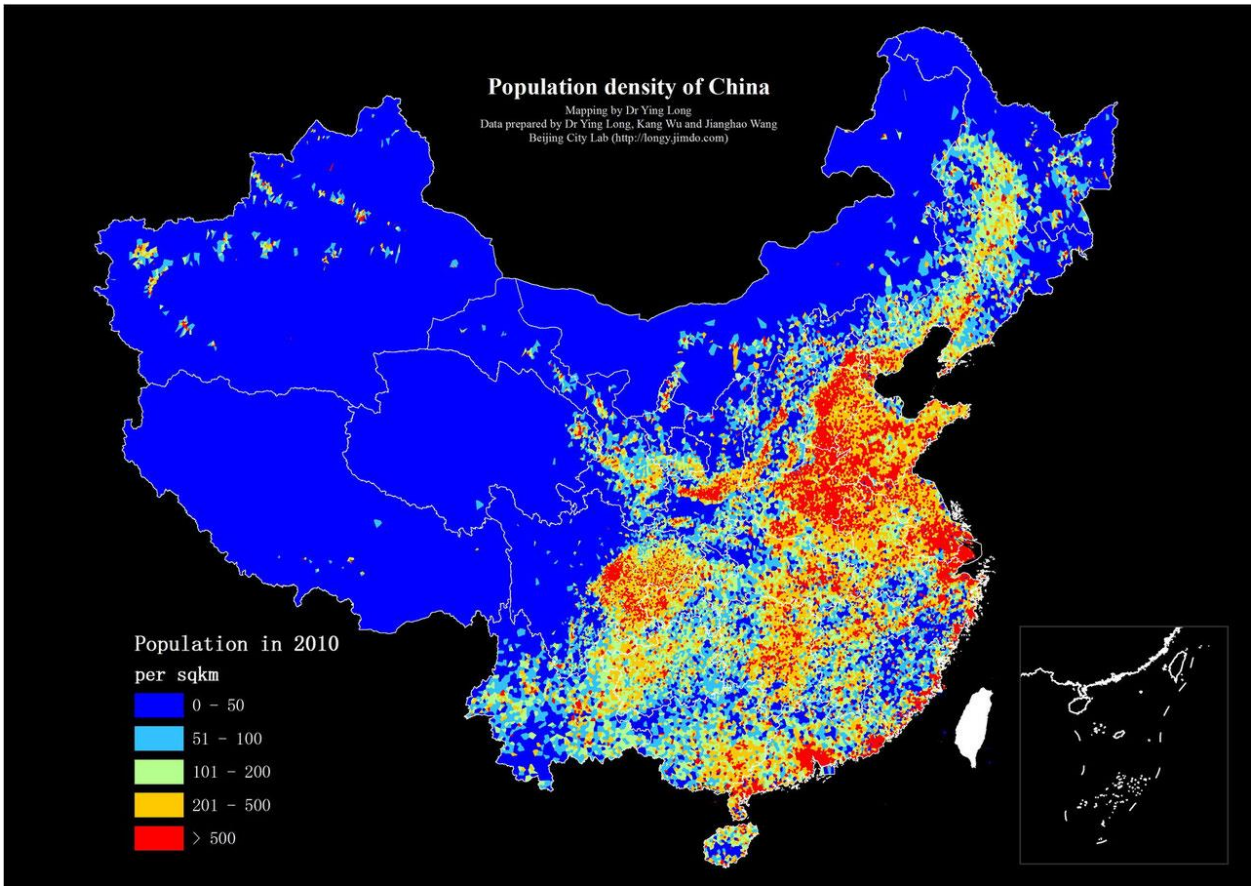


Figure 2-10 Population density in 2010 in China.

Source: (Mao et al., 2015).

This study evaluates the health impacts for different age group, so age-specific population projection from SSP2 scenario is adopted. *Figure 2-11* shows the age-specific population from 2005 to 2030 in 30 provinces. Henan, Shandong, Guangdong, Sichuan, Jiangsu, Hebei provinces have larger population. With the improvement of medicine and life quality, Chinese life expectancy is increasing every year, which is getting close to developed countries. Moreover, one child policy lasted over 30 years, China has a very low birth rate, comparing to other developing countries. China is becoming an aging country. Labor age population is decreasing and population over 65-year-old is increasing.

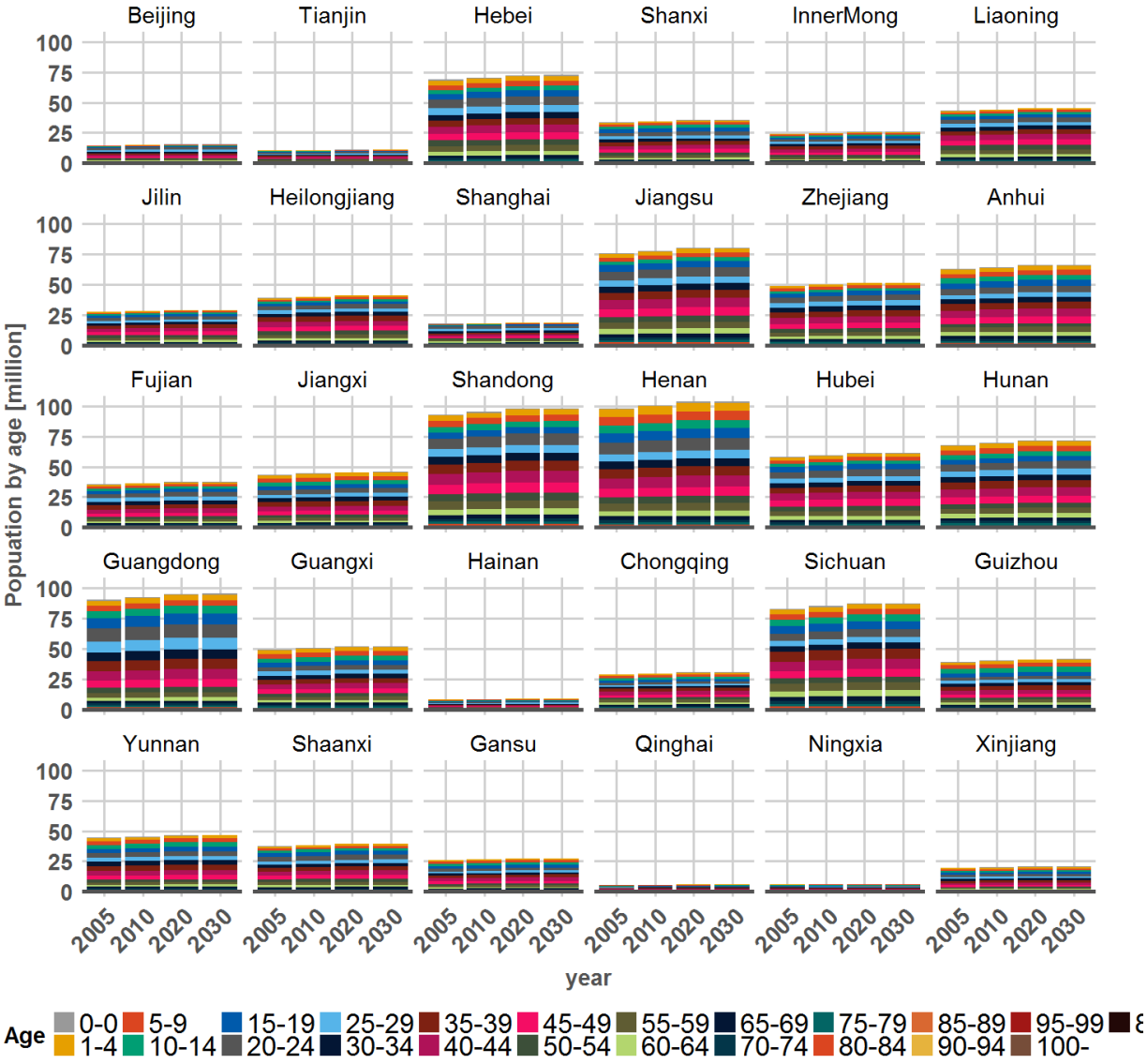


Figure 2-11 Age-specific population from 2005 to 2030 in 30 provinces in China.

3 Health and economic impacts of $PM_{2.5}$ pollution in China

This study evaluates the $PM_{2.5}$ pollution-related health impacts on the national and provincial economy of China using a Computable General Equilibrium (CGE) model. Results show that the health and economic impacts may be substantial in provinces with high $PM_{2.5}$ concentration. In the WoPol scenario without air pollution control policy, this study estimates that China experiences a 2.0% GDP loss and 210 billion CNY in health expenditure from $PM_{2.5}$ pollution in 2030. By contrast, with control policy in the WPol scenario, a control cost of 830 billion CNY (0.79% of GDP) versus a net benefit of 0.38% of China's GDP from improving $PM_{2.5}$ pollution are projected. At the provincial level, GDP loss in 2030 in the WoPol scenario is high in Tianjin (3.1%), Shanghai (3.0%), Henan (2.3%), Beijing (2.8%), and Hebei (2.6%). The top five provinces with highest additional health expenditure are Henan, Sichuan, Shandong, Hebei and Jiangsu. Controlling $PM_{2.5}$ pollution could bring net positive benefits in two-thirds of provinces in China, Tianjin, Shanghai, Beijing, Henan, Jiangsu, and Hebei experience most benefit from air pollution control technology, and these provinces have higher $PM_{2.5}$ pollution and dense population distribution. Conversely, net benefits are negative in Ningxia, Guizhou, Shanxi, Gansu and Yunnan provinces with low GDP loss but relatively high control cost.

3.1 Methodology

This study combines the GAINS-China model, Asia-Pacific integrated assessment AIM/CGE-China model, and a health assessment model. The GAINS-China model provides annual average $PM_{2.5}$ concentration data for 30 provinces in China. The health assessment model is developed to quantify the health impacts of $PM_{2.5}$ pollution in 30 provinces, separately. Health impacts as a result of mortality and morbidity are converted to annual total medical expenditure and per capita work loss caused by $PM_{2.5}$ pollution, which is then used as a change in the household expenditure pattern and labor participation rate by the CGE model to determine the macroeconomic impacts. AIM/CGE-China model has already been introduced in methodology chapter.

This study quantifies several kinds of health endpoints related to $PM_{2.5}$ pollution. By using statistical data of health expenditure for some health endpoint, this study does regression analysis with per capita GDP and predicts health service price for each health endpoint in the future.

3.2 Simulation result

3.2.1 $PM_{2.5}$ concentration

AIM/CGE-China model provides energy consumption data to GAINS-China model. The GAINS-China model calculates air pollutants and the annual average $PM_{2.5}$ concentration for 30 provinces in 2030 in China (*Figure 3-1*). In the most provinces, simulation results show that $PM_{2.5}$ pollution is very serious and $PM_{2.5}$ concentration in both scenarios is much higher than national standard 35 ug/m^3 and WHO standard 10 ug/m^3 in 2030. However, $PM_{2.5}$ concentration is different from region to region. The $PM_{2.5}$ concentration is much higher in the east of China, especially on the North China Plain, the populous region with more industry. While in the area with less industry and less population, $PM_{2.5}$ concentration is lower. Because $PM_{2.5}$ pollution is related to human activity, especially fossil fuel combustion. Developed area consume more energy and have larger air pollutant emissions.

$PM_{2.5}$ concentration is quite high in China, but air pollution control policy can reduce $PM_{2.5}$ concentration significantly. This study compares $PM_{2.5}$ concentration in two scenarios. In the WoPol scenario, $PM_{2.5}$ concentration far exceeds the national standard. Even in the WPol scenario, the $PM_{2.5}$ concentration in most provinces exceeds the national standard and the WHO standard. But in most provinces, $PM_{2.5}$ concentration reduction in WPol scenario is about 75% than WoPol scenario. In 2030 of WoPol scenario, the top six polluted provinces or cities are Shanghai (420 ug/m^3), Tianjin (420 ug/m^3), Beijing (380 ug/m^3), Hebei (350 ug/m^3), Henan (360 ug/m^3), and Shandong (330 ug/m^3). These most polluted provinces also encounter most reduction from air pollution control technology. In the WPol scenario, air pollution control technology significantly decreases the $PM_{2.5}$ concentration by around 65% to 80% in most provinces. The top six provinces in terms of the rate of reduction in the WPol scenario are Shanghai (by 82% to 77 ug/m^3), Tianjin (by 81% to 80 ug/m^3), Beijing (by 78% to 82 ug/m^3), Zhejiang (by 77% to 59 ug/m^3), Jiangsu (by 76% to 85 ug/m^3), Liaoning (by 75% to 47 ug/m^3), and Shandong (by 75% to 83 ug/m^3).

The $PM_{2.5}$ concentration is much lower in Hainan (76 and 24 ug/m^3), Gansu (95 and 33 ug/m^3), Qinghai (76 and 25 ug/m^3), Xinjiang (36 and 14 ug/m^3), and Heilongjiang (58 and 19 ug/m^3), undeveloped provinces without dense industry than in the developed provinces. Even so, the $PM_{2.5}$ concentration in the WPol scenario in these undeveloped provinces still exceeds the WHO standard. The reduction rate in these regions is lower than developed regions.

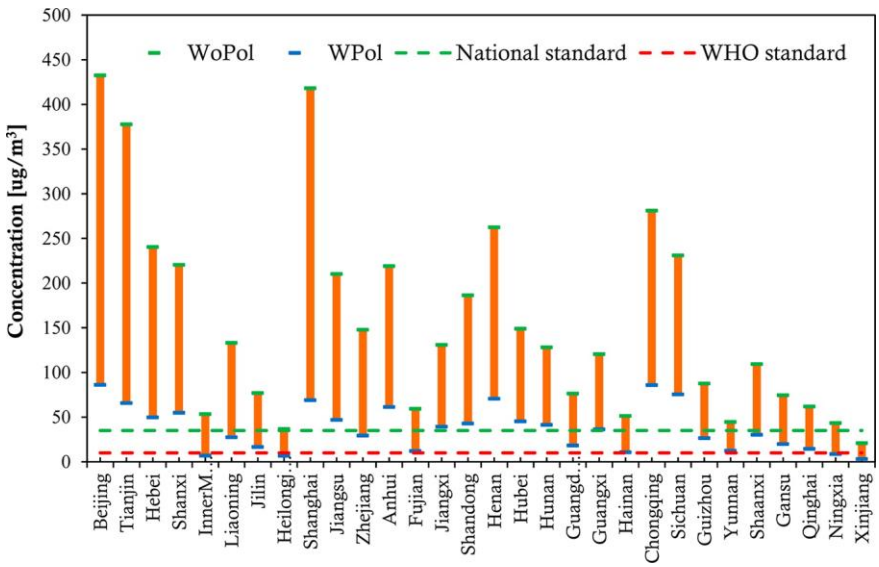


Figure 3-1 Provincial $PM_{2.5}$ concentration in WoPol and WPol scenario in 30 provinces in China.

GAINS-China model calculates the provincial annual average $PM_{2.5}$ concentration in 30 provinces. Beside provincial concentration, GEOS-Chem model is also used to simulate the grid $PM_{2.5}$ concentration and seasonal concentration data in WoPol and WPol. *Figure 3-2* shows the $PM_{2.5}$ concentration reduction from WPol to WoPol scenario and from WPol2 to WoPol scenario. $PM_{2.5}$ concentration reduction is significant in east part of China, where is the developed region. In the WPol2 scenario, $PM_{2.5}$ concentration reduction is higher than WPol scenario.

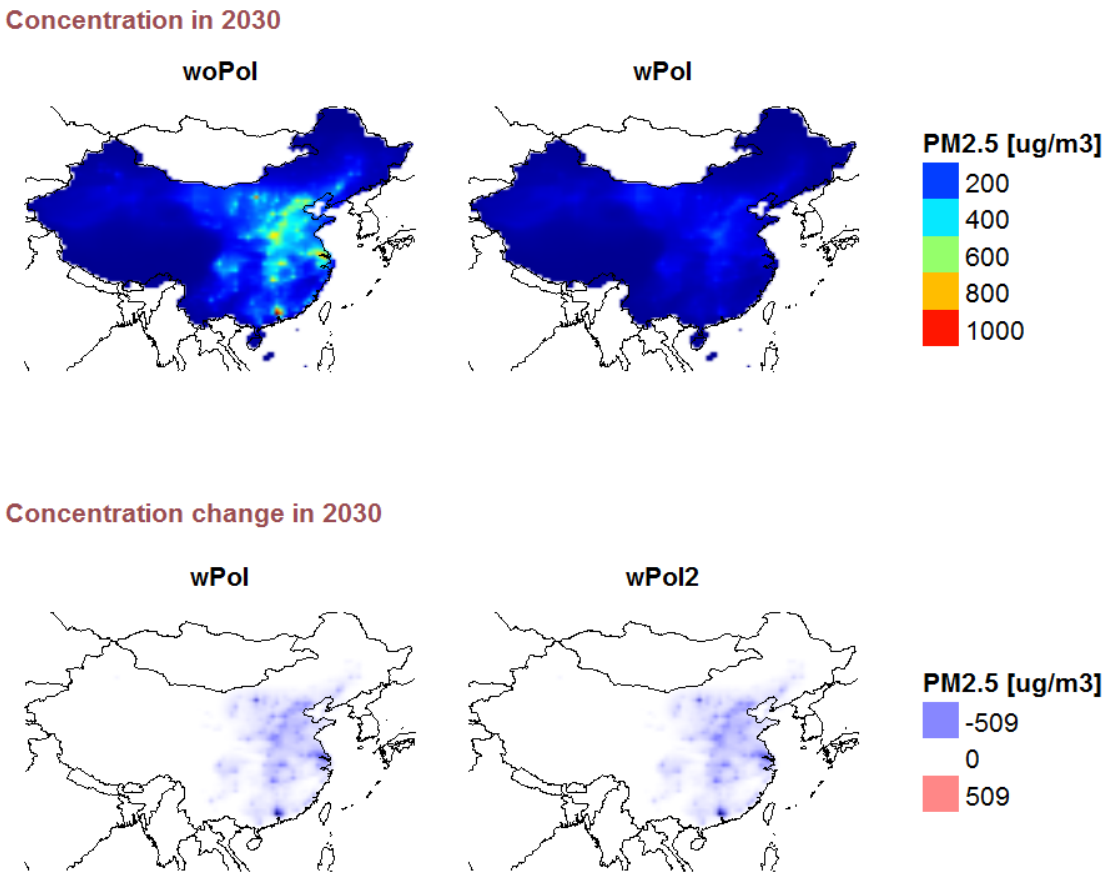


Figure 3-2 $PM_{2.5}$ concentration in WoPol and WPol scenarios (upper) and change from WoPol to WPol and WPol2 scenarios (lower).

Figure 3-3 shows the $PM_{2.5}$ concentration in different seasons and different scenarios. Results show that $PM_{2.5}$ concentration is highest in winter and lowest in summer. $PM_{2.5}$ concentration is almost similar in spring and autumn. One of the most important reasons is that north area consumes more energy for heating in winter, especially increasing in coal consumption. Moreover, in winter, most of the land in the north region is bare, which also increase the $PM_{2.5}$ concentration.

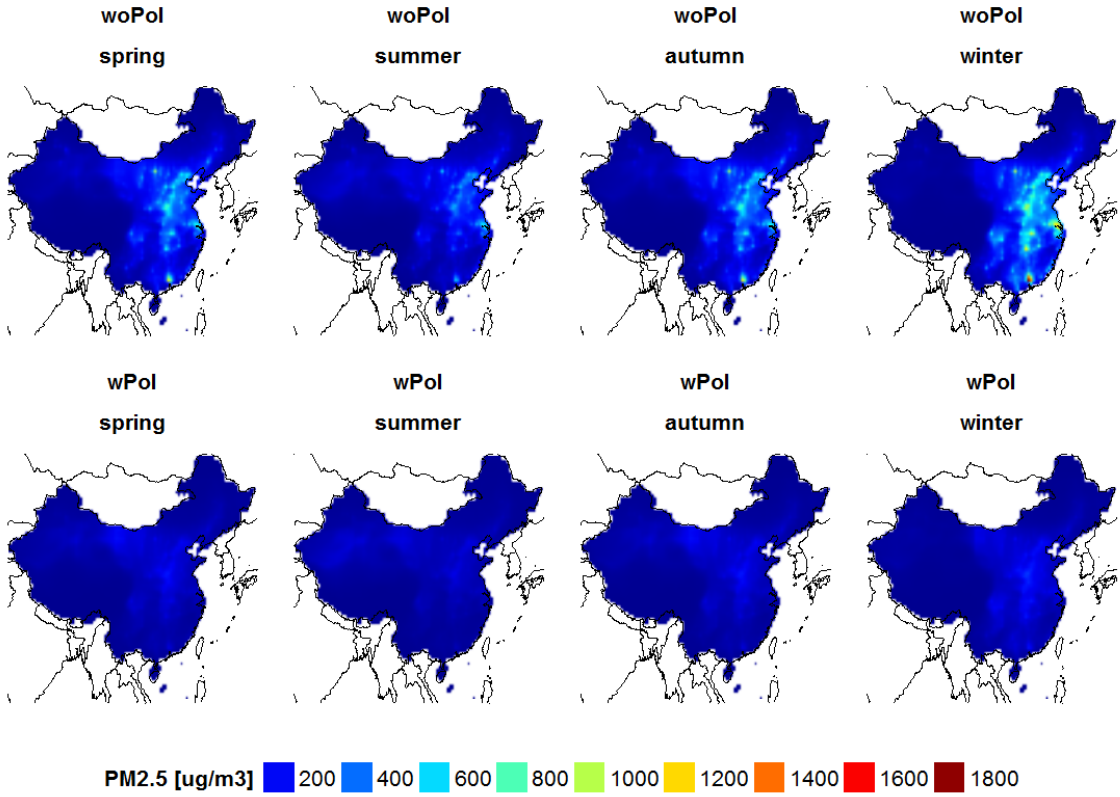


Figure 3-3 Seasonal variation of concentration of $PM_{2.5}$ in 2030 in China.

3.2.2 Health impact of $PM_{2.5}$

Many cohort studies show that $PM_{2.5}$ pollution increases all-cause mortality. *Table 3-1* shows the mortality and 95% confidence interval in 30 provinces in WoPol and WPol scenario based on the concentration from GAINS-China model. Mortality is 9.2 (0.36-9.7) million and 2.3 (0.09-2.4) million people in WoPol and WPol scenario in 2030 in China, which is similar to other studies. At the provincial level, provinces with higher population density, such as Henan, Shandong, Jiangsu, Hebei and Sichuan, have larger mortality. The mortality in these five provinces is 1000 (77-2100), 900 (67-1800),780 (58-1600),710 (53-1400) and 690 (53-1400) thousand people in WoPol scenario, respectively. While the mortality is 270 (20-550), 200 (15-410),170 (13-340), 140 (11-290) and 220 (17-450) thousand people in WPol scenario in 2030, respectively. In those provinces with better air quality and few population, such as Hainan, mortality is 16 and 3.4 thousand people in WoPol and WPol scenario in 2030.

Table 3-3 shows the mortality in 30 provinces under different solutions. Mortality is higher from GEOS-Chem simulation than GAINS-China. That because the urban area with higher population density has worse air quality. Provincial average concentration may underestimate the population conditioned exposure. Similar studies also can be found in the USA (Punger and West, 2013).

In most provinces, mortality from GEOS-Chem model concentration is higher than GAINS-China. *Table 3-3* shows the comparison of mortality from GEOS-Chem model and GAINS-China model. In the provinces or cities with higher population density, mortality in WoPol scenario from GAINS-China simulation is lower than GEOS-Chem model, such as Beijing, Tianjin and Shanghai. Provinces with lower population density mortality from GAINS-China simulation is higher than GEOS-Chem model in WoPol scenario, such as Hebei, Shandong, Sichuan, Guangxi and Guizhou. Mortality in these provinces are 710 and 700, 900 and 820, 690 and 200, 260 and 190, 230 and 140 thousand people from GAINS-China and GEOS-Chem model. The mortality in these provinces, such as Sichuan, Guizhou, Yunnan and Chongqing is quite different from two kinds of air quality models.

