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著者(和文)	LIGen
Author(English)	Gen Li
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Computable General Equilibrium Modeling for Assessing China's Environmental Policies:
Evaluation of the Environmental Tax Law in China

Author: LI Gen
Supervisor: Prof. YAMATO Takehiko, Prof. MASUI Toshihiko

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Department of Industrial Engineering and Economics
Tokyo Institute of Technology

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Abstract

China has been enjoying the rapid double-digit growth in the last few decades, but at a high environmental cost. As of today, the severe environmental pollution in China has become a major social issue and one of the most top priorities of governmental policies. In the meantime, global society requires China to make a significant contribution to combatting global warming as the current largest emitter of greenhouse gases. China has come to a turning point, where the traditional low-end, energy-intensive, and labor-intensive pathway of economic development needs sustainable transformation. In this transition period, governmental environmental policies play an essential role, and it is critical to have a thorough assessment of these environmental policies from the integrated perspectives of economy, energy, and environment.

The objective of this thesis is to construct a computable general equilibrium (CGE) model for assessing China's environmental policies. The CGE model is a quantitative economic tool which solves the general equilibrium situation of an economy where all the markets of commodities and production factors clear at the same time. Many researchers have applied CGE model to policy analyses in environmental protection, like the pollution tax or the emission cap. However, most environmental CGE models link pollutant emissions to the standard CGE models only by pollution coefficients per unit of sectoral outputs and the emission reduction process is not included within production structures. Apart from traditional CGE models, this thesis constructs separate pollution treatment sectors of solid waste management, wastewater management, and waste gas management, to describe the pollution treatment processes and reflect the policy impact on the production activities. Besides, this thesis compiles the satellite accounts of 18 kinds of pollutants from the dataset of China Environmentally Extended Input-Output (CEEIO) table, covering the primary gas, water, and solid pollutants, and disaggregates the electricity sector into six different production technologies: hydroelectricity, coal power, gas electricity, oil electricity, nuclear power, and renewable energies.

This thesis builds the CGE model following standard processes including the steps of the compilation of input-output table, social accounting matrix, building and configuring the parameters on the base year data and adding the recursive dynamic mechanism to fulfill a standard dynamic CGE model. We construct the policy scenarios based on two dimensions: the overall socioeconomic situation (S1, S2, and S3) as reference scenarios and the strictness of the environmental policies (LowET, HighET, LowETC, and HighETC). A socioeconomic status serves as a baseline scenario, and then we add the environmental policies of different degree of strictness to assess the policy impacts in different cases. At last, we conduct a sensitivity analysis to check the robustness of the simulation results. As for data, this thesis updates all the economic and environmental data to the year of 2012 which is one of the latest datasets among all CGE research works on China.

The simulation results show that the most sustainable socio-economic condition S1 achieves the highest GDP growth at the least cost of environmental protection, mainly due to technology improvement and green transition in the power sector. The least sustainable socio-economic condition S3 has the worst performance and the middle road socio-economic condition S2 behaves in the middle of S1 and S3. The expected GDP by 2030 in S1 could reach about 154.5 trillion RMB, almost 20% higher than that in S3; the total waste management cost will be 0.38 % of GDP by 2030 in S1, in contrast to 0.57 % in S3. Moreover, most kinds of pollutant emissions and the carbon emission in S1 could be lowered by 10% to 40% than that in S3. As for the environmental policies, they could help reduce emissions of most kinds of pollutants but bring negative effects on the GDP. If the middle road scenario S2 chosen as the baseline scenario, the GDP loss by 2030 would be 0.03 %, 0.06 %, 0.16 % and 0.34 % in the low environmental tax scenario LowET, the high environmental tax scenario HighET, the low environmental tax and low carbon tax scenario LowETC, and the high environmental tax and high carbon tax scenario HighETC, respectively. The SO_2 emission will decrease by 17.4 %, 21.0 %, 19.3 % and 24.5 %, respectively, and the CO_2 emission will reduce by 0.9 %, 1.7 %, 5.8 % and 11.0 %, respectively. The results also show that the heavily polluted sectors and energy-intensive sectors will suffer higher output loss, while the clean energy sectors and service sector will experience an increase in the output.

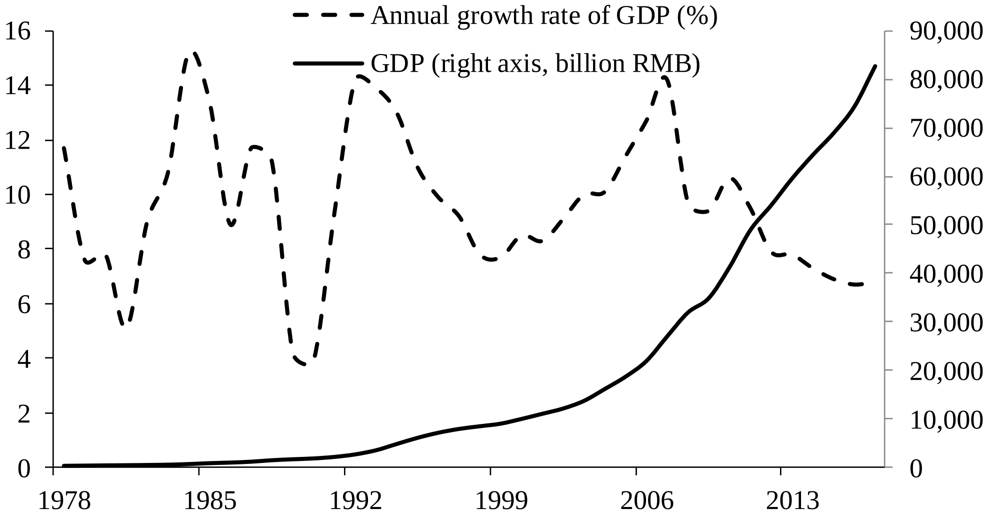
Keywords: Environmental tax; carbon tax; computable general equilibrium model; pollution treatment; macroeconomic impacts.

1. Introduction

1.1 China's environmental situation since 1980s

1.1.1 Rapid economic development in the past four decades

Since the Reform and Opening-Up policies in 1978, China's nominal Gross Domestic Product (GDP) has boosted from 367.9 billion RMB in 1978 to 82.7 trillion RMB in 2017, with an average annual growth rate of 9.27% (NBS, 2018a). After four decades of rapid development, China is currently the world's second-largest economy and largest developing economy, though its GDP is still behind the United States of America by about 37% in 2017 (WB, 2019).



Source: China's National Bureau of Statistics (NBS, 2018a)

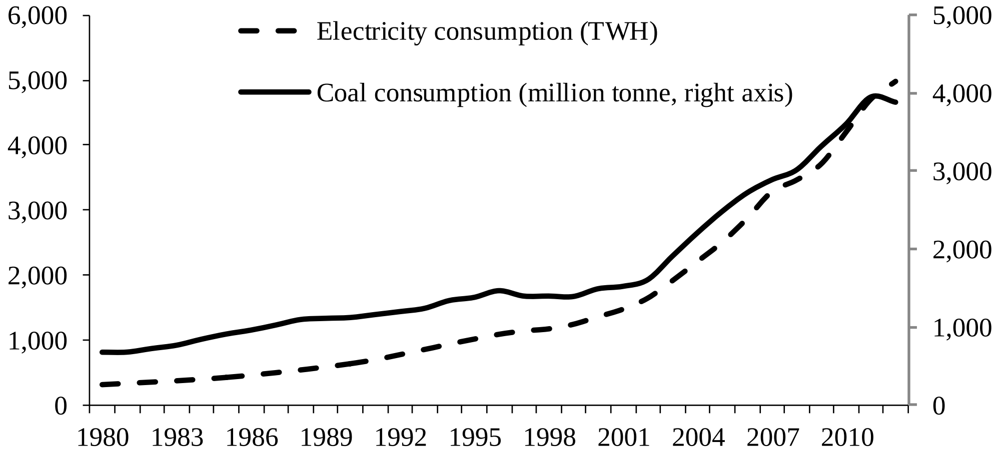
Figure 1-1: China's nominal GDP (billion RMB) and its annual growth rate (%)

There are several key characteristics in China's economic development during this period, which shape the specific economic and environmental situation of China in the present. These characteristics could be summarized as follows:

1. **Low-end and labor-intensive sectors**. China has been regarded as "the world's factory" since it joined the World Trade Organizations (WTO) in November 2001. At present, China produces about 60% of shoes and 70% of mobile phones for the

world (Economist, 2015). However, China's production activities are still mainly limited in the areas of low-end manufacturing sectors, which rely on the low labor and material cost. As China's labor cost starts to rise, the government aims to upgrade to the high-end industries and those low-end production activities will be gradually moved to other low labor cost regions, possibly towards southeast Asia and Africa.

2. **Energy-intensive and resource consuming activities**. An essential feature of the low-end manufacturing sectors is that they are usually energy-intensive or resource consuming, like the clothing sector and steel and iron sector. However, the efficiency of China's energy utilization and resource utilization is not as high as the developed economies, which exacerbate the problem of energy and resource consuming. As shown in Figure 1-2, China's electricity consumption has increased by 16 times in 30 years since 1980, and coal consumption has also increased by 5 times during that period (NBS, 2017). As a result, the traditional pathway of economic development is difficult to continue due to the limited natural resources and severe environmental problems.

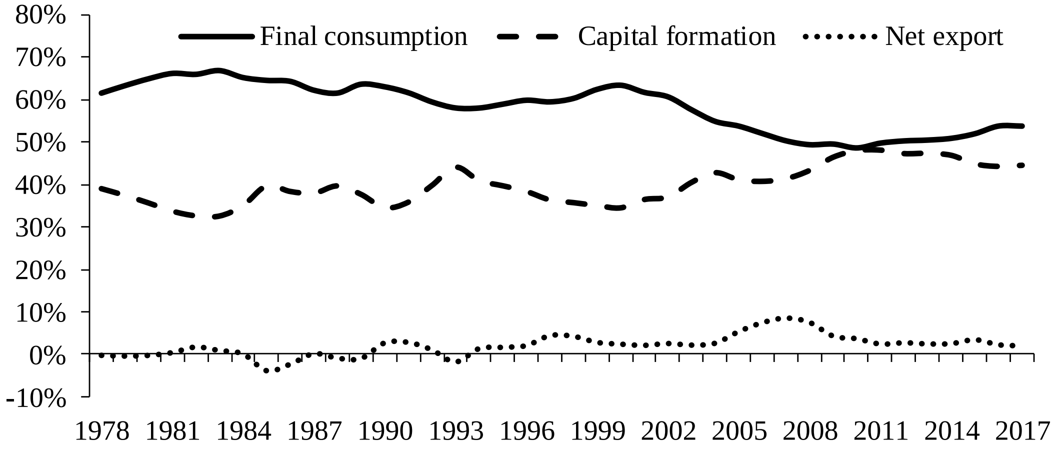


Source: China's National Bureau of Statistics (NBS, 2017)

Figure 1-2: China's electricity consumption and coal consumption

3. **Large capital formation.** From the perspective of expenditure, final consumption, capital formation, and net export are the three major components of GDP. In the case of China, capital formation, especially the housing sector and public infrastructure investment on railway and roads, has been a strong drive for

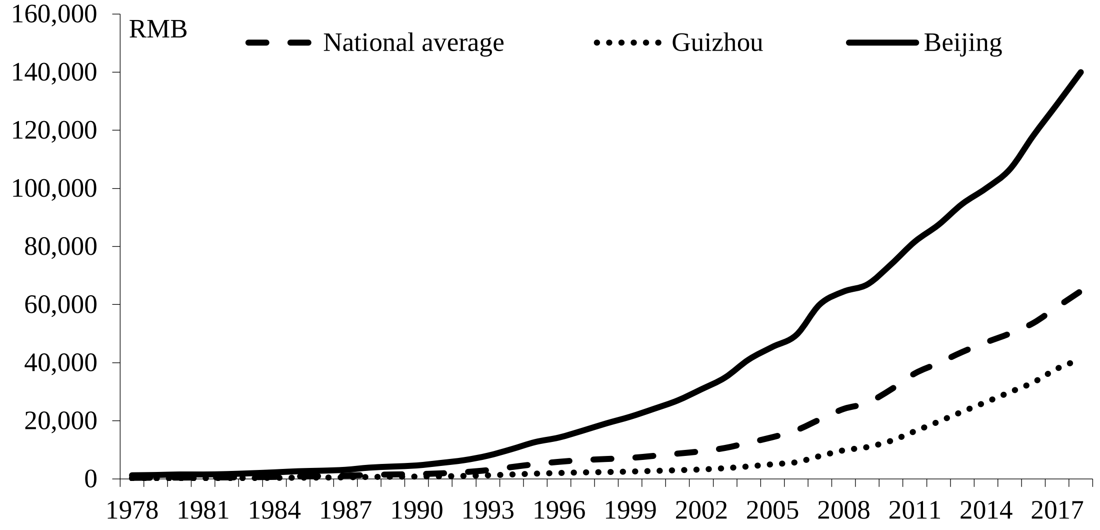
economic growth. On the other hand, the share of final consumption only makes up for about 50% of GDP, significantly lower than the level in developed economies, like the 80%-level in the United States (WB, 2018b). As for the net export, China's import and export have kept growing at a similar speed, and the net export remains a small share of GDP of less than 10%. As a result, when the need for infrastructure investment gradually satisfied, the growth driver will move to final consumption.



Source: China's National Bureau of Statistics (NBS, 2018b)

Figure 1-3: Share of GDP by component

4. **The disparity in regional development.** Induced by the different inflow and allocation patterns of capital and labor, the economic inequality among different regions has been enlarged in the past few decades (Wang and Fan, 2004). The most developed cities, like Beijing, Shanghai and Guangzhou are concentrated on the eastern coaster areas, while most towns under the poverty line locate in western regions. The economic disparity will be a primary challenge for the economy if it seeks a sustainable and balanced pathway for future growth. Figure 1-4 shows the gap in GDP per capita for Beijing, Guizhou (a western province), and the national average level.

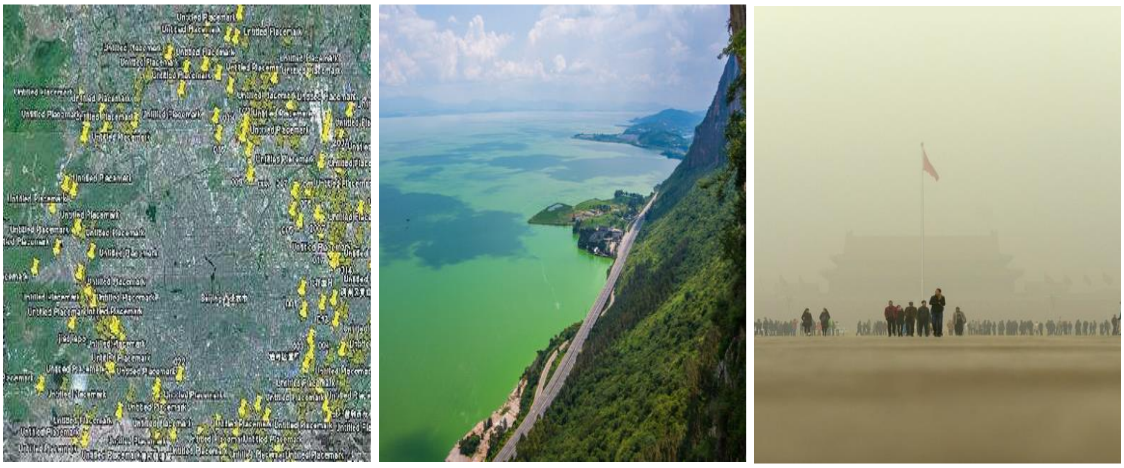


Source: China's National Bureau of Statistics (NBS, 2018b)

Figure 1-4: GDP per capita

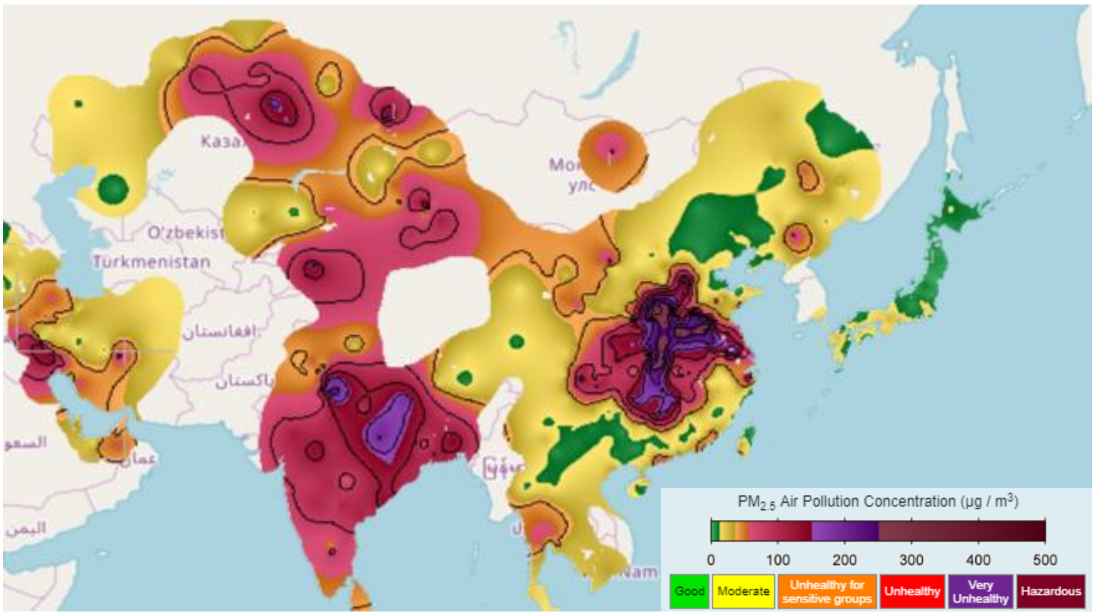
1.1.2 Serious environment problems along with economic development

Along with the rapid economic development, severe environmental pollution problems have also emerged as the side effects of unsustainable growth. The reasons behind the situation are quite complicated. On the one hand, at the early stage of economic development, environmental protection was not the priority and has been neglected in many situations. The environment policies were also not very strict, and there are insufficient supervision and enforcement of environmental regulations. On the other hand, low-end manufacturing sectors and resource intensive sector are usually high polluted in the meantime, not to mention that many efficient pollutant treatment technologies were not implemented in real practices. Take the chemical pollution incident in Yancheng city for an example. The local environmental authorities had fined a chemical company for exceeding discharge limitations in 2005 and issued a decree to order the company to relocate away from the river in 2008. However, these orders are not implemented. In 2009, that company discharged lots of toxic chemicals to the river and influenced the water supply for the residents for several days (Moore, 2013).



Source: Left, Beijing surrounded by waste landfill plants (Wang, 2010); Middle, Water pollution in Dianchi Lake, Yunnan Province (Scally, 2016); Right, Air pollution in Beijing (Guo, 2016)

Figure 1-5: Environment incidents in China



Source: Berkeley Earth Project (BE, 2019)

Figure 1-6: Air quality map

As the environmental problems continue to get worse, some influential environmental incidents broke up and drew much public attention. In Figure 1-5, the left picture shows that the metropolitan city of Beijing is almost besieged by waste landfill spots which are marked as yellow points in the map. Beijing is not the only case. As the explosion of urban areas, the municipal waste also explodes but mostly ends up by being landfilled in the suburban areas. The picture in the middle shows one of the most polluted lake, Dianchi Lake, due to severe eutrophication. The pollution in Dianchi Lake has lasted for almost 30 years despite the fact much money has already been used for the treatment, which signifies that it is far more difficult and costlier to treat than to pollute. The right picture is a snapshot of the terrible haze currently happening in northern China. Since the air quality has become a major concern for the public, the sales of masks and air purifiers are booming in recent years. Figure 1-6 (BE, 2019) shows the worrying air quality map of December 2018 in China.

Table 1-1 (NBS, 2018b) presents a rough sketch of the generated amount and the discharge amount of some major pollutants at the national level. The amount of generated industrial solid waste (ISW) triples and the discharged waste water increases by 50% since 2003, but they both reach a plateau and do not boost as fast as before. The emission of sulfur dioxide (SO_2) peaked around 2006 and then quickly dropped by about 2/3, because the government issued more stringent policies and most factory plants are required to install desulfurization equipment since 2007. However, the air quality in most northern cities did not get better, and the density of particulate matter 2.5 (PM 2.5) did not decrease as much as SO_2. The underlying reason for PM 2.5 is far more complicated than desulfurization, which also involves the emission of nitrogen oxides (NO_X), volatile organic compounds, and so on. To conclude, the emission numbers show a tendency to get better, but the real environment situation is far more complicated than the numbers.

From regional and sectoral perspectives, there are some other characteristics in China’s pollutant emissions. Firstly, most emissions concentrate on the northern and eastern regions where locate most factory plants, and residential density is higher. Secondly, industrial emissions account for most of the total discharge amounts, while the share of the household sector and the service sector is low but keeps growing. Thirdly, most kinds of emissions already start to peak or decrease, this is partly due to the slowdown of economic growth rate, and partly due to the stricter environmental policies, like the Circular economy promotion law in 2009 and the revised Environmental Protection Law in 2014.

Table 1-1: Environment pollutant emission data

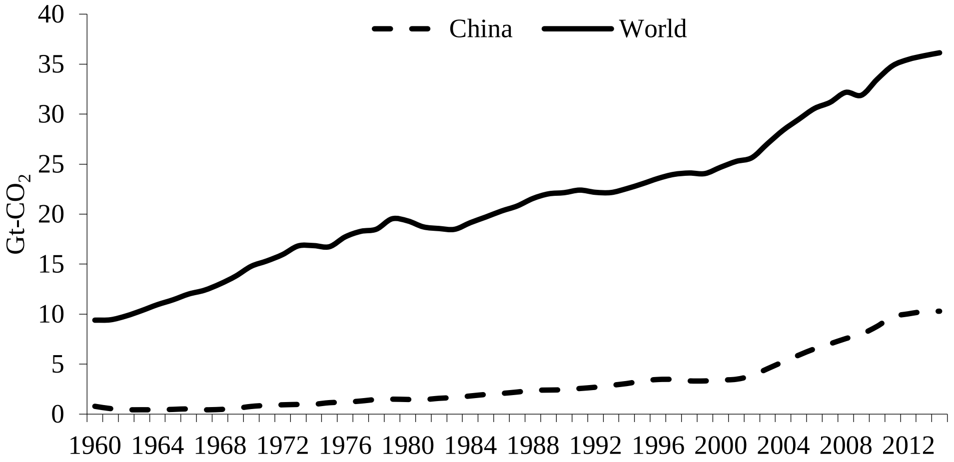
	Industrial Solid Waste Generated	Waste Water Discharge	Sulphur Dioxide Emission
2003	1,004.3	46,000.0	21.6
2004	1,200.3	48,240.0	22.5
2005	1,344.5	52,450.0	25.5
2006	1,515.4	53,680.0	25.9
2007	1,756.3	55,680.0	24.7
2008	1,901.3	57,170.0	23.2
2009	2,039.4	58,970.0	22.1
2010	2,409.4	61,730.0	21.9
2011	3,227.7	65,920.0	22.2
2012	3,290.4	68,480.0	21.2
2013	3,277.0	69,540.0	20.4
2014	3,256.2	71,620.0	19.7
2015	3,270.8	73,532.3	18.6
2016	3,092.1	71,109.5	11.0
2017	3,315.9	69,966.1	8.8

Source: National Bureau of Statistics (NBS, 2018b); unit: million tonnes

1.2 Major environmental challenges

Since 2012, China has faced an intense downturn pressure on the economy, and the GDP growth rates declined from the double-digit levels to around 7%, which is concluded as the New Normal by the government. The reasons for this situation are complicated. On the one hand, the 2007 global financial crisis brought massive shocks to China's economy as an essential player in the global value chain; on the other hand, China has already experienced double-digit growth for almost three decades, and the growth speed will slow down as the economy volume becomes larger. Moreover, the previous growth drivers no longer function as well as before as China's labor cost rises, and environmental and natural resource situation worsen. The central government defined several critical characteristics of the new normal (Xi, 2014). Firstly, the GDP growth rate will no longer keep at double-digit level but change to a middle tier, around 5% to 7% in the future. Secondly, the upgrading of the industry will be the focus of the governmental policy, from the low-end manufacturing sectors to high value-added manufacturing and service sector. Thirdly, the unbalanced situation among different regions or between cities and rural areas will be improved. Fourthly, environmental protection becomes the top priority in economic development. However, the economic transition might not be as easy and smooth as the government expects, and the environment problems have been accumulated for so long which makes the change very difficult and costly.