Table 3-1 Mortality due to $PM_{2.5}$ pollution in 30 provinces in 2030 in China based on GAINS-China model (Unit: thousand people)

Scenario	WoPol			WPol		
Region	C.I.95% low	ER function	C.I.95% high	C.I.95% low	ER function	C.I.95% high
Beijing	12	160	320	2.4	32	63
Tianjin	9.5	130	250	1.6	22	43
Hebei	53	710	1400	11	140	290
Shanxi	19	250	500	4.6	61	120
InnerMong	3.1	41	82	0.41	5.4	11
Liaoning	17	230	470	3.6	48	96
Jilin	6.1	82	160	1.3	18	35
Heilongjiang	4.2	57	110	0.80	11	21
Shanghai	16	220	430	2.6	35	70
Jiangsu	58	780	1600	13	170	340
Zhejiang	27	360	720	5.4	71	140
Anhui	41	540	1100	11	150	300
Fujian	10	140	270	2.1	28	56
Jiangxi	20	260	520	5.8	78	160
Shandong	67	900	1800	15	200	410
Henan	77	1000	2100	20	270	550
Hubei	33	440	870	10	130	260
Hunan	35	470	930	11	150	300
Guangdong	40	540	1100	10	130	260
Guangxi	19	260	510	5.7	76	150
Hainan	1.2	16	32	0.26	3.4	6.8
Chongqing	20	270	550	6.2	82	160
Sichuan	52	690	1400	17	220	450
Guizhou	17	220	450	5.0	67	130
Yunnan	8.2	110	220	2.3	30	61
Shaanxi	18	240	480	5.0	66	130
Gansu	5.0	66	130	1.3	18	35
Qinghai	0.80	11	21	0.19	2.5	5.0
Ningxia	1.3	18	35	0.27	3.6	7.1
Xinjiang	1.2	15	31	0.18	2.4	4.8
China	360	9200	9700	89	2300	2400

Table 3-2 Mortality due to $PM_{2.5}$ pollution in 30 provinces in 2030 in China based on GEOS-Chem model (Unit: thousand people).

scenario	WoPol			WPol		
Region	C.I.95% low	ER function	C.I.95% high	C.I.95% low	ER function	C.I.95% high
Beijing	31	200	510	10	66	170
Tianjin	27	180	450	7.6	49	130
Hebei	130	830	2100	38	250	630
Shanxi	62	400	1000	22	140	360
InnerMong	13	86	220	6.0	39	98
Liaoning	42	270	690	13	81	210
Jilin	12	79	200	3.7	24	61
Heilongjiang	6.4	42	110	1.7	11	29
Shanghai	47	300	770	7.5	49	120
Jiangsu	17	1100	2700	31	200	520
Zhejiang	48	310	800	7.6	50	130
Anhui	91	590	1500	24	150	390
Fujian	25	160	4100	4.3	28	71
Jiangxi	45	290	740	10	67	170
Shandong	150	960	2500	38	240	620
Henan	230	1500	3800	78	510	130
Hubei	90	590	1500	27	180	450
Hunan	86	560	1400	23	150	370
Guangdong	110	690	1800	16	100	260
Guangxi	34	220	5700	8. 8	57	140
Hainan	0.00	0.03	0.07	0.00	0.00	0.00
Chongqing	29	190	480	9.6	62	160
Sichuan	37	240	620	13	85	220
Guizhou	26	170	420	8.3	54	140
Yunnan	10	63	160	2.2	14	36
Shaanxi	43	280	700	17	110	280
Gansu	15	96	240	9.6	63	160
Qinghai	0.76	4.9	12	0.52	3.3	8.5
Ningxia	6.1	39	100	2.7	18	45
Xinjiang	3.6	23	60	3.1	20	51
China	1600	10000	27000	440	2900	7300

Table 3-3 Comparing mortality due to $PM_{2.5}$ pollution in 2030 in China between GAINS-China and GEOS-Chem models (Unit: thousand people).

model	GAINS-China		GEOS-Chem	
Region	WoPol	WPol	WoPol	WPol
Beijing	160	32	170	56
Tianjin	130	22	150	42
Hebei	710	140	700	210
Shanxi	250	61	340	120
InnerMong	41	5.4	73	33
Liaoning	230	48	230	69
Jilin	82	18	67	20
Heilongjiang	57	11	35	9.5
Shanghai	220	35	26	41
Jiangsu	780	170	910	170
Zhejiang	360	71	270	42
Anhui	540	150	500	130
Fujian	140	29	140	24
Jiangxi	260	78	250	57
Shandong	900	200	820	210
Henan	1000	270	1200	430
Hubei	440	130	500	150
Hunan	470	150	470	120
Guangdong	540	1200	580	87
Guangxi	260	76	190	48
Hainan	16	3.4	0.00	0.00
Chongqing	270	82	160	52
Sichuan	690	220	200	72
Guizhou	220	67	14	45
Yunnan	110	30	54	12
Shaanxi	240	66	230	94
Gansu	66	18	81	53
Qinghai	11	2.5	4.1	2.8
Ningxia	18	3.6	33	15
Xinjiang	15	2.4	20	17
China	9200	2300	8800	2400

Morbidity is another important impact of air pollution on human health. Many studies show that exposure to high level of $PM_{2.5}$ pollution is closely associated with numeric increases in emergency visits, outpatient visits, and hospital admissions for respiratory, cardiovascular, and cerebrovascular diseases.

Table 3-4 Morbidity due to $PM_{2.5}$ pollution in 2005 and 2030 in China (Unit: million case).

Year	2005		2030	
Health endpoint	WoPol	WPol	WoPol	WPol
Total health endpoint	140	60	280	70
Chronic bronchitis	7.4	3.1	14	3.6
Asthma	20	8.5	39	9.9
Upper respiratory symptoms	110	47	220	54
Respiratory hospital admissions	2.0	0.82	3.8	0.96
Cardiovascular hospital admissions	1.2	0.51	2.3	0.59
Cerebrovascular hospital admissions	1.4	0.59	2.7	0.69

In 2005, total morbidity from $PM_{2.5}$ pollution is about 140 million cases in WoPol scenario and 60 million cases in WPol scenario per year. Moreover, the morbidity increases to 230 million cases in WoPol scenario and 70 million cases in WPol scenario per year in 2030. *Table 3-4* shows pollution-induced health problems in both scenarios in 2005 and 2030. Upper respiratory symptoms are clearly the most frequent health problem about 220 million cases and 54 million cases induced by $PM_{2.5}$ pollution, followed by asthma attacks about 39 million cases and 10 million cases in WoPol scenario and WPol scenario. Chronic bronchitis is also a severe and long-term impact, and chronic bronchitis is about 14 million and 3.6 million in WoPol scenario and WPol scenario in 2030. Exposure to high level of $PM_{2.5}$ pollution also leads to hospital admissions. In 2005, respiratory hospital admissions are 2.0 million and 0.82 million cases, cardiovascular hospital admissions are 1.2 million and 0.51 million cases, cerebrovascular hospital admissions are 1.4 million and 0.59 million cases in WoPol and WPol scenario. While in 2030, respiratory hospital admissions are 3.8 million and 0.96 billion cases, cardiovascular hospital admissions are 2.3 million and 0.59 million cases; cerebrovascular hospital admissions are 2.7 million and 0.69 million cases in WoPol and WPol scenario.

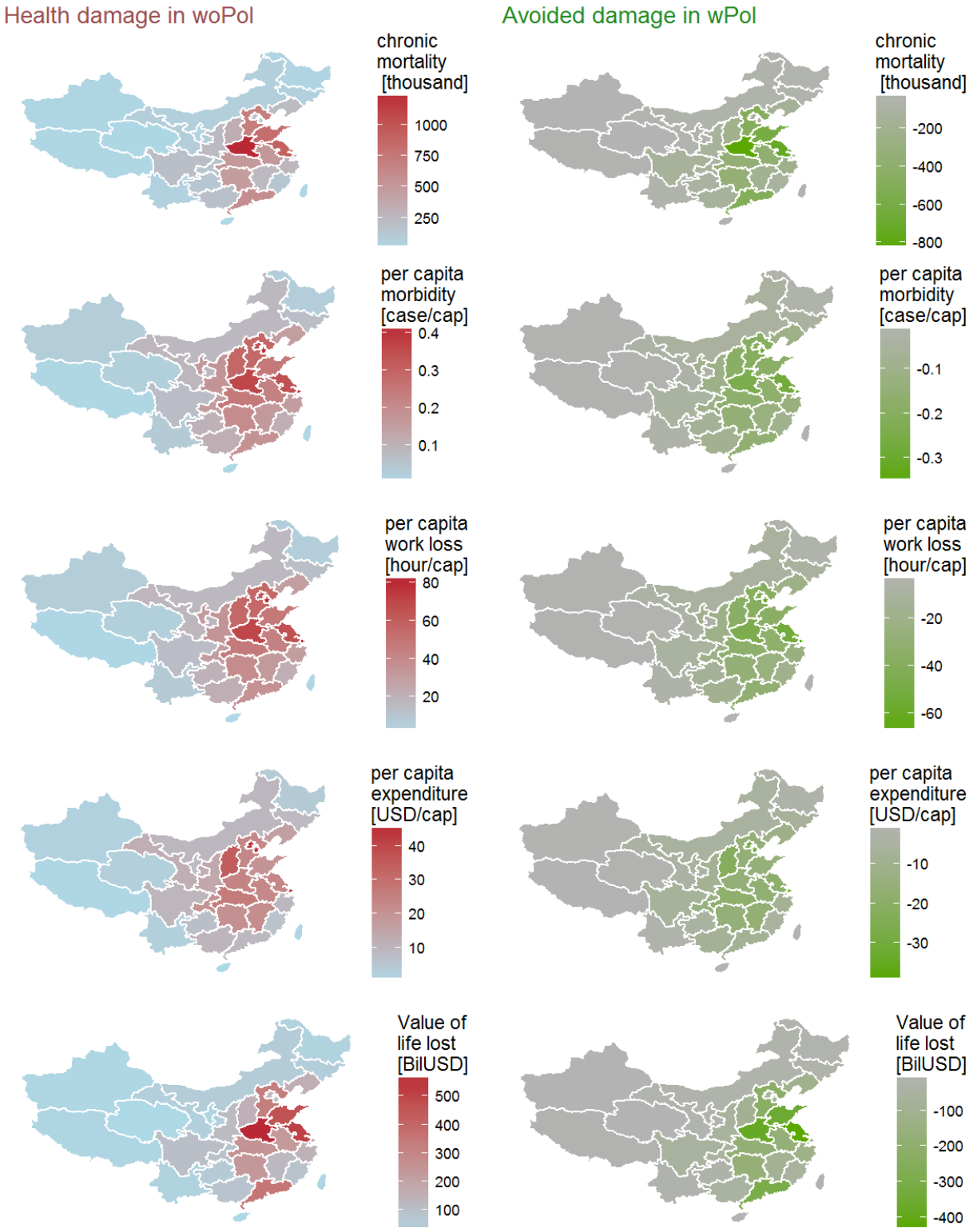


Figure 3-4 Health damage of $PM_{2.5}$ pollution (left/red) and benefit of mitigation (right/green).

3.2.3 Work time loss

$PM_{2.5}$ pollution leads to mortality and morbidity, significantly. At the same time, mortality and morbidity also lead to work day loss and school absence. This study quantifies the work hour loss from premature death and work time loss from health problems happened between 15-64 years old people. Many studies show that if pollution damages the health of an individual or his or her dependents, then a reduction of pollution will decrease the disutility from work and increase work loss hours. In other words, individuals living in an environment with better air quality may work more since they (or their children) are less likely to be sick.

Exposure to high concentrations of air pollutant can reduce work time by causing morbidity and premature death. The premature death happened in the adult under 65-year-old reduces the work time. The work time loss will be higher when the premature deaths happen in young labor. The national per capita work time loss in 2030 reaches 56 hours (2.7% of annual total annual work hours) in the WoPol scenario. The $PM_{2.5}$ reduction in the WPol scenario proves to be very effective at reducing the work time loss. In the WPol scenario, the per capital work time loss is 15 hours (0.71% of annual work hours) in 2030.

The provincial disparity in the per capita work time loss is consistent with the provincial disparity in $PM_{2.5}$ concentration. In the WoPol scenario, Tianjin (98 hours, or 4.7%), Henan (83 hours, or 4.0%), Shanghai (99 hours or 4.7%), Hebei (82 hours or 4.0%), and Beijing (88 hours or 4.2%) have the highest annual per capita work time loss in 2030. In contrast, the provinces with the highest work time loss in the WPol scenario in 2030 are Chongqing (24 hours, 1.1%), Henan (23 hours, 1.1%), Sichuan (22 hours, 1.1%), Hunan (18 hours, 0.88%), and Hubei (18 hours, 0.89%). These provinces are more developed areas with economies more adversely impacted by work time loss.

Table 3-5 Work time loss and loss rate on $PM_{2.5}$ pollution-related health outcome in 2005 and 2030.

Year	2005				2030			
Scenario	WoPol		WPol		WoPol		WPol	
Region	hour	rate	hour	rate	hour	rate	hour	rate
Beijing	48	2.3	12	0.60	88	4.2	18	0.85
Tianjin	48	2.3	12	0.60	98	4.7	17	0.83
Hebei	37	1.8	12	0.60	82	4.0	17	0.84
Shanxi	21	1.0	8. 8	0.42	57	2.7	15	0.70
InnerMong	3.5	0.17	0.84	0.04	13	0.61	1.7	0.08
Liaoning	18	0.85	6.0	0.29	43	2.1	9.2	0.44
Jilin	8.9	0.43	3.3	0.16	23	1.1	5.2	0.25
Heilongjiang	4.3	0.21	1.5	0.07	11	0.54	2.3	0.11
Shanghai	48	2.3	11	0.51	99	4.7	16	0.79
Jiangsu	33	1.6	12	0.55	81	3.9	18	0.89
Zhejiang	22	1.1	7.3	0.35	57	2.8	12	0.57
Anhui	25	1.2	11	0.55	68	3.3	20	0.96
Fujian	9.8	0.47	3.8	0.18	30	1.4	6.4	0.31
Jiangxi	18	0.85	9.0	0.43	48	2.3	15	0.72
Shandong	32	1.5	11	0.55	76	3. 7	18	0.87
Henan	32	1.5	14	0.68	84	4.0	23	1.1
Hubei	23	1.1	11	0.55	59	2.8	18	0.89
Hunan	20	0.98	11	0.54	54	2.6	18	0.88
Guangdong	16	0.76	6.9	0.33	46	2.2	12	0.55
Guangxi	14	0.67	7.8	0.37	41	2.0	13	0.63
Hainan	4.9	0.23	2.2	0.10	15	0.74	3.4	0.17
Chongqing	27	1.3	14	0.68	75	3.6	24	1.1
Sichuan	25	1.2	14	0.68	65	3.2	22	1.1
Guizhou	14	0.69	8.1	0.39	45	2.2	14	0.69
Yunnan	6.3	0.30	3.4	0.16	19	0.92	5.7	0.27
Shaanxi	16	0.76	8.1	0.39	49	2.3	14	0.68
Gansu	6.4	0.31	3.2	0.16	20	0.95	5. 6	0.27
Qinghai	4.8	0.23	1.9	0.09	15	0.73	3.7	0.18
Ningxia	7.2	0.35	2.8	0.13	23	1.1	5.0	0.24
Xinjiang	2.4	0.12	0.71	0.03	6.3	0.30	1.1	0.05
China	22	1.1	9.1	0.44	56	2.7	14	0.71

3.2.4 Economic impact

3.2.4.1 Health expenditure

$PM_{2.5}$ pollution not only leads to health problem, but also leads to additional health expenditure. *Table 3-6* shows the total health expenditure due to $PM_{2.5}$ pollution in 2005 and 2030 in 30 provinces. In 2005, China paid additional 37 billion CNY on the $PM_{2.5}$ pollution-related health problem in WoPol scenario, and in 2030 it increases to 210 billion CNY. While in the WPol scenario, additional health expenditure is about 15 billion CNY in 2005, and 53 billion CNY in 2030. In the 30 provinces in 2005, Jiangsu, Shandong, Henan, Guangdong, Hebei and Beijing encounter higher total expenditure, which is 4.4, 3.5, 2.6, 2.6, 2.5 and 2.3 billion CNY in WoPol scenario and 1.5, 1.3, 1.1, 1.1, 0.79 and 0.6 billion CNY in WPol scenario. In 2030, Sichuan, Shandong, Henan, Hebei, Anhui and Jiangsu encounter higher total expenditure, which is 24, 18, 17, 14, 13 and 13 billion CNY in 2005 in WoPol scenario and 7.6, 4.0, 4.5, 2.9, 3.7 and 2.9 billion CNY in WPol scenario. Provinces, such as Hainan, Qinghai, Ningxia and Xinjiang encounter lower additional health expenditure. Even in 2030, health expenditure on $PM_{2.5}$ pollution is only 0.32, 0.30, 0.22 and 0.22 billion CNY in WoPol scenario. The additional health expenditure in WPol scenario is much lower than in WoPol scenario.

This study finds, however, that the implementation of air-pollution-control technologies in WPol scenario could greatly reduce the numbers of patients. *Table 3-4* shows the annual per capita case due to the $PM_{2.5}$ pollution, which means the opportunity people get $PM_{2.5}$ pollution-related health problems. Such health endpoints lead to additional health expenditure, totaling 210 billion CNY (0.11% of GDP) in the WoPol scenario in 2030. Measures to control $PM_{2.5}$ emissions in the WPol scenario can reduce health expenditure significantly at the national level by nearly 75% to 53 billion CNY (0.03% of GDP).

Turning to per capita health expenditure incurred by $PM_{2.5}$ pollution (*Figure 3-4*), Beijing (340 CNY), Shanghai (320 CNY), and Tianjin (290 CNY) are the top-spending provinces in the WoPol scenario in 2030, each bearing more than double the national average of 150 CNY. These three cities are highly developed areas with high income and service prices. By contrast, in the WPol scenario, Beijing (66 CNY), Chongqing (86 CNY), and Sichuan (88 CNY) are the top-spending provinces in 2030. The $PM_{2.5}$ concentration remains quite high in Sichuan (100 ug/m^3)

and Chongqing (110 ug/m^3) even in the WPol scenario, which results in higher per capita health expenditure. On the contrary, the per capita health expenditure is relatively low in Guangdong, Jiangsu, Zhejiang, Liaoning, and Fujian provinces in the south of China, whose industry is more efficient and the environment is considerably better than that in the north. Xinjiang, Hainan, Inner Mongolia, Gansu, Qinghai, and Ningxia, most of which are in undeveloped regions of western China with low income and less industry, have the lowest per capita health expenditure in both scenarios.

Table 3-6 Total and per capita health expenditure in 2005 and 2030 in China.

Expenditure	Total expenditure (Unit: Billion CNY)				Per capita expenditure (Unit: CNY)			
Year	2005		2030		2005		2030	
Scenario	WoPol	WPol	WoPol	WPol	WoPol	WPol	WoPol	WPol
Beijing	2.3	0.60	5.2	1.0	160	41	340	66
Tianjin	1.0	0.25	3.2	0.54	98	25	290	50
Hebei	2.6	0.79	14	2.9	37	12	190	39
Shanxi	0.63	0.26	7.3	1.8	19	7.9	210	51
InnerMong	0.09	0.02	1.1	0.15	3.6	0.87	44	5.8
Liaoning	1.1	0.36	6.2	1.3	25	8.3	140	28
Jilin	0.24	0.09	2.6	0.57	8.8	3.3	91	20
Heilongjiang	0.21	0.07	2.0	0.38	5.4	1.8	49	9.2
Shanghai	1.9	0.42	5.9	0.95	110	24	320	52
Jiangsu	4.4	1.5	13	2.9	58	20	160	36
Zhejiang	2.2	0.70	5.5	1.1	44	14	110	21
Anhui	1.7	0.80	13	3.7	28	13	200	57
Fujian	0.47	0.18	1.8	0.38	13	5.2	49	10
Jiangxi	0.69	0.35	8.5	2.5	16	8.2	190	55
Shandong	3.5	1.3	18	4.0	38	14	180	41
Henan	2.6	1.1	17	4.5	26	12	160	43
Hubei	1.6	0.77	12	3.5	27	13	190	57
Hunan	1.9	1.0	12	3.8	28	15	170	54
Guangdong	2.5	1.1	6.7	1.6	28	12	71	17
Guangxi	0.61	0.34	5.8	1.8	12	6.9	110	34
Hainan	0.05	0.02	0.32	0.07	5.7	2.5	37	7.8
Chongqing	0.96	0.51	8.6	2.6	33	18	280	86
Sichuan	1.9	1.1	24	7.6	23	13	270	88
Guizhou	0.65	0.37	4.1	1.2	17	9.5	99	30
Yunnan	0.28	0.15	1.9	0.51	6.3	3.4	40	11
Shaanxi	0.68	0.35	4.6	1.3	18	9.3	120	32
Gansu	0.09	0.05	2.2	0.59	3.5	1.8	81	22
Qinghai	0.02	0.01	0.30	0.07	3.8	1.5	54	13
Ningxia	0.05	0.02	0.22	0.04	8.3	3.2	36	7.3
Xinjiang	0.04	0.01	0.25	0.04	2.2	0.66	13	1.9
China	37	15	210	53	28	11	150	39

3.2.4.2 GDP loss and Welfare loss

Both expenditure change and work time loss will lead to macroeconomic impact. In the WoPol scenario without $PM_{2.5}$ pollution control policy, China experiences a 2.0% GDP loss and 210 billion CNY in health expenditure from $PM_{2.5}$ pollution in 2030. In contrast, with control policy in the WPol scenario, a control investment of 830 billion CNY (0.79% of GDP) and a gain of 1.2% of GDP in China from improving $PM_{2.5}$ pollution are projected. About the welfare loss, China experiences 2.7% and 0.63% welfare loss in WoPol and WPol scenario in 2030. Result shows the welfare loss is higher than GDP loss.

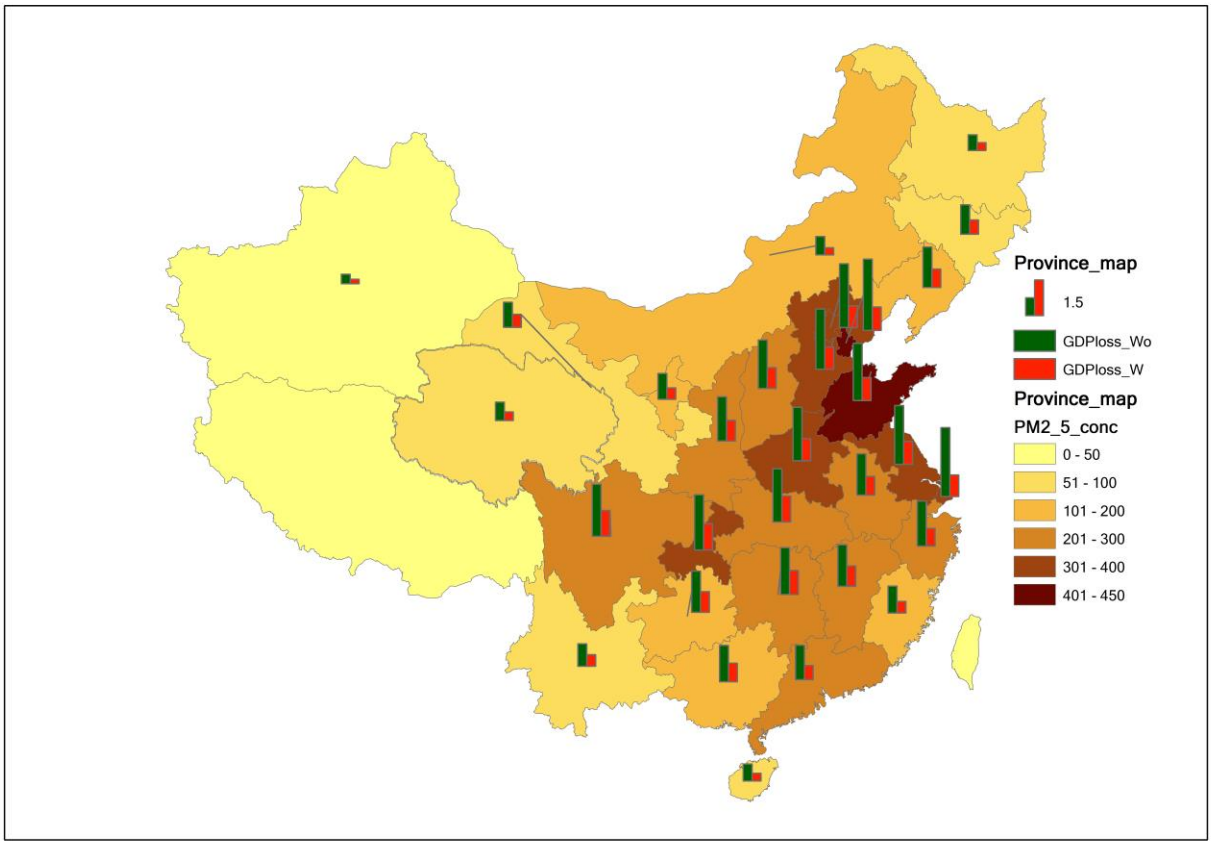


Figure 3-5 GDP loss due to $PM_{2.5}$ pollution in 30 provinces in 2030.

At the provincial level, *Figure 3-5* and *Figure 3-6* show that the developed areas incur more GDP and welfare loss in the WoPol scenario in 2030, e.g., Tianjin (3.1% and 5.4%), Shanghai (3.0% and 4.5%), Beijing (2.8% and 3.9%), Jiangsu (2.6% and 3.7%), Hebei (2.6% and 3.6%),

and Shandong (2.5% and 3.5%). Conversely, economic loss in 2030 is lower in the WPol scenario in every province, with the top five provinces being Chongqing (1.1% and 1.7%), Sichuan (1.1% and 1.5%), Hubei (1.1% and 1.4%), Hunan (1.0% and 1.3%), Jiangsu (0.99% and 1.4%) and Shandong (0.99% and 1.4%) and Henan (0.96% and 1.3%). The economic loss is quite low in both scenarios in Xinjiang, Heilongjiang, Inner Mongolia, Hainan, and Gansu, provinces with lower $PM_{2.5}$ concentrations and less sensitivity to air-pollution-control policy.

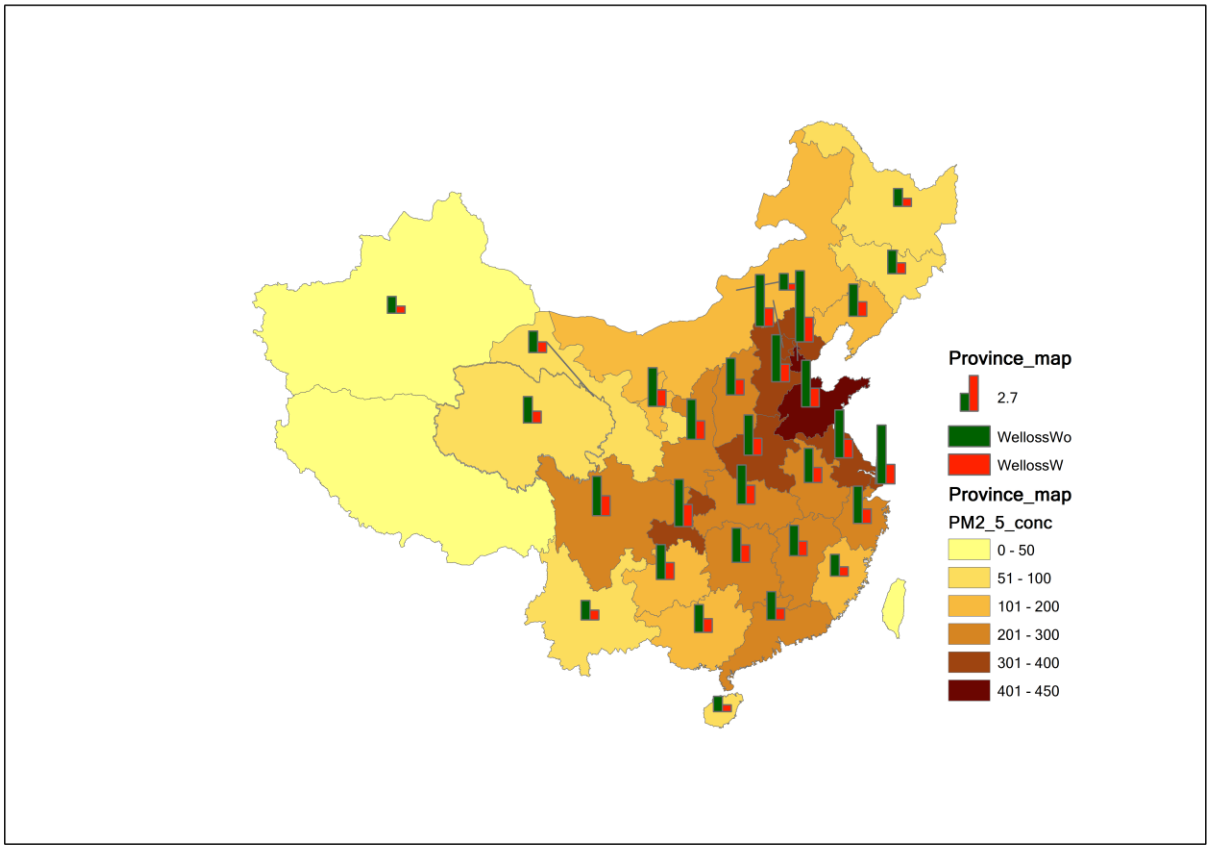


Figure 3-6 Welfare loss due to $PM_{2.5}$ pollution in 30 provinces in 2030.

3.2.4.3 Value of statistical life(VSL)

In most of studies, they use the no-market method willingness to pay to monetize the economic impact. This study not only evaluates the market impact of $PM_{2.5}$ pollution, but also the non-market impact VSL. The VSL reflects the value of premature death. This study adopts the latest study about the VSL in China (Xie, 2011). *Table 3-7* shows the VSL from $PM_{2.5}$ pollution

in 30 provinces in 2030 by GAINS- China model simulation. VSL is 39000 and 9700 billion CNY in WoPol and WPol scenario, which is about 40% and 9.8% of GDP from GAINS-China model simulation. VSL is 38000, 10000 and 9300 billion CNY in WoPol, WPol and WPol2 scenario, which is about 38%, 10% and 9.3% of GDP from GEOS-Chem model simulation. At the provincial level, VSL is higher in Shandong, Jiangsu, Hebei, Guangdong and Sichuan province, about 4200, 3600, 2700, 2700 and 2600 billion CNY in WoPol scenario in 2030.

Table 3-7 Value of statistical life from $PM_{2.5}$ pollution in 2030 from GAINS-China model (Unit: billion CNY*).*

Year	2005	2005	2030	2030
Scenario	WoPol	WPol	WoPol	WPol
Beijing	380	100	1000	200
Tianjin	240	59	710	120
Hebei	780	240	2700	550
Shanxi	200	82	870	210
InnerMong	27	6.4	200	27
Liaoning	280	95	1300	260
Jilin	73	27	370	80
Heilongjiang	52	18	260	49
Shanghai	480	110	1400	230
Jiangsu	970	340	3700	800
Zhejiang	460	150	1600	320
Anhui	380	170	2000	570
Fujian	120	49	650	130
Jiangxi	190	95	1000	310
Shandong	1000	370	4300	1000
Henan	800	360	3900	1000
Hubei	360	180	1800	550
Hunan	350	190	1900	610
Guangdong	570	250	2700	640
Guangxi	160	89	840	250
Hainan	11	4.9	55	12
Chongqing	210	110	1100	340
Sichuan	500	290	2600	850
Guizhou	100	57	630	190
Yunnan	63	34	340	96
Shaanxi	150	77	910	250
Gansu	36	18	210	57
Qinghai	6.7	2.7	38	8. 9
Ningxia	11	4.1	54	11
Xinjiang	13	3.9	50	7.9
China	9000	3600	39000	9800

Table 3-8 Value of statistical life from $PM_{2.5}$ pollution in 30 provinces in 2030 in China from GEOS-Chem model (Unit: billion CNY*).*

	2005			2030		
	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Beijing	430	160	160	1100	350	310
Tianjin	290	110	110	840	260	220
Hebei	860	340	340	2700	800	720
Shanxi	340	170	170	1200	420	400
InnerMong	83	55	55	360	160	160
Liaoning	320	130	130	1300	370	330
Jilin	67	30	30	300	92	77
Heilongjiang	37	15	15	160	44	36
Shanghai	610	120	120	1700	270	260
Jiangsu	1200	350	350	4300	810	770
Zhejiang	350	82	82	1200	190	170
Anhui	380	160	160	1900	490	430
Fujian	140	40	40	660	110	100
Jiangxi	190	73	730	980	220	200
Shandong	1000	380	380	3900	980	890
Henan	1100	560	560	4800	1600	1400
Hubei	480	220	220	2100	630	560
Hunan	400	170	170	2000	510	450
Guangdong	670	190	190	2900	430	410
Guangxi	140	62	62	620	160	140
Hainan	0.00	0.00	0.00	0.01	0.00	0.00
Chongqing	150	77	77	660	220	200
Sichuan	180	95	95	780	280	250
Guizhou	81	42	42	400	130	120
Yunnan	38	14	14	170	37	34
Shaanxi	200	120	120	890	360	340
Gansu	80	64	64	260	170	170
Qinghai	4.8	4.0	4.0	15	10	9.8
Ningxia	29	20	20	100	46	44
Xinjiang	29	27	27	65	56	56
China	10000	3900	3900	38000	10000	9300

3.2.5 Net benefit of air pollution control technology

Economic impact at the provincial level in this study can provide valuable policy insights. The GDP gain/control cost ratio is higher than 1 in nearly two-thirds of provinces with richer and denser population. That means that the benefit in these provinces is positive, such as Shanghai (5.2), Beijing (4.8), Tianjin (3.4), Jiangsu (2.8), Henan (2.5), and Zhejiang (2.3), because more productive people would benefit from improving $PM_{2.5}$ pollution in these provinces, because more productive people would benefit from improving $PM_{2.5}$ pollution in these provinces. Moreover, these findings demonstrate a much smaller economic benefit in less developed and populated provinces, where the adoption of air-pollution-control technology may incur a big burden and ultimately lead to negative economic impacts, such as Ningxia, Guizhou, Shanxi, Gansu, Heilongjiang, Qinghai, and Xinjiang.

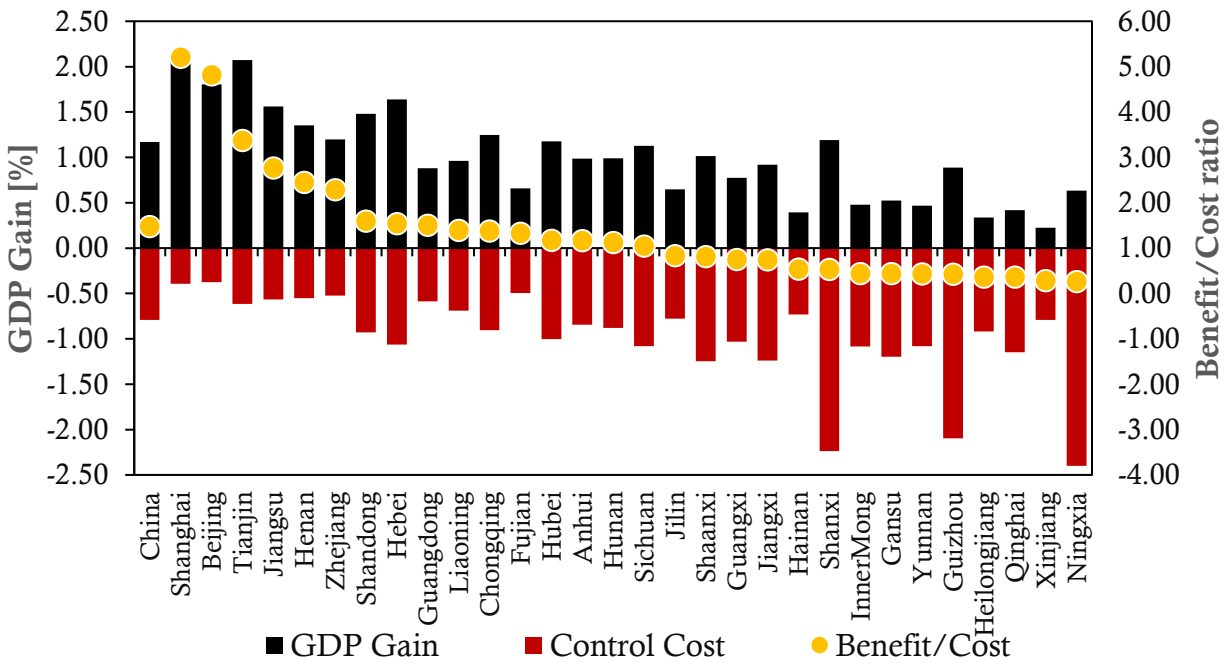


Figure 3-7 Cost and benefit of $PM_{2.5}$ control in 30 provinces in China in 2030.

3.3 Discussion of $PM_{2.5}$ pollution in China

3.3.1 Policy implications

Several studies have focused on the economic impacts of air pollution at the national and provincial level in China. For example, one study in Guangdong province showed an economic impact from $PM_{2.5}$ amounting to about 1.4% of GDP in 2006. Another study in Beijing-Tianjin-Hebei area showed an economic impact of about 4.7% of GDP. The economic impact was higher in Beijing-Tianjin-Hebei area than in Guangdong in both of these earlier studies, which is in line with this study. Welfare loss follows a trend similar to that of GDP loss, but slightly exceeds it. In 2030, this study uses the non-linear ERFs, GDP loss is 2.0% and 0.83% in WoPol and WPol scenario. With linear ERFs, GDP loss is 2.0% and 0.49% in WoPol and WPol scenario. By using China-specific ERFs, GDP loss is 1.5% and 0.27% in WoPol and WPol scenario. The welfare loss in WoPol scenario (2.8%) is somewhat lower than that reported (3.6%) in 24. This difference may be attributable to non-market impacts, such as mortality over 65-years-old population, suffering from diseases. The difference may also stem from the air pollutants examined, as Matus's study also investigated ozone and PM_{10}. Air pollution control technology not only reduces the $PM_{2.5}$ but also other air pollutants. The total real benefit will be higher than this result.

To control air pollution, the government has to spend money on air pollution control technology, including investment and maintenance. GAINS-China model can calculate the air pollution control cost. Results show SO_2 reduction cost will increase from 31 billion CNY in 2005 to 320 billion CNY in 2030 in WPol scenario, and to 440 billion CNY in 2030 in WoPol scenario. Reduction costs of $PM_{2.5}$ for WoPol and WPol will also change significantly, with values of 64 billion CNY and 53 billion CNY in 2030, respectively. While for NOx, reduction costs for WoPol and WPol are almost the same, increasing from 9.7 billion CNY in 2005 to 580 billion CNY in 2030. The reason is that NOx emission of WPol decreases slightly and its unit reduction cost increases slightly, leading to the total reduction cost to be almost the same.

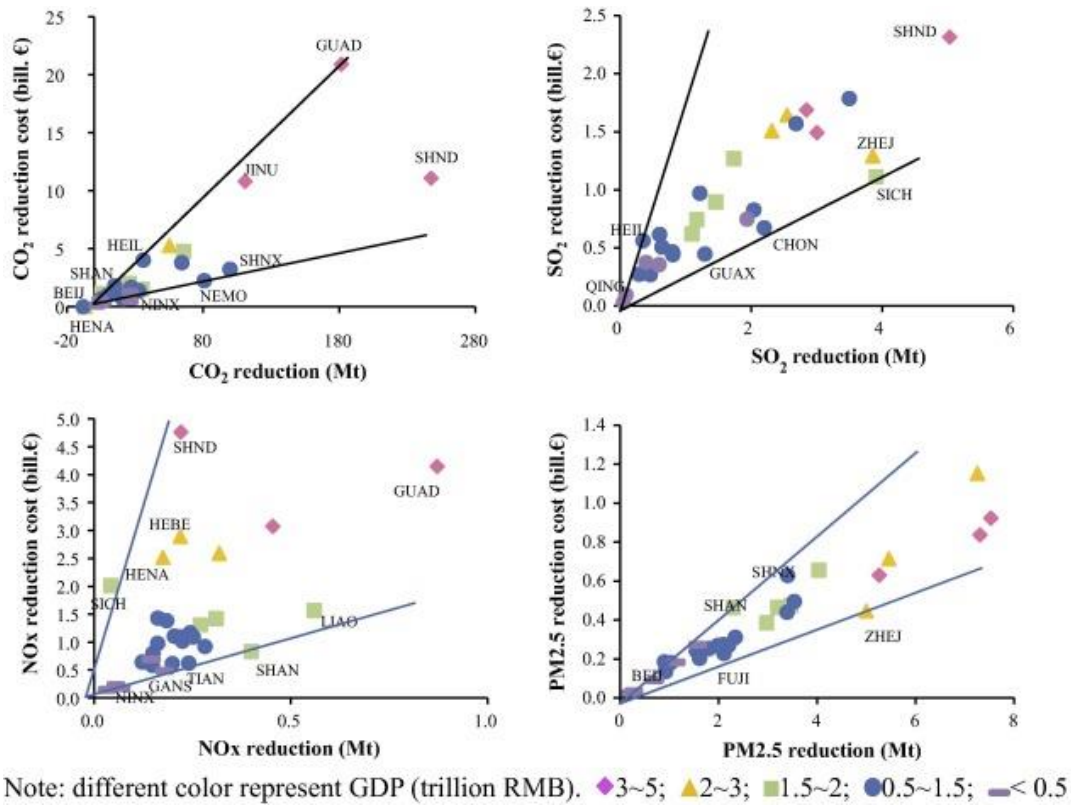


Figure 3-8 Air pollutants reduction cost in 30 provinces in China.

Source: (Dong et al., 2015)

Here, however, this study should consider the technology cost alongside the benefit from air-pollution-control policy. The air pollution control cost in this study exceeds the health expenditure incurred by $PM_{2.5}$ pollution, reaching about 830 billion CNY in 2030, or about 0.79% of GDP. The net benefit from air control technology is 0.38% increase in GDP in 2030. At this point, investment on such technology is quite beneficial in China. In this study, air pollution control cost is considered as a burden to the Economy. The investments into pollution control can be considered as income to other sectors, or the additional labor demand for installing pollution control equipment. That will be positive for the Economy. The real benefit will be much bigger than this study.

Economic impact at the provincial level in this study can provide valuable policy insights. The net benefit is high in provinces with larger economies and higher $PM_{2.5}$ concentrations, such as Shanghai (2.0%), Tianjin (1.8%), Beijing (1.8%), Jiangsu (1.3%), Zhejiang (1.1%) and Henan

(1.1%). These provinces have higher air pollutant concentration and dense population distribution. More people exposure to high $PM_{2.5}$ pollution. The health impact also higher than low $PM_{2.5}$ concentration areas. Moreover, these findings demonstrate a much smaller economic impact in less developed provinces. There are less population and lower $PM_{2.5}$ concentration in these provinces. The adoption of air-pollution-control technology incurs a big burden on smaller provincial economies and ultimately leads to negative net impacts, such as Ningxia (-1.1%), Guizhou (-0.88%), Shanxi (-0.67), Gansu (-0.10%), and Yunnan (-0.08%). Hence, this study indicates that air pollution control technology is more effective in more developed provinces than in less developed western provinces. The Chinese government should institute a suitable policy and provide necessary financial aid in these underdeveloped provinces. Several suggestions for policymakers can be derived from this results.

Moreover, these findings demonstrate a much smaller economic benefit in less developed and populated provinces, where the adoption of air-pollution-control technology may incur a big burden and ultimately lead to negative economic impacts, such as Ningxia, Guizhou, Shanxi, Gansu, Heilongjiang, Qinghai, and Xinjiang. However, this does not mean that there is no need to control $PM_{2.5}$ pollution in those provinces because air pollution depends upon not only emissions in one region but also transboundary emissions from neighboring regions. This calls for collaboration among regions to reduce air pollution. The Chinese central government should institute a suitable policy and provide necessary technological and financial aid in these underdeveloped provinces, and richer provinces that are winners could compensate for losers to abate pollution. This kind of welfare transfer could still leave China with an overall gain.

Air pollution concentration depends not only on emissions in one region, but also on transboundary emissions from neighboring regions. This calls for collaboration among regions to reduce air pollution. Net benefit is higher in developed regions such as Beijing and Shanghai and lower in undeveloped regions such as Ningxia and Guizhou. Policymakers should consider the differences and tailor suitable policies for different regions. To balance the gap, developed regions can provide technologic and financial aid to undeveloped regions.

3.3.2 Sensitivity analysis

A sensitivity analysis is carried out using the different ERFs, linear ERFs, non-linear ERFs and linear ERFs China. The upper and lower bounds of the ERFs acquired from the 95% confidence interval for linear ERFs and linear ERFs China (*Table 3-9*). It shows that GDP loss is 2.0% and 0.49% in WoPol and WPol scenario in 2030 for linear ERFs, and the lower and upper bounds are 1.2% and 2.8%, 0.29% and 0.70%. GDP loss is 1.5% and 0.36% in WoPol and WPol scenario in 2030 for linear ERFs China, and the lower and upper bounds are 1.1% and 1.9%, 0.27% and 0.45%. While GDP loss for nonlinear ERFs is 2.0% in WoPol scenario and 0.83% in WPol scenario in 2030, which is between linear ERFs and linear ERFs China.

Table 3-9 Sensitivity analysis of ERFs on GDP and Welfare loss in 2030 in China.

Economic impact		GDP loss (%)		Welfare loss (%)	
Scenario		WoPol	WPol	WoPol	WPol
	lower	1.2	0.29	1.7	0.41
Linear ERFs	central	2.0	0.49	2.8	0.68
	upper	2.8	0.7	3.9	0.98
Non-linear ERFs		2.0	0.83	2.8	1.2
	lower	1.1	0.27	1.6	0.37
Linear ERFs_China	central	1.5	0.36	2.1	0.51
	upper	1.9	0.45	2.6	0.63

3.3.3 Research limitations

Beyond work time loss, air pollution also hinders an economy by reducing labor productivity. If this study was also to consider the impact on productivity, we would find an even larger impact on the economy than current results. This study also underestimates the impact of $PM_{2.5}$ pollution from this perspective. Furthermore, the $PM_{2.5}$ concentration used for this study is annual provincial average value, yet the air pollutant concentration varies substantially from place to place within any one province and from time to time within a year. Considering the population distribution, air pollutant grid concentration data and periodical distribution of air pollution would serve better for

evaluating health impacts. Because of lacing of data, this study treats air pollution control cost as a burden to the Economy, but the investment in some sector can increase the income in these sector and additional labor demand for installing pollution control equipment.

3.4 Implication of air pollution control policy in local regions

In this section, the economic impacts of air pollution control actions are assessed in detail based on the simulation results in this chapter. The treated area is Beijing-Tianjin-Hebei area. This Beijing-Tianjin-Hebei area is the most air-polluted industrialized region in China despite under intensive air pollution control. To evaluate the health-related economic impacts of $PM_{2.5}$ in Beijing-Tianjin-Hebei area, this section applies the method to combine CGE model, the GAINS model and a health assessment model to Beijing-Tianjin-Hebei area.

3.4.1 Result

3.4.1.1 Air pollutants emissions and $PM_{2.5}$ concentration

Figure 3-9 shows the location of Beijing-Tianjin-Hebei area in China. With intensive heavy industries in Hebei, it has the largest air pollutant emissions in Beijing-Tianjin-Hebei area (*Table 3-10*). In 2020, SO_2 emission is 4400 kt, NO_x emission is 1700 kt and VOC emission is 1400 kt in WoPol scenario, while SO_2 emission is 1800 kt, NO_x emission is 1500 kt and VOC emission is 1200 kt in WPol scenario. Tianjin and Beijing have lower emissions, for example, in WoPol scenario, SO_2 emission is 1400 kt in Tianjin and 530 kt in Beijing. NO_x emission is 750 kt in Tianjin and 500 kt in Beijing. VOC emission is 640 kt in Tianjin and 590 kt in Beijing. With the air pollution control technology, SO_2 emission is reduced more than 50 % in this area. While NO_x and VOC reduction is less than SO_2 reduction. GAINS model simulated $PM_{2.5}$ concentration in this area. From *Table 3-10*, annual average $PM_{2.5}$ concentration is 88 ug/m^3 in Beijing, 87 ug/m^3 in Tianjin and 84 ug/m^3 in Hebei. Air pollutant emissions in Beijing is lower than Hebei and Tianjin, but most of the emission is from transportation and the transboundary from near regions.

Figure 3-9 Location of Beijing-Tianjin-Hebei area.

http://www.paulsoninstitute.org/economics-environment/climate-sustainable-urbanization/research/chinas-next-opportunity-sustainable-economic-transition/the-jjj-story (accessed time 5th April, 2017)

Table 3-10 Air pollutants emissions and $PM_{2.5}$ concentration in Beijing-Tianjin-Hebei area in 2020.

region	SO2 (kt)		NOx (kt)		VOC (kt)		PM2.5 Concentration (ug/m3)	
	WoPol	WPol	WoPol	WPol	WoPol	WPol	WoPol	WPol
Beijing	530	260	500	300	590	340	400	88
Tianjin	1400	460	750	490	640	350	450	87
Hebei	4400	1800	1700	1500	1400	1200	360	84

3.4.1.2 Health impact and health expenditure

Beijing-Tianjin-Hebei area is the most polluted area and the high population density area in China. Health impact from $PM_{2.5}$ pollution area is quite a big burden for these regions. $PM_{2.5}$ pollution increases 33% opportunity to get outpatient outcome in Beijing, 36% in Tianjin and 29% in Hebei in WoPol scenario in 2020, while it will decrease to 6.5% in Beijing, 6.4% in Tianjin and 6.2% in Hebei in WPol scenario. $PM_{2.5}$ pollution also increases the opportunity for respiratory, cardiovascular and cerebrovascular hospital admissions about 0.46%, 0.51% and 0.41% in WoPol scenario and 0.09% for these three kinds of hospital admissions in Beijing, Tianjin and Hebei in WPol scenario.

Additional per capita health expenditure on the $PM_{2.5}$ pollution-related health problem is about 290 CNY in Beijing, 250 CNY in Tianjin and 130 CNY in Hebei in WoPol scenario. Under intensive air pollution control policy, per capita health expenditure decreases to 58 CNY in Beijing, 45 CNY in Tianjin and 38 CNY in Hebei. Health expenditure on outpatient is about 20%~40% of total health expenditure in these regions.

3.4.1.3 Work time loss and labor price

$PM_{2.5}$ pollution not only leads to mortality and morbidity, but also reduces the work hours. Premature death between 15 and 65-year-old can reduce the labor supply. Morbidity also leads to work day loss. These two kinds of impacts can lower total work time. In 2020, per capita work hour loss is 81 hours per year in Beijing in WoPol scenario, while in WPol scenario work hour loss is 22 hours per year. Per capita work hour loss is 90 hours and 23 hours in Tianjin and 73 hours and 22 hours in Hebei in WoPol scenario and WPol scenario (*Table 3-12*). The reduction of work hour can increase the relative labor price, because the labor supply decreases. In 2020, comparing to 2002, labor price is 6.1 times in WoPol scenario and 5.9 times in WPol scenario in Beijing. And the labor price is 6.8 times and 6.6 times in Tianjin and 5.2 times and 5.1 times in Hebei, comparing to 2002 (*Table 3-11*).

Table 3-11 Labor price change in Beijing-Tianjin-Hebei area.

Region	Scenario	2002	2005	2007	2010	2015	2020
Beijing	Refer	1.0	1.4	1.7	2.4	3.8	5.9
	WoPol	1.0	1.4	1.8	2.5	3.9	6.1
	WPol	1.0	1.4	1.7	2.4	3.8	5.9
Tianjin	Refer	1.0	1.4	1.9	2.7	4.4	6.6
	WoPol	1.0	1.5	1.9	2.8	4.5	6.8
	WPol	1.0	1.5	1.9	2.7	4.4	6.6
Hebei	Refer	1.0	1.4	1.7	2.3	3.4	5.1
	WoPol	1.0	1.4	1.8	2.3	3.5	5.2
	WPol	1.0	1.4	1.7	2.3	3.4	5.1

3.4.1.4 Economic impact

$PM_{2.5}$ pollution also leads to economic impact, including GDP loss and welfare loss. Labor is the main driving force to the economy. Reduction of labor supply has negative impact on the economy. *Table 3-12* shows the GDP loss and welfare loss due to $PM_{2.5}$ pollution-related health outcome. Economic impact is highest in Tianjin, about 2.8% of GDP. Second is Beijing, about 2.5% of GDP. The last one is Hebei, about 2.2% of GDP. While in WPol scenario, work time loss is reduced to a low level. Average GDP loss is about 0.72% in Beijing-Tianjin-Hebei area. That means air pollution control technology can contribute 1.8%, 2.0% and 1.5% of GDP benefit in Beijing, Tianjin and Hebei provinces.

$PM_{2.5}$ pollution also reduces the welfare loss directly, because air pollution increases the additional health expenditure, and reduces income. Results show that welfare loss in Beijing-Tianjin-Hebei area is higher than GDP loss. In 2020, welfare loss is 5.1%, 8.1% and 3.4% in Beijing, Tianjin and Hebei, which is higher than 2.5%, 2.8% and 2.5% GDP loss in these three regions. Under intensive air pollution control policy, welfare loss is 1.5%, 2.4% and 1.1% in Beijing, Tianjin and Hebei province. From this result, air pollution control can improve welfare significantly in Beijing-Tianjin-Hebei area.

Table 3-12 GDP loss and welfare loss in Beijing-Tianjin-Hebei area.

Region	Work hour loss (Hour)		GDP loss (%)		Welfare loss (%)	
Scenario	WoPol	WPol	WoPol	WPol	WoPol	WPol
Beijing	81	22	2.5	1.8	5.1	1.5
Tianjin	90	23	2.8	2.0	8.1	2.4
Hebei	73	22	2.2	1.5	3.4	1.1

3.4.1.5 Output change

The increasing of labor price leads to additional cost of production. These sectors with higher wage are more attractive for works. This also has impact on output of each sector. *Table 3-13* shows the output loss in 20 sectors. Since the economic structure is different in Beijing, Tianjin and Hebei province, output change is also different. In Beijing, output decreases most in coal, food, textile sector, about 3.9%, 2.9% and 2.4% in WoPol scenario. In Tianjin, output loss is about water 4.2%, food 3.7% and agriculture sector 3.3% in WoPol scenario. While for Hebei output loss is higher in coal, transport and paper sector, about 4.2%, 3.6% and 3.3% in WoPol scenario. In WPol scenario, output loss is lower than WoPol scenario in the area.

Table 3-13 Output change in different sectors in Beijing-Tianjin-Hebei area in 2020 (Unit: %).