There are two types of environmental challenges for China in the new normal period. The first challenge is to solve the traditional pollution problem, which means to decrease the emission of solid, water, and gas pollutants. This arduous task needs to respond to the various environmental issues, like the haze in the northern area, the vast ocean and water pollution, and the sustainability of the waste incineration plants. The second challenge is the climate change which requires reducing the emission of greenhouse gases (GHG), mainly referring to the carbon dioxide. Figure 1-7 (WB, 2018a) shows the emission trajectories of China and the whole world. In 2014, the global carbon emission was about 36.1 Gt CO_2, and China was the largest emitter with 10.3 Gt CO_2.



Source: World Development Indicators, World Bank (WB, 2018a)

Figure 1-7: Carbon dioxide emissions

Although CO_2 is not considered as an environmental pollutant in current China' legal system, China has actively participated the international negotiation processes since the foundation of the United Nations Framework Convention on Climate Change (UNFCCC) in response to the global climate change. As developing countries, China was not required to hold responsibility for reducing emissions in the Kyoto Protocol (Protocol, 1997). But since the Paris Agreement (Agreement, 2015), China submitted the Nationally Determined Contributions (NDC) submitted to UNFCCC and made the pledges as follows (NDRC, 2015):

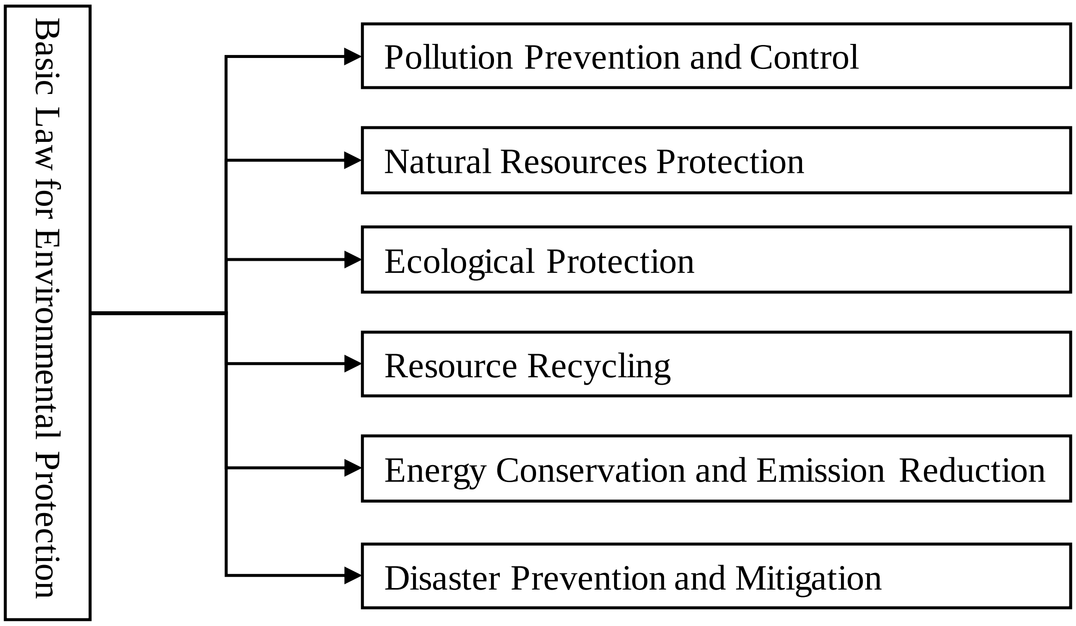
- to peak the CO_2 emission around 2030 and to achieve this goal as early as possible;
- to lower the CO_2 emissions per unit of GDP by 60 % to 65 % compared to the 2005 level;
- to increase the share of non-fossil fuels in primary energy consumption to around 20%;
- to improve the forest stock volume by about 4.5 billion cubic meters on the 2005 level;
- to effectively defend against climate change risks in critical areas such as agriculture, forestry, and water resources, as well as in cities, coastal and ecologically vulnerable areas; and
- to progressively strengthen early warning and emergency response systems and disaster prevention and reduction mechanisms.

To conclude, environmental pollutants and carbon reduction are the two main challenges of China in the years to come.

1.3 The evolution of China’s environmental policies

The increasing pollutant emissions have negative impacts on the ecosystem and economy. On the one hand, despite the nature possessing the restoration capacity, the human-induced pollution largely exceeds the carrying capacity of the natural system, resulting in the deterioration of the living environment of human beings and animals. On the other hand, severe pollution brings about substantial economic and health cost for the whole country. It is estimated that the economic loss caused by the pollution has nearly increased by three times, reaching about 3 % of the entire GDP from 2004 to 2013 (Wang, 2016), while ambient air pollution has become the fourth leading risk factors in China in terms of disability-adjusted life-years (Yang et al., 2013).

Faced with these problems, China has established a comprehensive system of environmental laws along with the economic reform since the 1980s. In the current legal system, the Environmental Protection Law (NPC, 2014) serves as the fundamental law in this field, whose legal status is only second to the Constitution. Under the Environmental Protection Law, there are mainly six categories of environmental laws as shown in Figure 1-8 (Huang and Shi, 2014): pollution prevention and control, natural resources protection, ecological protection, resource recycling, energy conservation, and emission reduction, and disaster prevention and mitigation. Among these six categories, this thesis will focus on the policies related to the reduction of pollutant emission and carbon emission, which are mostly included in the first, fourth, and fifth categories, as shown in Table 1-2.



Source: Huang and Shi (2014)

Figure 1-8: China’s environmental legal system

Table 1-2: China's environmental policies

Category	Law	First Execution Year*
Pollution Prevention and Control	Environmental protection tax law	2018
	Radioactive pollution prevention and control law	2003
	Noise pollution prevention law	1997
	Solid waste pollution prevention and control law	1996
	Air pollution prevention and control law	1988
	Water pollution prevention and control law	1984
	Marine environmental protection law	1983
Resource Recycling	Clean production promotion law	2003
	Circular economy promotion law	2009
Energy Conservation and Emission Reduction	Renewable energy law	2006
	Energy conservation law	1998
	Electricity law	1996
	Coal law	1996

*Source: Ministry of Ecology and Environment (MEE, 2019); *Note: Some laws have been revised for several times, and here only notes the year of the first execution.*

As the newly implemented Environmental Protection Tax Law will be the research focus of this paper, it could be found out how China's environmental policy system improves by tracing the evolution of this new law. China's government has introduced the regulation of pollutant discharge fees to control pollution since the 1980s. The first regulation, the Provisional Regulations for Collection of Compensation Fees for Pollutant Discharge, was issued by the government in 1982 (Wang and Wheeler, 1996). In this regulation, the charge standards were low and did not distinguish among different kinds of pollutants. For example, the charge standard of SO_2 was 0.04 yuan per kg, the same as that of carbon oxide (CO) and dust. In 2003, the second version of the regulation was issued by the government and has been implemented until the end of 2017 (SC, 2003). In this version, the charge standards were largely increased, and the notion of pollutant equivalent value was introduced to reflect different harmful levels of various pollutants. Dividing the physical emission amount by the pollutant equivalent value, the normalized emission amount was obtained and was used for calculating the payable amount of the pollution discharge fee.

However, the regulations of pollutant discharge fees did not prevent China’s environment from getting worse, and more and more public attention has been drawn to environmental issues. In response to the severe environmental problems and the growing public concerns, China’s first Environmental Protection Tax Law was officially passed in 2016 by the legislative institution and was scheduled to be put into practice since 2018 (NPC, 2016). From the legal perspective, this law changes the legal status of the pollutant discharge fee from an administrative fee to a tax, which increases the illegal cost of escaping the pollution bills. In the previous regulation system, those who refused or avoided the discharge fees could only be fined up to 3 times of the amount payable, while those who escape the environmental tax could be held criminally responsible in a severe case. Besides, this law gives a range of tax levels and allow local governments to adjust the tax levels according to their economic conditions, but the lowest tax levels were still doubled than before. It is reported that in some heavily polluted areas like Beijing, the local government would levy the highest tax levels which were almost raised by nine times, while in the other less developed or less polluted provinces, only low or medium tax level would be levied (He and Liao, 2017). It should be noted that CO_2 is not included in the current Environmental Protection Tax Law due to concerns about the economic impacts and many other aspects. Though carbon tax is not levied yet, many people are still arguing that China should introduce the carbon tax in the future.

As the evolution of Environmental Protection Tax Law, the development of China’s environmental policies could also be summarized into three phases. The first phase was from the 1980s to 2000 when the economy was the very priority. In this period, the standard of pollutant discharge fee was quite low, and only the fundamental laws in environmental protection were issued. This phase laid the foundation for China’s environmental legal system. The second phase was from 2000 to around 2015. In this phase, the economy kept growing rapid, but more and more environmental problems came out. The public started to understand the importance of pursuing a sustainable pathway. The government published the two laws for resource recycling and renewed many regulations in this period, and primarily increased the levels of pollutant discharge fees. The third period was from 2015 until now. Faced with the New Normal economic situation and severe pollution, the government was forced to issue more policies on environmental pollution. In the meantime, the global society required China to participate in combating climate change proactively, and China's NDC also came into force. In 2018, the upgrading of the pollutant discharge fee to environmental tax was regarded as the sign that the government has determined to implement the most stringent policy to face the environment situation. To conclude, China's environmental law system has kept improved and has now come to a new era when environment and economy become equally important priorities for the government and the whole society.

1.4 Assessing the impacts of environmental policies

Ever since the environmental policies were put into effect as a policy instrument, there have been discussions on their impacts that whether these policies achieve the goals in reducing pollutants, and there is any negative influence on the economy or the society. When analyzing the effects of environmental policies, the following aspects are usually taken into consideration:

- **Environmental impacts.** As the start point of the environmental policies, we need to check whether they could help reduce the pollutant emissions and to what extent. Usually, there are two types of policies in controlling the pollutant emissions: the mass-based approach and the rate-based approach (Fowlie et al., 2014). The mass-based plan usually sets a cap on pollutant emission allowed regardless of the size of the productive activities. Under this target, there may be a market for trading emission permits like the carbon trading market (Sorrell and Sijm, 2003), or the policymakers set precise up-limits for the major emitters. The rate-based approach is to put a limit on the pollutant emission rate per unit of the commodity produced or consumed. Like China's and India's NDCs (Chakrabarty and Chakraborty, 2018) submitted to the UNFCCC, the emission intensity of GDP is used rather than the total amount of CO_2. Moreover, the real situation could be more complex, that the policy will have different impacts on different kinds of pollutants. In some cases, the reduction of one pollutant might be accompanied by the increase of emission of another pollutant due to the substitutability. As a result, the environmental policies will not necessarily reduce the physical emission amount of all kinds of pollutants, and it needs to assess their actual impacts.

- **Economic impacts.** Economic analysis plays a vital role in evaluating environmental policies since policymakers are usually anxious about additional environmental constraints would lead to adverse effects on the economy. In many cases, this is the real case since additional restriction will lead to an increase in production cost and finally lead to a decrease in demand and output. However, some researchers also argue that some environmental taxes might provide the possibility of double dividend (Goulder, 1995), which means by introducing a revenue-neutral scheme of environmental tax, the total output will even increase. This kind of scheme usually is designed to collect tax revenue from the polluting sectors and then use the income to finance companies or households. Besides, some other factors might also influence the economic impacts, like the elasticity of substitution among different commodities. For example, if China's economy highly relies on the coal products and the demand elasticity is quite low. In such a case, the economic influence would be very different from the situation where consumers could quickly turn to other energy products. Therefore, a thorough and comprehensive economic analysis is needed when analyzing the economic impacts of environmental policies.
- **Social impacts**. Environmental policies are highly related to social issues. In most cases, the poor and the group of children and older people are more vulnerable to environmental problems (Pye et al., 2008). There have been more and more discussions from the social dimension of environmental policies. For instance, the distributional effects refer to the different impacts across different groups of people, and there are several channels of the distributional effects of environmental policy (Fullerton, 2011), including the increasing price levels, the changes in relative returns to factors, and so on.
- **Political impacts**. In domestic, severe environmental problems might provoke massive demonstration from the public which has taken place in many countries. Environmental policies in such cases also serve to soothe the public. Internationally, as global warming problems become more serious, the political negotiations across countries attract much public attention. The carbon policy

becomes a bargaining chip for policymakers, and a good example is the Trump Administration's withdrawal from the Paris Agreement.

- **Other impacts**, like the impacts on business and public health, and so on. Empirical studies show that environmental policies will also influence the competitiveness of companies from productivity, employment, innovation, and so on. (Dechezleprêtre and Sato, 2017). As for the health impacts, limiting the air pollutants from coal-fired sources could improve air quality and help reduce the morbidity and fatality rate due to cardiovascular and cerebrovascular (Kravchenko et al., 2018). These business impacts and health impacts could exert economic influence as well, which makes every impact related to each other.

In the case of China, the impacts above have also been observed. Take the SO_2 policy for an example. SO_2 was the leading cause for the acid rain which became severe environmental problems in China around the 1990s. Since then, the government has formulated the policy (SC, 2002) to control the SO_2 density and achieved significant results so far. In terms of emission amount, China's SO_2 emission has peaked in 2006 and decreased by two thirds until now. Zhao et al. (2013) show that the SO_2 policy has co-benefit in reducing the density of particulate matter. In terms of economic impacts, Xu and Masui (2009) simulated SO_2 control policies in China from 1997 to 2020 and found out a substantial GDP loss would be incurred if setting a cap on SO_2 emission. As for other impacts, China was criticized by the global society for the high SO_2 emission, and the local governments in the zones of acid rains were also harshly criticized by the residents. As the situation improves, the responses from domestic and abroad also become positive (Ying, 2017). However, it should also be noted that the SO_2 problem is relatively easy to solve since the major emitting sources are the coal-fired power plants. Besides, most power plants are state-owned enterprises in China and the government's policy exert more direct influence on these state-owned enterprises. Most importantly, the desulfurization technology is mature despite the high cost, so the reduction is mostly a matter of money. The situation would be quite different when it comes to other kinds of pollutants and needs to be carefully analyzed.

To conclude, the impacts of environmental policies are multi-dimensional, and the mechanisms are complicated as well. A thorough and comprehensive analysis of the policies is necessary for the policymakers to better decisions and for the researchers to understand better what the impacts are and why they occur. It should be noted that various factors might influence the outcome of policy: including the macroeconomic situation, the period of the policy, the way of implementation, and the public awareness and conception of the environmental policies. These factors picture the background for policy analysis and could determine the policy impacts.

As a developing country, China lacks experience in environmental policies and is still learning by doing. It is expected that China will complete the system of environmental policies step by step and seek a pathway for sustainable development. To realize this goal, we need more analyses on the policy impacts and update with the latest economic situations and government regulations.

1.5 Motivation and innovation of the paper

This thesis will focus on analyzing the socioeconomic impacts of the latest environmental tax and potential carbon tax policies. The Environmental Protection Tax Law was issued in 2018 and represented the government’s determination to upgrade the priority of environmental issues. As for the carbon tax, though it is not levied at present, it is a hot research topic, and many experts are arguing about introducing it in the next years. We will study the co-benefits of the existing environmental tax and the potential carbon tax.

Reviewing the current policy assessment tools for assessing environmental taxes or carbon taxes, the most used tools are as follows.

- Input-output (IO) model. The IO model is originally developed by the Nobel Prize Laureate Wassily Leontief and used mainly to analyze the impacts of macro-economic shocks based on the interdependences between the inflow and outflow of sectors (Miller and Blair, 2009). IO analysis has been used for analyzing environmental policies, like waste management policies. Nakamura and Kondo (2002) constructs the Waste IO table and connects the physical environmental accounts to traditional IO tables.
- Computable general equilibrium (CGE) model. The CGE model solves the general equilibrium situation of an economy where all the markets clear at the same time, and has been widely applied in the policy analysis of international

trade (De Melo and Robinson, 1989), energy (Fujimori et al., 2014), and environment (Hasegawa et al., 2016). The framework could be regarded as an extension of the IO table and Social Accounting Matrix (SAM), by adding the interactions among different accounts of governments, companies, and households.

- Econometrics. Econometrics apply the statistical method for empirical analysis and has been widely used in all fields of economics. Economics has also been widely used to analyze topics like carbon tax (Smith et al., 1995) and environmental taxation (Scholz, 1997).
- Life cycle assessment (LCA). The LCA technique is used to analyze the whole life of a product from raw material to be processed, retailed, consumed, and finally disposed of or recycled. The LCA could capture very detailed data like the emission rate or the technology cost. However, it is more used to analyzed problems at the scale of a product or a specific industry.
- Bottom-up energy system model. These models are named by contrasting to the up-down models like CGE. It traces the detailed information of energy and materials from the supply side to the end use side. There are already many existing models in this category applied to environmental policies, like the AIM/Enduse Model (Morita et al., 1996) and the TIMES model (Loulou and Labriet, 2008).

As this thesis aims to assess China’s environmental and carbon taxes, the CGE approach is selected for several reasons. First, in terms of the research goals, this thesis needs to analyze the cross-sectoral impacts of environmental policies and on a macroeconomic scale. CGE is a mature model for this purpose. Second, in terms of data availability, the CGE model only requires the IO table or the SAM table of the base year as the primary data input, while other approaches either require time-sequence data or detailed technology or product information, which is much more difficult. Third, in terms of extensibility, the CGE model could be incorporated with the physical emission data easily and allows a further extension if more data is available in the future. Fourth, it is already widely applied to analyze environmental policies and makes it easy to compare with different research results and provide policy implications for the policymakers.

However, there is still a research gap in how to assess the impacts of the latest environmental policies using CGE models. As explained, the CGE model is one of the widely used tools for evaluating environmental tax policies, but there are few CGE studies on the latest standards, since the Environmental Protection Tax Law had just been published in 2018. Besides, most current CGE studies on environmental tax like Xiao et al. (2015) only focus on the major pollutants like SO_2, CO, and NO_x, while there are 44 kinds of taxable gas pollutants, 61 kinds of taxable water pollutants and 4 kinds of taxable solid pollutants in the Environmental Tax Law. Moreover, the electricity sector is not disaggregated in some studies like Xiao et al. (2015) and Wang, Z. et al. (2017), which makes it challenging to observe the low-carbon transitions among different kinds of electricity generation technologies.

To bridge the research gap, this paper updates the tax levels from the latest regulations and uses the sectoral emission data of 18 pollutants from the China Environmentally Extended Input-Output (CEEIO) table, covering the primary gas, water, and solid pollutants. The electricity sector is also disaggregated into six different production technologies: hydroelectricity, coal power, gas electricity, oil electricity nuclear power and renewable energies, and various environmental tax scenarios with and without carbon tax have been constructed to study the potential policy impacts thoroughly.

1.6 The scope of work

This thesis aims to analyze the environmental impact and the economic impacts of China's environmental tax policies under the New Normal economic situation. The scope of work should be notified clearly from the following perspectives:

- **Environmental policy: the environmental tax law and the potential carbon tax.** As stated in Section 1.5, this thesis focuses on environmental tax and the carbon tax. It should be noted that some other specific tax regulations in the Environmental Protection Tax Law are not considered in this study due to the lack of detailed information. For example, it is regulated that only the top three kinds of gas pollutants in terms of emission amount will be charged in one vent, but the emission data of each vent is not available at present. Besides, according to the law, companies could enjoy a 75 % of tax exemption if the emission density is less than 30% of the legal standard, and a 50 % of tax emption if the emission density is less than 50 % of the government standard. Due to the lack of data, this thesis does not consider tax emption situations.

- **Level of policy: national-level policy.** Though many studies study the carbon tax in the global-wide or the environmental regulations at the provincial level, this thesis will only focus on the national level. However, the extension of the CGE model to the provincial level or global level is possible in future studies. A multi-regional CGE model has been developed and will be roughly introduced in the Chapter of CGE modeling.
- **The base year: the year of 2012.** Due to the data availability, this thesis will apply the national IO table of 2012 and the sectoral environmental emission data of 2012 from the China Environmentally Extended Input-Output (CEEIO) table (Liang et al., 2017). China's National Bureau of Statistics conducts the national IO survey and then compiles the national IO table every five years and will publish a version of the extended IO table in the 3rd year in each circle. By the end of 2018, the latest extended national IO table is the year of 2015, and the most recent national IO table by the survey is the year of 2012. As for the environmental data, the sectoral pollutant emission data is published every year, but the types of pollutants are limited and the consistency with the sectoral account of national IO table is not checked. The CEEIO database publishes more detailed sectoral pollutant data consistent with the National IO table. The latest CEEIO is the year of 2012. To include more environmental data and ensure the consistency with the IO table, this thesis chooses 2012 as the base year.
- **Simulation period: until the year of 2030.** China updates the national development strategy every five years, and the newest national development plan is until 2020. This thesis will expand the simulation period to 2030 to discuss the policy impacts in the longer term. Besides, the United Nations General Assembly issued the "Transforming our World: the 2030 Agenda for Sustainable Development" (UNDP, 2015) which makes 2030 a cornerstone in reviewing environmental protection and sustainable development in each country. The simulation period could also be extended to 2050 in the future if long-term policies are to be studied.

The rest of the thesis is organized as follows. Chapter 2 reviews the literature in the related fields of sustainable development, environmental tax and carbon tax, environmental policy assessment, and CGE modeling. Chapter 3 introduces the methods of CGE modeling. Chapter 4 presents the economic and environmental data. Chapter 5 presents the scenario settings. Chapter 6 analyses the results and conducts sensitivity analysis. Chapter 7 concludes the study with the main findings, policy implications, and future studies.

2. Literature review

2.1 Sustainable development and its practice in China

2.1.1 Concept of sustainable development

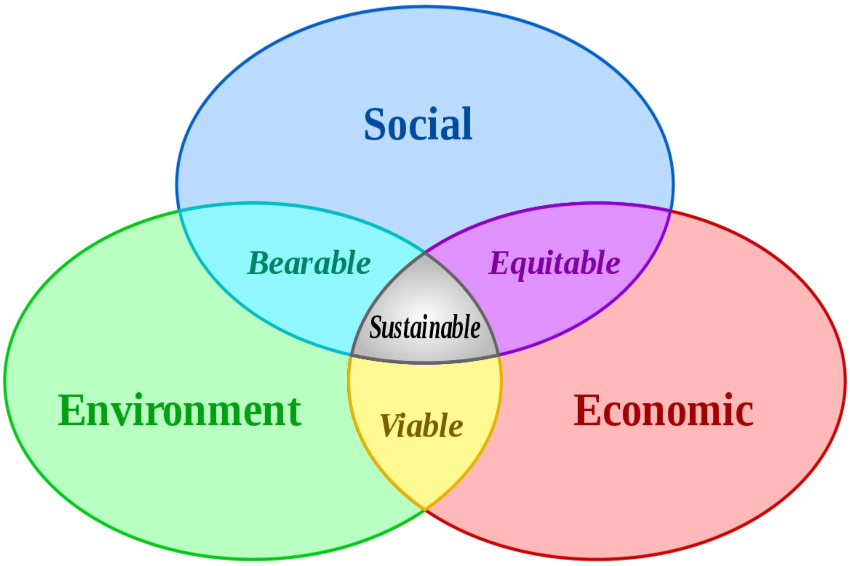
The concept of sustainable development has been gradually improved and developed as the increasing public and academic attention to it. One of the earliest works that discussed the sustainability issues was the influential but controversial report of “the Limits to Growth” (Meadows et al., 1972), published by the Club of Rome. This report built a global model by introducing the basic factors of global development: the world’s population, agricultural production, the nonrenewable resource depletion like oil, industrialization, and environmental pullulation. The simulation results show that to “establish a condition of ecological and economic stability that is sustainable far into the future,” the present growth mode needs to be changed and limited. Despite the controversies, this report shows the concerns from the public and academia over the limited natural resources and future world development.

In 1980, the International Union for Conservation of Nature and Natural Resources, in collaboration with s United Nations Environment Program (UNEP) and the World Wildlife Fund (WWF), published “World Conservation Strategy: living resource conservation for sustainable development” (Nature and Fund, 1980). The report defines sustainability as the economic development mode under the constraints of “the reality of resource limitation and carrying capabilities of ecosystems, and the needs of future generations.” The report regards sustainable development as a global priority and has summarized the main requirements and strategies to pursue sustainable development. This report has been very successful and attracted much public attention to sustainable development.