Region	Beijing		Tianjin		Hebei	
Sector	WoPol	WPol	WoPol	WPol	WoPol	WPol
Electricity	3.2	0.90	2.7	0.76	2.0	0.63
Agriculture	2.1	0.58	4.6	1.2	1.0	0.32
Coal	5.2	1.4	0.89	0.24	4.2	1.3
Mineral	2.2	0.52	1.3	0.29	1.0	0.27
Food	4.2	1.3	5.0	1.6	2.5	0.82
Textile	3.3	0.92	4.3	1.2	1.5	0.48
Paper	2.4	0.67	2.8	0.79	3.4	1.1
Petroloil	2.0	0.58	1.5	0.45	1.2	0.37
Chemicals	2.4	0.72	2.5	0.71	1.8	0.61
Nonmetal	1.2	0.26	2.2	0.52	1.2	0.36
Metal	2.3	0.62	1.8	0.44	1.1	0.33
Machinery	2.8	0.79	3.0	0.78	1.1	0.35
Electronic	1.8	0.52	1.5	0.40	1.3	0.41
OtherManu	2.6	0.72	2.8	0.77	2.3	0.72
Water	2.5	0.72	5.8	1.6	2.4	0.77
Construction	0.56	0.12	0.81	0.12	0.39	0.12
Transport	1.8	0.52	2.0	0.55	3.4	1.1
Service	2.6	0.76	3.6	1.0	3.0	0.97

3.4.1.6 Net benefit

Air pollutant control technology requires a lot of money on investment of equipment and maintenance. GAINS-China model can calculate the air pollution control cost. Reducing pollutants can reduce additional health expenditure and work time loss due to air pollution exposure, and have benefit on the economy. Considering the air pollution control cost, health expenditure and GDP benefit, the cost-benefit ratio of air pollution control is 3.3 billion in Beijing, 2.3 billion in Tianjin and 1.0 billion in Hebei (*Table 3-14*). From the benefit-cost ratio, the benefits of air pollutant control policy are higher than the cost in Beijing-Tianjin-Hebei area, and the benefits are highest in Beijing and lowest in Hebei. In addition, the investment on air pollution control also increases the employment in relative sectors, which is also a benefit to the economy. Even though

this study cannot quantify this benefit here. The net benefit would be much higher than previous results.

Table 3-14 Net benefit of air pollution control technology in Beijing-Tianjin-Hebei area in 2020 (unit: %).

Region	GDP gain	Air pollution control cost	Benefit
Beijing	1.8	0.53	3.3
Tianjin	2.0	0.87	2.3
Hebei	1.5	1.4	1.0

3.4.2 Discussion

This section shows the economic impacts of air pollution reduction in Beijing-Tianjin-Hebei, the most air-polluted industrialized region in China in detail. Results show Hebei province has highest air pollutants emissions, followed by Tianjin and Beijing, which is related to economic structure in this region. Hebei province has heavy industry and it is heavy chemical industry has become the main driving force of economic growth, so it has largest energy consumption and air pollutant emissions. The heavy industry will inevitably cause serious air pollution, especially in Baoding, Shijiazhuang, Tangshan and other industrial cities, which is becoming the world's most polluted cities. Tianjin also has a lot of industry, so air pollutant emission is larger than Beijing. The air quality in Tianjin is also quite bad. While for Beijing, as the capital of China, has lots of high technology companies. Air pollutants emissions are much lower than Hebei and Tianjin. Moreover, after the adjustment of industrial structure, most of air pollutants are from motor vehicle exhaust emissions in Beijing.

Although Beijing is not the high pollutant emissions region. Beijing is surrounded by Tianjin and Hebei and most of the air pollutants are from neighboring regions, which have much higher air pollutants emissions. Also, Beijing-Tianjin-Hebei area has a special geographical location, which leads to poor air pollutant dispersion. In the WoPol scenario, Tianjin has the highest $PM_{2.5}$ concentration, followed by Beijing and Hebei. Even in the WPol annual average $PM_{2.5}$ concentration exceeds the WHO standard 10ug/m^3 and the national standard 35ug/m^3. Current air

pollution control technology is not enough to improve air quality in this area. More activity should be carried out, such as adjusting industrial structure and energy structure together.

This study shows that additional health expenditure on $PM_{2.5}$ pollution-related health problem can be another economic burden. Total health expenditure is 4.4 billion CNY, 2.8 billion CNY, 9.8 billion CNY in Beijing, Tianjin and Hebei in the WoPol scenario in 2020, respectively. In the WPol scenario, it was reduced to 0.88 billion, 0.49 billion, and 2.1 billion, respectively.

The economic impact of work time loss due to $PM_{2.5}$ pollution-related health problem cannot be ignored, especially work day loss due to $PM_{2.5}$ pollution related morbidity, which is much higher than premature death. China is becoming an aging country, and the labor supply will decrease and become insufficient in the future. Improving workers' attendance is very important. The GDP loss due to $PM_{2.5}$ pollution-related health problem is about 0.6% to 2.8% GDP in 2020. Air pollution control cost is about 0.53%, 0.87% and 1.4% of GDP of Beijing, Tianjin and Hebei in WPol scenario, respectively.

3.4.2.1 Policy implication

Considering benefit and cost of air pollution control technology, the benefit and investment ratio is highest in Beijing (3.3), followed by Tianjin (2.3), and lowest in Hebei (1.0). Results show that air pollution control benefit is higher in Beijing and Tianjin than Hebei. However, this does not mean that air pollution control policy is more important in Beijing and Tianjin. The main source of air pollutant is different in Beijing, Tianjin and Hebei. The relationship between concentration and emission is not linear. To control air pollution effectively, collaboration with surrounding areas is quite necessary (Keating et al., 2004). Only terminal air pollutants emission reduction technology is not enough to reduce $PM_{2.5}$ pollution to a level to meet the national standard. More action should be taken to reduce air pollutants emissions further, such as industrial restructuring, reducing fossil fuel consumption, improving energy efficiency, development of clear energy, encouraging low-carbon lifestyle, and achieve environmental and economic sustainable development in Beijing-Tianjin-Hebei area.

3.4.2.2 Sensitivity analysis

A sensitivity analysis is carried out using the different ERFs, linear ERFs, non-linear ERFs and linear ERFs China. the upper and lower bounds of the ERFs acquired from the 95% confidence interval for linear ERFs and linear ERFs China (*Table 3-15*). This study makes sensitivity analysis about GDP loss and welfare loss caused by $PM_{2.5}$ pollution in Beijing-Tianjin-Hebei region. In WoPol scenario, in 2020 GDP loss in Beijing is between 1.8% and 2.6%, 1.9% ~ 3.7% in Tianjin and 1.5% ~ 3.0% in Hebei. While the welfare loss in Beijing is about 3.1% ~ 6.1%, 4.7% ~ 9.3% in Tianjin, 2.5% ~ 4.9% Hebei. In WPol scenario, the GDP loss and welfare loss due to $PM_{2.5}$ pollution are significantly lower than WoPol scenario. This study shows that economic impact of $PM_{2.5}$ pollution is highest in Tianjin, followed by Beijing and is lowest in Hebei. The GDP loss and welfare loss by using nonlinear ERFs is between the linear ERF abroad and the Chinese linear ERFs.

Table 3-15 Sensitivity analysis of GDP loss due to PM2.5 pollution in WoPol scenario in Beijing-Tianjin-Hebei area in 2020(Unit: %)

			GDP loss		Welfare loss	
Region	Function	Scenario	WoPol	WPol	WoPol	WPol
Beijing	ERFs	Lower	1.8	0.35	3.2	0.65
		Central	2.6	0.51	4.6	0.95
		Upper	3.4	0.68	6.1	1.3
	Nonlinear		2.4	0.69	4.3	1.3
	ERFs-China	Lower	1.7	0.33	3.1	0.62
		Central	2.2	0.43	3.9	0.79
		Upper	2.6	0.51	4.6	0.95
Tianjin	ERFs	Lower	2.0	0.35	4.9	0.92
		Central	2.8	0.50	7.0	1.4
		Upper	3.7	0.68	9.3	1.8
	Nonlinear		2.6	0.73	6.7	2.0
	ERFs-China	Lower	1.9	0.33	4.7	0.88
		Central	2.4	0.42	6.0	1.1
		Upper	2.8	0.51	7.1	1.4
Hebei	ERFs	Lower	1.6	0.33	2.6	0.55
		Central	2.3	0.49	3.7	0.81
		Upper	3.0	0.66	4.9	1.1
	Nonlinear		2.2	0.69	3.6	1.2
	ERFs-China	Lower	1.5	0.32	2.5	0.52
		Central	1.9	0.41	3.1	0.67
		Upper	2.3	0.49	3.7	0.81

3.4.2.3 Research limitation.

In this study, there are shortcomings in the calculation of $PM_{2.5}$ concentration, using the GAINS model of the provincial average concentration. The actual situation of pollutant concentration varies with different regions, should choose a smaller resolution air quality model and population distribution Model, more accurately reflect the impact of exposure to the population. The Beijing-Tianjin-Hebei region is a key area for air pollution control. The

government has issued a series of governance policies. This study provides a theoretical basis for cost-benefit analysis of air pollutants in Beijing-Tianjin-Hebei region.

4 Health and economic impacts of ozone pollution in China

Ozone is the common air pollutant all over the world, including both developing and developed countries. Many studies related to China have reported associations between ozone pollution and morbidity and mortality, but few study focuses on the health and economic effects in China's 30 provinces. This study evaluates the ozone pollution-related health impacts on China's national and provincial economy and compares it with the impacts from $PM_{2.5}$. This study also explored the mitigation potential across 30 provinces of China. This study developed an integrated approach that combines GAINS-China, GEOS-Chem, health assessment model using the latest exposure-response functions, medical prices and VSL, and AIM/CGE-China model. Results show that lower income western provinces encounter more severe health impacts and economic burden due to high natural background, whereas southern and central provinces have relatively lower impacts. Without control policy, China experiences a 34 billion CNY (equivalent to 0.34‰) GDP loss and 2300 billion CNY (2.3% of GDP) of life loss in 2030. In contrast, with control policy, GDP and VSL loss reduce to 30 billion CNY (0.03%) and 2000 billion CNY (2.0%), respectively. Health and economic impacts of ozone pollution are significantly lower than $PM_{2.5}$, but it is a non-ignorable economic burden for the low-income western provinces and much more difficult to mitigate, especially for provinces with high natural background. The central government needs to adopt preferential policies such as subsidies and monetary transfer to such provinces.

4.1 Methodology

This study develops an integrated approach to consider health and economic impacts of ozone pollution in China. GAINS-China model calculates air pollutants primary emissions in 30 provinces in China. GEOS-Chem model can provide more precise concentration data, which is more distinguishable geographically. An improvement from the previous study is that, instead of using the concentration results in the GAINS-China model. For ozone pollution, different exposure-response functions from $PM_{2.5}$ are used as shown in *Table 2-9.* Health impacts due to mortality and morbidity are converted to annual total medical expenditure and per capita work loss,

which are then used as a change in the household expenditure pattern and labor participation rate by the AIM/CGE-China model to determine the market impacts.

4.2 Scenario of ozone pollution impact

Four scenarios are constructed in this study, namely reference, WoPol, WPol and WPol2 scenarios, which have been introduced in scenarios of methodology part.

4.3 Simulation result of ozone pollution in China

4.3.1 Ozone concentration

The primary emissions of air pollutant are the same as used in (Xie et al., 2016) and (Dong et al., 2015). It could be seen that emissions in the WPol scenario are much lower than WoPol scenario in the whole periods, and emissions in WPol2 scenario in 2030 are further reduced. Using these emission pathways as inputs for the GEOS-Chem model the daily maximum 8-hour mean concentration of ozone is calculated in 30 provinces of China in both WoPol and WPol scenarios in 2030 (*Figure 4-1* (upper two panels)). It shows that ozone concentration is higher in the southwest and lower in the east in China in both scenarios. Provinces in the southwest such as Sichuan (130 ug/m^3), Qinghai (130 ug/m^3), and Gansu (120 ug/m^3) provinces in 2030 in the WoPol scenario. *Figure 4-1* (lower two panels) also shows change in ozone concentration under intensive air pollution control technology. It can be found that the relationship between reduction in ozone precursors emissions and concentration is not linear. In the WPol scenario, although air pollutants emission reduction is over 50%, ozone concentration decreases not that much. The ozone concentration reduction is most significant in the provinces such as Hunan, Anhui, but they only fall by less than 10%. Moreover, there is no significant reduction in Hebei, Shanxi and Inner Mongolia. Conversely, concentration even increases in Beijing, Shanghai, and Guangdong in the WPol scenario.

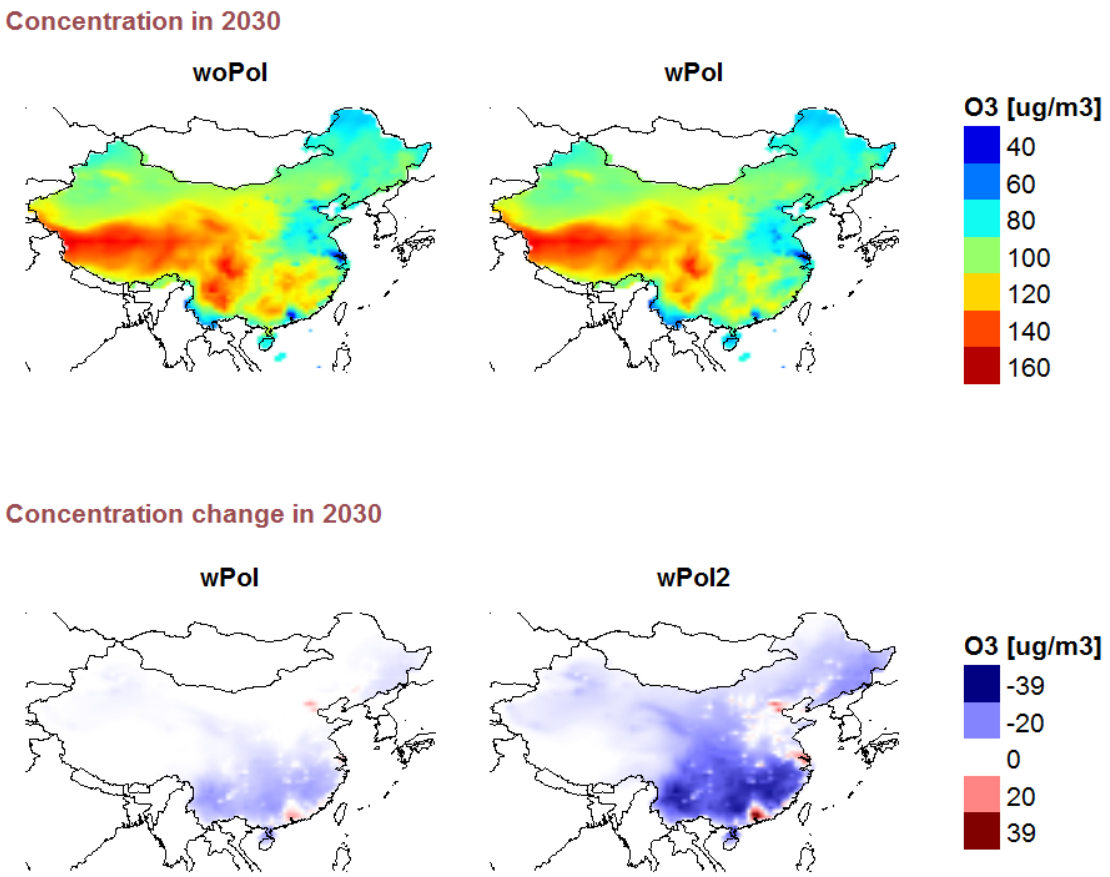


Figure 4-1 Ozone concentration in WoPol and WPol scenarios (upper) and change from woPol to WPol and WPol2 scenarios (lower).

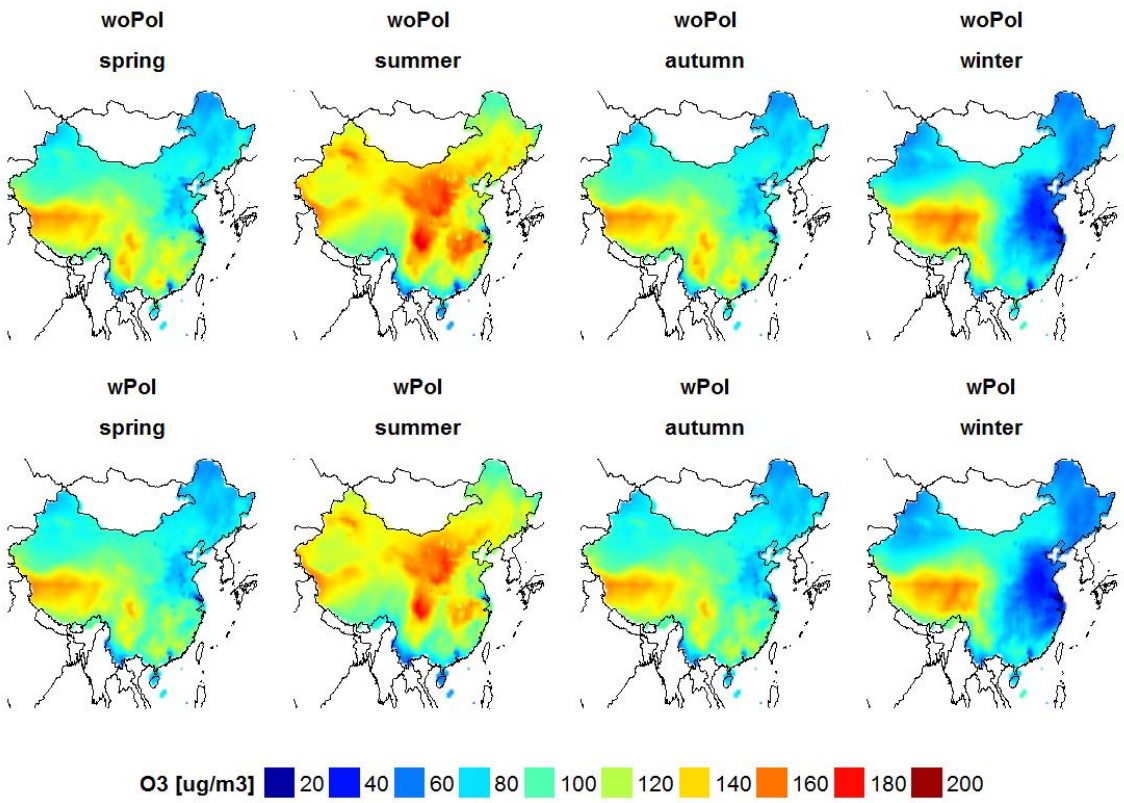


Figure 4-2 Seasonal variation of daily maximum 8-hour mean concentration of ozone in 2030.

The reason is that ozone concentration comes from two parts of natural background and human activity. To figure out the portion of natural contribution to ozone formation, this study conducted an additional simplified experiment in the GEOS-Chem model by reducing the human-related emissions to zero and calculating the ozone concentration. This concentration is defined as natural background. Further analysis (*Figure 4-3*) shows that the provinces could be divided into three groups based on the percentage of natural sources ozone in the WPol scenario. The first group is natural source dominated provinces where human activity source is lower than 20%, including Xinjiang, Hainan, Qinghai, Gansu, Tianjin, Shanghai and Inner Mongolia. In these provinces, ozone concentration reduction in WPol scenario is not significant. The second group is where human activity source is between 20% to 40%, including Beijing, Hebei, Shanxi, Liaoning, Jilin, Jiangsu, Heilongjiang, Shandong, Henan, Guangdong, Guangxi, Sichuan, Yunnan, Shaanxi, Ningxia. In the third group, human activity dominates (>40%), including Zhejiang, Anhui, Fujian,

Jiangxi, Hubei, Hunan, Chongqing, Guizhou. Ozone concentration decreases a lot in these provinces in WPol scenario.

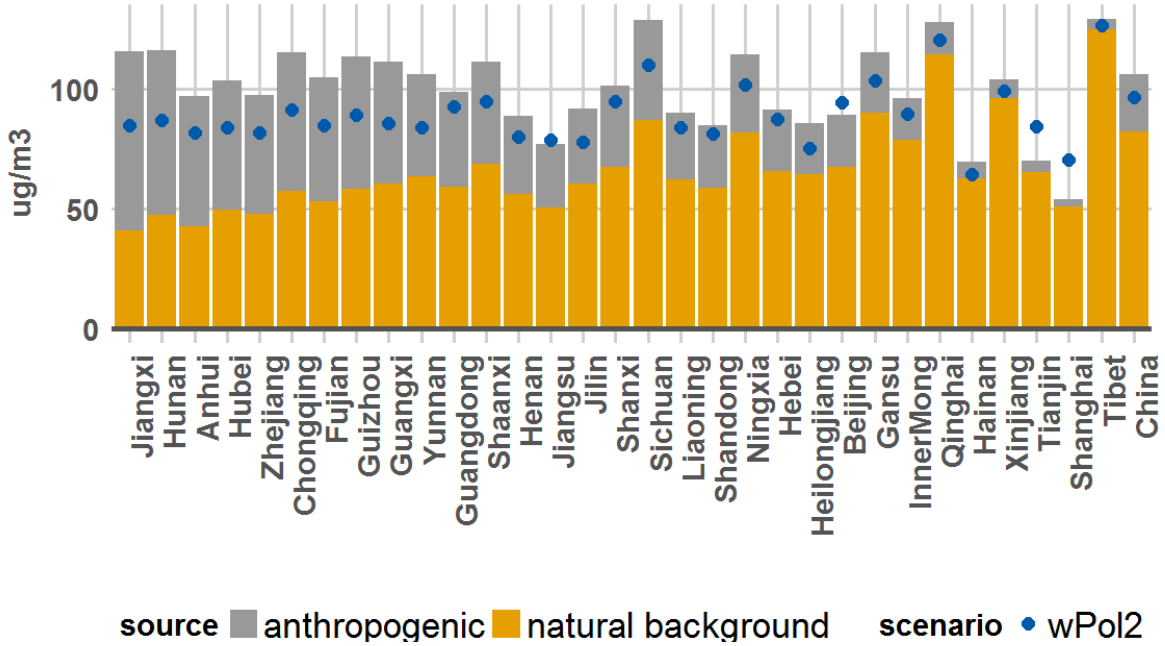


Figure 4-3 Ozone concentration from nature, artificial in WoPol and in WPol2 scenario in 2030.

4.3.2 Health impact of ozone pollution

Health endpoints from ozone pollution include mortality, morbidity and work day loss. In this study, the morbidity consists of cough, asthma, bronchodilator usage, lower respiratory symptoms, and respiratory hospital admissions. This study quantifies the opportunities to get ozone-related diseases, premature death and payment for these kinds of illness for people exposed to two level ozone concentration in 30 provinces in China (*Table 4-2*).

In the WoPol scenario, the concentration in most parts of China will be still above the standard level of 70 ug/m^3 in 2030. Only Hainan and Shanghai could meet the national standard, while in the populous regions, Beijing, Tianjin, and Jiangsu ozone concentration is still high, which will cause various health impacts as shown in *Figure 4-4* (left column), including per capita morbidity, mortality, per capita work hour loss, per capita health expenditure and non-market impact VSL in 30 provinces in 2030 in WoPol scenario in China. This study also calculates the

mitigation benefit (*Figure 4-4* right) from air pollution control policy in the WPol scenario (*Figure 4-4* right column).

Table 4-1 Mortality due to ozone pollution in 2030 in China (Unit: million people).

Scenario	WoPol			WPol			WPol2		
Function	C.I.95% low	ER function	C.I.95% high	C.I.95% low	ER function	C.I.95% low	C.I.95% low	ER function	C.I.95% high
Beijing	1.4	4.2	7.0	1.9	5.7	9.6	1.7	5.3	8.9
Tianjin	0.01	0.03	0.05	0.39	1.2	2.0	0.7	2.2	3.8
Hebei	7.2	22	37	7.2	22	37	5.9	18	30
Shanxi	5.2	16	27	5.1	16	26	4.1	13	21
InnerMong	3.1	9.6	16	3.0	9.3	16	2.4	7.3	12
Liaoning	4.3	13	22	4.2	13	22	3.0	9.2	15
Jilin	2.9	9.0	15	2.4	7.3	12	1.1	3.4	5.7
Heilongjiang	3.0	9.3	16	2.3	7.2	12	1.0	3.1	5.2
Shanghai	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.21	0.35
Jiangsu	2.6	8.1	14	1.9	5.8	9.7	3.2	9.9	17
Zhejiang	6.6	20	34	5.0	15	26	2.8	8.7	15
Anhui	8.3	26	43	6.2	19	32	3.7	11	19
Fujian	6.1	19	31	4.7	15	24	2.6	8.0	13
Jiangxi	9.7	30	50	7.0	22	36	3.1	9.7	16
Shandong	6.7	21	35	5.6	17	29	5.1	16	26
Henan	9.0	28	46	7.5	23	39	4.9	15	25
Hubei	9.5	30	49	7.5	23	39	4.0	12	20
Hunan	15	47	79	11	35	59	5.7	17	29
Guangdong	13	39	65	12	37	61	10	31	52
Guangxi	10	31	52	7.1	22	37	3.8	12	20
Chongqing	6.4	20	33	5.2	16	27	3.0	9.3	15
Sichuan	24	74	120	22	67	110	16	50	84
Guizhou	8.4	26	43	6.5	20	34	3.7	11	19
Yunnan	7.9	25	41	5.6	17	29	3.0	9.3	16
Shaanxi	7.6	24	40	7.0	21	36	4.6	14	24
Gansu	5.8	18	30	5.4	17	28	4.3	13	22
Qinghai	1.5	4.7	7.9	1.5	4.5	7.6	1.3	4.1	6.9
Ningxia	1.3	3.9	6.6	1.2	3.7	6.2	0.91	2.8	4.7
Xinjiang	3.2	9.9	17	3.0	9.3	16	2.8	8.5	14
China	230	580	1200	210	490	1100	170	340	870

Table 4-2 Morbidity due to ozone pollution in 2005 and 2030 in China (Unit: billion case).

Year	2005			2030		
Scenario	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Total health endpoint	2900	2700	2700	3800	3200	2200
Asthma	140	130	130	170	150	100
Respiratory hospital admissions	0.11	0.10	0.10	0.14	0.12	0.08
Bronchodilator usage	2300	2100	2100	3000	2500	1700
Lower respiratory symptoms	500	470	470	650	550	380

China could gain benefit from air pollution control. The provinces in the west and central China with higher ozone concentration have server health impacts, such as Sichuan, Qinghai, Jiangxi, Hunan and Chongqing. As indicated by per capita morbidity, people in these provinces have higher opportunity, about 4-5%, to get health effects such as asthma attacks, respiratory hospital admission, cough, and mortality from ozone exposure. While provinces in the east of China with lower ozone concentration, such as Tianjin, Jiangsu, Beijing, Shandong, have less opportunity, about 1-2%, to get health effect from ozone exposure.