In 1983, the United Nations General Assembly decided to establish the World Commission on Environment and Development (WCED) and appointed Gro Harlem Brundtland, the former Prime Minister of Norway, as the chairperson of the Commission. In 1987, the Brundtland commission published the report of Our Common Future (Brundtland et al., 1987) and gave one of the most widely accepted definitions of sustainable development, which indicates a social development mode where the needs of the presents are met without sacrificing future generations' ability to meet their own needs. There are three critical points about this definition in this report. Firstly, sustainable development requires the socioeconomic activities need to be limited within the range of tolerance of the natural system and be developed in harmony with the limited natural resources and fragile ecological system. Secondly, it is also emphasized that to meet the demands of society; a critical target is to eliminate poverty and ensure the poor to obtain a fair share of social resources that could sustain their lives and future development. Lastly, the definition and standard of sustainable development should be adjusted by the latest evolution of technology and social organizations. The current standards might not fit in the future, and the invention and application of disruptive technologies might also help solve problems in the past.

Since the Our Common Future report, sustainable development raised more and more support and became the consensus the international society. In June 1992, the United Nations summoned member states and many non-governmental organizations for a conference on environment and development in Brazil, which was also called as the Earth Summit (Parson et al., 1992). This was one of the most critical cornerstones in history of sustainable development. The productive results of this summer include the Rio Declaration on Environment and Development, Agenda 21, and the Forest Principles. More importantly, the legally binding agreements of Framework Convention on Climate Change, and the United Nations Convention to Combat Desertification were opened for signature in this summit. These international conventions laid the foundation for global cooperation towards a sustainable world, especially in the field of combating climate change and eliminating poverty. Lastly, the United Nations Commission on Sustainable Development was initiated and held regularly since this summit. Following the 1992 Earth Summit, two Earth Summits have been held in 2002 and 2012, respectively.

After decades of development, the definition of sustainable development becomes more precise and more comprehensive. In 2006, Professor Adams from the University of Cambridge summarized that there are three core dimensions in sustainability: economic, environmental, and social, as shown in Figure 2-1 (Adams, 2006). In the economic aspect, sustainable development pursues the quality of economic growth more than the output quantity. It requires to change the traditional economic mode of the high input of capital and resource and high pollution, to a greener production and consumption mode of reducing wastes of resources. In the environmental dimension, sustainable development emphasizes to limit economic activities within the earth's carrying capacity and ensure the sustainable use of natural resources and environmental costs. Some urging environmental topics like climate change need to be addressed with global cooperation in the social dimension. Sustainable development emphasizes public awareness of environmental and social issues and the green business to be a core business social responsibility. It also requires that all people be treated fairly in development issues.



Source: Adams (2006)

Figure 2-1: Three pillars of sustainable development

In 2015, the United Nations General Assembly issued the "Transforming our World: the 2030 Agenda for Sustainable Development" (UNDP, 2015) and listed the 17 global sustainable development goals (SDG), which was also called as 2030 Agenda. As shown in Figure 2-2, the 17 goals further explain the connotation of sustainable development from the social, economic, and environmental dimensions, which includes the aims of "no poverty", "zero hunger", "good health and well-being", "quality education", "gender equality", "clean water and sanitation", "affordable and clean energy", "decent work and economic growth", "industry, innovation and infrastructure", "reduced inequalities", "sustainable cities and communities", "responsible production and consumption", "climate action", "life below water", "life on land", "peace, justice and strong institutions", and "partnerships for the goals".

Source: United Nations (UNDP, 2015)

Figure 2-2: Sustainable development goals

Recalling the evolution of the definitions of sustainable development, it starts with the public concerns over limited natural resources and heavy pollution, enriches as the global cooperation on the urging issues like combating climate change, and further develops when more and more specific development issues like social equality are regarded as key elements to realize a fully sustainable society for all. The understanding of sustainable development has been deepened gradually with the constant efforts from academia, industries, business areas, and international communities, and it will become a primary goal for the human society to achieve in this century.

2.1.2 Sustainable development in China

China's sustainable development strategy has been progressing and keeping updated with the latest progress in the UN Earth Summits and the UN Sustainable Development Summit. After the 1992 Earth Summit, the Chinese government issued the "China's

Agenda 21: White Paper on Population, Environment and Development in the 21st Century" (SC, 1994), and the central government then promoted sustainable development as a national strategy in the 9th Five-Year Plan in 1996. After the 2002 Earth Summit, the China's government proposed the concept of scientific and sustainable development and addressed China's future development should be human-oriented and balanced between urban and rural development, economic and social development and nature protection, and domestic development and opening-up to the world. In 2012, China published the "National Report on Sustainable Development" (SC, 2012) in response to the 2012 Earth Summit. After the recent UN Sustainable Development Summit in 2015, China published the National Implementation Plan on Sustainable Development (SC, 2016a), which specified China's development strategy in each SDG goal.

As the largest developing country, China faces many challenges in pursuing sustainable development. China holds the largest population in the world, but the ecological system has been fragile, and natural resources per capita are far behind the average world level. In 2012, China's GDP per capita ranked behind more than 100 countries in the world, and there were still 122 million people living under the poverty line. Moreover, China's current economy still strongly relies on natural resource and labor inputs, and the high-end technological sectors are not at an advantageous position compared to international competitors. Besides, unbalanced development among different regions is also an urgent problem, and the low-end energy-intensive or resource-intensive sectors still play an essential role in the less developed areas. These challenges require China to innovate the development strategy in resolving the unbalanced, uncoordinated, and unsustainable problems in its development.

In the National Report on Sustainable Development" (SC, 2012), the government published the following five main strategies in pursuing sustainable development in China.

- Improve economic structure which means expanding domestic markets, developing high-end manufacture sectors, and balancing development in less developed areas;
- Control the total population and improve the social welfare system;

- Regard the eradication of poverty as an urgent task for advancing sustainable development strategies;
- Building a resource-conserving and environment-friendly society;
- Establish long-term sustainable development strategies and focus on environmental protection, resource management, and total population management.

2.2 Environmental policy studies and practices in China

2.2.1 Pollution control and treatment

Along with rapid economic development, China's environmental situation has been worsening seriously, and it is urgent to control and treat all kinds of pollution, including air pollutants, water pollutants, and solid pollutants.

For air pollution, it is reported that in China, only less than 1% of the 500 large cities reached the air quality criteria published by WHO (World Health Organization) in 2012 (Zhang and Crooks, 2012), and only 4.1% of the cities reached the $PM_{2.5}$ (particulate matter with diameters smaller than 2.5 mm) standard of 35 $\mu g/m^3$ in 2013 (Wang, J. et al., 2017). Chen et al. (2013) suggested that long-term exposure to a heavily polluted atmosphere (higher than 100 μg/m3) would cause about three years of loss of life expectancy, and the particulate air pollution has been causing 500 million residents to lose more than 2.5 billion life years of life expectancy in total.

Faced with the severe air pollution and public pressure coming along, the State Council published the Air Pollution Prevention and Control Action Plan in 2013 (SC, 2013). This action plan sets the five-year goals (2013-2017) to control the air pollution, including promoting the "Coal to Gas" and "Coal to Electricity" projects, installing the desulfurization, denitrification and dust removal equipment in high polluting industries. In 2018, the State Council issued the Three-Year Action Plan for Blue Sky (SC, 2018). This is the strictest action plan ever and sets Northern China as the key region for air pollution control, especially the cities around Beijing. Those cities in the key region need to take stricter measures to reduce the air pollutants as much as possible, like it is forbidden to increase the production capacities for the high polluting products, like steel and steel.

Studies have been done to examine the effectiveness of the policies to control air pollution. Wang et al. (2014) found the air pollution policy during the 12th Five-Year Plan (2011–2015) helped reduce the NOx emission in 2015 by 10% compared to the 2010 level. Gao et al. (2016) conducted a cost-benefit analysis of the Air Pollution Prevention and Control Action Plan and found that the average cost and benefit for air pollution management are 118.39 and 748.15 billion Yuan, respectively. Zhang et al. (2012) found the air pollution control in China could also benefit other countries, like reducing the number of air pollutants traveling from East Asia to the western United States. Wu et al. (2013) discussed how to increase the effectiveness of environmental policies by motivating local officials. They found that previously local governments' spending on environmental protection would not help promote the local GDP, land prices, and the odds of cadres' promotion. Therefore, local officials lack the incentives to participate in environmental protection projects proactively. Faced with this situation, the State Council issued the Evaluation and Assessment Measures for Ecological Protection, and for the first time weighs the environment protection more than GDP growth when judging the work performance of a local governor (SC, 2016b).

For water pollution, the first thing to be noted is that as a developing country with the largest population, China's most significant water challenges include the scarcity and imbalanced distribution of the limited water resources, especially in the areas with a dense population, like the areas around Beijing (Naughton, 2006). The severe water pollution even worsens the situation. It is reported that 57% of the monitored urban underground water sites are polluted or heavily polluted and about 300 million residents in rural area lack access to clean drinking water in 2012 (Xinhua, 2012). It is estimated that the deterioration of water quality increases the death rate of digestive cancer and doubling the charge fees for waste water could improve the water quality and saving about 17,000 lives per year in China (Ebenstein, 2012). The ecological impact of water pollution is also severe. The number of wild fish in freshwater is dropping sharply, and large animals such as baiji are at the risk of extinction (Moore, 2013).

China’s policy for controlling and treating water pollution can be traced as early as in the 1970s, and many national and provincial policies have been issued since then. The policy focus has been on the key river basins (Huai River, Liao River, Hai River, and so on) and key projects (Three Gorges Project, South-to-North Water Transfer Project), and the primary mode is to control the total emission amount of pollutants (mainly chemical oxygen demand and ammonia nitrogen) from industrial and municipal emitters (Chen et al., 2015). Besides, after establishing the pollution permit system nationwide, some provinces are trying to introduce a market-based trading system for water pollution permits. In 2014, the State Council issued the Guidelines for Promoting the Pollution Permit Trading (SC, 2014) and encouraged the local governments to adopt more market approaches to treating the pollution issues.

For solid waste pollution, China has already become one of the largest producers of solid waste. Zhang et al. (2010) calculated that the annual generation amount of municipal solid waste increase from 31.3 million tons in 1980 to 212 million tons in 2006, and the waste generation rate per capital almost doubled during this period. However, China’s waste management capacity is far behind rapidly increasing demand. The challenges include the limited land resources for disposable sites, the insufficient operation fund, inefficiency of the treatment system, and lack of public awareness. Take Beijing for an example. It is reported that the city generates about 1,840 tons of solid waste, but existing waste treatment plants can only process about 1,040 tons of waste. As a result, most of the waste treatment facilities operate at 67% of the standard load, and the life of the landfill is only 4 years (SGEP, 2019).

The government has been promoting the concept of circular economy to solve the waste problem as well as improve the efficiency of energy and materials use. The “Waste to Energy” is one of the solutions. In 2017, there were 744 “Waste to Energy” projects, with an installed capacity of 14.8 million KW and generating 79.5 billion KWH of electricity per year (LI, 2018). Another policy on waste management draws global attention: the ban on imports of foreign garbage. A UNEP report estimated that the imported waste increased China’s total waste by 10% to 13% (UNEP, 2018) and the State Council imposed the ban on 24 kinds of solid waste in 2017 (SC, 2018). This policy that in a globalization world, the environmental problems in one country are highly connected to another and a more integrated and systematic plan for waste management is important for all the nations as a one.

2.2.2 Carbon pricing

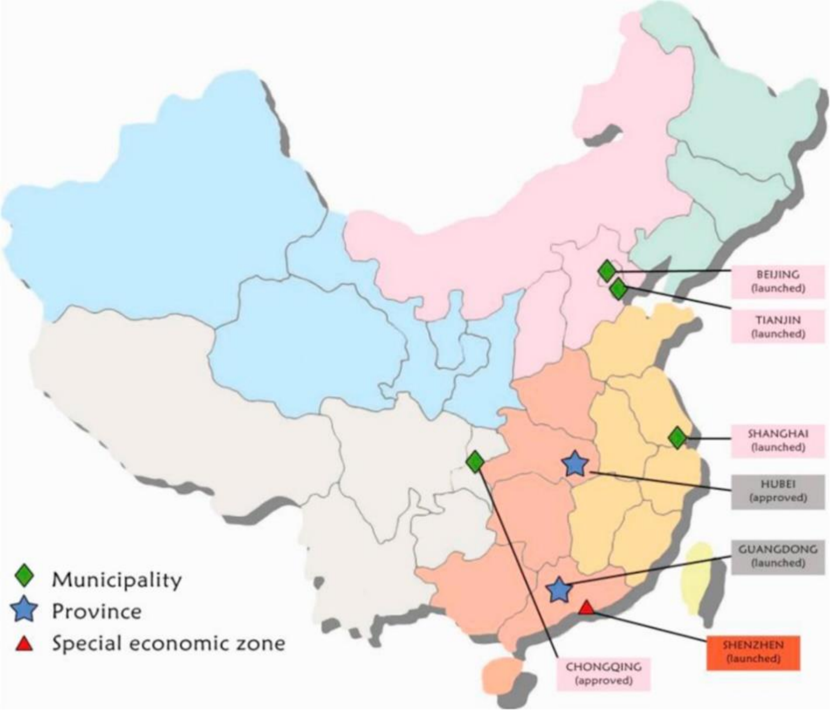
Carbon emissions result in negative externalities for the whole society (Rezai et al., 2012) and economists and policy advisors have been arguing for market-based solutions to pricing the carbon dioxide to reduce emissions. Before the Kyoto Protocol negotiation in 1997, many economists including Nobel Prize laureates published the Economists' Statement on Climate Change (RP, 1997) which argued that “the most efficient approach to slowing climate change is through market-based policies.” Among the many market solutions like pollution charges, tradable permits, market barriers, elimination of government subsidies, nudging consumer behaviors, and so on (Hockenstein et al., 1997), the two most discussed forms are the carbon tax, and carbon emission trading system.

Carbon tax refers to the mechanism that the government levies taxes at the same rate per carbon dioxide emitted (Metcalf and Weisbach, 2009). In practice, since the primary anthropogenic carbon emissions come from the combustion of fossil fuels and carbon tax are often taxed according to the consumption of fuels. The carbon tax is regarded as a form of Pigouvian tax that aims to solve the market inefficiency by monetarizing the social cost of negative externalities. Currently, carbon taxes have been implemented in many countries including Japan, many European countries, and some states in the U.S. and Canada.

Carbon emission trading is also called cap and trade. It usually refers to the mechanism that the government first regulates an emission cap for an entity, a polluter who emits more carbon dioxide than his cap can purchase the right from another entity who has additional emission permit to meet his cap (Sorrell and Sijm, 2003). The carbon emission trading could also take place among different counties, where were authorized by Article 17 of the Kyoto Protocol (Protocol, 1997). Currently, the European Union Trading Scheme is the world’s largest carbon trading market which was established in 2005 (Ellerman et al., 2010) and covers almost half of the total anthropogenic carbon emissions in Europe (Wagner, 2004).

Many studies compare the different impacts of carbon tax and cap and trade schemes. Avi-Yonah and Uhlmann (2009) point out that carbon tax and cap and trade both as market-based solutions could help reduce carbon emissions. However, their difference mainly lies in the benefit/cost certainty. Cap and trade pose an overall cap which is very clear in benefit certainty but lacks certainty in the cost side. On the other hand, the carbon tax is more transparent on the cost since the tax level is pre-set but could not assure the overall emission. However, transparent carbon pricing could convey a simple and clear policy signal to the market. The polluters are forced to pay the carbon tax due to its negative externalities and carbon tax makes it much clearer than the cap and trade. Also, Wittneben (2009) argues that the cap and trade system may not be most cost-efficient compared to the carbon tax in terms of the generated tax revenue, which could be used for other public expenses. Goulder and Schein (2013) also find that the exogenous emission pricing scheme like the carbon tax is more attractive in terms of preventing the carbon price volatility.

In the case of China, China has begun to consider and deploy GHG policies, especially carbon policies, since the beginning of the 12th Five-Year Plan. In 2011, the State Council issued the guideline for controlling GHG emissions 2011 to 2015 (SC, 2011), which required that the CO_2 per GDP in 2015 should reduce by 17% compared to the level in 2010. In this guideline, it also proposed to adopt market-based measures to establish a carbon emission total control system, carry out carbon emission trading pilots, study the emission rights allocation, and gradually form regional carbon emission trading systems.



Source: Liu et al. (2015)

Figure 2-3: Pilot projects of emission trading system in China

Following this guideline, the National Development and Reform Commission started the pilot projects of carbon trading system in seven regions: Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong Province, and Shenzhen, as shown in Figure 2-3. The selection of these pilot areas was designed to cover the regions with different socioeconomic situations to explore how to create the carbon market scheme for each part. In total, these seven pilot regions account for 18% of the population and 30% of GDP in China (Liu et al., 2015), and Beijing, Shanghai, Guangdong Province, and Shenzhen represent the most developed areas in China, while Tianjin, Hubei, and Chongqing represent the vast developing regions. The economic structure in these regions is also quite different, that the service sector makes up of more than 50% of GDP in Beijing, Shanghai, and Shenzhen, while industry sector remains high share in other regions. The earlies pilot market was officially launched in Shenzhen in June 2013.

Table 2-1: China's pilot projects of emission trade system

Region	Population (million)	GDP per capita (k RMB)	Total CO_2 emission (Mt)	Launch time	Share of covered emission
Beijing	19.6	71.8	157	11/2013	50%
Tianjin	13.0	71.1	133	12/2013	45%
Shanghai	23.0	74.5	219	11/2013	60%
Chongqing	28.9	27.8	168	6/2014	40%
Hubei	57.2	27.8	250	4/2014	33%
Guangdong	104.3	33.9	522	09/2013	42%
Shenzhen	10.4	91.4	84	06/2013	40%

Source: Zhang et al. (2014); Data in 2010.

In December 2017, issuing the "National Carbon Emission Trading Market Construction Plan (power generation industry)," the National Development and Reform Commission took the first step to launch the national emission trading system (NDRC, 2017). The power sector emits about 3.6 Gt of CO_2 equivalent in 2015, accounting for about 40% of total carbon emission in China. The national pilot market in the power sector will include all the power plants whose annual emissions are more than 26 Kt CO_2-equivalent (annual energy consumption around 10 Ktce) and aim to solve the various problems of integration of different regional markets and lay the foundation for expanding the national carbon trading market towards other sectors.

Contrast to the expanding carbon trading system, China's carbon tax policy has been quite a low key and has not been adopted so far. It was expected the carbon tax would be included in the new Environmental Tax Law which did not happen in the end. The concerns were mainly from economic perspectives. Simulation results show that carbon tax will bring a negative economic impact. Zhou et al. (2011) show that the carbon tax of 30 to 90 RMB per ton CO_2 will cause a decline of GDP by 0.11 % to 0.39 % in 2020. Zhang and Li (2011) also show that carbon tax will hinder the economy in less developed regions like in the middle and western areas more. However, it is reported that the carbon trading market will enlarge the coverage and include all the companies whose annual energy consumptions are around 5 Ktce since 2020, and the carbon tax will be levied on the rest companies who are not included in the carbon trading market (Zhu, 2018).

2.2.3 Low-carbon transition in the power sector

Combating climate change requires to lower the atmospheric density of greenhouse gases, especially carbon dioxide. As one of the largest energy consumers and carbon emitters, the power sector takes the primary responsibility for the decarbonized transition. In the case of China, this low-carbon transition in the power sector involves many perspectives, including developing the renewable energies in place of the traditional fossil fuel energies, reducing the emission levels of conventional power plants, improving the energy efficiency, deploying the smart grid, conducting research on the carbon-neutral technologies, and so on (Zhang, 2010).

Table 2-2 shows China's total energy consumption and composition (NBS, 2017). Along with rapid economic development, the total energy consumption also rises rapidly and reaches 4.3 billion tce in 2015. Among the primary energy sources, coal products dominate the consumption structure with a share of 60-70%. Taking the hydropower and nuclear power into consideration, the total renewables makes 12.1% of total primary energy consumption in 2015.

Table 2-2: Total energy consumption and composition

	Total energy consumption	Coal	Petroleum	Natural gas	Hydro power	Nuclear power	Other renewables
	(10^4 tce)	%	%	%	%	%	%
2010	360,648	69.2	17.4	4	6.4	0.7	2.3
2011	387,043	70.2	16.8	4.6	5.7	0.7	2
2012	402,138	68.5	17	4.8	6.8	0.8	2.1
2013	416,913	67.4	17.1	5.3	6.9	0.8	2.5
2014	425,806	65.6	17.4	5.7	7.7	1	2.6
2015	429,905	63.7	18.3	5.9	8	1.2	2.9
2016	435,819	62	18.5	6.2	8.3	1.5	3.5

Source: Energy Balance Table (NBS, 2017)

In 2017, the National Development and Reform Commission published the 13th Five-Year Plan (2015-2020) on Renewable Energies and sets the short-term low-carbon development goal (NDRC, 2016a), including:

- renewable energies should account for 15% for total primary energy consumption by 2020, and 20% by 2030;
- the total energy consumption should be lower than 5.0 tce in 2020;
- the cap for coal consumption in 2020 is 4.1 tce;
- the share of coal products in total energy consumption should be smaller than 58%.

As for the long-term low-carbon strategy, in the report of China’s Low Carbon Development Pathways by 2050, Dai et al. (2009) simulate the primary energy consumption structure by 2050 in three different scenarios: energy-saving scenario, low-carbon scenario, and the intensively low-carbon scenario. As shown in Table 2-3, the low-carbon strategy requires the coal share to be lower than 40%, much lower than the current 62% level. The percentage of petroleum and hydropower will stay at the same level, but the percentage of natural gas, nuclear power, and other renewables (wind power, solar power, and so on) should boost in a short period.

Table 2-3: Primary energy composition in different long-term scenarios

	2016	2050 Energy-saving scenario	2050 Low-carbon scenario	2050 Intensively low-carbon scenario
Coal	62.0%	41.1%	36.0%	28.6%
Petroleum	18.5%	26.6%	19.7%	19.9%
Natural gas	6.2%	10.0%	11.9%	12.6%
Hydro power	8.3%	5.4%	7.0%	7.8%
Nuclear power	1.5%	8.7%	11.6%	14.8%
Other renewables	3.5%	8.2%	13.8%	16.4%
Total	100%	100%	100%	100%

Source: Dai et al. (2009)

Moreover, as power market is one of the most monopoly industries in China and the energy market is still under the process of marketization, deepening the market reform also plays a vital role in the low carbon transition in the power sector (Cherni and Kentish, 2007). In 2015, the State Council published the guidelines for deepening reforms in the power market requiring to separate the business of power transmission and power retailing and introduce market competition in both the upstream and downstream market

(SC, 2015). The market reform will help strengthen the pricing signal in the power market and reduce market inefficiency (Ngan, 2010), and also contribute to the green transition in the power sector (Ye et al., 2018).

2.3 CGE model and applications

2.3.1 The origin of CGE and its main applications

In 1874, French Economist Leon Walras first discussed the concept of general equilibrium in his work “Elements of Pure Economics” (Walras, 2013). In his theory, the complex economy system is regarded as an interconnected and integrated system and could reach an equilibrium status when all the consumers maximize their utilities under their budget constraint; all the producers maximize their profits given the technology, resource, and market situation; all the demands and supplies are met, and there is no satisfying demand. However, Walras could not prove the existence or the uniqueness of the general equilibrium point. In 1912, the fixed-point theorem was developed in the field of topology. Using the fixed-point theory, three economists, Kenneth Arrow, Gerard Debreu, and Lionel W. McKenzie proved the existence and uniqueness under certain conditions and established the modern theory of general equilibrium. Dr. Arrow and Dr. Debreu were awarded the Nobel Memorial Prize in Economic Sciences for their contribution in this area. After developing the modern theory of general equilibrium, the economists after that worked on how to quantitatively calculate the equilibrium and apply the theory to practical economic analysis. Under such background, Norwegian economist Dr. Leif Johansen developed the first Computable General Equilibrium model, the so-called MSG (multi-sectoral growth) model in 1960 (Johansen, 1985). Since then, the CGE model became popular for economic and policy analysis. With the development of computer sciences, CGE model and analysis became more accessible and more and more research has been done using this method.

The primary application fields for CGE models include international trade, fiscal and tax policies, environmental and energy policies, and so on. In international trade analysis, the Global Trade Analysis Project (GTAP) is currently the most extensive global CGE project for analyzing trade policies. It was initiated by Professor Hertel from Purdue University (Hertel, 1998) and expanded by the cooperation with many influential international organizations and university researchers. Other representative works include that De Melo et al. (1992) established a single-country model for the US and analyzed various US foreign trade policies in multiple sectors including textiles and apparel, automobiles, and steel, and found that deep and extensive impacts of nontariff barriers in the economy. This work showed the superiority of CGE models over the traditional partial equilibrium models when assessing the overall and intersectoral effects of trade policies. In China, CGE has also been extensively used for trade policy analysis. Li et al. (2000) established a dynamic CGE model to assess the economic and welfare impacts if China joined the World Trade Organization, and the results showed that China could gain more benefits than cost if accessing to WTO and should seize the opportunity as early as possible.