Table 4-3 Work hour loss due to ozone pollution in China in 2005 and 2030 (Unit: hour)

Year		2005			2030	
Region	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Beijing	0.96	0.96	0.96	0.88	1.1	1.1
Tianjin	0.57	0.59	0.59	0.14	0.41	0.64
Hebei	0.78	0.77	0.77	0.94	0.93	0.80
Shanxi	1.1	1.0	1.0	1.4	1.3	1.1
InnerMong	0.76	0.74	0.74	1.1	1.1	0.86
Liaoning	0.69	0.66	0.66	0.87	0.85	0.65
Jilin	0.51	0.45	0.45	0.87	0.71	0.39
Heilongjiang	0.35	0.31	0.31	0.63	0.50	0.26
Shanghai	0.00	0.00	0.00	0.00	0.00	0.03
Jiangsu	0.60	0.54	0.54	0.39	0.31	0.43
Zhejiang	0.65	0.58	0.58	1.1	0.87	0.55
Anhui	0.76	0.69	0.69	1.2	0.88	0.60
Fujian	0.78	0.69	0.69	1.4	1.1	0.69
Jiangxi	0.98	0.87	0.87	1.9	1.4	0.75
Shandong	0.62	0.59	0.59	0.67	0.58	0.54
Henan	0.60	0.56	0.56	0.81	0.69	0.50
Hubei	0.85	0.78	0.78	1.4	1.1	0.68
Hunan	1.0	0.95	0.95	1.9	1.4	0.84
Guangdong	1.1	0.99	0.99	1.3	1.2	1.0
Guangxi	0.82	0.76	0.76	1.7	1.2	0.76
Chongqing	1.0	0.95	0.95	1.9	1.5	1.0
Sichuan	1.7	1.6	1.6	2.5	2.3	1.8
Guizhou	0.92	0.84	0.84	1.8	1.4	0.91
Yunnan	0.68	0.61	0.61	1.5	1.1	0.65
Shaanxi	1.1	1.0	1.0	1.7	1.6	1.1
Gansu	1.4	1.3	1.3	1.9	1.8	1.5
Qinghai	1.9	1.9	1.9	2.5	2.4	2.2
Ningxia	1.3	1.2	1.2	1.9	1.8	1.4
Xinjiang	1.1	1.1	1.1	1.5	1.4	1.3
China	0.84	0.79	0.79	1.2	1.1	0.79

In 2030, the national total number of mortality is about 580 thousand people (230-1200) in WoPol and 490 thousand people (210-1100) in WPol scenario (*Table 4-1*). The total number of mortality in each province from ozone exposure is also quantified. At the provincial level, Sichuan, Gansu Shaanxi and Hunan encounter most of the mortality, about 74 (24-120), 18 (5.8-29), 23 (7.6-39) and 47 (15-79) thousand people in WoPol scenario. Even in the WPol scenario, a total number of mortality in these four provinces are 67, 17, 21, 35 thousand people.

Ozone exposure also leads to work day loss. However, there is no exposure-response function about work day loss for ozone exposure. This study uses the minor restricted day as work day loss. Premature death between 15 to 65 years old people would reduce labor supply and total work time. *Figure 4-4* shows the per capita work loss hours due to cumulative mortality. In 2030, the average work hour loss is 1.2 and 1.1 hours in WoPol and WPol scenario in China, respectively. At the provincial level, Qinghai, Sichuan, Gansu and Xinjiang encounter more work hour loss, about 2.5, 2.5, 1.9 and 1.5 in WoPol scenario, respectively. In the WPol scenario, work hour loss is lower than WoPol scenario.

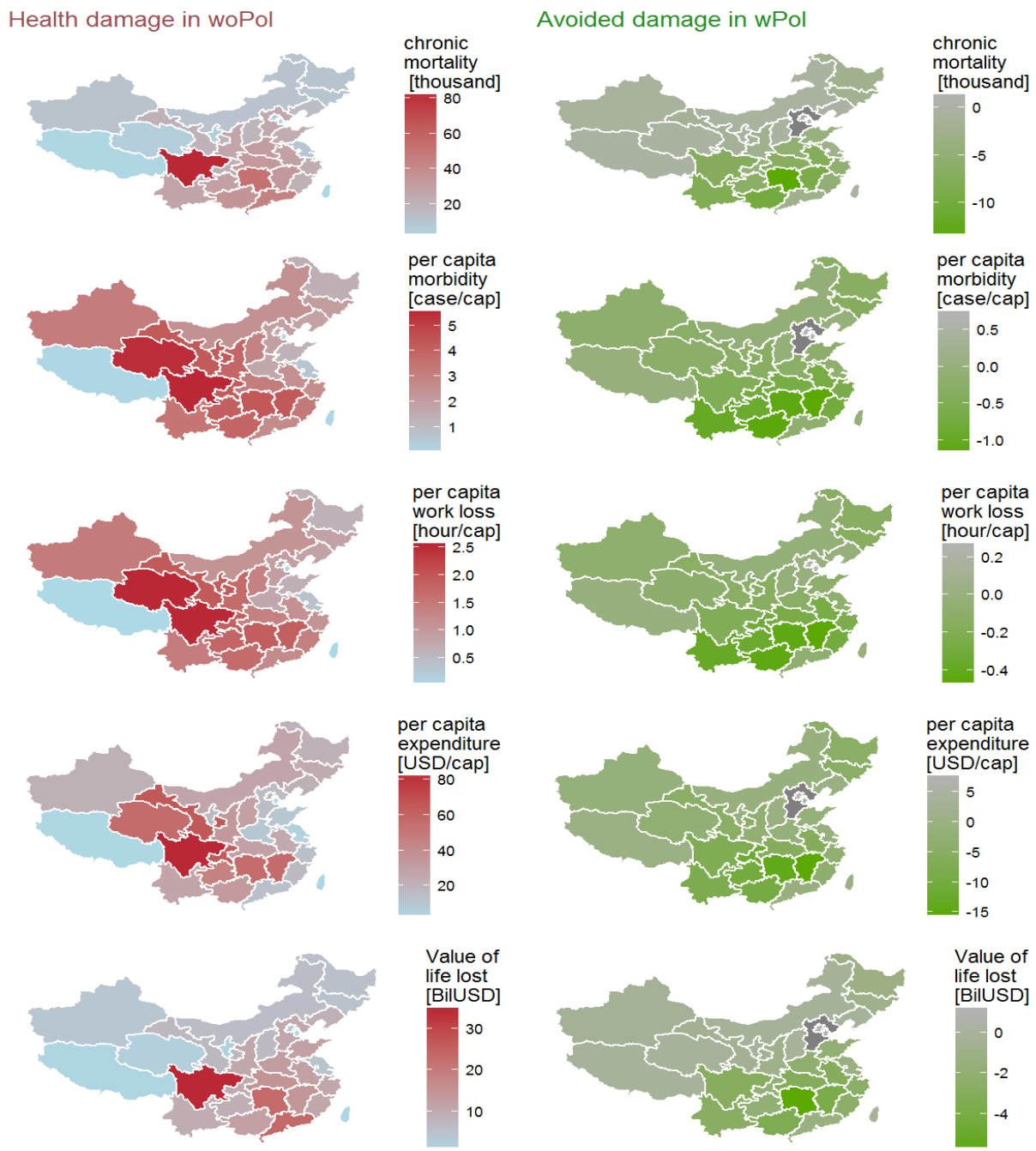


Figure 4-4 Health damage of ozone pollution (left/red) and benefit of mitigation (right/green)in 2030 in China.

4.3.3 Economic impact of ozone pollution

Figure 4-4 (fourth and fifth rows) and *Figure 4-5* show the economic loss due to ozone-related health impacts, including health expenditure, value of life lost, GDP loss and welfare loss.

4.3.3.1 Medical expenditure

The total health expenditure on ozone exposure related morbidity in China in 2030 is estimated to be 310 and 260 billion CNY in WoPol and WPol scenario, respectively, equivalent to per capita expenditure of 230 and 190 CNY. The top five provinces account for most of the health expenditure in WoPol scenario, such as Sichuan, Gansu, Hunan, Jiangxi and Shaanxi. While in WPol scenario, reduction rate of total expenditure in these five provinces is -8.7% (Sichuan), -6.2% (Gansu), -8.3% (Hunan), -26% (Jiangxi), -28% (Shaanxi). Top 3 provinces with highest per capita expenditure in WoPol scenario are different, the highest province is still Sichuan (690 CNY), the following two provinces are Qinghai (460 CNY), and Gansu (530 CNY), which is the relatively poorer provinces. This implies that ozone pollution could become a non-ignorable economic burden to the low-income residents in the west of China.

4.3.3.2 GDP loss and welfare loss

Both labor supply loss and medical expenditure increasing will affect the macroeconomic indicators such as GDP and residential welfare. As indicated in *Figure 4-5*, in 2030, China will experience GDP loss of about 0.35‰ (0.29~0.64‰) in WoPol scenario and 0.31 ‰ (0.26~0.56 ‰) in WPol scenario. At the provincial level, provinces in the west and southwest have higher GDP loss, for example, Qinghai (0.83 ‰, 0.80 ‰ in WoPol and WPol scenarios, respectively), Sichuan (0.82 ‰, 0.76 ‰), Gansu (0.66 ‰, 0.62 ‰), Ningxia (0.63 ‰, 0.59 ‰), Hunan (0.65 ‰, 0.49 ‰). By contrast, Shanghai and Hainan have lowest GDP loss from ozone pollution in China.

Table 4-4 GDP loss and welfare loss due to ozone pollution in 2030 (Unit: ‰)

Economic impact	GDP loss			Welfare loss		
Scenario	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Beijing	0.30	0.38	0.36	0.47	0.55	0.50
Tianjin	0.05	0.14	0.22	0.28	0.38	0.44
Hebei	0.31	0.31	0.27	0.45	0.44	0.37
Shanxi	0.50	0.49	0.41	0.60	0.59	0.49
InnerMong	0.35	0.34	0.27	0.48	0.46	0.37
Liaoning	0.30	0.29	0.22	0.41	0.40	0.30
Jilin	0.31	0.26	0.14	0.39	0.33	0.21
Heilongjiang	0.19	0.15	0.07	0.30	0.25	0.14
Shanghai	0.00	0.00	0.01	0.13	0.11	0.10
Jiangsu	0.13	0.10	0.14	0.21	0.17	0.22
Zhejiang	0.36	0.28	0.18	0.51	0.41	0.27
Anhui	0.30	0.23	0.16	0.42	0.34	0.24
Fujian	0.44	0.35	0.21	0.58	0.46	0.29
Jiangxi	0.64	0.48	0.26	0.78	0.59	0.32
Shandong	0.22	0.19	0.17	0.32	0.28	0.26
Henan	0.24	0.21	0.15	0.32	0.27	0.20
Hubei	0.50	0.41	0.25	0.65	0.53	0.32
Hunan	0.65	0.49	0.28	0.80	0.62	0.36
Guangdong	0.39	0.37	0.33	0.51	0.48	0.41
Guangxi	0.54	0.40	0.25	0.67	0.51	0.32
Hainan	0.03	0.03	0.02	0.11	0.09	0.07
Chongqing	0.56	0.47	0.30	0.82	0.69	0.46
Sichuan	0.82	0.76	0.60	1.1	0.97	0.76
Guizhou	0.61	0.49	0.31	0.86	0.69	0.44
Yunnan	0.48	0.35	0.21	0.66	0.49	0.31
Shaanxi	0.60	0.55	0.39	0.88	0.81	0.58
Gansu	0.66	0.62	0.51	0.89	0.83	0.69
Qinghai	0.83	0.80	0.74	1.5	1.4	1.3
Ningxia	0.63	0.59	0.47	1.4	1.3	1.1
Xinjiang	0.52	0.49	0.46	0.72	0.67	0.61
China	0.35	0.31	0.24	0.49	0.43	0.33

Welfare loss is defined as total consumption change which is measured by Hicks's equivalent variation (Fujimori et al., 2015). In China, welfare loss from ozone-related health impact in 2030 is about 0.49 ‰ (0.41 ‰, 0.90 ‰) and 0.43 ‰ (0.37 ‰, 0.79 ‰) in WoPol and WPol scenario, respectively *(Figure 4-5*). Welfare loss is higher in the provinces such as Qinghai (1.5 ‰ and 1.4 ‰), Ningxia (1.4 ‰ and 1.3 ‰), Sichuan 1.1 ‰ and 0.97 ‰) in WoPol and WPol scenario in 2030. All the provinces are in the west of China, where ozone from nature source is quite high. The differences in economic impact between two scenarios are not significant in these provinces.

4.3.3.3 Value of statistical life

The market impact of ozone pollution in China is not significant, because some of health impact of ozone pollution cannot be quantified by economic model, such as comfort, wellbeing and premature death in children and elder people. This study uses the non-market method on market choices that involve implicit tradeoffs between risk and money. Economists have developed VSL. These VSL estimates can provide government with reference point for assessing the benefits of risk reduction. Co-benefits of avoided air pollution mortality and morbidity are monetized using VSL. In 2030, the national VSL lost is about 2300 and 2000 billion CNY in WoPol and WPol scenarios, respectively, which is about 2.3% and 2.0% of the GDP of China. At the provincial level, Sichuan has the highest mortality and moderate per capita GDP. VSL is the highest (320 billion CNY, or 7.6% of GDP in WoPol) in Sichuan, followed by the western provinces Gansu (64 billion CNY, or 6.5 % of GDP), Xinjiang (37 billion CNY, or 3.3 % of GDP), and Shaanxi (100 billion CNY, or 5.5 % of GDP).

Table 4-5 Value of statistical life in China in 2030

	VSL(Unit: billion CNY)			Comparsion with GDP (Unit:%)		
Scenario	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Beijing	30	40	37	0.89	1.2	1.1
Tianjin	0.20	7.7	14	0.01	0.45	0.84
Hebei	96	96	79	2.2	2.2	1.8
Shanxi	63	62	50	4.1	4.1	3.3
InnerMong	54	52	41	2.3	2.2	1.7
Liaoning	81	80	56	1.8	1.8	1.2
Jilin	46	37	17	2.7	2.2	1.0
Heilongjiang	48	37	16	2.3	1.8	0.77
Shanghai	0.0	0.0	1.6	0.0	0.0	0.04
Jiangsu	43	31	53	0.45	0.32	0.55
Zhejiang	100	78	44	1.4	1.1	0.61
Anhui	110	81	48	3.4	2.5	1.5
Fujian	100	78	43	2.6	2.0	1.1
Jiangxi	130	96	43	7.6	5.5	2.5
Shandong	110	93	85	1.3	1.1	1.0
Henan	120	99	65	1.7	1.4	0.91
Hubei	140	110	58	4.9	3.8	2.0
Hunan	220	160	80	7.4	5.5	2.8
Guangdong	220	210	180	2.0	1.9	1.6
Guangxi	110	81	43	5.2	3.7	2.0
Chongqing	92	75	43	5.1	4.1	2.4
Sichuan	320	290	220	8.3	7.6	5.7
Guizhou	82	64	36	8.6	6.7	3.8
Yunnan	86	61	33	4.4	3.1	1.7
Shaanxi	100	92	60	5.5	5.0	3.3
Gansu	64	60	47	6.5	6.0	4.8
Qinghai	19	18	16	6.5	6.3	5.7
Ningxia	14	13	9.8	4.8	4.6	3.5
Xinjiang	37	34	32	3.3	3.1	2.8
China	2300	2000	1400	2.3	2.0	1.4

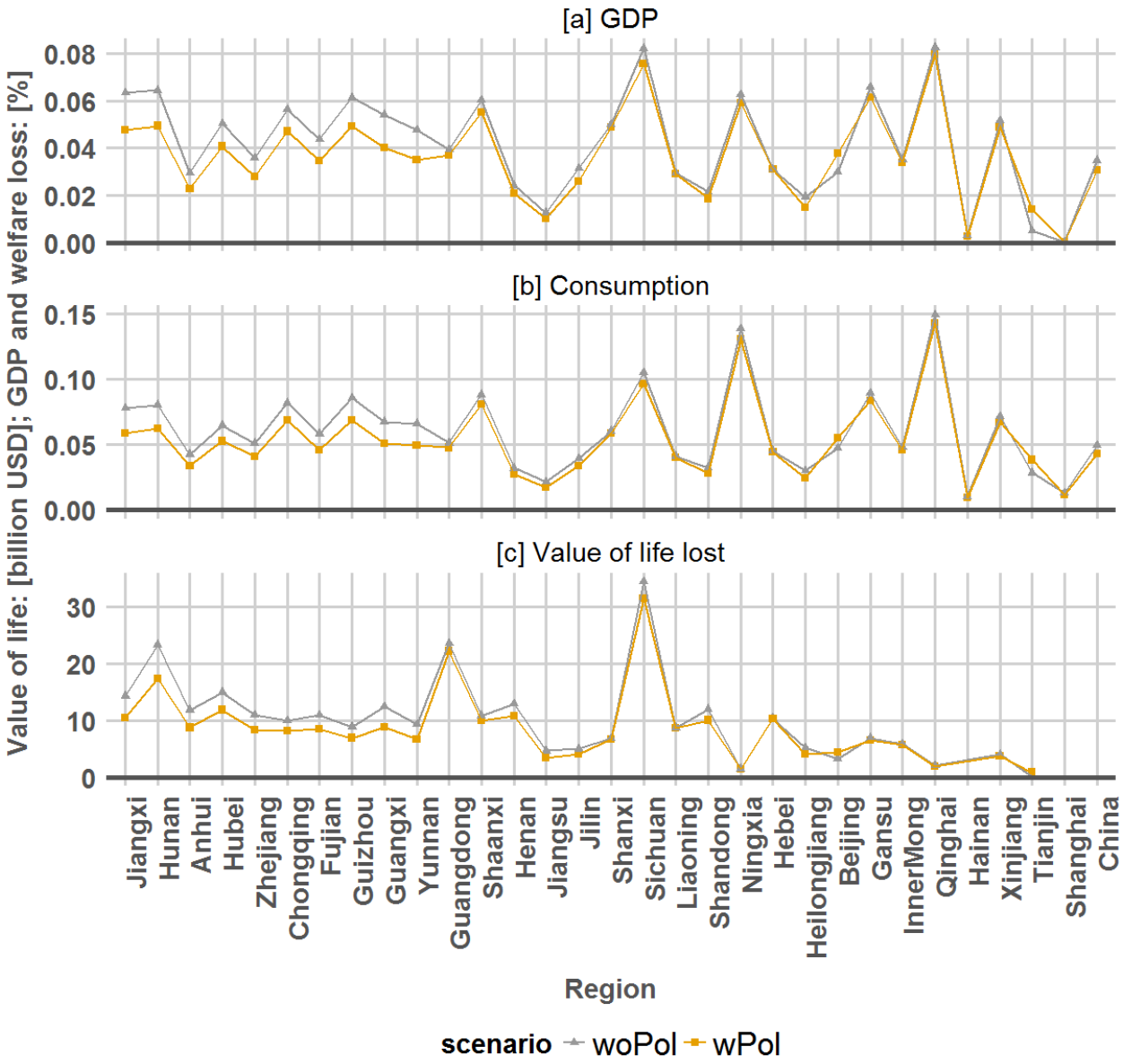


Figure 4-5 GDP loss, Welfare loss and VSL due to ozone pollution in 30 provinces in 2030.

4.4 Discussion of ozone pollution

Ozone concentration is featured in source, regional and seasonal disparity (*Figure 4-2*). It is higher in west of China whereas lower in the east; higher in summer due to higher active reaction of photochemical production from human activity. Ozone concentration is lower in winter in most of provinces and cities, dominated by natural background in some provinces whereas by

anthropogenic sources elsewhere. When national and local governments launch new air pollution control policy, they should consider the regional differences.

In accordance with the features of ozone concentration distribution, ozone-related health impacts are more severe in the western provinces with higher ozone concentration and moderate population density. Provinces of Qinghai, Sichuan, Gansu and Jiangxi suffer from higher per capita morbidity, more work hour loss and higher economic impacts. In contrast, health impacts are lower in the east of China, where the population density is much higher than Southwest. Ozone pollution will lead to higher economic impact in the southwest and lower economic impact in the east. However, southwest provinces are in developing phase with lower GDP. Ozone control technology would be a relatively heavier burden for these regions, while the control effects would be very limited. Therefore, the central government needs to adopt preferential policies such as subsidies and monetary transfer to such provinces.

Considering air pollutants concentration, exposure population and CRFs including the mortality and most morbidity, safety standard(70ug/m^3), health impact from ozone is much smaller than $PM_{2.5}$ pollution in China. $PM_{2.5}$ concentration is much higher in high population density areas, while ozone concentration is higher in relatively low populated western provinces. Economic impact from health-related problem is also smaller than $PM_{2.5}$. Especially provinces in the west of China with highest ozone concentration have lower population density.

Comparing exposure-response functions for ozone and $PM_{2.5}$, ozone has smaller ERFs than $PM_{2.5}$, including the mortality and morbidity. For $PM_{2.5}$, WHO standard is 10 ug/m^3. $PM_{2.5}$ concentration over 10 ug/m^3 will lead to health effects. However, for ozone the threshold value is 35ppbv (or 70 ug/m^3). Comparing $PM_{2.5}$ and ozone concentration in China, $PM_{2.5}$ concentration is much higher in higher population density areas, but ozone concentration is higher in lower population density areas.

It is found that health and economic impacts from ozone are much smaller than $PM_{2.5}$ pollution except for per capita morbidity and expenditure. Taking WPol scenario in 2030 for example, total mortality is 490 thousand people from ozone pollution whereas 2900 thousand people from $PM_{2.5}$ pollution. Per capita work loss is only 1.1 hours from ozone while 15 hours caused by $PM_{2.5}$. Conversely, upper respiratory symptoms dominate $PM_{2.5}$-related endpoint while the overwhelming endpoints related to ozone are bronchodilator usage and lower respiratory

symptoms. Per capita morbidity caused by ozone (2.3 times per capita per year) is more than 20 times higher than $PM_{2.5}$ mainly due to bronchodilator usage. Furthermore, ozone causes less GDP loss (0.03%) than $PM_{2.5}$ (0.36%-0.83%) in WPol scenario and 1.1-2.8% in WoPol scenario as reported in (Xie et al., 2016). Moreover, the GDP loss due to both $PM_{2.5}$ and ozone pollution in WoPol scenario in this study is comparable to that reported in (OECD, 2016b) (2.6% in 2060).

Despite pioneering efforts in quantifying health and economic impacts in this study, there are some limitations. Many epidemiological studies show exposure to higher ozone concentration not only leads to health problem, but also leads to reduction the amount of effective labor, lower productivity (Brauer et al., 1996; Korrick et al., 1998). But the effects on productivity cannot be quantified in this study. If this study considers these kinds of impacts, the economic impact from ozone pollution will be higher than current results. besides, these results may be underestimated because this study neglect mortality younger than 30, including effects on children and neonatal effects (West et al., 2013). Furthermore, as noted in the supplementary information, there is no ERFs for work day loss for ozone, which leads to uncertainty for quantifying the market economic impacts in this study. This study expects future epidemic studies could fill this gap.

5 Concluding remarks

This study evaluates the economic impacts on health damages caused by $PM_{2.5}$ and ozone pollution in 30 provinces in China, and conducts a cost-benefit analysis of air pollution control policy at the provincial level. Air pollution has negative impact on human health and China's economy, which has been a heavy burden for China. Air pollution control policy can reduce air pollutant concentration significantly and bring net benefit for China. This study also finds significant regional disparity among China's provinces in terms of air quality, health and economic impacts, and the costs and benefits of control air pollution. Provinces with higher GDP and population density have higher benefit from air pollution control policy. Regional collaboration is very important for air pollution reduction.

This study finds that it is more difficult to reduce ozone concentration compared with $PM_{2.5}$ pollution (*Figure 5-1*)(Xie et al., 2016) because ozone generation process is not in a linear relationship with precursor emissions, implying that in the longer term. Ozone pollution will be a more persistent problem in China, and adaptation, e.g. wearing protective masks, adjust lifestyle etc., is more important than mitigation, especially in the urban area. Although ozone precursor emissions have been reduced a lot from WoPol to WPol scenario, ozone concentration reduction is very limited (less than 10%) in WPol scenario. Even more aggressive reduction efforts are made in the WPol2 scenario, in contrast to $PM_{2.5}$ whose concentration reduces by over 70% in almost all provinces, reduction rates of ozone concentration are merely around 20% in most provinces. Conversely, in urban areas around Beijing, Shanghai and Guangzhou, it even increases. A similar phenomenon has been reported in previous studies in China. For instance, (Chou et al., 2011) found that the mixing ratio of ozone increased with the increasing NO_2/NO ratio, whereas the NO_z mixing ratio leveled off when $NO_2/NO_{>8}$. Consequently, the ratio of ozone to NO_z increased to above 10, indicating the shift from VOC-sensitive regime to NO_x-sensitive regime. (Xue et al., 2014) found that varying and considerable impacts of ozone generation processes in different areas of China depending on the atmospheric abundances of aerosol and NO_x. This is partly due to the fact that most of $PM_{2.5}$ is from artificial activities like industry and transportation, while relatively less portion from natural sources, such as desert, farmland, burning forest and sea salt. But for ozone, a significant source is nature emissions, which is beyond the control of human activity.

This study also compared the impacts of ozone and $PM_{2.5}$ pollution in China (*Figure 3-2*). Take WPol scenario in 2030 for example, it is found that the per capita morbidity caused by ozone is around 10 times higher than $PM_{2.5}$ mainly due to bronchodilator usage (*Figure 5-3*). There are several reasons:

5.1 Findings of the impacts of $PM_{2.5}$

5.1.1 Air pollution

Under fast development, China is emitting a lot of air pollutants and encountering severe air pollution. However, $PM_{2.5}$ concentration is different from region to region. The $PM_{2.5}$ concentration is much higher in the east of China, and lower in less industrialized and less populated regions. Air pollution control policy can reduce $PM_{2.5}$ concentration significantly. With intensive use of end-of-pipe technologies in the WPol scenario, $PM_{2.5}$ reduction is about 75% compared with the WoPol scenario in which air pollution control policy is in absence. However, even under intensive air pollution control technology, $PM_{2.5}$ concentration is still much higher than the national standard. In the most provinces of China, $PM_{2.5}$ concentration in both scenarios is much higher than the national standard (35 ug/m^3) and WHO standard (10 ug/m^3).

5.1.2 Health impact

$PM_{2.5}$ pollution leads to millions of morbidity and mortality in China per year. The mortality due to $PM_{2.5}$ pollution is 9.2 million and 2.3 million in WoPol and WPol scenario in 2030, respectively. At the provincial level, Henan, Shandong, Jiangsu, Hebei and Sichuan provinces have larger amount of premature death. On the contrary, in the provinces with better air quality and lower population density such as Hainan, mortality is lower than other provinces.