In fiscal and tax policy analysis, CGE has been world widely used to simulate and assess tax reform plans. Hertel and Tsigas (1988) discussed the effects of eliminating farm and food tax preferences in the US and indicated that the low agricultural tax benefited the consumers but brought fiscal burden to the government. Radulescu and Stimmelmayr (2010) discussed the corporate tax reform in German and its impacts on households' welfare. In the case of China, Mun-Heng and Qian (2005) evaluated the 1994 tax reform in China and its impacts on households' welfare. Ye et al. (2010) and Tian and Hu (2013) analyzed the recent tax reform from business tax to value-added tax, discussing its impacts on GDP, employment, the short-term and long-term burden on the enterprises.

In policy assessment for environment and energy policies, CGE as a top-down modeling method is also one of the major tools in this field (Böhringer, 1998), and has been applied to many reports issued by the Intergovernmental Panel on Climate Change (IPCC) to assess the mitigation and adaptation policies. In China, many researchers also apply CGE for policy analysis in this field. Zhang (1998) used CGE to assess the macroeconomic effects if limiting the total carbon emission. Wang et al. (2009) calculated China's abatement cost for climate change mitigation in different climate policy scenarios incorporating endogenous technological change. Dai et al. (2011) analyzed the GDP loss and environmental benefits if China implements the non-fossil energy plan. To conclude, CGE is a popular and useful tool for conducting policy assessment in various fields.

2.3.2 CGE for assessing China's environmental tax policies

Xie and Saltzman (2000) sorted the environmental CGE models into three types depending on how the pollution-related activities are introduced into the model. The first type of models treats the environmental emissions as an outside block and connects to the standard CGE models only by pollution coefficients per unit of material inputs or sectoral outputs. In these models, the environmental costs will not change the production function or utility function, and the environmental emissions are merely the results of the activities. The second type of models builds the influence channel where environmental costs could affect the production or consumption mode in reverse. For example, Robinson (1990) introduced the pollution parameter in the consumer welfare function which reflected the fact that pollution reduced social welfare and would affect consumer behavior. The third type of models constructs environmental treatment or pollution abatement sectors which shows the cost structure of the environmental industries. Since pollution treatment sector is not disaggregated in most input-output tables or social accounting matrix, the third type of models needs to first collect basic data for the sectoral disaggregation.

In the CGE studies for assessing China's environmental tax policies, most models applied to belong to the first or second type of models. Wang, Z. et al. (2017) used CGE to analyze the synergistic effect of SO_2 tax and CO_2 tax using the IO data from the year of 2007; they introduced sectoral emission coefficients to the production sectors, which could be regarded as a typical first-type model. The sectoral emissions are in proportion to the output level, and there is no pollution treatment technology or sector. Xiao et al. (2015) adopted a similar methodology but updated the base year data to the year of 2010. Besides, they considered another two types of pollutants: CO and NO_x and discussed the tax levels about the new Environmental Tax Law. Li and Masui (2019) updated the work to the dataset of 2007 and considered more than 15 kinds of pollutant, but the way of introducing pollution to the model was still like previous works. In Ma (2008), his work focused on SO_2 tax and built a second-type model by considering different types of coal products. The sulfur content varied among different products, like less in clean coal products. By doing so, the emission levels will not only be affected by the production levels but also by the substitution of inputs. This work used the data of 2002 and showed that the SO_2

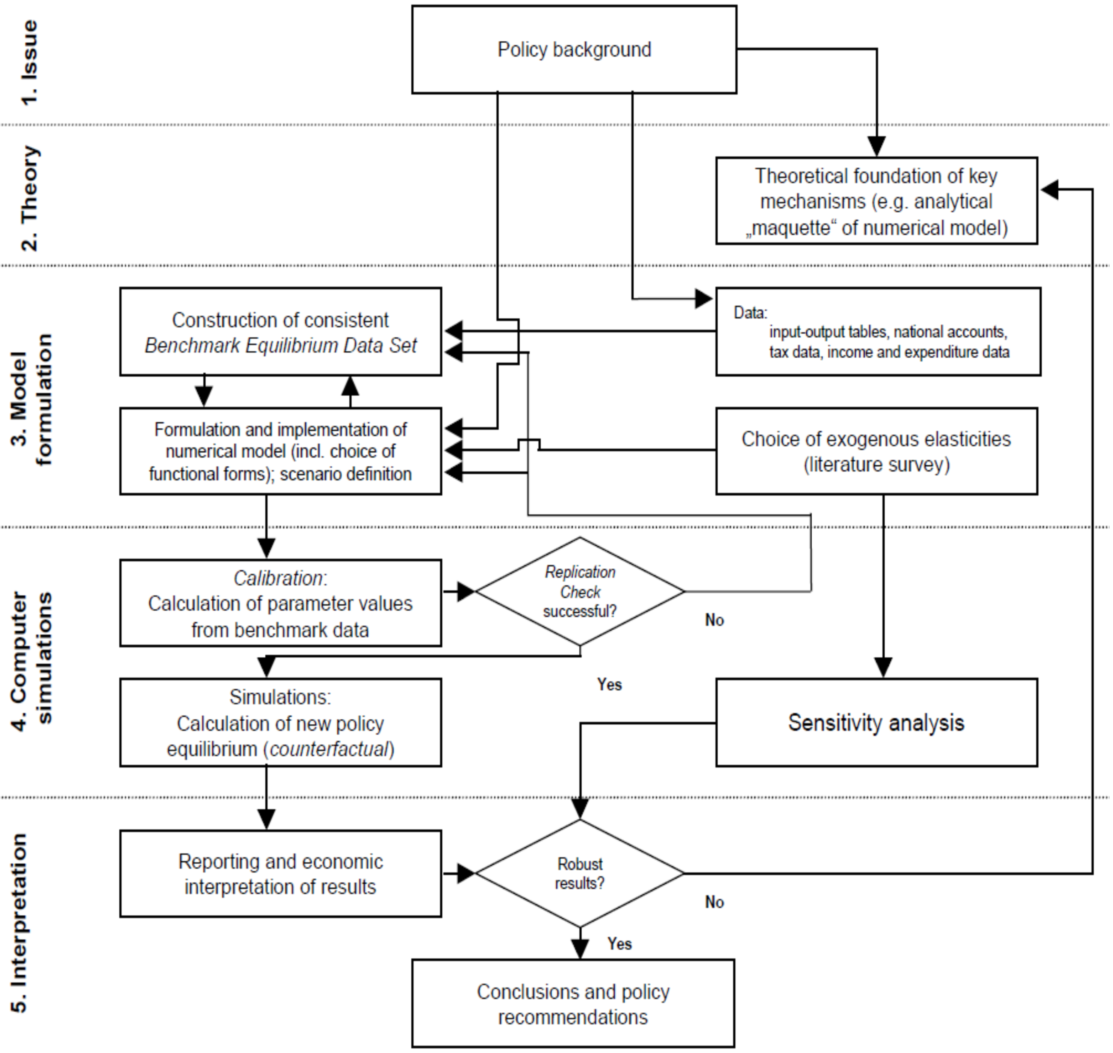
tax could not only reduce the SO_2 amount but also improve the energy production structure.

There are not many works on the type-three models. Xie and Saltzman (2000) used the data of 1990 and separated the environmental treatment sectors from other sectors and reconstructed the IO table and SAM. There were two types of environmental cost in the paper: pollution abatement cost and pollution emission taxes. The pollution abatement cost came from the consumption of services from the pollution treatment sector, and the pollution taxes were levied and collected by the government. Gao (2006) used the data of 2000 and constructed the SAM from three dimensions: economy, resources, and environment and built a CGE model to simulate the energy tax and pollutant tax policies. Zhao and Lei (2010) further updated the economy-resource-environment SAM to the year of 2007, but no CGE work has been published using that database. To conclude, there is a research gap in disaggregating pollution treatment sectors in CGE models and analyzing the new environmental tax policies using updated data. This thesis will try to fill in the research gap, and the model and data details will be presented in the following chapters.

3. CGE Modelling

Böhringer et al. (2003) summarize the five steps to conduct CGE analysis, as shown in Figure 3-1. The first step is to thoroughly understand the policy to be analyzed, including the policy incentive, the policy measures, and potential impacts. The second step is to understand the economic theory and mechanisms to be applied for the policy assessment. For CGE modeling, it requires to understand the theoretical formulation in different blocks and the macro closure. The third step is to collect necessary data, including input-output table, social accounting matrix, satellite account information. Based on the data, the modeler should build the base year dataset or the so-called benchmark equilibrium dataset. The fourth step is to conduct numerical simulations in different policy scenarios and sensitivity analysis. Lastly, the fifth step is to interpret the simulation results and provide policy implications.

After thoroughly analyzing the policy background, we will move forward to discuss the details of CGE theory and represent the theory in the quantitative formulation or explanatory figures in this chapter. To be noted, a static CGE model usually consists of the production module, the income and expenditure module of the final demand accounts, and the international trade module. Under the macro closure constraints, we could then calculate the equilibrium meeting the constraints. To formulate a dynamic CGE model, it needs to define the dynamic mechanism based on the static model. These blocks will be explained in this chapter one by one.



Source: Böhringer et al. (2003)

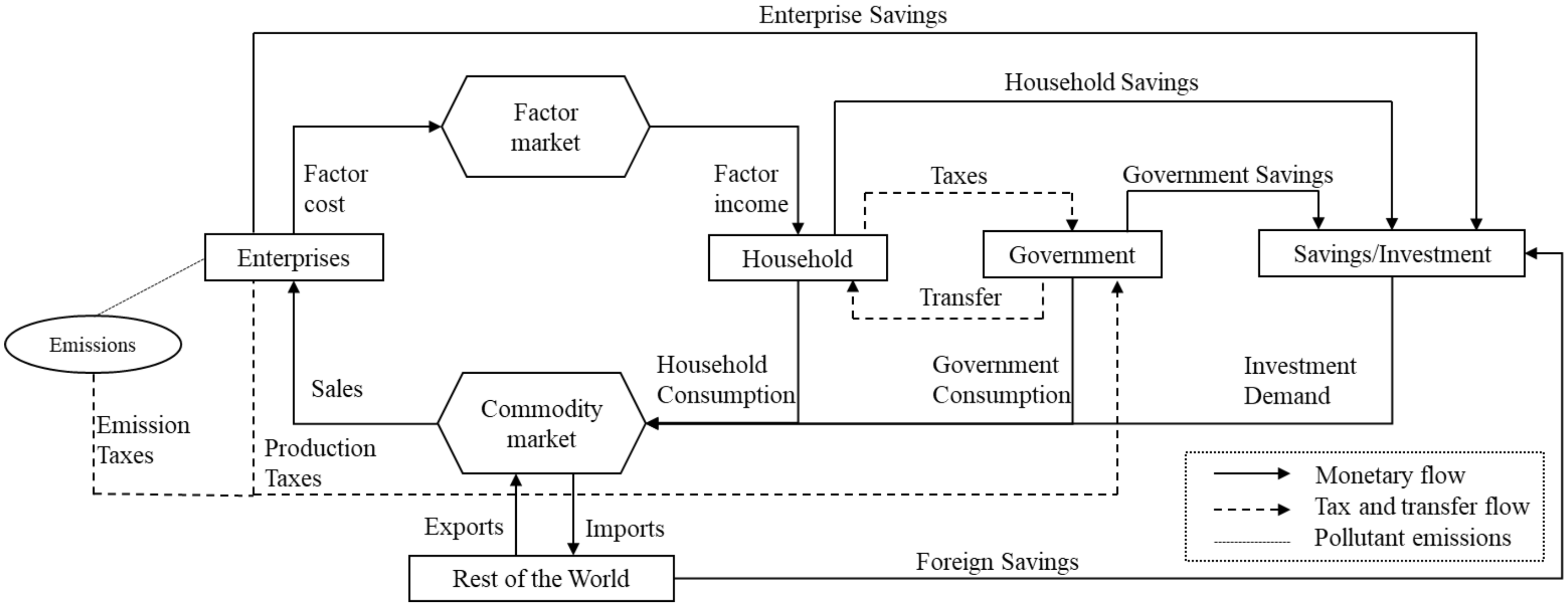
Figure 3-1: Basic framework in CGE analysis

Moreover, the CGE model in this thesis is formulated in the GAMS software of the MS Windows 24.3.3 version. It is solved as a 1,194-variable mixed complementarity problem (MCP) by the PATH/MCP (Ferris and Munson, 2000) and MPSGE solvers (Rutherford, 1999).

3.1 The overarching framework of CGE

Figure 3-2 shows the overarching framework for a simplified CGE model. The essential components include: final demand accounts, factor market, and commodity market, and production activities and inter-account transfers to connect the final demand account and markets, and the model will calculate the equilibrium where all the markets clear and all the accounts are balanced in terms of income and expense.

In a CGE model, the household account owns all the labor endowment and part of the capital endowment. Providing the labor endowment and capital endowment in the factor market, the households earn factor income which is paid for governmental tax, consumptions, and savings and investments. The enterprise account owns the other part of the capital endowment and put it in the factor market for earning capital returns. The enterprise account also organizes the production activities and produce end products by inputs from the factor market and intermediate inputs from the commodity market. The enterprise account's expenditures consist of the income tax, transfer payments to the households and savings in the investment and savings account. As for the government, its income comes from all kind of taxes and its expenditures include the purchase of commodities, transfer payments, and savings. There is also an account representing the rest of the world (ROW), to describe the import and export activities. For the sake of simplification, the ROW account is balanced by the foreign savings in the investment and savings account.



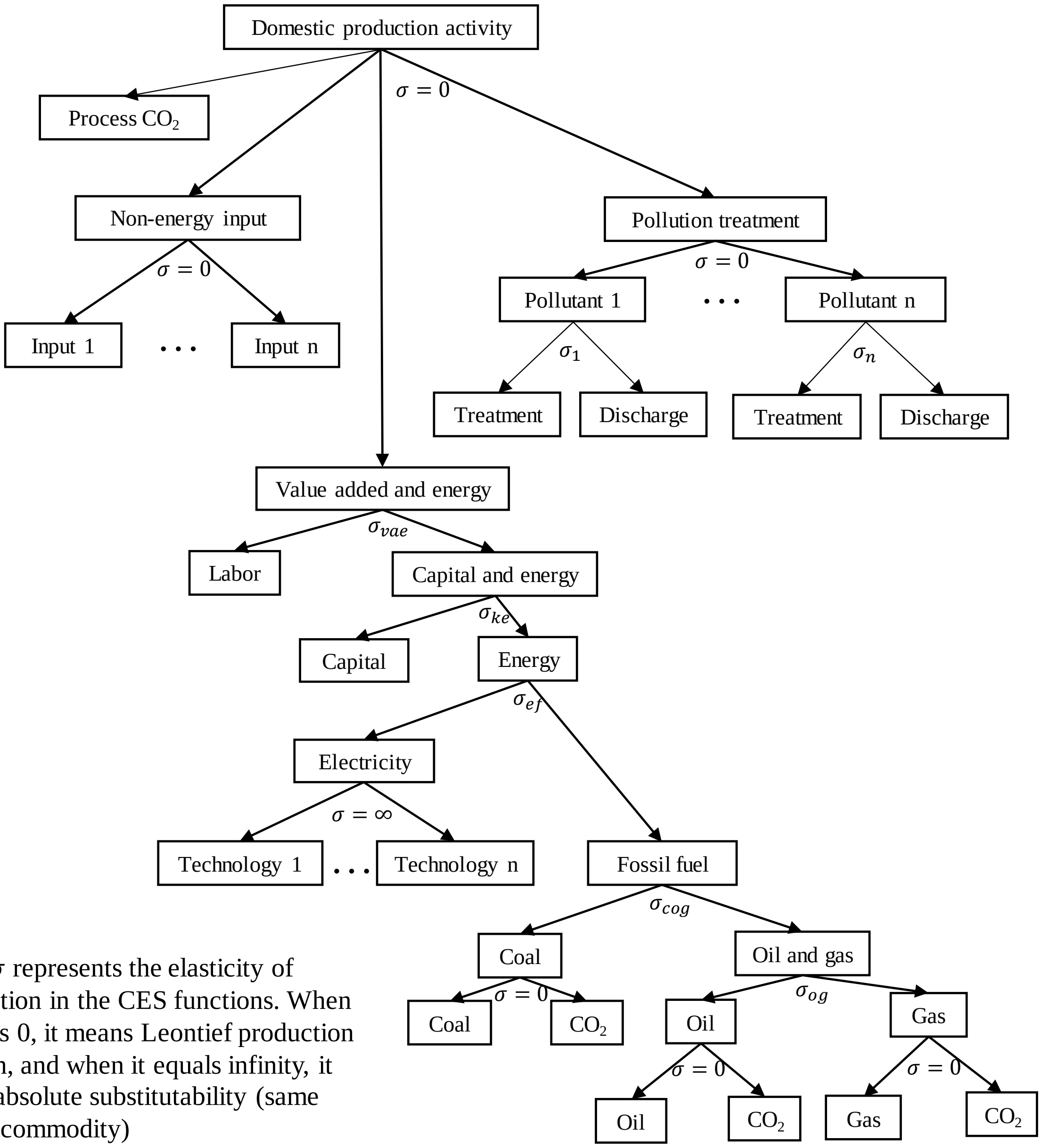
Source: Revised based on Lofgren et al. (2004)

Figure 3-2: A simplified CGE framework

3.2 Production activities

Figure 3-3 shows the multi-layer nested structure of the production module, which follows the constant elasticity of substitution (CES) production functions. In the top layer, the total sectoral output is determined by the non-energy input, the pollution treatment input, and the composite input of value-added and energy with the elasticity of substitution of 0. The process emission amount of CO_2 is also calculated in the top layer, and the emission factor is calculated by dividing the emission amount by the total output. The non-energy input is composited by the intermediate input from all the non-energy sectors with the elasticity of substitution of 0. The pollution treatment input is composited with the elasticity of substitution of 0 by three types of treatment: water pollutants, air pollutants, and solid pollutants.

The composite of value-added and energy is aggregated by labor and the composite of capital and energy, which is aggregated by the input of capital and energy, and the elasticities of substitution are σ_{vae} and σ_{ke} respectively. The energy input is disaggregated into electricity inputs and fossil fuels with the elasticity of substitution of σ_{ef}. As for the fossil fuel goods, there are still two layers with the elasticities of substitution of σ_{cog} and σ_{og}. The elasticities of substitution used in this paper are adopted from Xiao et al. (2015) and Dai et al. (2011).



Note: σ represents the elasticity of substitution in the CES functions. When σ equals 0, it means Leontief production function, and when it equals infinity, it means absolute substitutability (same type of commodity)

Figure 3-3: Production structure in CGE

In mathematical formulation, the producer of sector j maximizes its profit by choosing an appropriate output level QX_j in the following maximization problem. The intermediate inputs are determined by the production functions according to the output level.

$$\max_{\{QX_j\}} \ \pi_j^z = PX_j \cdot QX_j - \sum_i P_i \cdot X_{i,j} - PVAE_j \cdot QVAE_j - \sum_w PW_{w,j} \cdot QW_{w,j} - pco2 \cdot QPC_j - PX_j \cdot QX_j \cdot tprod_j$$

where the endogenous variables include:

- π_j^z is the profit of sector j;
- PX_j is the output price of commodity j;
- QX_j is the output quantity in sector j;
- P_i is the price of commodity i in the domestic market; the sales price is a function of the output price PX_j, import price, and export price which will be explained in Section 3.4;
- $X_{i,j}$ is the intermediate input of non-energy commodity i in the production processes of sector j;
- $PVAE_j$ is the price of the composite of value-added and energy in sector j;
- $QVAE_j$ is the input of the composite of value-added and energy in sector j;
- $PW_{w.j}$ is the price of waste treatment of type w in sector j;
- $QW_{w,j}$ is the input of waste treatment of type w in sector j;
- QPC_j is the CO_2 emission from the production processes of sector j;

and the exogenous parameters include:

- $pco2$ is the unit price of carbon dioxide and it's given according to the policy scenario settings;
- $tprod_j$ is the production tax ratio, so the production tax in sector j equals to $PTax_j = PX_j \cdot QX_j \cdot tprod_j$.

Since the model assumes the Leontief production function in the first layer, $X_{i,j}$, $QVAE_j$, $QW_{w,j}$, and QPC_j should all be proportional to Q_j as follows.

- $X_{i,j} = QX_j \cdot a\_x_{i,j}$
- $QVAE_j = QX_j \cdot a\_qvae_j$
- $QW_{w,j} = QX_j \cdot a\_qw_{w,j}$
- $QPC_j = QX_j \cdot a\_qpc_j$

where

$a\_x_{i,j}$, a_qvae_j and $a\_qw_{w,j}$ are the exogenous input coefficients and are calibrated according to the base year data; a_qpc_j is the exogenous emission factor and is also calibrated using the base year data.

The treatment input is composited by the waste treatment cost and the pollutant emission charge fee with the elasticity of substitution of σ_w. With more treatment input, the pollutant emission levels will be reduced, and the due discharged fee will be lower. As for determining the parameter σ_w, since there are few studies in related areas, this thesis refers to Xiao et al. (2015) and finds out most elasticity parameters are between 0.2 and 0.7. This thesis chooses 0.2 from this reasonable range and conducts a sensitivity analysis on this parameter in Section 6.4.2 to discuss how this parameter would affect the simulation results. The simulation results show that the value of the elasticity parameters will affect the absolute results but will change the relative changes much. The calibration of the elasticity parameters is also an important job for future studies.

Besides, disaggregating the pollution treatment sectors is an important feature of this thesis's model. In most CGE models, there is not separated pollution treatment sectors and pollution discharges are linked directly to sectoral outputs. In Section 6.2.5, we compare with CGE models not disaggregating pollution treatment sectors. In this thesis, when pollution treatment sectors introduced, they can be formulated as follows.

$$\max_{\{QT_{w,j},QDIS_{w,j}\}} \pi_{w,j}^{env} = PW_{w,j} \cdot QW_{w,j} - (PT_w \cdot QT_{w,j} + PDIS_w \cdot QDIS_{w,j})$$

$\mathrm{s.t.}$

$$QW_{w,j} = \alpha_{w,j}^{env} \cdot \left(\delta_{w,j}^{env} \cdot QT_{w,j}^{-\rho_{j,w}^{env}} + \left(1 - \delta_{w,j}^{env}\right) \cdot QDIS_{w,j}^{-\rho_{j,w}^{env}}\right)^{-\frac{1}{\rho_{w,j}^{env}}}$$

where the endogenous variables include:

- $\pi_{w,j}^{env}$ is the profit of subsector of pollution treatment for pollutant w in sector j;
- $PW_{w,j}$ is the output price of subsector of pollution treatment for pollutant w in sector j;
- $QW_{w,j}$ is the output quantity of subsector of pollution treatment for pollutant w in sector j;
- PT_w is the treatment price for pollutant w, and the treatment cost for the same types of pollutant is assumed the same in different sectors; To be noted, commodity PT_w is the output of pollution treatment sectors, whose production structure is generally the same as other sectors as shown in Figure 3-3. Moreover,

the unit cost of pollution management is assumed to be the same in different sectors. This might be different from the real case and could be studied in detail in future studies.

- $QT_{w,j}$ is the treatment input for pollutant w in sector j;
- $PDIS_w$ is the discharge price for pollutant w;
- $QDIS_{w,j}$ is the discharge demand for pollutant w in sector j;

and the exogenous parameters include:

- $\alpha_{w,j}^{env}$ and $\delta_{w,j}^{env}$ are the parameters in CES functions;
- $\rho_{w,j}^{env}$ is the substitution parameter, and the elasticity of substitution is $\sigma_{w,j}^{env} = \frac{1}{1+\rho_{w,j}^{env}}$.

Solving the optimization problem, we could get the following results.

$$QT_{w,j} = \frac{1}{\alpha_{w,j}^{env}} \cdot \left(\delta_{w,j}^{env} + \left(1-\delta_{w,j}^{env}\right) \cdot \left(\frac{\delta_{w,j}^{env} \cdot PDIS_w}{\left(1-\delta_{w,j}^{env}\right) \cdot PT_w}\right)^{1-\sigma_{w,j}^{env}}\right)^{\frac{\sigma_{w,j}^{env}}{1-\sigma_{w,j}^{env}}} \cdot \mathrm{QW}_{\mathrm{w,j}}$$

$$QDIS_{w,j} = \frac{1}{\alpha_{w,j}^{env}} \cdot \left(\delta_{w,j}^{env} \cdot \left(\frac{\left(1-\delta_{w,j}^{env}\right) \cdot PT_w}{\delta_{w,j}^{env} \cdot PDIS_w}\right)^{1-\sigma_{w,j}^{env}} + \left(1-\delta_{w,j}^{env}\right)\right)^{\frac{\sigma_{w,j}^{env}}{1-\sigma_{w,j}^{env}}} \cdot \mathrm{QW}_{\mathrm{w,j}}$$

The composite of value-added input and energy is aggregated by the labor input and the composite of capital and energy with the elasticity of substitution of σ_{vae}.

$$\max_{\{QL_j, QKE_j\}} \pi_j^{vae} = PVAE_j \cdot QVAE_j - (PL \cdot QL_j + PKE_j \cdot QKE_j)$$

s.t.

$$QVAE_j = \alpha_j^{vae} \cdot \left(\delta_j^{vae} \cdot QL_j^{-\rho_j^{vae}} + \left(1-\delta_j^{vae}\right) \cdot QKE_j^{-\rho_j^{vae}}\right)^{-\frac{1}{\rho_j^{vae}}}$$

where the endogenous variables include:

- π_j^{vae} is the profit of the subsector for value added and energy in sector j;
- $\mathrm{PVAE}_{\mathrm{j}}$ is the price of the composite of value-added and energy in sector j;

- $QVAE_j$ is the input of the composite of value-added and energy in sector j;
- PL is the labor price;
- QL_j is the labor input in sector j;
- PKE_j is the aggregated price of capital and energy inputs in sector j;
- QKE_j is the aggregated input of capital and energy in sector j;

and the exogenous parameters include:

- α_j^{vae} and δ_j^{vae} are the parameters in CES functions;
- ρ_j^{vae} is the substitution parameter, and the elasticity of substitution is $\sigma_j^{vae} = \frac{1}{1+\rho_j^{vae}}$;

Solving the optimization problem, we could get the following results.

$$QL_j = \frac{1}{\alpha_j^{vae}} \cdot \left(\delta_j^{vae} + \left(1 - \delta_j^{vae}\right) \cdot \left(\frac{\delta_j^{vae} \cdot PKE_j}{\left(1 - \delta_j^{vae}\right) \cdot PL} \right)^{1-\sigma_j^{vae}} \right)^{\frac{\sigma_j^{vae}}{1-\sigma_j^{vae}}} \cdot QVAE_j$$

$$QKE_j = \frac{1}{\alpha_j^{vae}} \cdot \left(\delta_j^{vae} \cdot \left(\frac{\left(1 - \delta_j^{vae}\right) \cdot PL}{\delta_j^{vae} \cdot PKE_j} \right)^{1-\sigma_j^{vae}} + \left(1 - \delta_j^{vae}\right) \right)^{\frac{\sigma_j^{vae}}{1-\sigma_j^{vae}}} \cdot QVAE_j$$

Then, the composite of capital and energy is aggregated by the capital input and the composite of energy with the elasticity of substitution of σ_{ke}.

$$\max_{\{QK_j, QENE_j\}} \pi_j^{ke} = PKE_j \cdot QKE_j - (PK_j \cdot QK_j + PENE_j \cdot QENE_j)$$

s.t.

$$QKE_j = \alpha_j^{ke} \cdot \left(\delta_j^{ke} \cdot QK_j^{-\rho_j^{ke}} + \left(1 - \delta_j^{ke}\right) \cdot QENE_j^{-\rho_j^{ke}} \right)^{-\frac{1}{\rho_j^{ke}}}$$

where the endogenous variables include:

- π_j^{ke} is the profit of the subsector for capital and energy in sector j;
- PKE_j is the aggregated price of capital and energy inputs in sector j;

- QKE_j is the aggregated input of capital and energy in sector j;
- PK_j is the capital price in sector j;
- QK_j is the capital input in sector j;
- $PENE_j$ is the aggregated price of energy inputs in sector j;
- $QENE_j$ is the aggregated input of energy in sector j;

and the exogenous parameters include:

- α_j^{ke} and δ_j^{ke} are the parameters in CES functions;
- ρ_j^{ke} is the substitution parameter, and the elasticity of substitution is $\sigma_j^{ke} = \frac{1}{1+\rho_j^{ke}}$;

Solving the optimization problem, we could get the following results.

$$QK_j = \frac{1}{\alpha_j^{ke}} \cdot \left(\delta_j^{ke} + \left(1 - \delta_j^{ke}\right) \cdot \left(\frac{\delta_j^{ke} \cdot PENE_j}{\left(1 - \delta_j^{ke}\right) \cdot PK_j} \right)^{1-\sigma_j^{ke}} \right)^{\frac{\sigma_j^{ke}}{1-\sigma_j^{ke}}} \cdot QKE_j$$

$$QENE_j = \frac{1}{\alpha_j^{ke}} \cdot \left(\delta_j^{ke} \cdot \left(\frac{\left(1 - \delta_j^{ke}\right) \cdot PK_j}{\delta_j^{ke} \cdot PENE_j} \right)^{1-\sigma_j^{ke}} + \left(1 - \delta_j^{ke}\right) \right)^{\frac{\sigma_j^{ke}}{1-\sigma_j^{ke}}} \cdot QKE_j$$

In the first layer of energy inputs, the composite of energy is aggregated by the electricity input and the composite of fossil fuels with the elasticity of substitution of σ_{ef}.

$$\max_{\{QELE_j, QFF_j\}} \pi_j^{ef} = PENE_j \cdot QENE_j - \left(PELE \cdot QELE_j + PFF_j \cdot QFF_j\right)$$

s.t.

$$QENE_j = \alpha_j^{ef} \cdot \left(\delta_j^{ef} \cdot QELE_j^{-\rho_j^{ef}} + \left(1 - \delta_j^{ef}\right) \cdot QFF_j^{-\rho_j^{ef}} \right)^{-\frac{1}{\rho_j^{ef}}}$$

where the endogenous variables include:

- π_j^{ef} is the profit of the subsector for energy inputs in sector j;
- $PENE_j$ is the aggregated price of energy inputs in sector j;
- $QENE_j$ is the aggregated input of energy in sector j;

- $PELE$ is the electricity price;
- $QELE_j$ is the electricity input in sector j;
- PFF_j is the aggregated price of fossil fuel inputs in sector j;
- QFF_j is the aggregated input of fossil fuel in sector j;

and the exogenous parameters include:

- α_j^{ef} and δ_j^{ef} are the parameters in CES functions;
- ρ_j^{ef} is the substitution parameter, and the elasticity of substitution is $\sigma_j^{ef} = \frac{1}{1+\rho_j^{ef}}$;

Solving the optimization problem, we could get the following results.

$$QELE_j = \frac{1}{\alpha_j^{ef}} \cdot \left(\delta_j^{ef} + \left(1 - \delta_j^{ef}\right) \cdot \left(\frac{\delta_j^{ef} \cdot PFF_j}{\left(1 - \delta_j^{ef}\right) \cdot PELE} \right)^{1- \sigma_j^{ef}} \right)^{\frac{\sigma_j^{ef}}{1- \sigma_j^{ke}}} \cdot QENE_j$$

$$QFF_j = \frac{1}{\alpha_j^{ef}} \cdot \left(\delta_j^{ef} \cdot \left(\frac{\left(1 - \delta_j^{ef}\right) \cdot PELE}{\delta_j^{ef} \cdot PFF_j} \right)^{1- \sigma_j^{ef}} + \left(1 - \delta_j^{ef}\right) \right)^{\frac{\sigma_j^{ef}}{1- \sigma_j^{ef}}} \cdot QENE_j$$

For electricity inputs, the electricity sector is further disaggregated into six different technologies, including hydroelectricity, coal power, gas electricity, oil electricity, nuclear power, and renewable energies. As different technologies produce a homogeneous product of electricity, the elasticity of substitution is positive infinity.

For fossil fuel inputs, the composite of fossil fuels is first aggregated by coal inputs and the composite of oil and gas with the elasticity of substitution of σ_{cog}.

$$\max_{\{QCOAL_{j,}QOG_j\}} \pi_j^{cog} = PFF_j \cdot QFF_j - (PCOAL \cdot QCOAL_j + POG_j \cdot QOG_j)$$

s. t.

$$QFF_j = \alpha_j^{cog} \cdot \left(\delta_j^{cog} \cdot QCOAL_j^{-\rho_j^{cog}} + \left(1 - \delta_j^{cog}\right) \cdot QOG_j^{-\rho_j^{cog}} \right)^{-\frac{1}{\rho_j^{cog}}}$$

where the endogenous variables include:

- π_j^{ef} is the profit of the subsector for fossil fuel inputs in sector j;
- PFF_j is the aggregated price of fossil fuel inputs in sector j;
- QFF_j is the aggregated input of fossil fuel in sector j;
- $PCOAL$ is the coal price;
- $QCOAL_j$ is the coal input in sector j;
- POG_j is the aggregated price of oil and gas inputs in sector j;
- QOG_j is the aggregated input of oil and gas in sector j;

and the exogenous parameters include:

- α_j^{cog} and δ_j^{cog} are the parameters in CES functions;
- ρ_j^{cog} is the substitution parameter, and the elasticity of substitution is $\sigma_j^{cog} = \frac{1}{1+\rho_j^{cog}}$;

Solving the optimization problem, we could get the following results.

$$QCOAL_j = \frac{1}{\alpha_j^{cog}} \cdot \left(\delta_j^{cog} + \left(1 - \delta_j^{cog}\right) \cdot \left(\frac{\delta_j^{cog} \cdot POG_j}{\left(1 - \delta_j^{cog}\right) \cdot PCOAL} \right)^{1-\sigma_j^{cog}} \right)^{\frac{\sigma_j^{cog}}{1-\sigma_j^{cog}}} \cdot QFF_j$$

$$QOG_j = \frac{1}{\alpha_j^{cog}} \cdot \left(\delta_j^{cog} \cdot \left(\frac{\left(1 - \delta_j^{cog}\right) \cdot PCOAL}{\delta_j^{cog} \cdot POG_j} \right)^{1-\sigma_j^{cog}} + \left(1 - \delta_j^{cog}\right) \right)^{\frac{\sigma_j^{cog}}{1-\sigma_j^{cog}}} \cdot QFF_j$$

The composite of oil and gas is then aggregated by oil inputs and gas inputs with the elasticity of substitution of σ_{og}.

$$\max_{\{QOIL_j, QGAS_j\}} \pi_j^{og} = POG_j \cdot QOG_j - \left(POIL \cdot QOIL_j + PGAS_j \cdot QGAS_j\right)$$

s.t.

$$QOG_j = \alpha_j^{og} \cdot \left(\delta_j^{og} \cdot QOIL_j^{-\rho_j^{og}} + \left(1 - \delta_j^{og}\right) \cdot QGAS_j^{-\rho_j^{og}} \right)^{-\frac{1}{\rho_j^{og}}}$$

where the endogenous variables include:

- π_j^{og} is the profit of the subsector for oil and gas inputs in sector j;
- POG_j is the aggregated price of oil and gas inputs in sector j;
- QOG_j is the aggregated input of oil and gas in sector j;
- $POIL$ is the oil price;
- $QOIL_j$ is the oil input in sector j;
- $PGAS_j$ is the gas price;
- $QGAS_j$ is the gas input in sector j;

and the exogenous parameters include:

- α_j^{og} and δ_j^{og} are the parameters in CES functions;
- ρ_j^{og} is the substitution parameter, and the elasticity of substitution is $\sigma_j^{og} = \frac{1}{1+\rho_j^{og}}$;

Solving the optimization problem, we could get the following results.

$$QOIL_j = \frac{1}{\alpha_j^{og}} \cdot \left(\delta_j^{og} + \left(1 - \delta_j^{og}\right) \cdot \left(\frac{\delta_j^{og} \cdot PGAS_j}{\left(1 - \delta_j^{og}\right) \cdot POIL} \right)^{1-\sigma_j^{og}} \right)^{\frac{\sigma_j^{og}}{1-\sigma_j^{og}}} \cdot QOG_j$$

$$QGAS_j = \frac{1}{\alpha_j^{og}} \cdot \left(\delta_j^{og} \cdot \left(\frac{\left(1 - \delta_j^{og}\right) \cdot PCOAL}{\delta_j^{og} \cdot POIL} \right)^{1-\sigma_j^{og}} + \left(1 - \delta_j^{og}\right) \right)^{\frac{\sigma_j^{og}}{1-\sigma_j^{og}}} \cdot QOG_j$$

Lastly, for fossil fuel inputs, there is an additional layer taking CO_2 into consideration. Take the coal input for an example.

$$PCCoal \cdot QCCoal_j = PCoal \cdot QCoal_j + pco2 \cdot QCoal_j \cdot ef\_coal$$

where the endogenous variables include:

- $PCCoal$ is the price of the composite of coal and CO_2;
- $QCCoal_j$ is the composite of coal input and CO_2 input in sector j;
- $PCoal$ is the price of coal;

- $QCoal_j$ is coal input in sector j;

and the exogenous parameters include:

- $pco2$ is the unit price of carbon dioxide;
- ef_coal is the emission factor of coal;

3.3 Final demand accounts

There are mainly four types of final demand accounts: households, enterprises, governments, foreign accounts. For the final demand accounts, their activities consist of consumptions and savings, and savings are changed to investment goods and counted in the investment-saving account. This section explains the consumption activities of the domestic final demand accounts and foreign activities will be explained in Section 3.4.

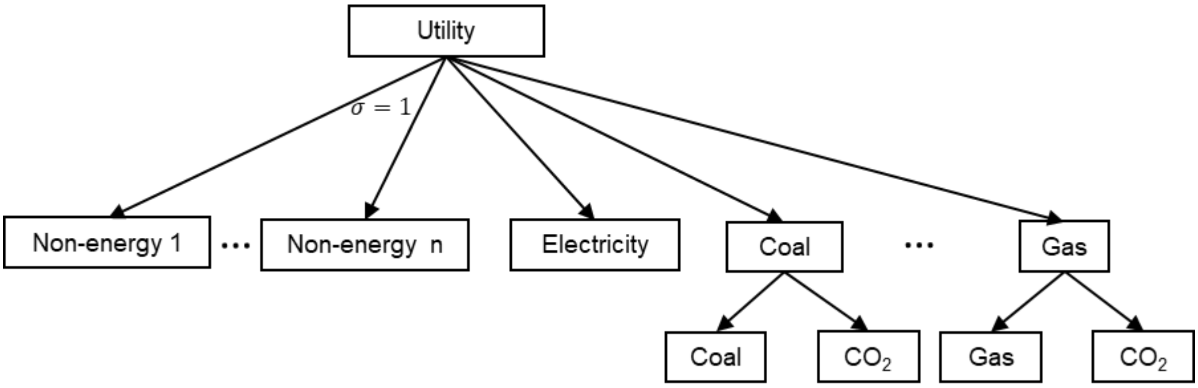


Figure 3-4: Household utility structure in CGE

For the households, they receive factor income of labor and capital and after paying tax, savings and investments, and transfers from the government, they could use the rest money to maximize their utility in the consumption activities. Figure 3-4 shows the households' utility structure in the CGE model, which is aggregated by all the non-energy products, electricity, and non-electricity energy products, with the Cobb-Douglas elasticities of substitution of 1. As for consuming fossil fuel products, the carbon emission is calculated based on the emission factor per product. This consumption structure is similar to that in Dai et al. (2011).

In mathematical formulation, the households' utility function can be expressed as follows. Here n refers to the number of commodity types: 28.

$$\max_{\{X_1^h,\dots,X_n^h\}} U^h = \prod_i \left(X_i^h\right)^{\alpha_i}$$

s. t.

$$HE = \sum_i X_i^h \cdot P_i = PL \cdot hendl + PK \cdot hendk + tsf_{\mathrm{g}} + tsf_{ent} - hsav - HTax$$

where the endogenous variables include:

- U^h stands for the Cobb-Douglas utility function for households;
- X_i^h is the household consumption of commodity i;
- P_i is the price of commodity i in the domestic market;
- HE is the total consumption expenditure of households;
- PL is the labor price;
- PK is the aggregated capital price;
- $HTax$ is households' income tax to the government based on fixed income tax ratio.

and the exogenous parameters include:

- α_i is the parameter in the Cobb-Douglas function and $\sum_i \alpha_i = 1$;
- tsf_g is the transfer from the government account to the household account;
- tsf_{ent} is the transfer from the enterprise account to the household account;
- $hendl$ is household's endowment of labor, set according to the scenario assumptions.
- $hendk$ is household's endowment of capital, set according to the scenario assumptions.
- $hsav$ is households' savings;

Since the objective function is in Cobb-Douglas form function, we will get the following results after solving the optimization problem.

$$X_i^h \cdot P_i = \alpha_i \cdot HE$$

The exogenous share parameters α_i are calibrated on the base year data, and we assume that the consumption mix keeps the same structure during the whole simulation period for simplicity. Therefore,

$$\alpha_i = \frac{X0_i^h \cdot P0_i}{HE0}$$

where

- $X0_i^h \cdot P0_i$ is the value of household consumption of commodity i in the base year 2012, which could be got from the IO table;
- $HE0$ is the total consumption expenditure of households in the base year 2012, which equals to $\sum X0_i^h P0_i$.

The share parameters α_i are listed in Appendix D. It shows that households' main consumptions are service products (45.7%), food and tobacco products (18.9%), other agriculture products (10.4%), other industrial products (7.5%), and textiles (7%).

For enterprises accounts, their spending structure is treated similarly to households in the thesis. Deducting the tax, transfers, savings, and investments from their income, they also maximize their utility within their budget following the utility function.

For the government accounts, its income is mainly from the production tax and the income taxes from households and enterprises. In the expenditure side, besides savings and transfers, its main consumptions are the service products. Following the GTAP model (Hertel, 1998), we use the Cobb-Douglas function to determine how to allocate governmental spending among different commodities. The government's demand function can be expressed as follows. Here n refers to the number of commodity types: 28.

$$\max_{\{X_1^g,\dots,X_n^g\}} D^g = \prod_i \left(X_i^g\right)^{\beta_i}$$

$\mathrm{s.t.}$

$$GE = \sum_i X_i^g \cdot P_i$$

$$= \sum_{\mathrm{j}} PTax_j + HTax + ENTTax + \sum_{\mathrm{w,j}} PDIS_w \cdot QDIS_{w,j} + pco2 \cdot QTCO2 - tsf_{\mathrm{g}} - gsav$$

where the endogenous variables include:

- D^g stands for the Cobb-Douglas demand function for the government;
- X_i^g is the governmental consumption of commodity i;
- GE is the total consumption expenditure of the government;
- P_i is the price of commodity i in the domestic market;
- $PTax_j$ is production tax in sector j;
- $HTax$ is households' income tax to the government;
- $ENTTax$ is enterprises' income tax to the government;
- $PDIS_w$ is the discharge price for pollutant w, and an exogenous variable set by the government;
- $QDIS_{w,j}$ is the discharge demand for pollutant w in sector j;
- $QTCO2$ is the total carbon emissions from fossil fuel combustion and industrial processes;

and the exogenous parameters include:

- β_i is the parameter in the Cobb-Douglas function and $\sum_i \beta_i = 1$;
- $pco2$ is the unit price of carbon dioxide;
- tsf_g is the transfer from the government account to the household account;
- $gsav$ is governmental savings;

Like the households' accounts, the share parameters of governmental consumption β_i are calibrated according to the base year data as follows.

$$\beta_i = \frac{X0_i^g \cdot P0_i}{GE0}$$

where

- $X0_i^g \cdot P0_i$ is the value of governmental consumption of commodity i in the base year 2012, which could be got from the IO table;

- $GE0$ is the total consumption expenditure of the government in the base year 2012, which equals to $\sum X0_i^g P0_i$.

The share parameters β_i are listed in Appendix D. Different from the households account, governmental consumptions only include transport (2.65%) and service products (97.35%) in the IO accounting system.

3.4 International trade

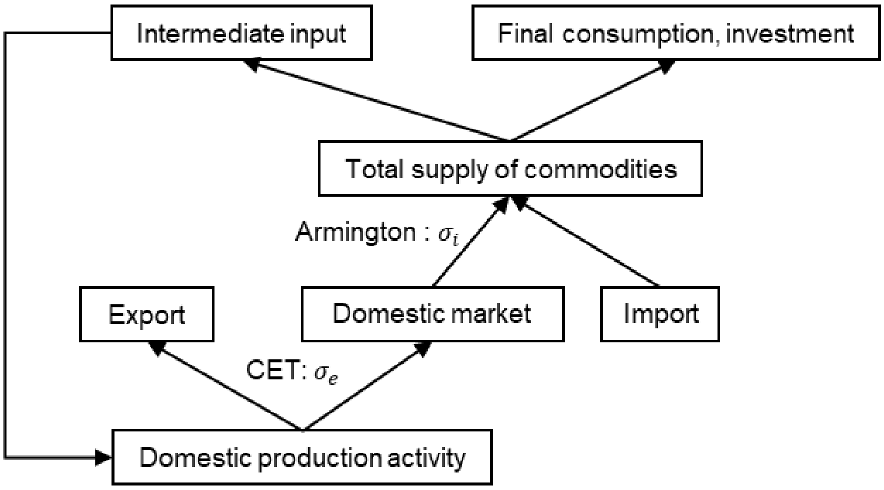


Figure 3-5: International trade structure in CGE

This structure of the international trade module is presented in Figure 3-5. It is assumed that the domestic production outputs are the aggregates following the Constant Elasticity of Transformation (CET) function with the elasticity of transformation of σ_e, while the total supply of commodities is the aggregates following the Armington condition with the elasticity of substitution of σ_i. The elasticities of transformation and substitution are adopted from Xiao et al. (2015).