$PM_{2.5}$ pollution also leads to work time loss, because of health problem. The national per capita work time loss in 2030 reaches 56 hours in the WoPol scenario, and 15 hours in the WPol scenario. The provincial disparity in the per capita work time loss is consistent with the provincial disparity in $PM_{2.5}$ concentration. Tianjin, Henan, Shanghai, Hebei, and Beijing have the highest annual per capita work time.

5.1.3 Economic impact

Health expenditure on $PM_{2.5}$ pollution-related is about 210 billion CNY (0.11% of GDP) in the WoPol scenario and 53 billion CNY (0.027% of GDP) in the WPol scenario in 2030. Per capita health expenditure in the WoPol and WPol scenarios 151 and 39 CNY in 2030 in China. The provinces with higher health expenditure are Henan, Sichuan, Shandong, Hebei, and Jiangsu province, which have severe air quality and high population density.

China experiences a 2.0% GDP loss from $PM_{2.5}$ pollution in 2030 in the WoPol scenario. Furthermore, China experiences 2.7% and 0.63% this welfare loss in WoPol and WPol scenario in 2030.

At the provincial level, the GDP loss and this welfare loss is higher in Tianjin (3.1% and 5.4%), Shanghai (3.0% and 4.5%), Beijing (2.8% and 3.9%), Jiangsu (2.6% and 3.7%), Hebei (2.6% and 3.6%), and Shandong (2.5% and 3.5%) in the WoPol scenario in 2030. Conversely, economic loss in 2030 is lower in the WPol scenario in every province. The economic loss is quite low in both scenarios in Xinjiang, Heilongjiang, Inner Mongolia, Hainan, and Gansu, provinces with lower $PM_{2.5}$ concentrations and less sensitivity to air-pollution-control policy.

VSL is about 39000 and 9800 billion CNY in WoPol and WPol scenario in China. At the provincial level, VSL is higher in Shandong, Jiangsu, Hebei, Guangdong and Sichuan province, about 4300, 3700, 2700, 2700 and 2600 billion CNY in WoPol scenario in 2030, respectively. In WPol scenario, VSL is about 970, 810, 550, 640 and 850 billion CNY in these five provinces, respectively.

5.1.4 Net-benefit analysis

The cost-benefit analysis reveals that a control investment of 830 billion CNY (0.79% of GDP) in the WPol scenario would lead to a gain of 1.2% of GDP in China from improving $PM_{2.5}$ pollution, indicating that air pollution control is cost-effective at the national level. At the provincial level, about two-thirds of provinces in China can obtain net benefit from air pollution control policy, which means the benefit in these provinces is positive. Most of such provinces have higher GDP and denser population, such as Shanghai, Beijing, Tianjin, Jiangsu, Henan, and Zhejiang. This study also demonstrates a much smaller economic benefit in less developed and populated provinces, where the adoption of air-pollution-control technology may incur a big

burden and ultimately lead to negative economic impacts, such as Ningxia, Guizhou, Shanxi, Gansu, Heilongjiang, Qinghai, and Xinjiang. This implies that the central government needs to initiate fiscal transfer schemes to help the underdeveloped western provinces to tackle air pollution.

5.1.5 Beijing-Tianjin-Hebei area

This study also took a closer look at the Beijing-Tianjin-Hebei area, which is one of the most developed regions in China as well as the most polluted region with severe health problems caused by $PM_{2.5}$ pollution. The results show that $PM_{2.5}$ pollution also has significant impact on GDP and welfare in this region. The GDP loss related to $PM_{2.5}$ pollution is about 2.8% in Tianjin, 2.5% in Beijing and 2.2% in Hebei in the WoPol scenario, while welfare loss is 5.1%, 8.1% and 3.4% in Tianjin, Beijing and Hebei, respectively. However, under intensive air pollution control technology, Beijing, Tianjin and Hebei could obtain benefits equivalent to 1.8%, 2.0% and 1.5% of GDP in the WPol scenario. The benefits of air pollutant control technology are higher than the cost in Beijing-Tianjin-Hebei area, and the benefits are highest in Beijing, lower in Tianjin and lowest in Hebei.

When shedding light on the impacts on the sectors, this study found that the labor-intensive sectors will encounter more significant negative impacts since air pollution-related work time decreases will lead to increase in labor price. The increasing of labor price leads to the additional cost of production. These sectors include coal mining, food production, textile, water supply, transport and agriculture.

5.2 Findings of the impacts of ozone

5.2.1 Air pollution

Ozone concentration is lower than $PM_{2.5}$ in China and it varies in different seasons (Wang et al., 2011). This simulation shows that ozone concentration is higher in the southwest of China. In these provinces, it is quite difficult to reduce ozone concentration by policy intervention since most of ozone precursor emissions are from natural sources.

Conversely, in the eastern provinces such as Zhejiang, Anhui, Fujian, Jiangxi, Hubei and Hunan, ozone precursor emissions from human activity are relatively dominant source. Ozone

concentration could decrease a little bit in most of such provinces under intensive application of air pollution control technologies. However, in some cities, ozone concentration increases even though the primary air pollutants is reduced, this is because of the non-linear relationship between primary emissions and secondary formation process of ozone which are found by many other studies (Chou et al., 2011; Xue et al., 2014).

5.2.2 Health impact

The national total mortality related to ozone pollution is about 580 thousand people in WoPol and 490 thousand people in WPol scenario in 2030. Sichuan, Gansu Shaanxi and Hunan encounter most of the mortality. As for morbidity, the provinces in the west and central China with higher ozone concentration have server health impacts, such as Sichuan, Qinghai, Jiangxi, Hunan and Chongqing. Per capita morbidity in these provinces is about 4-5%, which is much higher than lower ozone concentration provinces.

5.2.3 Economic impact

The total health expenditure on ozone exposure related morbidity in China in 2030 is estimated to be 310 and 260 billion CNY in WoPol and WPol scenario, equivalent to a per capita expenditure 230 and 190 CNY, respectively. Health expenditure related to ozone exposure is higher in Sichuan, Gansu, Hunan, Jiangxi and Shaanxi provinces. Ozone pollution could become a non-ignorable economic burden to the low-income residents in the west of China.

China experiences GDP loss of about 0.35‰ in the WoPol scenario and 0.31‰ in the WPol scenario and the welfare loss is about 0.49‰ and 0.43‰ in WoPol and WPol scenario, respectively. The provinces with higher GDP loss and this welfare loss are in the west of China, where the shares of ozone emissions from nature source are quite high.

5.2.4 Net-benefit analysis

Although the economic impacts of ozone are significantly lower than $PM_{2.5}$, the feature of its regional disparity deserves concern by the policy makers since it is a non-ignorable economic burden for the low-income western provinces. Moreover, it is much more difficult to mitigate ozone pollution, especially for provinces with high natural background in West of China which is home to tens of millions of people. For these areas, adaptation is a more feasible option to avoid

health damage, and the central government needs to adopt preferential policies such as subsidies and monetary transfer to such provinces. To better understand the implications of ozone-related health damage for the macroeconomy, this study expects the future epidemic studies could provide concentration-response functions on work day loss and age-specific mortality.

5.3 Comparison of impacts between $PM_{2.5}$ and ozone pollution

This study also compared the impacts caused by $PM_{2.5}$ and ozone systematically under the same assumptions of the driving forces such as economic growth and primary emission trajectory. This study compared concentration, mortality, morbidity and economic impacts and policy implications caused by these two kinds of air pollutants in China.

5.3.1 Concentration change to emission reduction

Figure 5-1 shows the annual average $PM_{2.5}$ concentration and daily-maximum-8-hour-mean ozone concentration in WoPol, WPol and WPol2 scenarios in 30 provinces in 2030 in China. From the simulation of the air quality model, $PM_{2.5}$ concentration is highest in WoPol scenario, lower in WPol scenario and lowest in WPol2 scenario. Air pollution control policy can reduce $PM_{2.5}$ concentration effectively in most provinces of China. However, in most provinces, $PM_{2.5}$ concentration is still higher than national standard of 35 ug/m^3 in all scenarios. Comparing with $PM_{2.5}$, ozone pollution is much less serious in China at present. However, ozone concentration reduction is very limited in the WPol and WPol2 scenarios comparing to WoPol scenario. Like the $PM_{2.5}$, ozone concentration is highest in WoPol scenario, lower in WPol scenario and lowest in WPol2 scenario in most provinces in China. However, for some cities or provinces, such as Beijing, Shanghai and Guangdong, even though primary air pollutants emissions reduce a lot, ozone concentration in these cities does not decrease but even increases. Ozone generation reaction is not in a linear relationship with primary emissions. Even in the developed countries, such as USA and Japan, they still face significant ozone pollution in urban area.

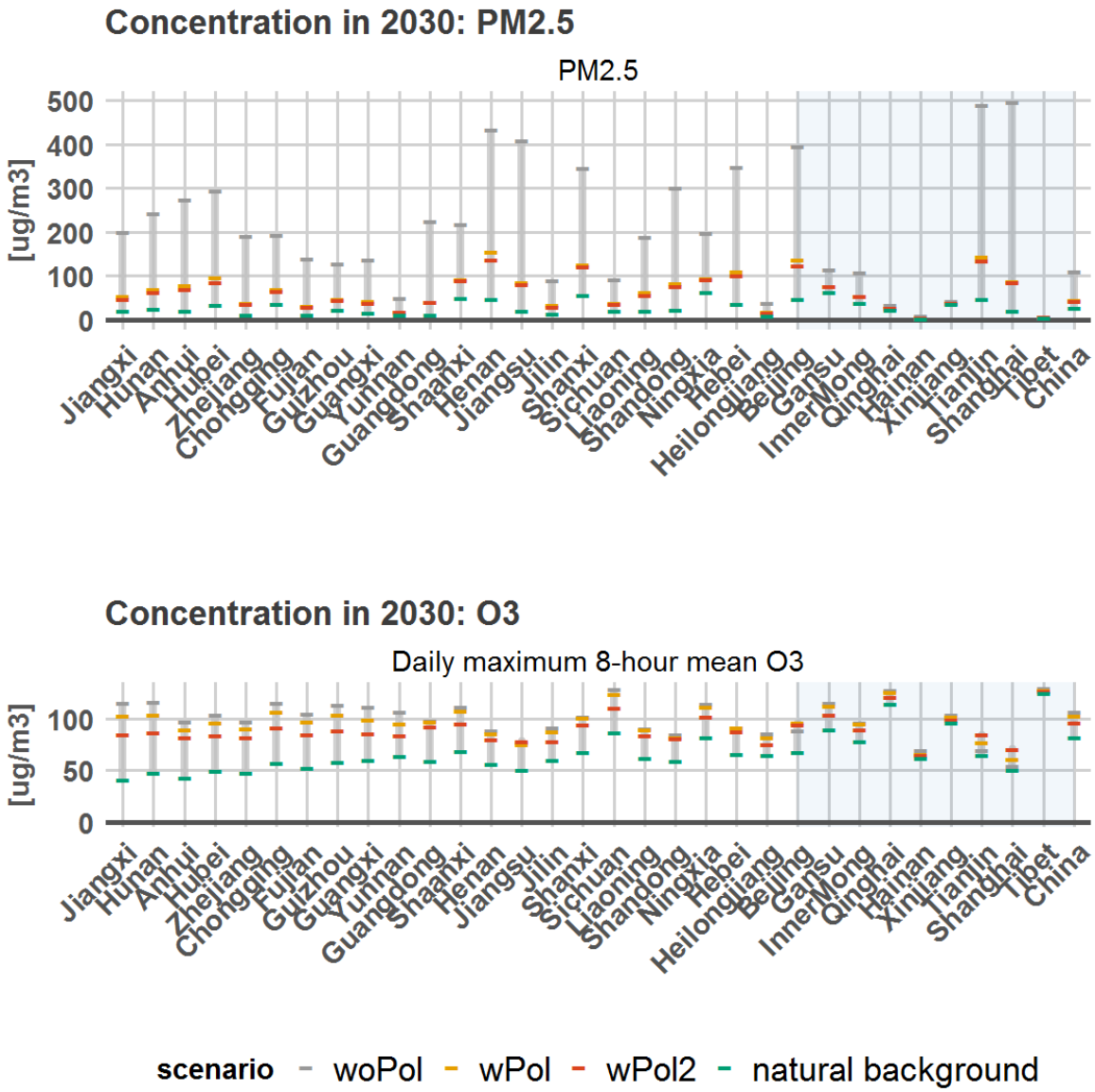


Figure 5-1 $PM_{2.5}$ (upper) and ozone (lower) concentration in WoPol, WPol and WPol2 scenarios and the natural background level in 2030.

5.3.2 Mortality

Premature death is the most severe health impact of air pollution. Mortality is associated with toxicity of air pollutants. For the same air pollutant, mortality is related to air pollutant concentration level. In the methodology part, the exposure-response Functions for both $PM_{2.5}$ and

ozone have been presented. To compare mortality from both $PM_{2.5}$ and ozone, concentration data from GEOS-Chem simulation is used here.

Figure 5-2 shows the mortality from $PM_{2.5}$ and ozone pollution in 2030 in China. Mortality from $PM_{2.5}$ is much higher than ozone pollution. In 2005, mortality from $PM_{2.5}$ is about 5200, 2100 and 2100 thousand in WoPol, WPol and WPol2 scenarios, respectively. In 2030, mortality increases to 8800, 2400 and 2200 thousand people in WoPol, WPol and WPol2 scenarios, respectively. By contrast, for ozone pollution, mortality is about 450, 420 and 420 thousand people in WoPol, WPol and WPol2 scenarios in 2005, respectively, and changes to 580, 490 and 340 thousand people in WoPol, WPol and WPol2 scenarios in 2030, respectively. Avoiding premature death is quite significant from $PM_{2.5}$ reduction, but not so promising for ozone pollution.

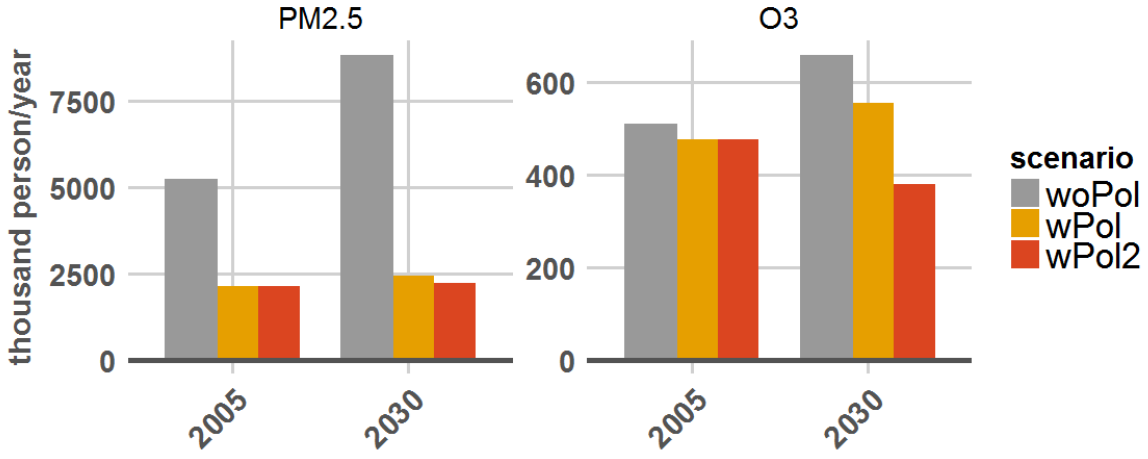
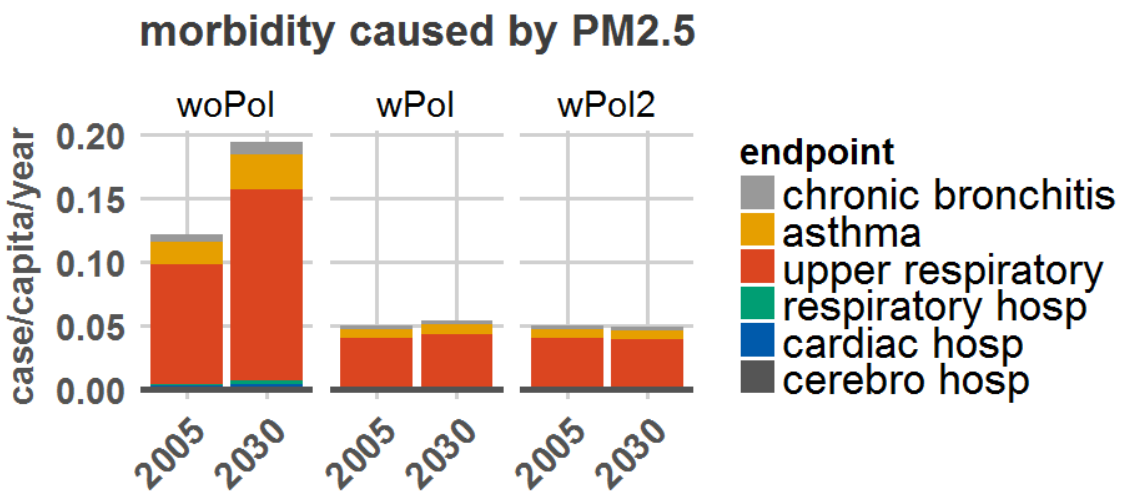


Figure 5-2 Mortality from $PM_{2.5}$ and ozone pollution in WoPol, WPol and WPol2 scenarios.

5.3.3 Morbidity

Health effect is different between $PM_{2.5}$ and ozone pollution. $PM_{2.5}$ pollution leads to huge amount of morbidity. From *Figure 5-3*, $PM_{2.5}$ pollution leads to more health effect than ozone related to chronic bronchitis, asthma, upper respiratory symptom, respiratory hospital admission, cardiovascular hospital admission and cerebrovascular hospital admission. Upper respiratory symptom is the dominant disease of $PM_{2.5}$ pollution. While asthma is the overwhelming effect

exposed to ozone pollution. Lower respiratory symptoms are also common diseases from ozone pollution. Asthma and lower respiratory symptoms contribute to the most of the morbidity caused by ozone pollution. There is no significant evidence on the relationship with cardiovascular hospital admission and cerebrovascular hospital admission.



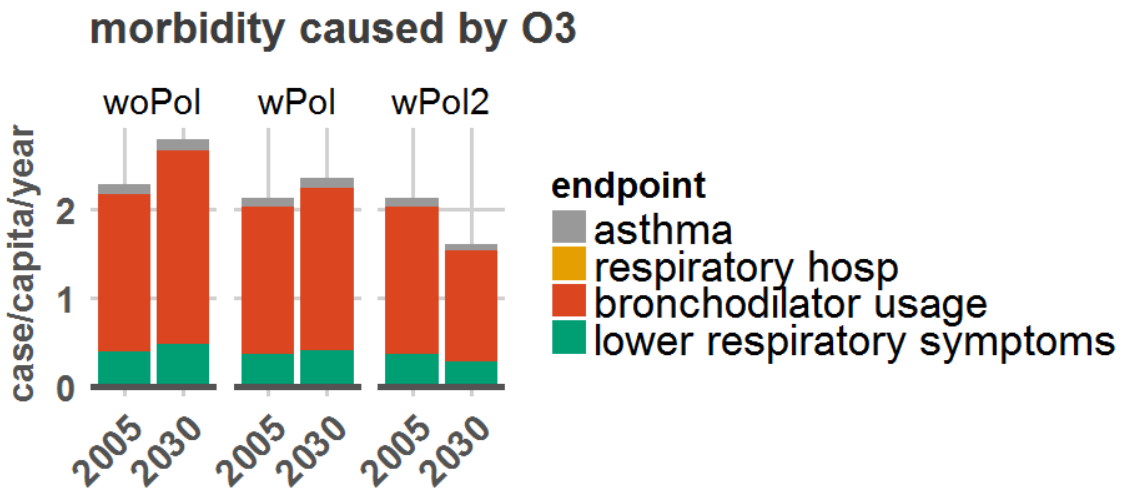


Figure 5-3 Per capita morbidity from $PM_{2.5}$ and ozone pollution in WoPol, WPol and WPol2 scenarios.

The total health expenditure on $PM_{2.5}$ is about 210 and 53 billion CNY in WoPol and WPol scenario in 2030, respectively. Per capita health expenditure is 150 CNY in WoPol scenario and 39 CNY in WPol scenario in 2030. By contrast, the total health expenditure on ozone-related morbidity is estimated to be 310 and 260 billion CNY in WoPol and WPol scenario in 2030, respectively, equivalent to per capita expenditure of 230 and 190 CNY (*Figure 5-4* and *Figure 5-5*). Health effects from $PM_{2.5}$ are more than ozone pollution. But ozone leads to lots of asthma and bronchodilator usage, which need regular medicine. The total health expenditure and per capita expenditure of ozone-related health problem is higher than $PM_{2.5}$.

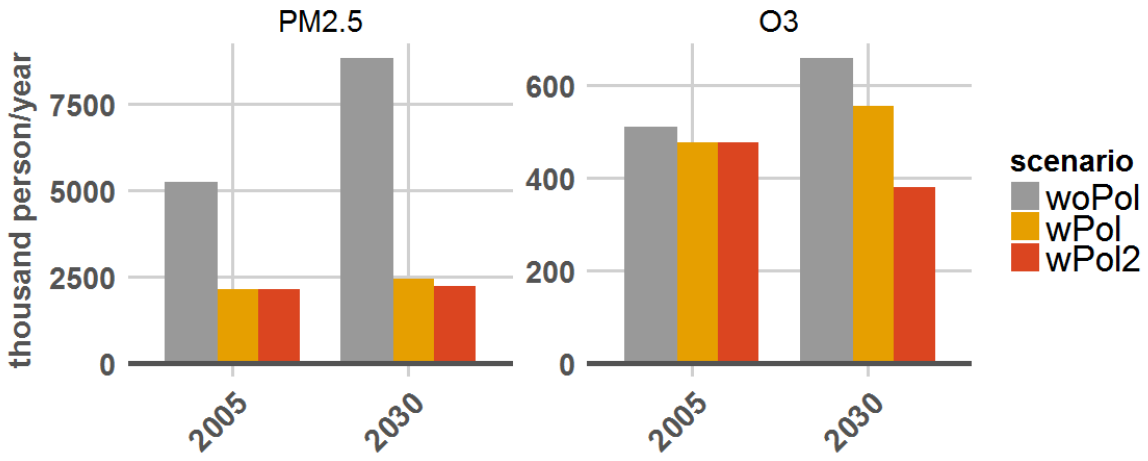


Figure 5-4 Total medical expenditure from $PM_{2.5}$ and ozone pollution in WoPol, WPol and WPol2 scenarios.

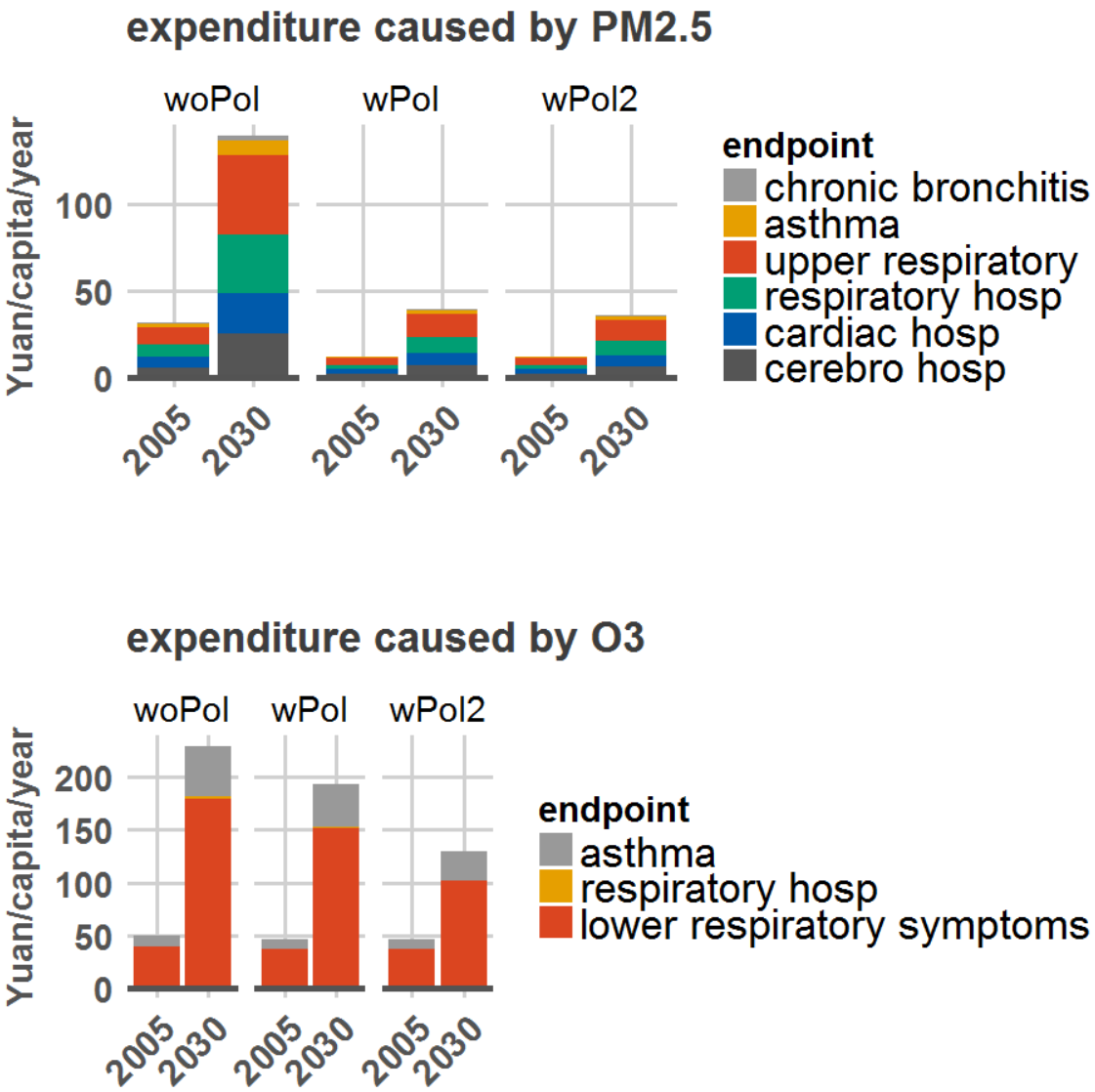


Figure 5-5 Per capita medical expenditure from $PM_{2.5}$ and ozone pollution in WoPol, WPol and WPol2 scenarios.