For imports, the mathematical formulations are as follows.

$$\max_{\{QM_i,QD_i\}} \pi_i^{imp} = P_i \cdot Q_i^d - [(1 + trf_i) \cdot P_i^{imp} \cdot QM_i + P_i^d \cdot QD_i]$$

s.t.

$$Q_i^d = \alpha_i^{imp} \cdot \left(\delta_i^{imp} \cdot QM_i^{-\rho_i^{imp}} + \left(1 - \delta_i^{imp}\right) \cdot QD_i^{-\rho_i^{imp}}\right)^{-\frac{1}{\rho_i^{imp}}}$$

where the endogenous variables include:

- π_i^{imp} is the profit in the import activities for commodity i;
- P_i is the price of commodity i in the domestic market;
- Q_i^d is the supply of commodity i in the domestic market;
- P_i^{imp} is the price of imported commodity i;
- QM_i is the imported quantity of commodity i;
- P_i^d is the price of commodity i which is both produced and sold in the domestic market;
- QD_i is the imported quantity of commodity i which is both produced and sold in the domestic market;

and the exogenous parameters include:

- trf_i is the tariff rate of commodity i;
- α_i^{imp} and δ_i^{imp} are the parameters in the Armington function;
- ρ_i^{imp} is the parameter in the Armington function, and the elasticity of substitution is $\sigma_i^{imp} = \frac{1}{1+\rho_i^{imp}}$;

Solving the optimization problem, we could get the following results.

$$QM_i = \frac{1}{\alpha_i^{imp}} \cdot \left(\delta_i^{imp} + \left(1-\delta_i^{imp}\right) \cdot \left(\frac{\delta_i^{imp} \cdot P_i^d}{\left(1-\delta_i^{imp}\right)(1+trf_i)P_i^{imp}} \right)^{1-\sigma_i^{imp}} \right)^{\frac{\sigma_i^{imp}}{1-\sigma_i^{imp}}} \cdot Q_i^d$$

$$QD_i = \frac{1}{\alpha_i^{imp}} \cdot \left(\delta_i^{imp} \cdot \left(\frac{\left(1-\delta_i^{imp}\right)(1+trf_i)P_i^{imp}}{\delta_i^{imp} \cdot P_i^d} \right)^{1-\sigma_i^{imp}} + \left(1-\delta_i^{imp}\right) \right)^{\frac{\sigma_i^{imp}}{1-\sigma_i^{imp}}} \cdot Q_i^d$$

For exports, the mathematical formulations are as follows.

$$\max_{\{QE_i, QD_i\}} \pi_i^{exp} = \left[P_i^{exp} \cdot QE_i + P_i^d \cdot QD_i\right] - PX_i \cdot QX_i^d$$

$\mathrm{s.t.}$

$$QX_i^d = \alpha_i^{exp} \cdot \left(\delta_i^{exp} \cdot QE_i^{\rho_i^{exp}} + \left(1 - \delta_i^{exp}\right) \cdot QD_i^{\rho_i^{exp}}\right)^{\frac{1}{\rho_i^{exp}}}$$

where the endogenous variables include:

- π_i^{exp} is the profit in the export activities for commodity i;
- P_i^{exp} is the price of exported commodity i;
- QE_i is the exported quantity of commodity i;
- P_i^d is the price of commodity i which is both produced and sold in the domestic market;
- QD_i is the imported quantity of commodity i which is both produced and sold in the domestic market;
- PX_j is the output price of commodity j;
- QX_j is the output in sector j;

and the exogenous parameters include:

- α_i^{exp} and δ_i^{exp} are the parameters in the CET function;
- ρ_i^{exp} is the parameter in the CET function, and the elasticity of transformation is $\sigma_i^{exp} = \frac{1}{\rho_i^{exp} - 1}$;

Solving the optimization problem, we could get the following results.

$$QE_i = \frac{1}{\alpha_i^{exp}} \cdot \left(\delta_i^{exp} + \left(1 - \delta_i^{exp}\right) \cdot \left(\frac{\delta_i^{exp} \cdot P_i^d}{\left(1 - \delta_i^{exp}\right) \cdot P_i^{exp}}\right)^{\frac{-1}{\sigma_i^{exp}+1}}\right)^{\frac{\sigma_i^{exp}+1}{\sigma_i^{exp}}} \cdot QX_i^d$$

$$QD_i = \frac{1}{\alpha_i^{exp}} \cdot \left(\delta_i^{exp} \cdot \left(\frac{\left(1 - \delta_i^{exp}\right) \cdot P_i^{exp}}{\delta_i^{exp} \cdot P_i^d}\right)^{\frac{-1}{\sigma_i^{exp}+1}} + \left(1 - \delta_i^{exp}\right)\right)^{\frac{\sigma_i^{exp}+1}{\sigma_i^{exp}}} \cdot QX_i^d$$

The mathematical formulations of the international prices and exchange rate are shown below. The prices of P_i^{imp} and P_i^{exp} are labeled in domestic currency, and they could be also priced in foreign currency. Like other China CGE models (Dai et al., 2011; Guo et al., 2014; Li and Jia, 2016; Wang et al., 2009), the small open economy assumption is made in this thesis, which means the domestic market is not big enough to influence international prices P_i^{wm} and P_i^{we}. This is indeed a very strong assumption, especially because China's has already become the world's second largest economy. We make this assumption mainly for simplification, but also point out that this could be extended in future studies.

$$P_i^{imp} = EXR \cdot p_i^{wm}$$

$$P_i^{exp} = EXR \cdot p_i^{we}$$

where the endogenous variables include:

- EXR is the exchange rate;
- P_i^{imp} is the price of imported commodity i labeled in domestic currency;
- P_i^{exp} is the price of exported commodity i labeled in domestic currency;

and the exogenous parameters include:

- P_i^{wm} is the international price of the imported commodity;
- P_i^{we} is the international price of the exported commodity;

In a simplified model, when the international trade is balanced, the following equation is balanced as well.

$$\sum_{\mathrm{i}} p_i^{we} \cdot QE_i + fsav = \sum_{\mathrm{i}} p_i^{wm} \cdot QM_i$$

where the endogenous variables include:

- QE_i is the exported quantity of commodity i;
- QM_i is the imported quantity of commodity i;

and the exogenous parameters include:

- fsav is the foreign saving which is defined as an exogenous variable.
- p_i^{we} is the international price of the exported commodity;
- p_i^{wm} is the international price of the imported commodity;

3.5 Macro-closure conditions

In CGE models, there are several closure options to be chosen. The first is the so-called neoclassical closure where the factor prices and commodity prices are all endogenous variables, and all the factor supplies are utilized, and the employment market reaches full employment condition. The second option is the Keynesian closure where the factor prices are fixed exogenous variables, and there are redundant labor and capital endowment in the factor markets. The third option is followed by the theory of Nobel Laureate Dr. Arthur Lewis that the in developing countries, there might be lack of capital but surplus labor in the factor markets, so the capital price is endogenous variable, but the labor price is exogenous. This thesis chooses the first option where all the factor variables are endogenous variables considering the current economic situation is still very promising in China.

Based on the modules above, the CGE model solves the general equilibrium where all the factor markets and commodity markets clear and all the account's expenditure equals their income at the same time.

In the commodity market:

$$QX_i = \sum_j X_{i,j} + X_i^h + X_i^g + X_i^{inv} + QE_i - QM_i$$

where

- QX_j is the output in sector j;
- $X_{i,j}$ is the intermediate input of commodity i in sector j;
- X_i^h is the household consumption of commodity i;
- X_i^g is the government consumption of commodity i;
- X_i^{inv} is the investment and savings consumption of commodity i;
- QE_i is the exported quantity of commodity i;
- QM_i is the imported quantity of commodity i;

In the factor markets:

$$\sum_{j} QL_j = hendl$$

$$\sum_{j} QK_j = endk = hendk + eendk$$

where the endogenous variables include:

- QL_j is the labor input in sector j;
- QK_j is the capital input in sector j;

and the exogenous parameters include:

- $hendl$ is household's endowment of labor;
- $endk$ is the total endowment of capital;
- $hendk$ is household's endowment of capital;
- $eendk$ is enterprises' endowment of capital;

As for the emissions, they are either treated by the pollution treatment sectors or discharged and then taxed according to the environmental tax standards. Therefore, the pollution discharge cost should equal to the exogenous tax level.

$$PDIS(p) = entax(p)$$

where the endogenous variables include:

- $PDIS(p)$ is the discharge cost of pollutant p;

and the exogenous parameters include:

- $entax(p)$ is the environmental tax standard for emitting pollutant p;

3.6 Recursive dynamic mechanism

Like other CGE studies (Dai et al., 2011), we use a recursive dynamic mechanism to depict the future development. A static CGE model could only represent the economic situation of the base year, and the recursive dynamic is used to do the iterative calculations and simulate the next year's situation based on the previous year's data. There are two types of driving forces of economic growth for the recursive dynamic in this study: the technology efficiency improvement, and the increase of factor supplies of labor and capital. The improvement rate of technology efficiency and the growth rate of labor and capital are estimated according to the real situation and calibrated to meet the scenario settings.

The improvement rate of labor productivity, capital productivity, energy efficiency, material input, and the scenario settings are explained in detail in Chapter 5. As for the growth rate of labor endowment, this thesis assumes that the total labor endowment grows at the same speed of China's total population as follows.

$$HENDL_{t+1} = HENDL_t \cdot (1 + labg_t)$$

where

- $HENDL_t$ is the labor endowment in year t;
- $labg_t$ is the growth rate of national population in year t, which is given exogenously in the scenario assumption;

The capital endowment is also updated year by year as follows. A linear relationship is assumed between capital stock and capital endowment.

$$ENDK_t = KSTC_t \cdot kp$$

where

- $\mathrm{ENDK_t}$ is the capital endowment in year t;
- $KSTC_t$ is the capital stock in year t;
- kp is the exogenous conversion rate from capital stock to capital endowment;

Capital stock is renewed every year by adding the investment and subtracting the depreciated amount.

$$KSTC_{t+1} = KSTC_t(1 - dep) + Inv_t$$

where

- dep is the depreciation rate of capital goods and is set at 5.73 % (Li, 2016);
- Inv_t is the investment or fixed capital formation in year t;

To calculate the $KSTC_t$ in the base year, we assume that the growth rate of capital stock is an exogenous variable. In a simple case, we assume the growth rate of capital stock equals to the GDP growth rate.

$$KSTC_{t+1} = KSTC_t(1 + kstcg_t)$$

where

- $kstcg_t$ is the growth rate of capital stock;

Therefore, the capital stock is calculated as follows.

$$KSTC_t = \frac{Inv_t}{kstcg_t + dep}$$

With the formulations and parameters above, we could update the factor endowments year by year.

4. Data

CGE modeling is a very complicated and comprehensive system and requires both the input of economic data and physical data. Regarding the research purpose of this thesis, the datasets used in this thesis mainly include the national input-out (IO) table with disaggregated energy sectors and environmental management sectors, social accounting matrix (SAM), and CO_2 and pollutant emission data. The IO table presents the sectoral production and consumption structure. The SAM completes the IO table with the information of capital flow among the final demand accounts, like the income tax paid by the households and the transfer payments paid by the government. The sectoral emission data is used to calculate the emission factors for CO_2 and different kinds of pollutants.

4.1 Input-output table

Table 4-1: Sectors and commodities in the IO table

Sector code	Explanation	Commodity
COAL	Coal mining and processing	Coal products
COKE	Coking	Coke products
COIL	Crude petroleum extraction	Crude oil
NGAS	Natural gas extraction	Natural gas
PETR	Petroleum refining and nuclear fuel	Refined oil products
FGAS	Fuel Gas production and supply	Fuel gas
HELE	Hydroelectricity	Electricity
CELE	Coal-fired electricity	Electricity
OELE	Oil-fired electricity	Electricity
GELE	Gas-fired electricity	Electricity
NELE	Nuclear electricity	Electricity
RELE	Renewable energies	Electricity
AGRI	Agriculture	Agricultural products
MINE	Mining	Mining products

Table 4-1: Sectors and commodities in the IO table (continued)

Sector code	Explanation	Commodity
FOOD	Food and tobacco	Food and tobacco products
TEXI	Textile	Textile products
PAPE	Paper industry	Paper products
CHEM	Chemical industry	Chemical products
PLAS	Plastic industry	Plastic products
NMET	Non-metallic production	Non-metallic products
STEEL	Steel and iron production	Steel and iron products
NMTL	Nonferrous metal production	Nonferrous metal products
MPDT	Metal product industry	Metal-made products
OIND	Other industries	Other industrial products
SCRA	Scrap and waste recycling products	Recycled products
WATE	Water production and supply	Water
CONS	Construction	Construction
TRAN	Transport	Transport
SERV	Service	Service
ESER	Environmental public service	Environmental service
WMAN	Waste water management	Waste water management
GMAN	Waste gas management	Waste gas management
SMAN	Solid waste management	Solid waste management

For the research needs and the and simplicity of the model, this thesis aggregates and disaggregates the sectors in the original IO statistics into 33 sectors and 28 commodities, as shown in Table 4-1. Some major changes are as follows.

- Disaggregation of the oil extraction sector and natural gas extraction sector. In the original IO table, these two sectors are combined as one sector, mainly because their extraction activities are usually conducted simultaneously and are very similar in terms of intermediate inputs. However, the emission factor of CO_2

varies a lot between crude oil and natural gas and to better calculate the carbon emission accounts, and it is necessary to disaggregate these two sectors.

- Disaggregation of the electricity sector. There is also only one aggregated electricity sector in the original IO table. However, the CO_2 and pollutant emission factors vary a lot among different power generation technologies, especially between the traditional fossil fuel generation technologies and the low-carbon power generation technologies. As China is trying to limit the coal-fired power plants and promote clean energy transition, it is necessary to disaggregate the electricity sector to have a deeper understanding of the policy impacts on different generation technologies.
- Introduction of the environmental management sectors. In the current IO system, there is only one environmental governance sector which is accounted as a service sector. However, this does not account for all the inputs into the waste management activities because many activities of pollutant treatment are treated by each sector using pollutant treatment machines. This thesis follows the methodology of (Zhao and Lei, 2010) to disaggregate the environmental management sectors and adds three waste management sectors: wastewater management, gas pollutant management and solid waste management.
- Aggregation of other sectors. This is mainly for the simplicity of the CGE model. CGE is a large macroeconomic model, and there are usually more than 1,000 variables in a dynamic CGE model. It is difficult for the model to solve the equilibrium if there are many variables. As this thesis focuses on the environmental management sectors and energy commodities, this thesis follows the methods of many other CGE studies and aggregate the rest sectors into one agricultural sector, fourteen industrial sectors, and one service sector as shown in Table 4-1.

The disaggregation and aggregation methods are explained in detail in the following sections. The data used in the model could be found in Appendix A. To be noted, we round the data in Appendix A to the nearest one hundred million with one decimal for simplification. Our simulation results find the impact of data rounding is very little due to the huge magnitude of the macroeconomic data.

4.1.1 Disaggregating the oil and natural gas extraction sector

We need to disaggregate both the column and the row of the oil and natural gas extraction sector in the original IO table.

- Disaggregating the column. Since the extraction activities of crude oil and natural gas are quite similar, we assume the same input coefficients in these two sectors. As for the ratio of the sectoral output, we disaggregate by the primary business income in each sector. the output quantity multiplying by the average commodity price. In China, the extraction activities are mainly performed by three state-owned companies: China National Petroleum Corporation, Sinopec, China National Offshore Oil Corporation. We use the average energy prices from the financial reports of these companies. The output quantity of crude oil and natural gas could be obtained from the Energy Balance Table.

Table 4-2: Crude oil and natural gas data

	Production quantity	Average price	Revenue	Ratio
Crude Oil	207.48 mil tonnes	4,579 RMB/tonne	950.04 bil RMB	6.9
Natural Gas	107.15 G m^3	1.281 RMB/m^3	137.26 bil RMB	1

Source: Energy Balance Table (NBS, 2017), National Petroleum Corporation (data from Wind Dataset); Unit: million tonnes. Data in 2012.

- Disaggregating the row. For the sake of simplicity, we assume that the ration of the use of crude oil and natural gas in most sectors is the same as the ratio of their outputs. However, we assume in the oil-fired power sector, all the inputs from the original oil and natural gas extraction sector are the inputs of oil, and in the gas-fired power sector, all the inputs are the natural gas. As for the accounts of final consumption, import, export, and stock change, the results are adjusted according to the consumption information from the Energy Balance Table.

4.1.2 Disaggregating the electricity sector

Following the methodology in Wing (2006) and Lindner et al. (2013), the electricity sector is disaggregated into six technologies: hydroelectricity, coal-fired electricity, oil-fired electricity, gas-fired electricity, nuclear electricity, and renewable energies. It should be noted that there are also many other new or detailed technologies in the power sector, but due to the lack of detailed technology and industry data, these new technologies are not considered in the current study but could be added in the future research.

Table 4-3 presents the production output by different generation technologies from the dataset of the International Energy Agency (IEA). We use the share of production output in 2012 to disaggregate the output account of the electricity account, i.e. coal-fired electricity accounts for 75.52%, oil-fired for 0.22%, gas-fired for 1.98%, nuclear for 1.95%, hydroelectricity for 17.46%, and the renewables for 2.87%. We only need to disaggregate the column of the IO table for the electricity account, because we assume the electricity produced by different technologies is homogeneous. As for the intermediate inputs into different technologies, we mainly focus on the input coefficients of energy commodities. As Lindner et al. (2013), we assume all the inputs of coal and coke products go to the coal-fired sector, and the inputs of natural gas and fuel gas go to the gas-fired sector. Besides, we assume that the inputs of fossil fuels account for 70-80% in the oil-fired and gas-fired sector (Liu and Zhong, 2016). The rest accounts are disaggregated according to the output shares of different technologies.

Table 4-3: Electricity production by technology

	Coal-fired	Oil-fired	Gas-fired	Nuclear	Hydro	REs	Total
2007	2,656,748	28,094	33,907	62,130	485,264	15,647	3,281,790
2008	2,730,426	18,809	34,566	68,394	585,187	29,803	3,467,185
2009	2,911,964	12,124	57,188	70,134	615,640	48,011	3,715,061
2010	3,239,704	14,856	78,063	73,880	722,172	79,318	4,207,993
2011	3,711,059	12,130	95,935	86,350	698,945	111,342	4,715,761
2012	3,771,394	10,937	98,776	97,394	872,107	143,437	4,994,045

Source: International Energy Agency (IEA, 2018); Unit: GWh; Note: RE represents other renewable energies except hydroelectricity, like solar power and wind power.

4.1.3 Introducing pollutant treatment sectors

There two types of environmental management costs: internal management cost and external management cost. The internal cost mainly refers to the cost of running pollutant treatment machines in each sector and this kind of activities is conducted by the factories themselves to reduce the pollutant emissions. The external cost mainly refers to the inputs by the municipal or local pollutant management entities, whose activities including transport and dumping of the municipal wastes, managing municipal sewage, and so on. Table 4-4 shows the environmental management cost in 2007 (Yu et al., 2007) and it shows that the internal management cost covers most of the total cost and it is necessary to estimate the internal environmental management cost. However, in the current IO system, there is one environmental governance sector under the category of services. According to the explanations in the sector classification in NBS, this sector mainly refers to the external environmental management activities. Thus, we need to introduce pollutant treatment sectors to study environmental management activities fully.

Table 4-4: Environmental protection cost accounting in 2007

	External cost		Internal cost
Municipal sewage	101.7	Tier 1 industries	96.0
Municipal waste	97.5	Tier 2 industries	1,249.8
Others	219.3	Tier 3 industries	540.9
Total	418.5	Total	1,886.7

Source: (Yu et al., 2007); Unit: 100 million RMB

Zhao and Lei (2010) introduce 3 additional pollutant treatment sectors in the national IO system: waste water management sector, waste gas management sector, and solid waste management sector. This thesis follows their methods and input coefficients to introduce three pollution treatment sectors in the column of the IO table. As for disaggregating the row, we only consider the internal environment management cost in the industrial sectors, not in the service sector and the final demand accounts. It is assumed that the intermediate demand for waste management is in proportion to the generation amounts of waste. The sectoral pollutant generation data is summarized based on the China Environmental Statistics Yearbook and is shown in Appendix B. Besides, for calculating the output of each pollutant management sector, we subtract the external environmental governance cost from the accounted actual treatment cost of each category of pollutant, and the outputs of waste water treatment, waste gas treatment, and solid waste treatment are 139.6, 267.5, and 50.0 bil RMB, respectively. Last, it is assumed that the internal waste management should be accounted as part of the manufacturing inputs in each sector since internal waste management mainly is running the treatment machines (Lei, 2010). To balance the rows and columns of the IO table, we abstract the intermediate inputs and demands of waste treatment sectors form the original sector of other manufacturing. So far, a disaggregated IO table has been constructed and the result is shown in Appendix A.

4.2 Energy balance table and CO_2 emission coefficient

To calculate the carbon emission, we need first to understand the emission sources and the emission mechanisms. Table 4-5 shows China's official national carbon inventory of 2012 submitted to the UNFCCC (NDRC, 2016b), and it indicates that energy activities which refer to burning fossil fuels account for most of China's carbon emission. Besides, industrial production processes also contribute by about 12.0% of the carbon emission. The land use/cover change (LUCC) refers to the agricultural activities like returning farmland to the forest to increase the forest carbon sinks, which is regarded as negative emissions. China has kept restoring forests to prevent extreme weather like sand storms, and these practices are also beneficial to reduce carbon emissions. This thesis will focus on the emissions from the energy activities and industrial production processes.

Table 4-5: China's carbon emission inventory of 2012

	Emission amount (G tonnes)	Share (not including LUCC)
Energy activities	8.69	87.9%
Industrial production processes	1.19	12.0%
Waste treatment activities	0.01	0.1%
Land use/cover change (LUCC)	-0.58	
Total (not including LUCC)	9.89	100%
Total (including LUCC)	9.31	

Source: NDRC (2016b)

There are mainly two methods of calculating carbon emissions in IO or CGE approach, depending on the emission resources. For process-related CO_2 emissions, a sectoral emission factor is usually calculated by dividing the process emissions by the sectoral output. For example, in the production process of cement products, the raw materials like limestone and clay are first ground into the powder and then sent to a high-temperature boiler for calcination, and a lot of carbon dioxide is emitted during the complex chemical reactions other than burning fossil fuels. It would be challenging to identify the accurate carbon sources in complex chemical reactions, so an overall sectoral emission factor is the conventional approach. Nevertheless, it would always be more accurate if the reaction processes could be divided into more detailed stages with specific carbon emission factors.

Table 4-6: Carbon emission factors in industrial processes

	Emission amount (10 000 tonnes)	Sectoral output (100 bil RMB)	Emission factor (100 tonnes/bil RMB)
Chemical sectors	83403.4	100375.0	0.83
Non-metallic sectors	13107.6	46604.6	0.28
Metal product sectors	22805.5	32226.5	0.71

Source: NDRC (2016b) and (NBS, 2009)

For energy-related emissions, we intend to calculate the sectoral emission by different fossil fuel source as the following equation.

$$\mathrm{EF_i} * CM_{ij} * CR_{ij} = EM_{ij}$$

where $\mathrm{EF_i}$ if the emission factor of different fossil fuel commodity i; $\mathrm{CM_{ij}}$ is the consumption amount of fossil fuel i in sector j; $\mathrm{CR_{ij}}$ is the combustion rate of fossil fuel i in sector j, and $\mathrm{EM_{ij}}$ is the sectoral carbon emission due to the consumption of fossil fuel i in sector j. The set of I includes the fossil fuel commodities of raw coal, coke, crude petroleum, refined petroleum, natural gas, and fuel gas (town gas). The set of J refers to all the 33 activity sectors in this thesis.

There are several points to be noted in the equation above. First, the emission factor for electricity is 0. This is mainly used to avoid double accounting of the carbon emissions. The power sector utilizes fossil fuels to generate electricity and emits a lot of CO_2, and this thesis only considers the emission from the primary fossil fuel commodities.

Second, the emission factor $\mathrm{EF_i}$is only by commodity but not by both commodity and by sector. This is because, in the basic setting of CGE model, it is assumed that the same commodity is homogenous among different sectors in terms of its physical characteristics and monetary price. Although the energy prices vary in different sectors and final demand accounts, it is still assumed the emission factor of one fossil fuel commodity is the same across all the sectors. Therefore, to keep the consistency among different sectors, we sum both sides of the equation by all sector j, which becomes

$$\mathrm{EF_i} * \sum_j CM_{ij} * CR_{ij} = \sum_j EM_{ij}$$

Thirdly, the unit of $\mathrm{EF_i}$ is tonne- CO_2/RMB, which combines physical emission unit and monetary emission unit. This is because all the entries in the IO table or SAM are in monetary unit and we need to calculate the carbon emissions based on the monetary data, usually by multiplying the physical unit by the average price.

Lastly, we introduce the coefficient of the combustion rate CR_{ij} is because a part of fossil fuel commodities is used for material input not for burning in some industrial sector, and a part of fossil fuel commodities is used for being turned into other types of energy commodities in the energy transformation sectors. For example, coke is an important material input in the iron-making sector, and the oil refining sector consumed a large amount of crude oil but transformed most of the crude oil into refined oil products, like gasoline, diesel, and so on.

We use the data from the Energy Balance Table to calculate CR_{ij} and EM_{ij}. Table 4-7 summarizes the Energy Balance Table according to the sector classification of this thesis. Here we assume the emission factor of natural gas is the same as fuel gas (mainly town gas) and only shows the data of total gas in the table. The table presents the final energy combustion amount, and we need to find additional information from other sheets in the Energy Balance Table to calculate the final consumption amount and then obtain the combustion rate. The necessary information includes that the coal mining and processing sector inputs 584.82 million tce of raw coal to produce cleaned coal and other washed coal; the oil refining sector inputs 656.21 million tce of crude oil to produce refined oil products; the steel and iron production sector inputs 15.23 million tce of coke as material input, and so on. Therefore, the combustion rate of coal in the coal mining and processing rate is 8.13%; the combustion rate of crude petroleum in the oil refining sector is only 0.11%. The combustion rate of coke in the steel and iron production sector is 95.37%.