5.3.4 Work time loss

The work day loss from $PM_{2.5}$ exposure is much higher than ozone. *Figure 5-6* compares the work hour loss from $PM_{2.5}$ and ozone. In China, per capita annual work hour loss from $PM_{2.5}$ is about 56 and 15 hours in WoPol and WPol scenarios, respectively, which is much higher than the work hour loss from ozone (1.2 and 1.1 hours in WoPol and WPol scenarios in 2030, respectively). Furthermore, work hour improvement is very limited in ozone pollution control scenario.

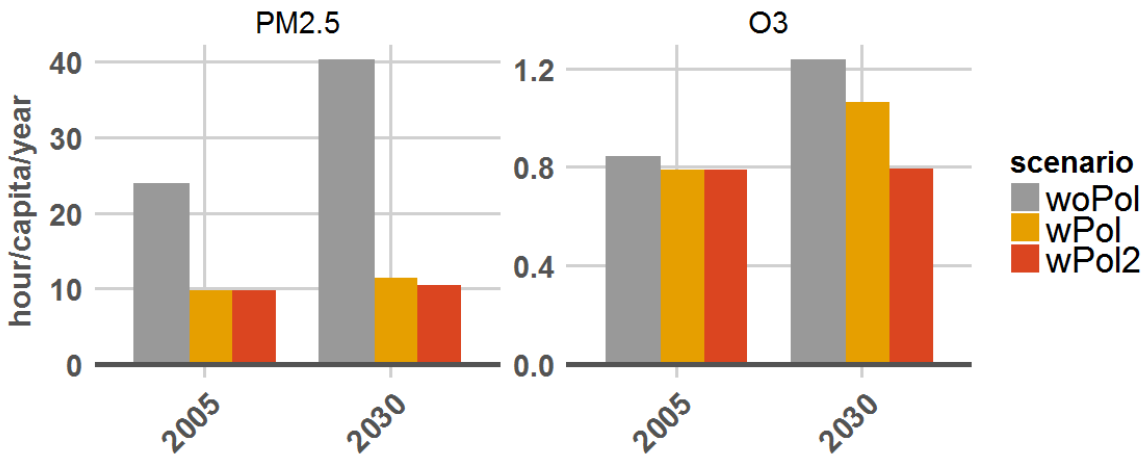


Figure 5-6 Per capita work hour loss from $PM_{2.5}$ and ozone pollution in WoPol, WPol and WPol2 scenarios.

5.3.5 Macroeconomic impacts

This study also compares the macroeconomic impacts from both $PM_{2.5}$ and ozone pollution, including GDP loss, consumption loss and VSL. In the WoPol scenario without $PM_{2.5}$ pollution control policy, China will experience a 2.0% GDP loss from $PM_{2.5}$ pollution in 2030. In the WPol scenario, a control investment of 800 billion CNY (0.79% of GDP) and a gain of 1.2% of GDP in China from improving $PM_{2.5}$ pollution are projected. About the welfare loss, China will experience 2.7% and 0.63% welfare loss in WoPol and WPol scenario in 2030. The results show the welfare loss is higher than GDP loss. About ozone pollution, China will experience GDP loss of only about 0.35‰ in WoPol scenario and 0.31‰ in WPol scenario in 2030. Welfare loss from ozone-related health impacts in 2030 is about 0.49 ‰ and 0.43 ‰ in WoPol and WPol scenario, respectively.

5.4 Conclusion of this thesis

China's energy consumption and carbon emissions have been accelerating under the influence of urbanization and industrialization. China is also suffering quite severe air pollution, especially $PM_{2.5}$ and ozone pollution. Air pollution in China has led to millions of mortality and morbidity every year and increased health expenditure. It is also a big burden on China's economy. The Chinese government is promoting series of air pollution control policies, which could improve air quality and bring positive impact on the people's health and the economy. The net benefit is different in 30 provinces. Provinces with higher population density, worse air quality and higher development, have higher benefit from air pollution control technology. These provinces in undeveloped regions have less or negative impact on the economy from air pollution control policy. Air pollution control needs collaboration among provinces in China.

5.5 Limitations and future work

Despite pioneering efforts in quantifying the health and economic impacts of ambient ozone and $PM_{2.5}$ pollution, there are some limitations which need further investigation. The limitations are listed but not limited to:

Model:

The model integration framework is only a one-way process instead of a closed circle. In other words, the CGE model provides energy data for calculating emissions. In the end, CGE model also evaluates the economic impacts of air pollution, but the feedback effects of changed economic activity are not considered in the emission model. There is no ERFs for work day loss for ozone, and as a second best approach this study converted it from the restricted activity day, which leads to uncertainty for quantifying the market economic impacts in the CGE model. To better understand the implications of ozone-related health damage for the economy, future epidemic studies could provide concentration-response functions on work day loss and age-specific mortality.

Data:

These results may be underestimated because this study neglects mortality younger than 30, including effects on children and neonatal effects (West et al., 2013). This study only assesses the health impacts of ozone and $PM_{2.5}$ pollution in China. There are some other air pollutants, which also have impact on human health and economy. Other air pollutants should be included in the impacts of air pollution.

Impact:

Economic impacts only include the work time loss due to mortality and morbidity but don't include the impacts on labor productivity. Many epidemiological studies show exposure to higher ozone concentration not only leads to health problem, but also leads to reduction the amount of effective labor, which is measured in labor productivity (Brauer et al., 1996; Korrick et al., 1998). However, the effects on productivity cannot be quantified in this study. If this study considers these kinds of impacts, the economic impact from ozone pollution will be higher than current results. Impacts on welfare only focus on consumption, but this study does not include the leisure time.

Appendix

Appendix A1: The locations of provinces in China.

Figure A-1 locations of 30 provinces in China

Source: http://www.chinatoday.com/china-map/china-map-atlas.htm(accessed time 5th April, 2017)

Appendix A2: Air pollutants emissions inventory

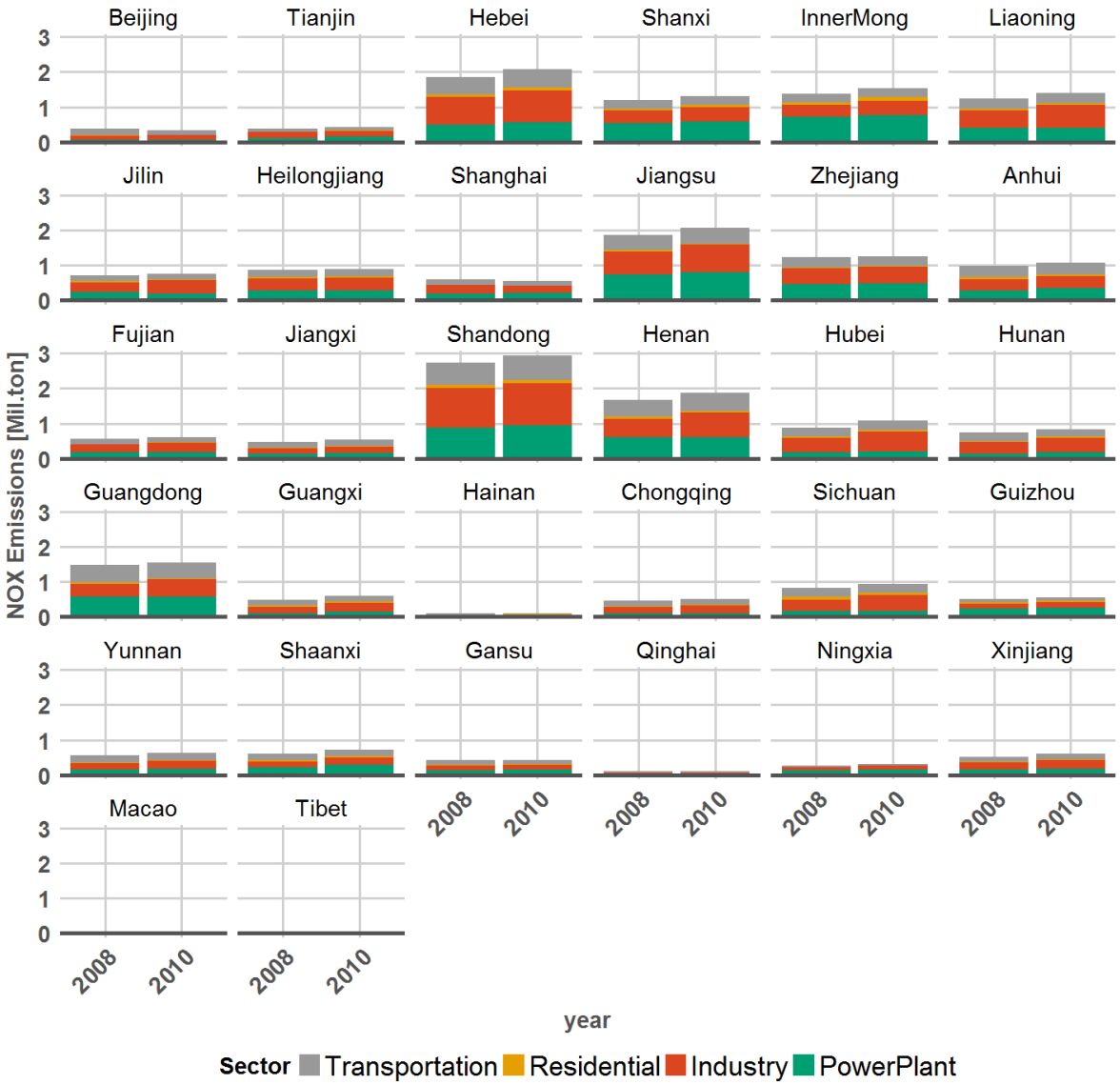


Figure A-2 NO_x emissions in China.

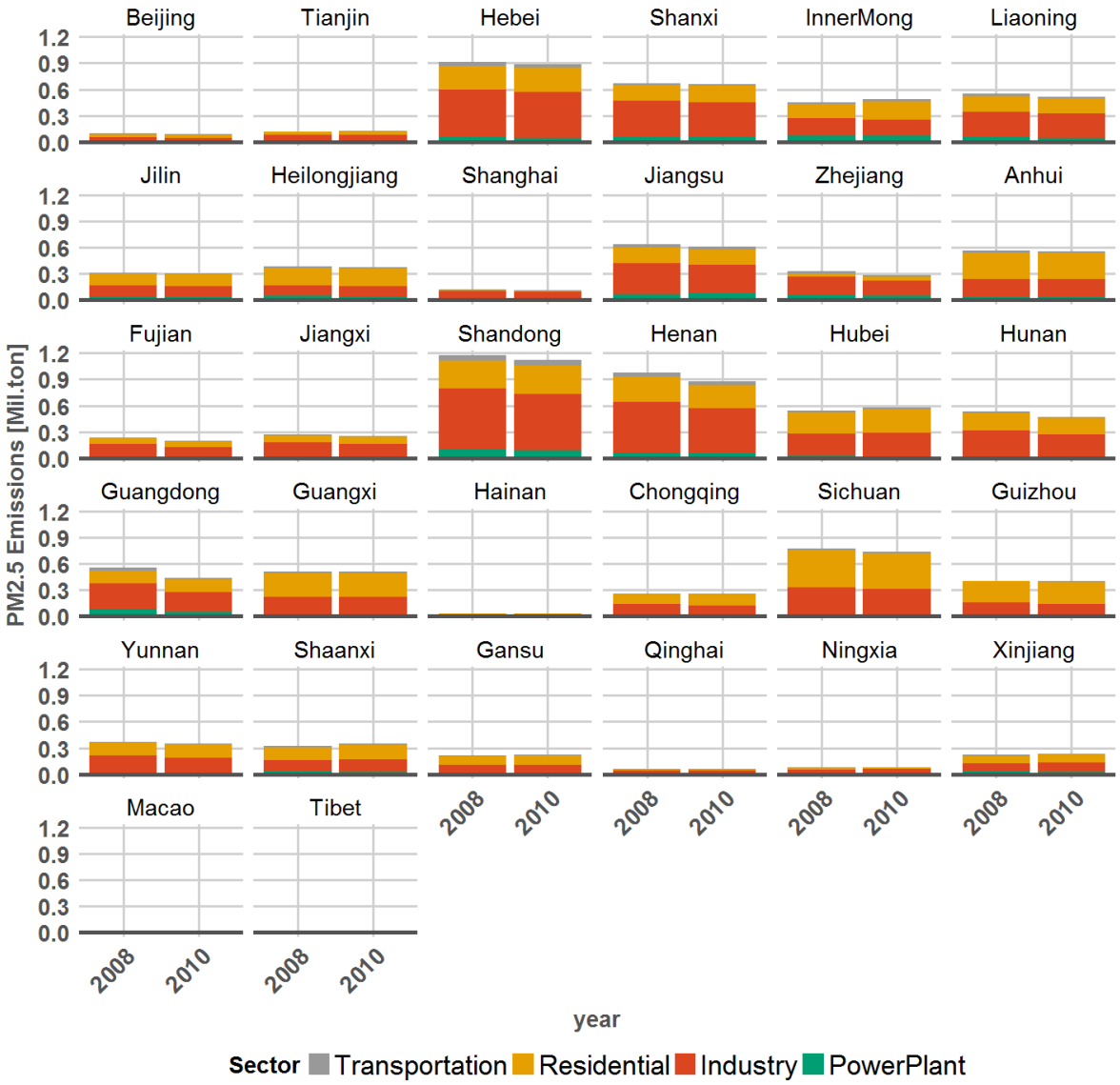


Figure A-3 $PM_{2.5}$ emissions in China.

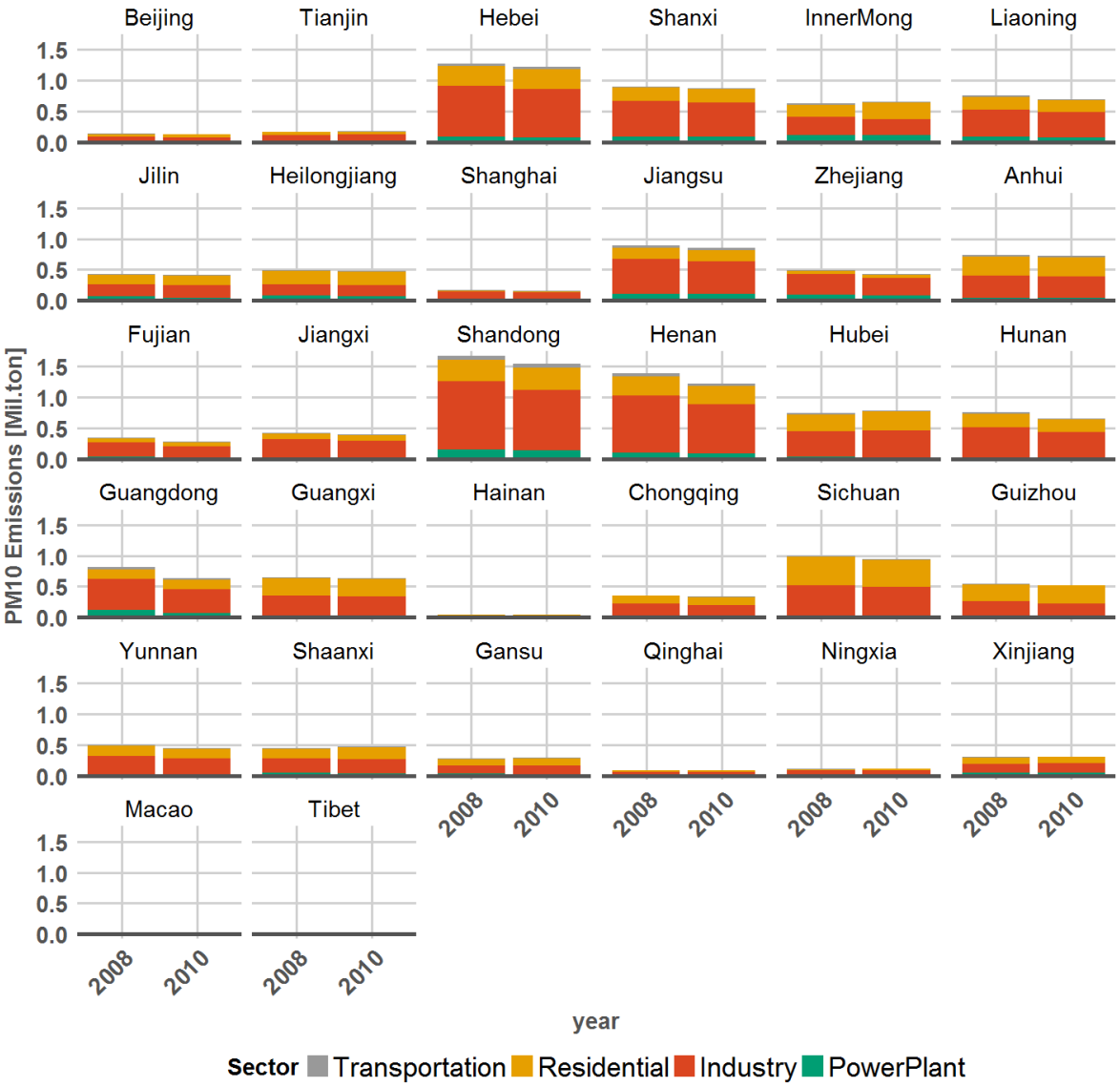


Figure A-4 PM_{10} emissions in China.

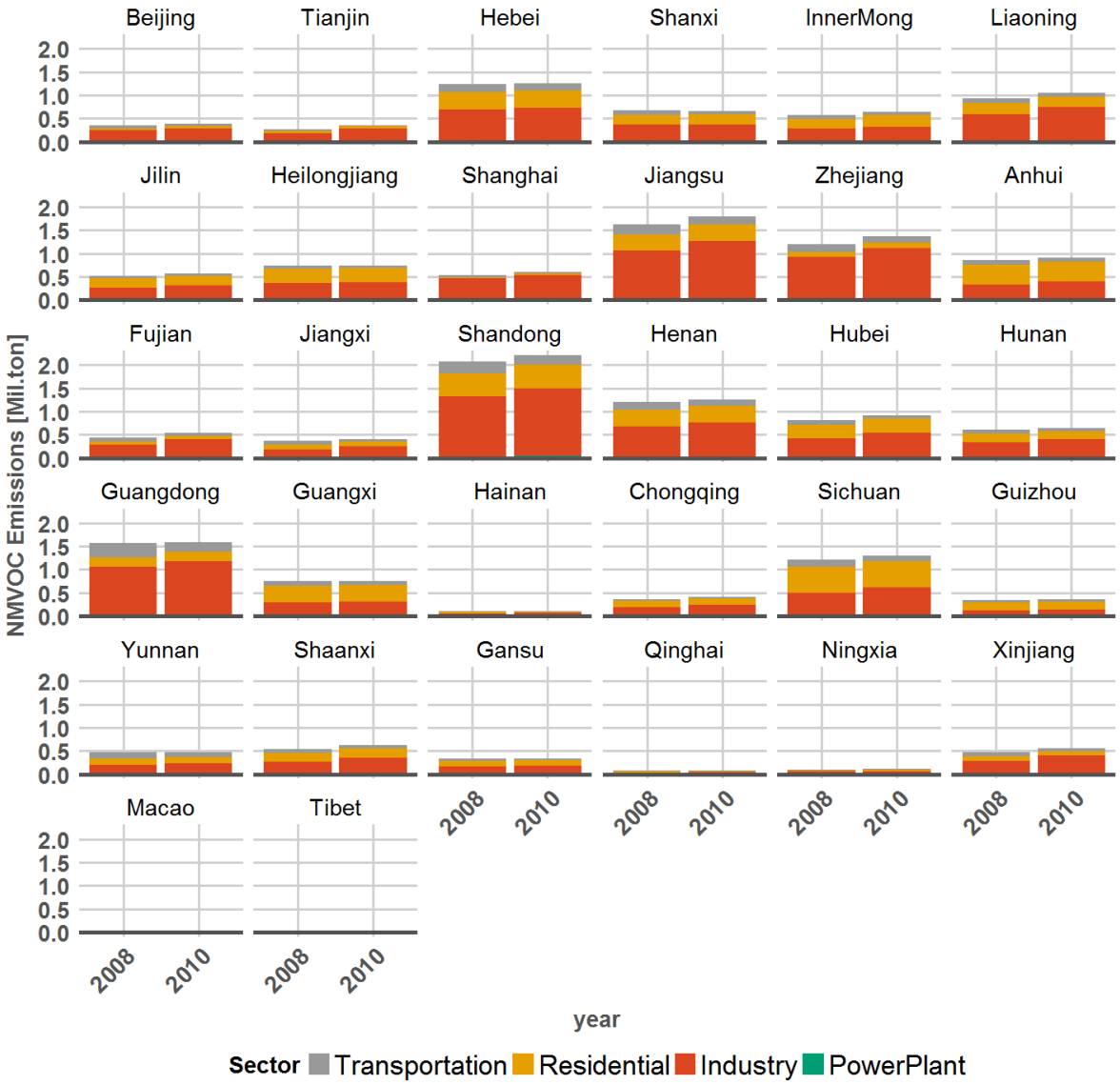


Figure A-5 VOC emissions in China.

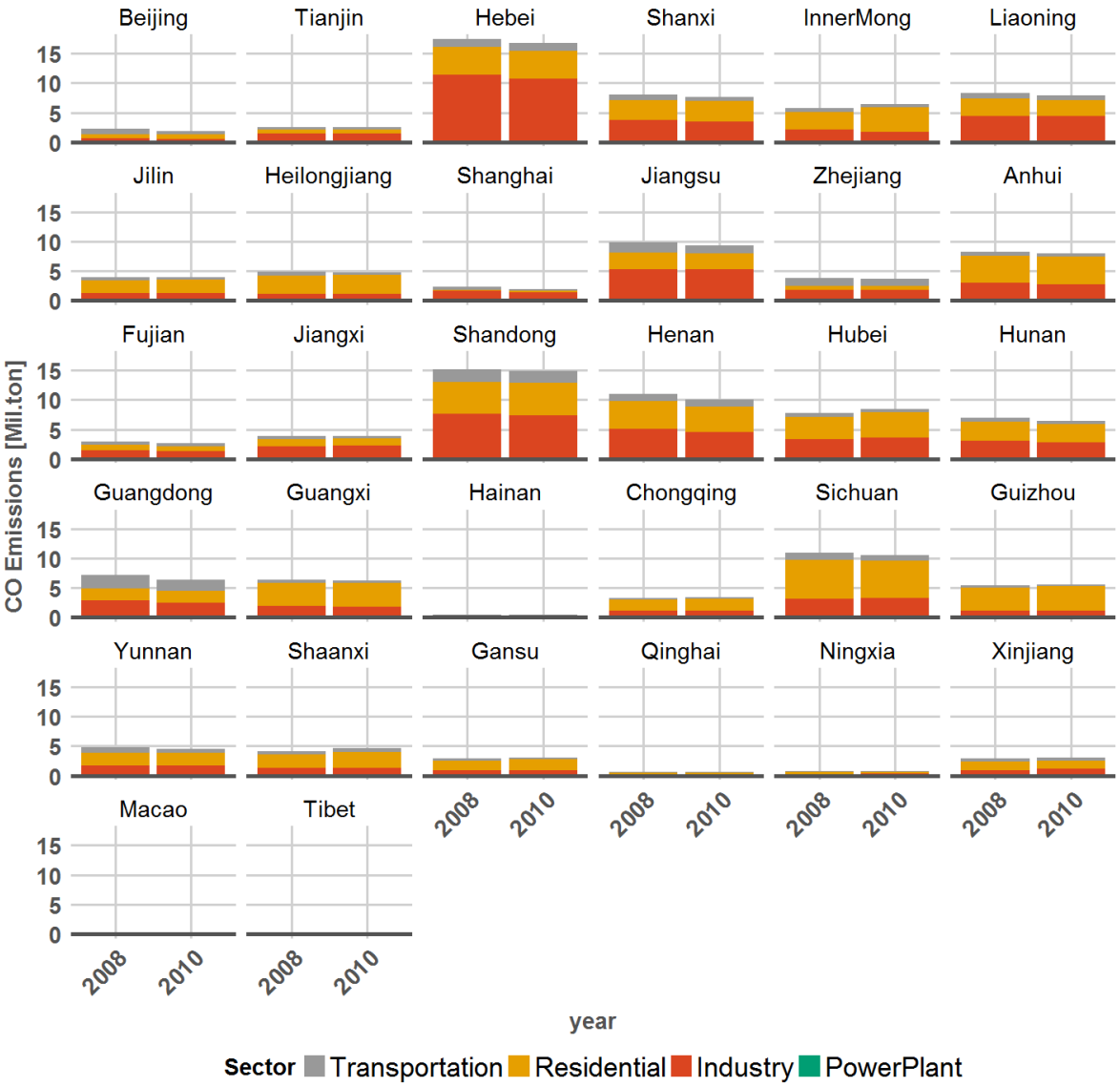


Figure A-6 CO emissions in China.