Table 4-7: Energy combustion amount in industrial sectors and households

	Coal	Coke	Crude Oil	Petroleum	Gas
COAL	5,172.41	65.07		343.96	74.08
COKE	816.79	184.42	0.23	57.69	311.58
COIL	80.48		577.84	135.37	1,160.42
NGAS	11.66		83.74	19.62	168.18
PETR	52.14		75.16	5,710.94	3,583.22
FGAS	49.41	0.14		8.24	85.39
ELE	128,635.26	5.23	17.63	827.59	7,191.64
AGRI	1,297.91	55.84		2234.27	19.34
MINE	488.62	182.21	1.30	563.70	59.03
FOOD	1,889.10	14.17	0.11	231.53	178.36
TEXI	1,362.45	16.28	0.49	260.40	114.53
PAPE	1,302.01	0.88	0.14	53.70	45.88
CHEM	9,319.83	2,978.10	42.56	6,193.54	3,891.49
PLAS	310.52	3.36	0.04	71.39	42.64
NMET	16,121.33	832.62	11.11	2,216.31	1,232.59
STEEL	8,404.05	31,412.99	0.01	191.00	4,324.54
NMTL	926.00	542.44	0.33	448.08	426.90
MPDT	232.19	101.65	0.01	104.80	132.52
OIND	1,121.18	1,099.74	0.31	636.76	766.08
SCRA	10.76	19.47		7.91	4.85
WATE	21.74	0.04		7.63	2.30
CONS	547.92	6.13		3,655.18	28.07
TRAN	426.62	0.09		25,759.19	1,954.78
SERV	3,405.72	20.43		5,076.92	1,216.24
ESER	6.14	0.04		9.15	2.19
HOUSEHOLD	6,660.99	36.85		3,894.53	6,938.27
TOTAL	188,673.26	37,578.18	811.03	58,719.39	33,955.14

Source: Energy Balance Table (NBS, 2013); Unit: 10 000 tce

The next step is to calculate $\sum_j EF_{ij}$, which is the carbon emission amount by fossil fuel from all the sectors. In this step, we use the energy data from the Energy Balance Table and the physical CO_2 emission factor from 2006 IPCC Inventory Guide using the equation below. Here CB_{ij} is the energy combustion amount, and DEF_i is the default emission factor from IPCC as shown in Table 4-8.

$$\mathrm{EF_{ij}} = CB_{ij} * DEF_i$$

Table 4-8: Carbon emission factors in industrial processes

	Default emission factor	Lower	Higher
Coal	94,600	87,300	101,000
Coke	107,000	95,700	119,000
Crude petroleum	73,300	71,100	75,500
Refined oil products	73,300	71,100	75,500
Gas	56,100	54,300	58,300

Source: 2006 IPCC Inventory Guide (IPCC, 2006); Unit: kg/TJ

After converting the energy units of TJ and tce, we could then multiply the coefficients and calculate the monetary emission factor. The emission factors for coal, coke, crude oil, refined oil, and gas, are 28.43, 23.82, 0.93, 3.49, 11.53 t-CO_2 per 10 000 RMB. The total carbon emission from energy activities is 8.25 Gt, close to the 8.69 Gt in the government official report. Adding the process-related emissions, the total CO_2 emission is 9.44 Gt. Shan et al. (2018) summarizes the various studies on China's CO_2 emission accounting and shows that China's estimated CO_2 emission in 2012 varies from 8.8 Gt to 10.3 Gt by different research institutes and different calculation method. Thus, we consider the CO_2 accounting method in this thesis is acceptable and would use the emission factor for the simulation analysis.

4.3 CEEIO table and pollutant emissions coefficient

This section introduces the environmental data from the Chinese Environmental Extended Input-Output (CEEIO) database, which is an open database developed by Dr. Xu and Dr. Liang from the University of Michigan. Compared to other existing environmental extended IO tables, there are mainly four reasons for choosing CEEIO:

- Open access data. This is an important feature to avoid repeated and very time-consuming efforts.
- Constructed based on the publicly available data source and having checked the consistency. The sectoral definition in China's environmental data is not consistent with that in the IO system, which makes it challenging to combine the two datasets directly. CEEIO helps resolve this problem by using a compatible sectoral classification.
- Updated regularly. This thesis uses the latest version of CEEIO of 2012, and the dataset is still to be updated.
- Comprehensive coverage of environmental accounts. This thesis introduces 18 kinds of pollutants from CEEIO as shown in Table 4-9.

The environmental dataset of CEEIO used in this thesis could be found in Appendix C.

Another important concept is the pollutant equivalent value. Since CEEIO only gives the physical emission amount, we still need a metric to evaluate the environmental impacts of different kinds of pollutants to set the tax standards. According to the Environmental Protection Tax Law, the pollutant equivalent value is introduced to reflect both the physical impacts of different pollutants and the general treatment cost. When calculating the tax payables, the physical emission amount should be converted into standard units using the pollutant equivalent value. Emitting two kinds of pollutant with same standard units, their environmental impacts are generally at the same level. The equivalent values for the 18 pollutants are shown in Table 4-9.

Table 4-9: Pollutant equivalent value table

Pollutants	Type	Pollutant equivalent value
SO_2	Gas pollutant	0.95 kg
Nitrogen oxides	Gas pollutant	0.95 kg
Soot and dust	Gas pollutant	2.18 kg
Atmospheric Hg	Gas pollutant	0.0001 kg
Chemical oxygen demand	Water pollutant	1 kg
Ammonia nitrogen	Water pollutant	0.8 kg
Phosphorus	Water pollutant	0.25 kg
Petroleum pollutants	Water pollutant	0.1 kg
Volatile phenol	Water pollutant	0.08 kg
Cyanide	Water pollutant	0.05 kg
Aquatic Hg	Water pollutant	0.0005 kg
Aquatic Cd	Water pollutant	0.005 kg
Aquatic Cr	Water pollutant	0.04 kg
Aquatic Pb	Water pollutant	0.025 kg
Aquatic As	Water pollutant	0.02 kg
Aquatic Cu	Water pollutant	0.1 kg
Aquatic Zn	Water pollutant	0.2 kg
ISW	Solid pollutant	1 t

Source: The Environmental Protection Tax Law (NPC, 2016)

$$\text{Emission amount (normalized value)} = \frac{Emission\ amount\ (tonne)}{Pollutant\ equivalent\ value}$$

$$\text{Environmental tax payable} = Emission\ amount\ (normalized\ value) * tax\ level$$

Using the physical emission amount data from CEEIO and the pollutant equivalent value from Table 4-9, we could then calculate the emission amount in standard value and then further calculate the environmental tax payable using the formula above. The information on environmental tax payable will then be used in the CGE model to assess the economic impacts of environmental emissions.

4.4 Social accounting matrix

Compared to the IO table, the Social Accounting Matrix (SAM) incorporates the monetary flows among different economic accounts within an economy in the given period and is essential to build the CGE model. The monetary flow data from the commodity accounts to the activity accounts and the final demand accounts could be found in national IO table. We still need to find additional information of the monetary flow among the rest accounts. Since there is no publicly available SAM of the year 2012, this thesis formulates a simplified version of the 2012 national SAM following the methodology indicated in Fan et al. (2010).

There are 10 types of accounts in the SAM: including the sector accounts which represents the production activities, the commodity accounts which represent different types of products, two factor accounts of labor and capital, 5 domestic final demand accounts of households, enterprises, governments, investment-saving and stock change, and one foreign account of rest of the world (ROW). The SAM structure is shown in Table 4-10, and the data of the year 2012 is shown in Table 4-11.

The compilation methods for each column and row in the SAM are as follows:

- Sector accounts: the data is extracted directly from the national IO. Due to lack of data, the production tax is not further disaggregated into more specific tax items, but this work could be done in future studies.
- Commodity accounts: the data is extracted directly from the national IO. It is assumed that one sector corresponds to only one commodity for the sake of simplicity in CGE modeling.
- Labor account: it is assumed that the households provide all the labor factors and owns all the labor income. The labor inputs from overseas is not considered.
- Capital account: both households and enterprises provide capital factors. To disaggregate the capital income to households and enterprises, we use the data of capital income of households from China Funds Flow Statement including interest income, dividend income, and other income. The enterprises' capital income is the balancing item.

- Household account: the households' income tax and savings data are from NBS. The government transfer to households comes from the item of social benefits expense from the government from China Financial Yearbook. The transfer from enterprises to households is the balancing item.
- Enterprise account: the enterprises' income tax comes from China Financial Yearbook. The enterprise saving is the balancing item.
- Government account: the government saving is the balancing item.
- Investment and savings account: according to the national account, the total investment should equal to the overall savings. The data is extracted directly from the national IO.
- Row (rest of the world): only one aggregated account of foreign account is considered. This could be further expanded in a multi-regional CGE modeling framework.

After finishing constructing the SAM, we could then assign the values in the SAM to the variables in the formulations in Section 3 and calibrate the parameters in the CES functions. These parameters are used for the whole simulation period. Ideally, these parameters should be updated every year. However, due to lack of data, most CGE models including this thesis will not update it year by year, but this could be left for future works.

Table 4-10: National SAM structure

	Sector	Commodity	Labor	Capital	Household	Enterprise	Gov.	Investment-Saving	Stock	Row	Total
Sector		Outputs									Total outputs
Commodity	Intermediate demand				HH demand		Gov. demand	Fixed capital formation	Stock change	Exports	Total demand
Labor	Labor input										Factor income
Capital	Capital input										Factor income
Household			Labor income	HH Capital income		Transfer	Transfer				HH income
Enterprise				Ent Capital income							Ent income
Government	Production tax				HH income tax	Ent income tax					Gov income
Investment-Saving					HH saving	Ent saving	Gov. saving			Row saving	Total saving
Stock								Stock change			Stock
Row		Imports									Foreign currency expense
Total	Total inputs	Total supply	Factor expense	Factor expense	HH expense	Ent expense	Gov expense	Total investment	Stock	Foreign currency income	

Source: Revised based on (Fan et al., 2010)

Table 4-11: 2012 National SAM

Unit: billion RMB

	Sector	Commodity	Labor	Capital	Household	Enterprise	Gov.	Investment-Saving	Stock	Row	Total
Sector		160,162.7									160,162.7
Commodity	106,482.7				19,853.7		7,318.2	23,775.1	1,269.2	13,666.6	172,365.4
Labor	26,413.4										26,413.4
Capital	19,906.0										19,906.0
Household			26,413.4	2,433.4		3,411.8	1,258.5				33,517.1
Enterprise				17,472.6							17,472.6
Government	7,360.6				582.0	1,965.4					9,908.0
Investment-Saving					13,081.4	12,095.4	1,331.3			-1,463.9	25,044.3
Stock								1,269.2			1,269.2
Row		12,202.7									12,202.7
Total	160,162.7	172,365.4	26,413.4	19,906.0	33,517.1	17,472.6	9,908	25,044.3	1,269.2	12,202.7	

Source: compiled by the author

5. Socio-economic conditions and policy scenarios

Scenario analysis is a standard tool to study possible future situations by considering a series of important factors and is widely used in the fields of energy, climate change, and environment-related studies. Take the policy research in climate change for an example. There are so many uncertainties in the world that might influence the effects of climate change policies, and it would be necessary to assume to a reference setting so that we could compare the impacts with or without a specific policy. The reference setting should include the underlying assumptions like global economic growth rate, population volume, land use and change situation, and so on. The policy researchers could then simulate the impacts of a specific policy by imposing a policy shock to the reference setting. The reference setting is then often called the baseline socio-economic conditions, and the policy settings are often called policy scenarios.

Similarly, in the research of environmental policies, we also need to study the baseline socio-economic conditions and policy scenarios and draw the conclusions of policy effects by comparing the environmental and economic performances in the different scenarios. This thesis learns from the methods in the climate policy community to construct three baseline SSP socio-economic conditions and further build the policy scenarios of environmental tax and carbon tax, as explained in detail in the following sections.

5.1 Baseline socio-economic conditions

This thesis constructed the baseline socio-economic conditions based on the Shared Socio-Economic Pathway (SSP) framework (O’Neill et al., 2014). The SSP framework is to facilitate the integrated modeling and policy analysis in the climate change research community (Riahi et al., 2017). They are developed by six integrated assessment modeling teams including the Asia-pacific Integrated Model (AIM) team from Japan’s National Institute for Environmental Studies. The socio-economic datasets mainly include the following categories: population, GDP, urbanization, land-use, emissions, and so on.

Source: O'Neill et al. (2017)

Figure 5-1: SSP socio-economic conditions

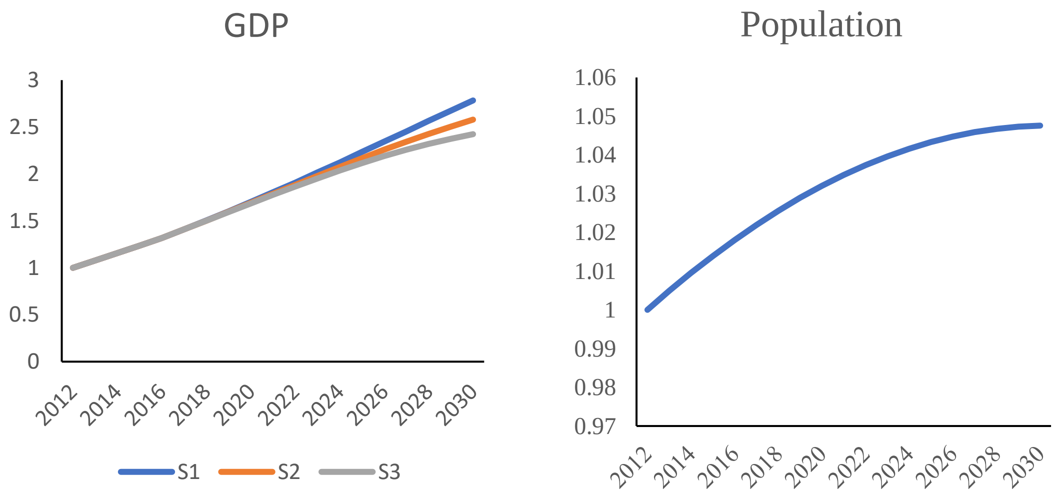
There are five basic socio-economic conditions in the SSP framework as shown in Figure 5-1 (O'Neill et al., 2017). The horizontal axis represents the challenges for adaptation, and the vertical axis poses the challenges for mitigation.

- SSP1 shows a highly sustainable socio-economic condition. The economic development is high, with high resource efficiency and low emissions.
- SSP2 shows a middle-road socio-economic condition in the five SSPs.
- SSP3 shows a lowly sustainable socio-economic condition. Despite the low economic development, energy efficiency and land utilization efficiency are also low.
- SSP4 and SSP5 show two unbalanced socio-economic conditions in terms of mitigation and adaptation. Since mitigation and adaptation are not the research focus of this thesis, this thesis will not further discuss SSP4 and SSP5, but focus on the SSP1 to SSP3.

Though the SSP framework provides future socio-economic conditions for the whole world and the time range is by 2100, this thesis will only focus on the case of China and cut the simulation period by 2030. Given such a specific application, there are some modifications based on the original SSP socio-economic conditions:

- Extract the data of GDP growth rate and population growth rate. These two kinds of data are the most important data in CGE simulation. Due to the difference in model setting, this thesis will not refer to the other datasets in the SSP framework like the urbanization data, but this could be improved in the future as the model incorporates more features.

- Choose 2012 as the start year. Though original SSPs simulate from 2005, the thesis uses the growth rate from the year of the 2012.
- Replace the data between 2012 and 2016 with the real data from the World Bank. The SSPs give long-term projections, so the tolerance for short-term accuracy is high. As the thesis only focuses the period up to 2030, we will try to update the dataset with the real situation. For example, China's GDP growth rate of SSP2 in 2016 is 7.78% in contrast to 6.90% in the actual case. The thesis then replaces the previous data with real value and modifies the future projections in proportion to the current level.
- Choose only one population socio-economic condition. In the short period until 2030, the population forecast is relatively stable. According to China's National Population Pathway 2016-2030 (SC, 2016c), the overall population is projected to peak around 2030. This thesis chooses the SSP2 as the basic population socio-economic condition and modifies so that the population peaks at 2030.



Note: the base year levels (GDP or population) are set as 1; modified based on SSP.

Figure 5-2: Modified SSP socio-economic conditions

The modified SSPs are then represented in Figure 5-2. To differ from the original SSPs, these modified socio-economic conditions will be called as S1, S2, and S3, respectively.

Table 5-1: General parameter settings in baseline socio-economic conditions

	S1	S2	S3
Labor efficiency annual improvement rate (until 2017)	3%	3%	3%
Capital efficiency annual improvement rate (until 2017)	3%	3%	3%
Material efficiency annual improvement rate (until 2017)	3%	3%	3%
Energy efficiency annual improvement rate in different power sectors (until 2017)	2% ~ 4%	2% ~ 4%	2% ~ 4%
Energy efficiency annual improvement rate in non-power sectors (until 2017)	3%	3%	3%
Waste management efficiency annual improvement rate (until 2017)	3%	3%	3%
Sectoral pollutant emission rate annual improvement rate (until 2017)	10%	10%	10%
Labor efficiency annual improvement rate (since 2018)	2%	1.5%	1%
Capital efficiency annual improvement rate (since 2018)	2%	1.5%	1%
Material efficiency annual improvement rate (since 2018)	2%	1.5%	1%
Energy efficiency annual improvement rate in different power sectors (since 2018)	5~10%	4%	1%
Energy efficiency annual improvement rate in non-power sectors (since 2018)	5~10%	4%	1%
Waste management efficiency annual improvement rate (since 2018)	6%	3%	1%
Sectoral pollutant emission rate annual improvement rate (since 2018)	10%	5%	1%

Table 5-1 presents the general parameter settings in the baseline socio-economic conditions. All these future parameters are calibrated to meet the original SSPs' forecasts of economic indicators, especially the expected GDP growth rate shown in Figure 5-2. The factor efficiency growth rates in the different socio-economic conditions are calibrated to meet various features including the power generation mix in corresponding socio-economic condition and related studies. A validation of these parameters will be conducted in Section 6.1.6 to compare the simulation results with socio-economic condition settings and the real situation. It should be noted that since the CGE model is a large macroeconomic framework and contains many variables, the set of parameter settings is only to simulate one future socio-economic condition but not used for predicting the future development situation.

Also, as shown in Table 5-1, this thesis distinguishes the period of parameter setting into two parts: until 2017 and since 2018. The parameter setting of until 2017 is mainly to accommodate the real situation and is the same among different socio-economic condition, while the future settings vary among different situations. In a more sustainable socio-economic condition like S1, the improvement rate tends to be higher and the waste management efficient also tends to be higher. Due to the lack of detailed technology data, we do not introduce the additional cost to improve efficiency but simply assume the technology updates as time goes by. Besides, we calibrate the energy efficiency improvement rate in different power sectors until 2017 to match the real case but assume the same growth rate among various technologies since 2018 for simplicity. It should be noted that these combinations of parameters might not be entirely consistent with reality, and the socio-economic conditions only provide several options.

Lastly, to fully understand the effect of each parameter, the sensitivity analyses on the key parameters will be necessary.

5.2 Policy scenarios

There are mainly two types of policies to be studied in this thesis: the environmental tax and the carbon tax. As explained in Section 1, China has started to implement the new Environmental Protection Tax Law since the beginning of 2018, in place of the previous pollutant charge system. The tax level or charge level per pollutant has been increased compared to the earlier standards. According to the law, the local governments hold the authority to determine the tax level and could increase the charge level by 1 to 19 times according to the local situation. As for the carbon tax, although it is not included in the tax scheme currently, many scholars are arguing about introducing it soon, so this thesis will also discuss the potential policy impacts if the carbon tax is levied in addition to the pollutant taxes.

Though there is a wide range of potential tax levels, this thesis mainly constructs four policy scenarios based on the baseline scenario to simplify the discussions as follows

- the baseline scenario (BaU)
- the low environmental tax without carbon tax scenario (LowET)
- the high environmental tax without carbon tax scenario (HighET)
- the low environmental tax plus low carbon tax scenario (LowETC)
- the high environmental tax plus high carbon tax scenario (HighETC)

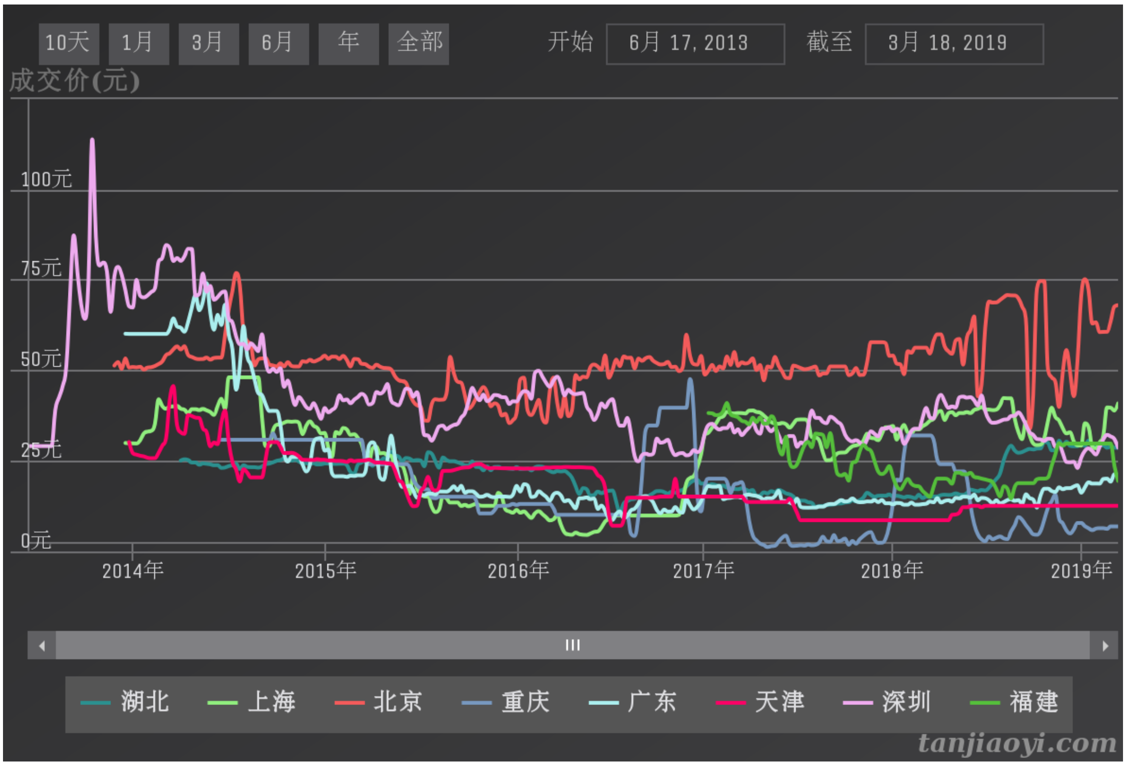
The BaU scenario is the reference scenario for the policy analysis. In Section 6.2, the middle road S2 is chosen as the BaU scenario. In Section 6.3, the more sustainable socio-economic condition S1 is chosen as the BaU scenario. By comparing the different policy impacts, it could help us better estimate how the economic situation affects the policy outcomes. In the BaU scenarios, the levels of pollutant discharge fees are assumed to keep at the same level as before 2018, which were adopted from the previous regulations for Collecting Pollutant Discharge Fees (SC, 2003).

Table 5-2: Environmental and carbon tax levels in different policy scenarios

	unit	BaU	LowET	HighET	LowETC	HighETC
Gas pollutant	yuan per normalized unit	0.6	6	12	6	12
Water pollutant	yuan per normalized unit	0.7	7	14	7	14
Industrial solid waste	yuan per t	5	10	15	10	15
CO_2	yuan per t	0	0	0	40	80

The four policy scenarios are designed to assess the policy impacts if different tax levels are levied. It is assumed that the policy shocks take place in 2018, and all the scenarios follow the same assumptions as of the BaU scenario before 2018. According to the Environmental Protection Tax Law, the range for a normalized unit of gas pollutant is from 1.2 to 12 yuan, the range for a unit of water pollutant is from 1.4 to 14 yuan, the scope for a unit of industrial solid waste of coal ore and tailings is from 5 to 15 yuan (NPC, 2016). As shown in Table 4, it is assumed that the environmental tax levels are in the middle in the LowET and LowETC scenarios and the highest level in the HighET and HighETC scenarios.

As for the carbon tax, it is assumed that the carbon price is embodied in the price of each commodity and is all collected by the government, and the further redistribution of the carbon tax revenue is not considered in this study. Since the carbon tax scheme has not been implemented in China and its price varies from several dollars to more than a hundred dollars (IBRD and ECOFYS, 2015). As shown in the figure below, the market price of carbon dioxide in different pilot markets range from 5 to 80 RMB per ton. Also, it is reported that the carbon tax has been discussed to set around 10 to 100 RMB per ton though failed to be included in the Environmental Tax Law (Zhu, 2018). In this thesis, to simplify the discussions, we propose an assumptive carbon tax of 40 yuan and 80 yuan in the LowETC scenario and HighETC scenario, respectively.



Source: http://k.tanjiaoyi.com/ (As of Aug 5^{tn}*, 2019)*

Figure 5-3:Carbon price in China's pilot carbon trading markets

It should be noted that some other specific tax regulations in the Environmental Protection Tax Law are not considered in this study due to the lack of detailed data. For example, it is regulated that only the top three kinds of gas pollutants in terms of emission amount will be charged in one vent, but the emission data of each vent is not available at present. Besides, according to the Environmental Protection Tax Law, companies could enjoy a 75 % of tax exemption if the emission density is less than 30% of the governmental standard, and a 50 % of tax emption if the emission density is less than 50 % of the government standard. Due to the lack of data, this paper does not consider the tax emption situations.