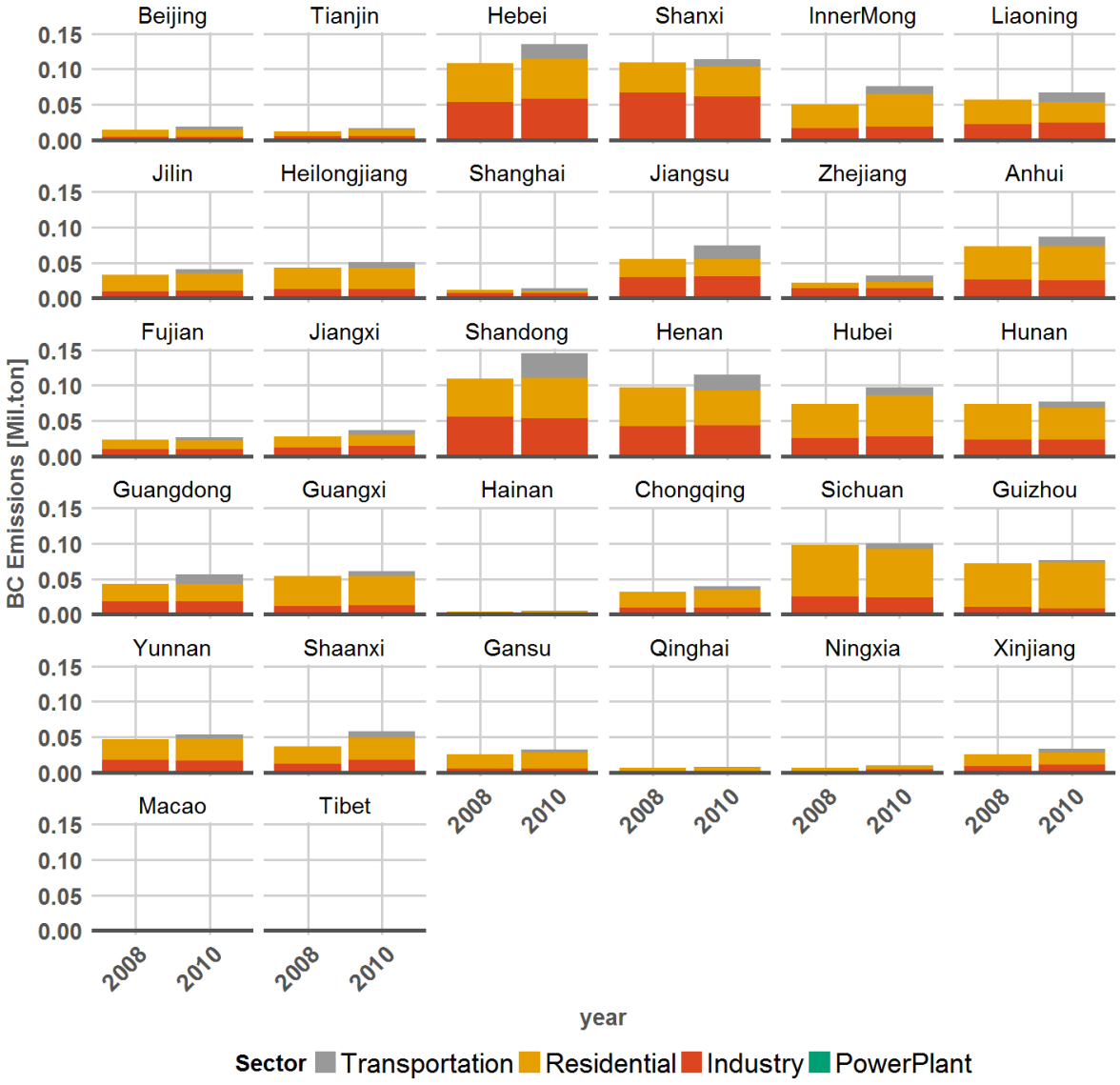


Figure A-7 BC emissions in China.

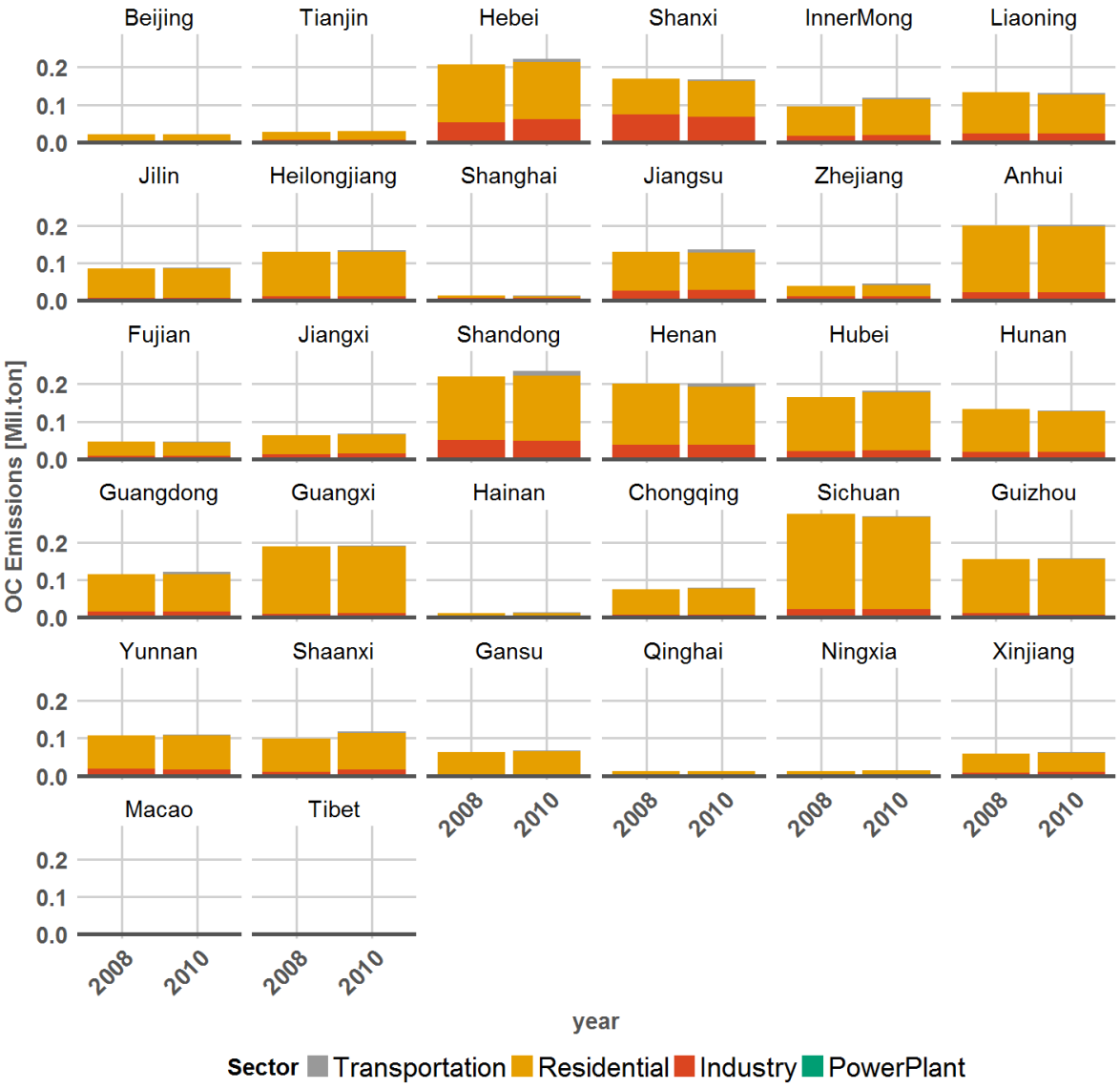


Figure A-8 OC emissions in China.

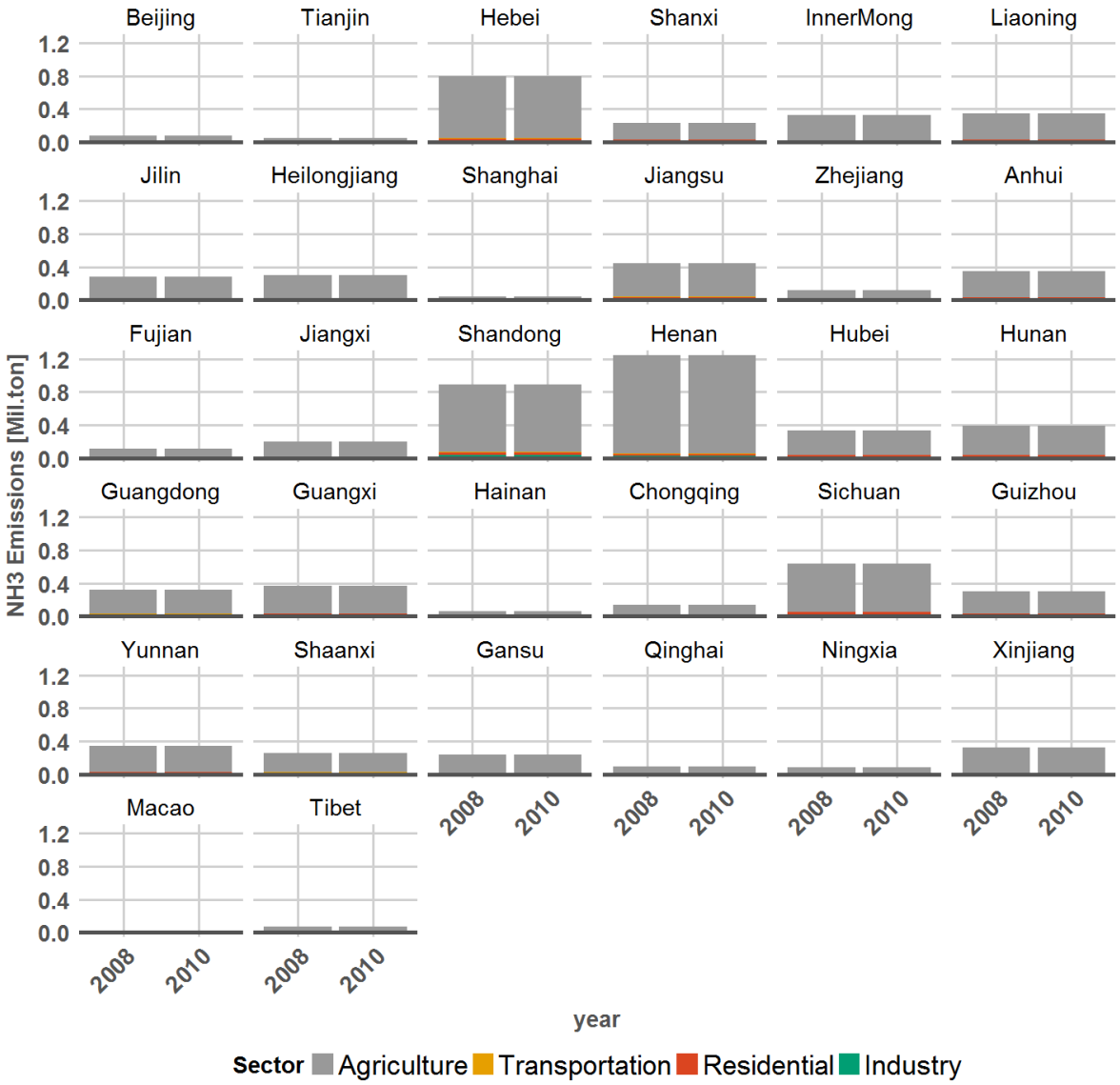


Figure A-9 NH_3 emissions in China.

Appendix A3: Air pollutant control technology in GAINS-China model

There are more than thousands of emission air pollutant control options in GAINS model, but not all the technologies are selected and only a few mitigation technologies are selected in GAINS-China model based on China's real situation.

Appendix A3-1: The key technologies for air pollution control.

1. **Stationary sources emission control options.**

   Cyclones

   Wet scrubbers

   Electrostatic precipitators

   Wet electrostatic precipitators

   Fabric filters;

   Regular maintenance of oil fired industrial boilers;

   Two stages (low and high efficiency) of fugitive emissions control measures.

2. **Mobile sources emission control options**

   Changes in fuel quality, e.g., decreases in sulfur content. Changes in fuel specifications may provide engine manufactures with greater flexibility to use new emission reduction technologies.

   Changes in engine design, which result in better control of the combustion processes in the engine.

   Flue gas post-combustion treatment, using various types of trap concepts and catalysts to convert or capture emissions before they leave the exhaust pipe.

   Better inspection and maintenance. Examples are: in-use compliance testing, in-service inspection and maintenance, on-board diagnostic systems.

The mitigation technologies in this study are listed in *Table A-1*. As for the technology penetration rates, they are given according to sectors, fuel types, regions and air pollutants (SO_2, NOx, PM).

Hence, it is difficult to list all the penetration rates. *Table A-1*and *Table A-2* show the SO_2 mitigation technology penetration rate in different scenario years by taking Beijing as an example.

Table A-1 *Mitigation technologies in GAINS-model.*

Air pollutant		Abbreviation	Name	Application sector
SO_2	1	LINJ	Limestone injection	Industry, power plants
	2	WFGD	Wet flue gas desulfurization	Industry, power plants
NOx	1	PHCCM	Combustion modification on existing hard coal power plants	Power plants
	2	HDSE	Stage control on heavy duty vehicles with spark ignition engines	Transport
	3	CAGEU	Stage control on construction and agriculture mobile sources	Transport
	4	HDEU(I-VI)	EURO I-VI on heavy duty diesel road vehicles	Transport
	5	MMO2(1-3)	Stage control on motorcycles and mopeds (2-stroke engines)	Transport
	6	LFEU(I-VI)	EURO I-VI on light duty spark ignition road vehicles (4-stroke engines)	Transport
	7	MDEU(I-VI)	EURO I-VI on light duty diesel road vehicles	Transport
PM	1	CYC	Cyclone	Industry, power plants
	2	ESP	Electrostatic precipitator	Industry, power plants, industrial process
	3	HED	High efficiency deduster	Industrial process
	4	GP	Good practice	Industrial process

Appendix A3-2: Mitigation technology and penetration rate

Mitigation technology and penetration rate are different in different sectors, process and provinces. GAINS-China model can provide very detailed data for 30 provinces.

Table A-2 SO_2 mitigation technology and penetration rate (%)in Beijing under with-tech scenario.

Sector-Fuel-Technology	Region	2005	2010	2015	2020	2030
CON_COMB-HC1-IWFGD	BEIJ	9	15	15	15	15
CON_COMB-HC1-LINJ	BEIJ	10	14	24	34	53
CON_COMB-HC2-IWFGD	BEIJ	9	15	15	15	15
CON_COMB-HC2-LINJ	BEIJ	10	14	24	34	53
IN_BO_OTH_S-HC1-IWFGD	BEIJ	9	15	15	15	15
IN_BO_OTH_S-HC1-LINJ	BEIJ	10	14	24	34	53
IN_BO_OTH_S-HC2-IWFGD	BEIJ	9	15	15	15	15
IN_BO_OTH_S-HC2-LINJ	BEIJ	10	14	24	34	53
IN_BO_OTH_S-HC3-IWFGD	BEIJ	16.25	25	30	35	50
IN_BO_OTH_S-HC3-LINJ	BEIJ	10	10	10	10	10
IN_OC-HC1-IWFGD	BEIJ	9	15	15	15	15
IN_OC-HC1-LINJ	BEIJ	10	14	24	34	53
IN_OC-HC2-IWFGD	BEIJ	9	15	15	15	15
IN_OC-HC2-LINJ	BEIJ	10	14	24	34	53
IN_OC-HC3-IWFGD	BEIJ	16.25	25	30	35	50
IN_OC-HC3-LINJ	BEIJ	10	10	10	10	10
PP_EX_L-HC1-LINJ	BEIJ	0	0	40	40	40
PP_EX_L-HC1-PRWFGD	BEIJ	18	60	60	60	60
PP_EX_L-HC2-LINJ	BEIJ	0	0	40	40	40
PP_EX_L-HC2-PRWFGD	BEIJ	18	60	60	60	60
PP_EX_L-HC3-LINJ	BEIJ	0	0	20	30	40
PP_EX_L-HC3-PWFGD	BEIJ	38.89	60	60	60	60
PP_EX_S-HC1-LINJ	BEIJ	0	0	40	40	40
PP_EX_S-HC1-PRWFGD	BEIJ	18	60	60	60	60
PP_EX_S-HC2-LINJ	BEIJ	0	0	40	40	40
PP_EX_S-HC2-PRWFGD	BEIJ	18	60	60	60	60
PP_EX_S-HC3-LINJ	BEIJ	0	0	20	30	40
PP_EX_S-HC3-PWFGD	BEIJ	38.89	60	60	60	60
PP_MOD-HC1-LINJ	BEIJ	0	0	30	30	30
PP_MOD-HC1-PWFGD	BEIJ	18	60	70	70	70
PP_MOD-HC2-LINJ	BEIJ	0	0	30	30	30
PP_MOD-HC2-PWFGD	BEIJ	18	60	70	70	70
PP_MOD-HC3-LINJ	BEIJ	0	0	25	25	30
PP_MOD-HC3-PWFGD	BEIJ	38.89	60	65	70	70
PP_NEW_L-HC1-LINJ	BEIJ	0	0	30	30	30
PP_NEW_L-HC1-PWFGD	BEIJ	18	60	70	70	70
PP_NEW_L-HC2-LINJ	BEIJ	0	0	30	30	30
PP_NEW_L-HC2-PWFGD	BEIJ	18	60	70	70	70
PP_NEW_L-HC3-LINJ	BEIJ	0	0	25	25	30
PP_NEW_L-HC3-PWFGD	BEIJ	38.89	60	65	70	70

Note: HC1, HC2 and HC3 represent hard coal grade 1, grade 2 and grade 3, respectively.

CON_COMB represents other energy sector-combustion. IN_BO_OTH_S, IN_OC represent Industry: other sectors; combustion of brown coal/lignite and hard coal in small boilers (<20 MWth) and Industry: other combustion, respectively.

PP_EX_L, PP_EX_S, PP_MOD and PP_NEW_L represent Exist large scale power plants, Exist small scale power plants, Modern power plants (supercritical, ultra-supercritical) and New large scale power plants, respectively.

Appendix A3-3 Conversion tables

Conversion tables are developed to make the database of the two models match each other. There are two types of conversion tables, namely conversion table for sector integration and for fuel type integration. Each type of conversion tables are given in *Table A-3* by taking Beijing 2005 as an example.

Table A-3 Conversion table for sector match (BEIJ 2005 as an example).

		2005 Activity by GAINS-China [PJ]	AIM/CGE Sectors								
			powerplant	DOM	IN_CHEM	IN_CON	IN_PAP	IN_IS_NFME	IN_NMMI	IN_OTH	TRA
GAINS Sectors	PP_EX_WB	0.0	0%								
	PP_EX_OTH	23.5	23%								
	PP_EX_L	0.0	0%								
	PP_EX_S	15.3	15%								
	PP_NEW	2.1	2%								
	PP_NEW_CCS	2.1	2%								
	PP_NEW_L	58.8	58%								
	PP_MOD	0.0	0%								
	PP_MOD_CCS	0.0	0%								
	PP_IGCC	0.0	0%								
	PP_IGCC_CCS	0.0	0%								
	PP_ENG	0.0	0%								
	CON_COMB	54.2									
	CON_LOSS	46.2									
	IN_BO_CHEM	0.0			50%						
	IN_BO_CON	0.0				100%					
	IN_BO_OTH	139.6								73%	
	IN_BO_OTH_L	4.5								2%	
	IN_BO_OTH_S	45.8								24%	
	IN_BO_PAP	0.0					50%				
	IN_OC_ISTE	0.0						50%			
	IN_OC_CHEM	0.0			50%						
	IN_OC_NFME	0.0						50%			
	IN_OC_NMMI	0.0							100%		
	IN_OC_PAP	0.0					50%				
	IN_OC_OTH	0.0								0%	
	NONEN	238.9									
	DOM	399.2		100%							
	TRA_OT	0.0									0%
	TRA_OTS_L	16.2									5%
	TRA_OTS_M	16.2									5%
	TRA_OT_AGR	7.3									2%
	TRA_OT_AIR	0.0									0%
	TRA_OT_CNS	11.0									4%
	TRA_OT_INW	0.0									0%
	TRA_OT_LB	0.0									0%
	TRA_OT_LD2	0.0									0%
	TRA_OT_RAI	16.2									5%
	TRA_RD	0.0									0%
	TRA_RD_HDB	20.7									7%
	TRA_RD_HDT	76.2									25%
	TRA_RD_LD2	0.2									0%
	TRA_RD_LD4C	95.6									32%
	TRA_RD_LD4T	38.1									13%
	TRA_RD_M4	1.4									0%

Appendix A4: Health service price

Based on the statistical data, this study did regression analysis about average hospital admission fee and outpatient fee with per capita GDP, and calculate the coefficient for hospital admission fee and outpatient fee for 30 provinces in health assessment model. From these coefficient, the average hospital admission fee and outpatient fee in the future can be predicted in the tables below.

Table A-5 Average outpatient fee in 30 provinces (unit: CNY*).*

Region	2005	2010	2015	2020	2025	2030
Beijing	220	240	280	330	380	430
Tianjin	160	170	200	220	240	260
Hebei	100	130	160	200	240	280
Shanxi	10	130	180	240	310	370
InnerMong	90	150	200	270	340	410
Liaoning	120	150	200	270	340	420
Jilin	91	140	190	270	360	440
Heilongjiang	180	160	220	310	410	520
Shanghai	180	190	200	220	240	260
Jiangsu	120	150	160	180	200	230
Zhejiang	130	140	160	170	180	190
Anhui	99	130	170	230	290	360
Fujian	99	110	130	150	170	190
Jiangxi	87	130	190	280	380	490
Shandong	120	140	160	180	210	240
Henan	77	90	110	130	160	190
Hubei	110	140	170	230	290	350
Hunan	120	160	220	300	390	490
Guangdong	110	120	130	150	160	180
Guangxi	75	110	150	210	270	320
Hainan	100	120	150	170	200	230
Chongqing	110	160	240	340	450	570
Sichuan	80	140	210	320	440	570
Guizhou	110	140	190	260	340	420
Yunnan	76	100	140	190	250	300
Shaanxi	98	130	170	210	270	330
Gansu	48	100	180	300	430	580
Qinghai	60	100	160	230	310	390
Ningxia	100	110	120	130	140	150
Xinjiang	91	110	140	180	220	250

Table A-6 Average respiratory hospital admission fee in 30 provinces (unit: CNY*).*

Region	2005	2010	2015	2020	2025	2030
Beijing	11063	11646	12803	14465	16243	17963
Tianjin	6953	8711	11105	13572	15743	17433
Hebei	2969	4258	5777	7842	10025	12079
Shanxi	2988	5013	8066	11996	16128	20048
InnerMong	3284	5577	7652	10375	13276	16040
Liaoning	4266	5496	7095	9308	11812	14407
Jilin	3269	5558	8189	11872	16027	20294
Heilongjiang	3966	5834	8486	12259	16539	20996
Shanghai	7421	8545	10603	13473	16448	19279
Jiangsu	5849	6594	7190	7919	8657	9352
Zhejiang	6540	6940	7320	7761	8127	8403
Anhui	3444	4748	6531	9019	11802	14559
Fujian	4306	4764	5249	5898	6600	7269
Jiangxi	2859	4357	6792	10340	14454	18732
Shandong	3521	4923	6406	8452	10653	12765
Henan	2524	3623	4919	6814	8967	11092
Hubei	3611	5145	7154	9980	13243	16610
Hunan	3915	4660	5814	7454	9351	11306
Guangdong	6002	5983	5960	5928	5894	5862
Guangxi	3055	4823	6652	9098	11692	14067
Hainan	3783	5246	6992	9142	11338	13305
Chongqing	3846	5199	7087	9587	12407	15267
Sichuan	3169	4941	7259	10516	14283	18177
Guizhou	3231	3509	3842	4334	4903	5495
Yunnan	3240	3732	4445	5564	6710	7825
Shaanxi	3437	4255	5197	6494	7959	9427
Gansu	2193	3801	6066	9405	13261	17272
Qinghai	3099	5003	7564	10905	14550	18114
Ningxia	3487	4229	5145	6226	7220	8070
Xinjiang	2821	3715	4918	6574	8177	9467

Table A-7 *Average cardiovascular hospital admission fee in 30 provinces (unit:* CNY*).*

Region	2005	2010	2015	2020	2025	2030
Beijing	18096	18679	19836	21498	23276	24996
Tianjin	9748	11506	13901	16367	18538	20228
Hebei	3340	4629	6148	8213	10396	12450
Shanxi	1432	3457	6510	10439	14572	18492
InnerMong	4303	6596	8671	11393	14294	17058
Liaoning	6206	7437	9035	11248	13752	16347
Jilin	3488	5777	8409	12091	16246	20514
Heilongjiang	4539	6408	9059	12833	17113	21569
Shanghai	10006	11130	13188	16058	19033	21864
Jiangsu	9753	10498	11094	11823	12562	13257
Zhejiang	11222	11622	12002	12443	12809	13085
Anhui	4745	6049	7832	10320	13103	15860
Fujian	7258	7716	8201	8850	9552	10220
Jiangxi	3169	4666	7102	10650	14763	19041
Shandong	4657	6059	7542	9588	11789	13901
Henan	3268	4367	5663	7558	9711	11836
Hubei	4746	6280	8289	11115	14379	17745
Hunan	6158	6902	8057	9697	11594	13549
Guangdong	10986	10968	10945	10913	10879	10847
Guangxi	3596	5364	7192	9639	12232	14607
Hainan	4599	6061	7808	9958	12154	14121
Chongqing	5359	6711	8600	11099	13919	16780
Sichuan	3730	5502	7821	11077	14845	18739
Guizhou	5577	5855	6188	6680	7249	7841
Yunnan	5071	5563	6276	7395	8541	9655
Shaanxi	5357	6174	7116	8413	9878	11346
Gansu	1486	3094	5359	8698	12554	16565
Qinghai	2826	4730	7291	10631	14277	17841
Ningxia	5161	5904	6820	7901	8895	9745
Xinjiang	3198	4091	5294	6950	8553	9844

Table A-8 Average cerebrovascular hospital admission fee in 30 provinces (unit: CNY*).*

region	2005	2010	2015	2020	2025	2030
Beijing	12875	13458	14615	16277	18055	19775
Tianjin	7673	9431	11826	14292	16463	18153
Hebei	3064	4353	5872	7937	10120	12174
Shanxi	2588	4612	7665	11595	15728	19648
InnerMong	3547	5840	7915	10637	13538	16302
Liaoning	4765	5996	7595	9808	12312	14907
Jilin	3325	5614	8246	11928	16083	20351
Heilongjiang	4114	5982	8633	12407	16687	21143
Shanghai	8087	9211	11269	14139	17114	19945
Jiangsu	6854	7599	8196	8925	9663	10358
Zhejiang	7746	8146	8526	8967	9333	9609
Anhui	3779	5083	6866	9355	12137	14894
Fujian	5066	5524	6009	6659	7361	8029
Jiangxi	2939	4436	6872	10420	14534	18811
Shandong	3813	5216	6699	8745	10945	13058
Henan	2716	3815	5111	7006	9159	11284
Hubei	3904	5437	7446	10273	13536	16902
Hunan	4493	5237	6392	8032	9929	11884
Guangdong	7286	7267	7244	7212	7178	7146
Guangxi	3194	4963	6791	9237	11831	14206
Hainan	3993	5456	7202	9353	11549	13515
Chongqing	4236	5588	7477	9977	12796	15657
Sichuan	3313	5086	7404	10661	14428	18322
Guizhou	3836	4113	4446	4938	5507	6100
Yunnan	3712	4204	4917	6036	7182	8296
Shaanxi	3932	4749	5691	6988	8453	9922
Gansu	2011	3619	5884	9223	13079	17089
Qinghai	3029	4933	7494	10834	14480	18044
Ningxia	3918	4661	5576	6658	7652	8501
Xinjiang	2918	3811	5015	6671	8274	9564

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