It also should be noted that though the tax scenarios are added on the baseline socioeconomic conditions, the tax scenarios might also influence the baseline situations. For example, according to the Environmental Protection Tax Law (NPC, 2016), the local governments will support companies to improve pollution treatment techniques via financial or policy aid. This indicates that in a high tax scenario, the pollution treatment efficiency might also increase faster, which is a basic parameter in baseline scenario setting. For simplicity, this thesis does not take these matters into consideration, but this could be left for future studies.

To conclude, the scenarios in this thesis are constructed mainly from two dimensions: the dimension of general socioeconomic situation, and the dimension of the strictness of the environmental policies. The first dimension is to design the baseline socio-economic conditions (like S1 without policies and S2 without policies), and the second dimension is to levy additional policies on the baseline conditions. The scenario analyses are elaborated in Section 6.1 and Section 6.2, respectively.

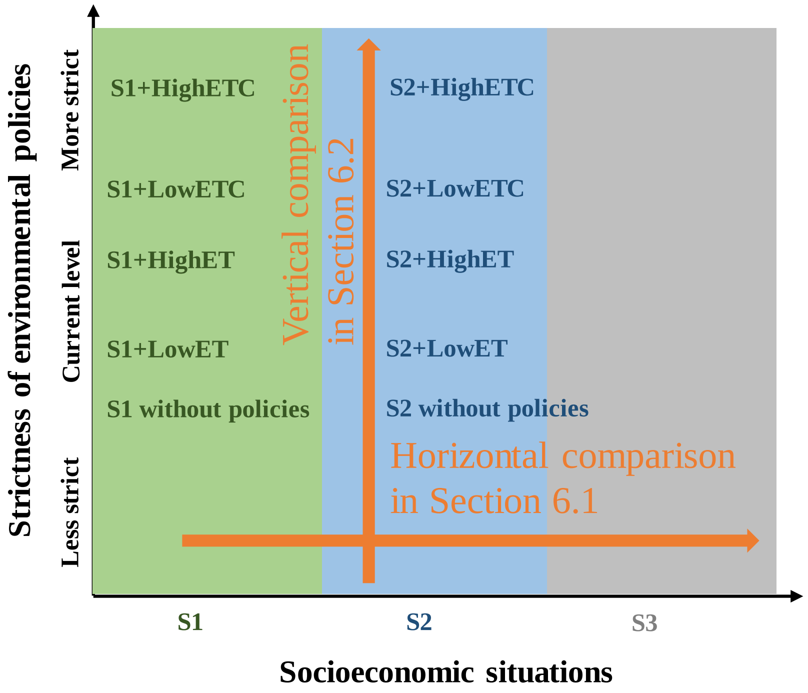


Figure 5-4: Scenario settings

6. Results and Discussions

6.1 Simulation results of baseline socio-economic conditions

6.1.1 Macroeconomic indicators

As shown in Table 6-1, the macroeconomic situations in different baseline socio-economic conditions vary a lot from each other. In the most sustainable socio-economic condition S1, the expected GDP by 2030 could reach about 154.5 trillion RMB, almost 20% higher than that in the least sustainable socio-economic condition S3. The other main indicators also show a similar trend that the economic situation in S1 is the best among three baseline socio-economic conditions, and the S3 is the worst, and the S2 is in the middle.

Table 6-1: Macroeconomic indicators (2030) in different socio-economic conditions

	S1	S2	S3
GDP	154,508.44	137,031.79	122,924.12
		(-11.31%)	(-20.44%)
Household consumption	91,509.95	84,412.46	77,497.92
		(-7.76%)	(-15.31%)
Government consumption	12,026.11	11,174.90	10,838.35
		(-7.08%)	(-9.88%)
Export	34,900.21	30,475.95	27,533.95
		(-12.68%)	(-21.11%)
Import	33,436.32	29,012.06	26,070.06
		(-13.23%)	(-22.03%)

Unit: billion RMB; numbers in parentheses are the changes compared to S1.

Since the labor condition is the same in S1 to S3, the different economic performances are mainly caused by the different technology improvement rates. In Table 5-1, the technology improvement rates start to be different since 2019 in different socio-economic conditions. Though many factors have been listed in Table 5-1, the three most important parameters that influence economic performance are the efficiency improvement rate of labor, capital, and material inputs. The efficiency improvement rate stays at 1% in S3 in contrast to 1.5% in S2 and 2% in S3, which leads to different productivities and thus different economic outcomes.

It should be noted that the general economic situations like the GDP are more like given in the baseline socio-economic conditions, and the efficiency parameters are only set to meet the expected economic performances. The original settings only provide a situation where the future economic condition could be like. In such settings, the relative changes are more meaningful than absolute values. For example, the results show that if overall productivity in labor, capital and all kinds of material inputs increase by 1% more (like 1% in S3 to 2% in S1), the GDP could rise by almost 20% by 2030. Thus, the technology improvement rate determines the overall productivity and has a profound impact on the future economy.

6.1.2 Electricity generation mix

The electricity generation mix is another important feature in different baseline socio-economic conditions. As shown in Figure 6-1, there is a common trend in all the conditions that the share of coal-fired electricity will decrease gradually, and the percentage of less carbon-intensive sources will increase. The difference is mainly the speed of transition. The results show that in a more sustainable condition, the coal-fired electricity will be replaced by renewables or other sources at a quicker pace.

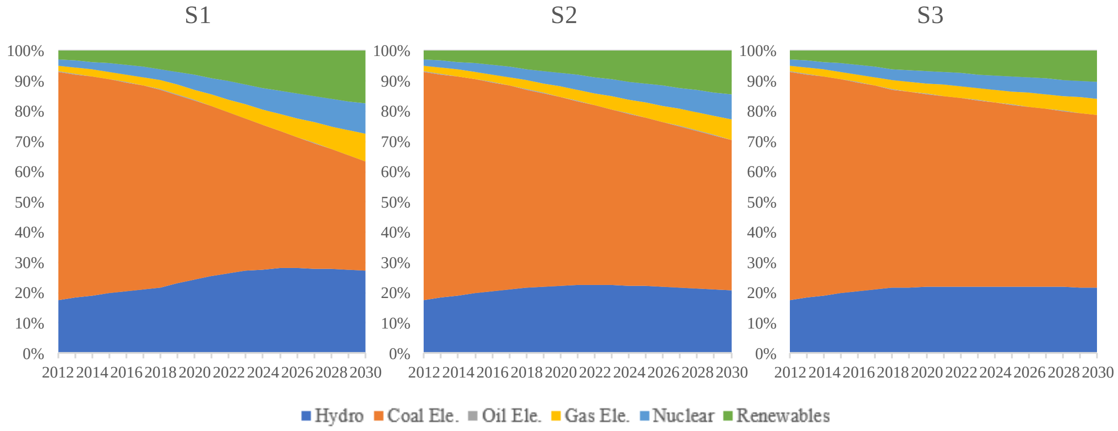


Figure 6-1 Electricity generation mixes in baseline socio-economic conditions

Table 6-2 shows this trend more explicitly. In 2012, the coal-fired electricity dominated China's power market with a share of 75.52%. However, by the end of 2030, its share will be reduced to about 40% to 60% in different socio-economic conditions.

Table 6-2: Electricity generation mix (2030) in baseline socio-economic conditions

	Hydro	Coal Ele.	Oil Ele.	Gas Ele.	Nuclear	Renewables
2012 level	17.46%	75.52%	0.22%	1.98%	1.95%	2.87%
S1	27.14%	36.22%	0.12%	9.08%	9.96%	17.47%
S2	20.68%	49.83%	0.11%	6.84%	8.09%	14.44%
S3	21.60%	57.17%	0.11%	5.30%	5.61%	10.22%

Figure 6-2 then shows the primary energy mixes in the baseline socio-economic conditions. In 2012, fossil fuels like coal, petroleum oil, and natural gas makes up for 66.6%, 18.8%, and 5.2% of total primary energy consumption, while the share of non-fossil fuels is only 9.4%. By 2030, the share of non-fossil fuels will be 26.0%, 20.7%, and 17.8% in the socio-economic conditions S1, S2, and S3. According to China's 13th Five-Year Plan on renewable energies (NDRC, 2016a), the share of non-fossil fuels in primary energy mix aims to reach 15% in 2020 and 20% in 2030, which could satisfied in S1 and S2.

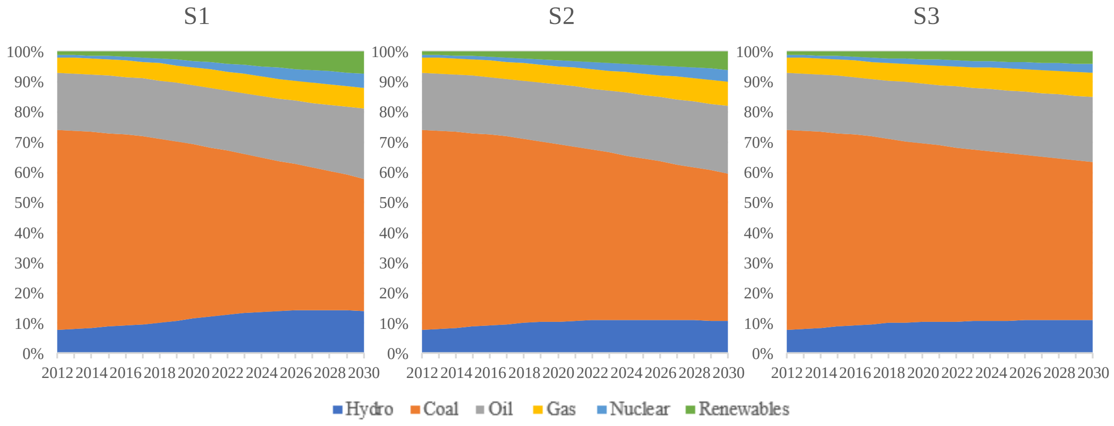


Figure 6-2 Primary energy mixes in baseline socio-economic conditions

To realize the green transition, the other energy sources, especially the shares of gas-fired electricity, nuclear electricity, and the renewables must boost in a short period. In the case of China, the government is also determined to realize green transitions in the energy sector. Natural gas and gas-fired electricity is regarded as the “bridge” source of energy and will play an important role in the next few decades. The long-term goal in the energy sector focuses on zero-carbon techniques, like nuclear electricity and multiple types of renewables of energies.

However, there are also many uncertainties in the future energy transition that are not considered in constructing future socio-economic conditions. Firstly, is the cost competitiveness of other sources versus coal-fired electricity. In the current stage, the development of renewable energies largely relies on massive fiscal subvention which will surely exist in the following few years, will the renewable energies retain the high rate growth rate without the subsidy? Secondly, are uncertainties of nuclear electricity. The technology of nuclear power plants has already evolved into the fourth generation, and many researchers are working on the fifth generation. However, given the fact that the public has concerns about the safety issues of nuclear power plants since the Fukushima incident, it remains a big issue if the public will accept the share of nuclear electricity triples or quadruples in less than two decades. Thirdly, is how to exit the existing coal-fired plants. Coal-fired plants provide a lot of job opportunities from the mining sector to the generation sector. When reducing the share of coal-fired plants, the government needs to find a solution to arranging the jobless workers in the related industries with the economy also facing downturn pressure. To conclude, the above uncertainness reminds that the designed socio-economic conditions only provide a possible pathway under a set of assumptions, and many practical problems might not be included but still need to be tackled in the real practice.

6.1.3 CO_2 emission and CO_2 intensity

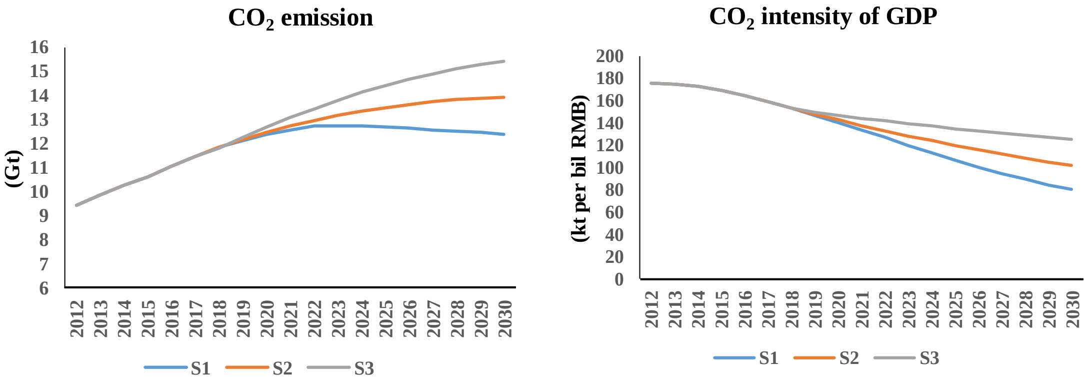


Figure 6-3: Carbon emissions

Figure 6-3 shows the simulation result for total CO_2 emission amount and CO_2 intensity of GDP which is measured in the monetary unit of bil CNY in 2012 level. The results show that S1 has the lowest CO_2 emission amount and CO_2 intensity of GDP, and CO_2 emission might peak around 2022. In the case of S3, it has the highest CO_2 emission amount and CO_2 intensity of GDP, the CO_2 emission keeps rising until 2030 and seems no to peak before 2030. S2 shows the middle situation of S1 and S3 and the CO_2 emission will reach a plateau in the last few years before 2030. Besides, the accumulated CO_2 emissions from 2012 to 2030 is 224.9 Gt in S1, 233.7 Gt in S2, and 243.6 Gt in S3. Most of the emitted CO_2 will stay in the atmosphere and gradually increase the global warming effects, so it's also important to understand the accumulated emissions in addition to the annual emission level.

A very important policy related to the carbon emission is China's Nationally Determined Contributions (NDC) in the Paris Agreement. The Chinese government promised to decrease CO_2 intensity by 40 to 45 % in 2020 and by 60 to 65 % in 2030, compared to the level in 2005, and try to peak the carbon emission as early as possible before 2030. In 2005, China's GDP was 18.73 trillion RMB (WB, 2019) and the carbon emission was 5.5 Gt (WB, 2018a), and the carbon intensity per GDP was 296.1 Kt per bil RMB. Compared to the 2005 level, the carbon intensity per GDP of 2030 in the baseline socio-economic conditions will decrease by 73%, 66%, and 58%, respectively. Though the three socio-economic conditions all fulfill China's international promise, the situation in S1 is greener and more sustainable with better economic performance but lower emissions. The second goal of peaking carbon emissions is more difficult to realize. The results show that only S1 and S2 could peak the carbon emissions before 2030, but whether peaking at the level of 13 Gt or 14 Gt makes a big difference to the global carbon budget.

6.1.4 Pollutant emission

Table 6-3: Pollutant emissions (2030) in socio-economic conditions

Pollutants	2012 level	S1	S2	S3
SO_2	294.42	113.69	141.87	171.06
		(-61.38%)	(-51.81%)	(-41.90%)
Nitrogen oxides	223.56	106.09	151.96	199.52
		(-52.55%)	(-32.03%)	(-10.75%)
Soot and dust	97.65	89.50	116.08	142.56
		(-8.34%)	(18.87%)	(46.00%)
Atmospheric Hg	130.78	134.35	166.45	200.13
		(2.73%)	(27.27%)	(53.03%)
Chemical oxygen demand	220.32	125.10	167.49	207.61
		(-43.22%)	(-23.98%)	(-5.77%)
Ammonia nitrogen	31.76	21.75	27.27	32.55
		(-31.51%)	(-14.11%)	(2.50%)
Phosphorus	34.89	19.92	26.78	33.28
		(-42.92%)	(-23.25%)	(-4.62%)
Petroleum pollutants	203.13	174.71	205.10	234.64
		(-13.99%)	(0.97%)	(15.52%)
Volatile phenol	0.185	0.128	0.157	0.194
		(-31.10%)	(-15.39%)	(4.75%)
Cyanide	0.034	0.024	0.028	0.032
		(-29.74%)	(-18.95%)	(-7.29%)

Unit: 100 million standard unit; numbers in parentheses are the changes compared to 2012 level.

Table 6-3: Pollutant emissions (2030) in socio-economic conditions (continued)

Pollutants	2012 level	S1	S2	S3
Aquatic Hg	0.022	0.015	0.017	0.018
		(-34.09%)	(-25.00%)	(-16.36%)
Aquatic Cd	0.053	0.039	0.044	0.048
		(-27.63%)	(-18.23%)	(-9.02%)
Aquatic Cr	0.018	0.013	0.015	0.016
		(-27.27%)	(-17.05%)	(-8.52%)
Aquatic Pb	0.039	0.026	0.030	0.033
		(-32.47%)	(-23.20%)	(-13.92%)
Aquatic As	0.064	0.041	0.048	0.054
		(-35.52%)	(-25.04%)	(-14.87%)
Aquatic Cu	0.067	0.023	0.038	0.053
		(-65.82%)	(-42.43%)	(-20.69%)
Aquatic Zn	0.066	0.023	0.038	0.053
		(-65.81%)	(-42.51%)	(-20.57%)
ISW	12.90	5.57	7.22	9.03
		(-56.79%)	(-44.00%)	(-29.99%)

Unit: 100 million standard unit; numbers in parentheses are the changes compared to 2012 level.

Table 6-3 presents the pollutant emissions in 2030 in different baseline socio-economic conditions. It should be noted that the numbers in Table 6-3 are in standard units rather than in physical units, but this does not influence the comparison results among the conditions. The detailed explanation of changing physical units to standard units could be found in Table 4-9 in Section 4.3.

The results show that most kinds of pollutant emissions in all three socio-economic conditions will decrease compared the baseline situation of the 2012 level, except the soot and dust, atmospheric Hg, petroleum pollutants, volatile phenol, and aquatic Cr. On the one hand, the overall decrease of emissions is because of the reduction of emission coefficients due to technology improvements and the increased environmental management cost. Some pollutants like SO_2 are highly correlated to the fossil fuel related activities, and their emissions will decrease as the energy structure turns greener. On the other hand, the differences among different kinds of pollutants could be explained by the major sources of different pollutants. For example, the major emitting sources of soot and dust are the agriculture sector and the construction sector. In all the three socio-economic conditions, these sectors will experience a high growth rate which leads to high emission of soot and dust. As for other pollutants like petroleum pollutants and volatile phenol, their major sources are the service sectors which will also enjoy a high growth rate in the future.

The results also show that S1 is the ideal socio-economic condition in terms of pollutant emissions. The emissions of almost all kinds of pollutants will reduce significantly compared to the other two socio-economic conditions. The S3 is still the worst case. From the parameter settings in Table 5-1, we could find the difference could be explained from the technology efficiency improvement rate and the sectoral emission rate. With higher technology efficiency improvement rate, the material inputs are lower, and the process emissions are also lower. The sectoral pollutant emission rate annual improvement rate for newly installed technologies since 2019 in S1 keeps at 10%, much higher than the level of 1% in S3. With the new technologies put into practice, the average emission rate will decrease significantly. As for the pollutant reduction targets, in China’s Thirteenth Five-year Plan (2015-2020, the 12th FYP), the policy mainly focuses on certain types of pollutants: SO_2, nitrogen oxides, and chemical oxygen demand. The 12th FYP aims to reduce the annual emissions of SO_2, nitrogen oxides, and chemical oxygen demand by 15%, 15%, and 10% compared to the emission levels in 2015, as shown in the second column in Table 6-4. The last three column shows the simulation results in the three conditions, in contrast to the policy targets.

Table 6-4: Reduction rates of targeted pollutant emissions (2015-2020)

	Policy targets in the 12th FYP	S1	S2	S3
SO_2	15%	23.5%	21.7%	19.9%
Nitrogen oxides	15%	11.9%	8.7%	5.9%
Chemical oxygen demand	10%	12.4%	9.1%	6.5%

The simulation results show that all the socio-economic conditions could fulfill the reduction targets in SO_2, but have difficulty achieving the goals on nitrogen oxides and chemical oxygen demand in S2 and S3. The situation of SO_2 is very promising is mainly because its emission amount has already begun to decrease since 2010 due to the massive installments of desulfurizing equipment in power plants and factories, as explained in the introduction chapter. As for other pollutants, the reduction rate is not as high as SO_2. The results indicate that extra efforts need to be input in the socio-economic conditions to fulfill the reduction targets. Moreover, this is only the target of 2015 to 2020. As China reviews the national targets every five years, the analysis also needs to be updated periodically.

6.1.5 Environmental management cost

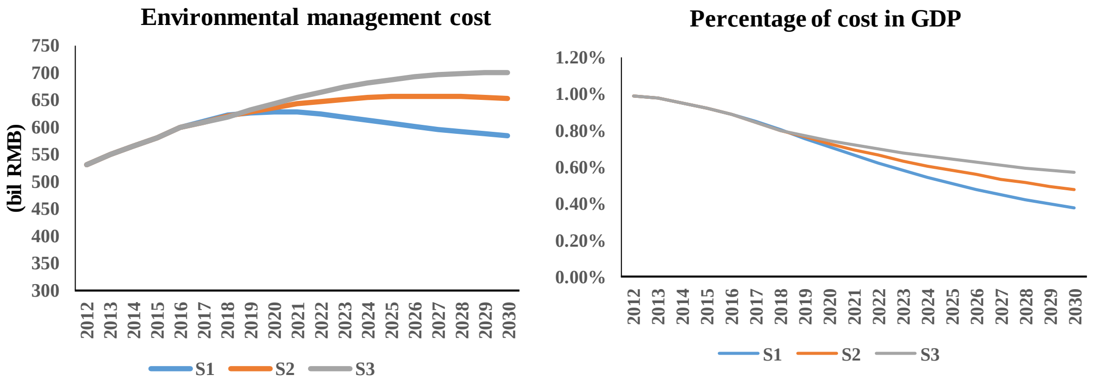


Figure 6-4: Environmental management cost

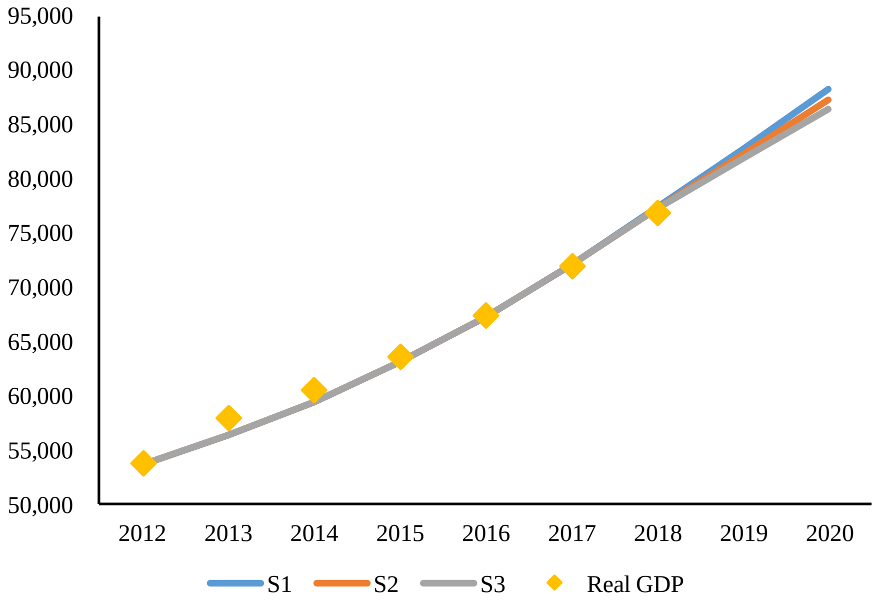
Figure 6-4 shows the environmental management cost and its percentage of GDP in three socio-economic conditions. This cost is the sum of the outputs of the pollution treatment sectors, not including the collected pollution tax. As shown in the graph, the environmental management cost in S3 is the highest in terms of both absolute value and relative percentage of GDP, and the most sustainable condition S1 shows the opposite and most promising results. In S1, the total waste management cost will rise to 58.5 bil CNY, and the percentage of GDP will decrease to 0.38% by 2030. While in the least sustainable condition S3, the total waste management cost will rise to 70.0 bil CNY with a percentage of 0.57% of GDP by 2030.

The different costs among the conditions is mainly determined by the parameter of the waste management efficiency annual improvement rate, namely the waste treatment efficiency. In the parameter settings, the treatment efficiency in new technologies improves 6% per year in S1 since 2019, which doubles the improvement rate in S2 and even much larger than that in S3. Therefore, the result in S1 is the most satisfying that the total environment management cost would also start to decrease since around 2020. However, it should be noted that these parameter settings are just assumptive situation that with fast technology improvement, the emission generation falls, and the treatment efficiency increases so fast that the overall treatment cost would peak as early as 2020. In a more middle-road conditions like S2, the situation continues to improve, but the total cost keeps at a plateau. The worst situation S3 is more like we have experienced before, that with limited technology improvement, economic development means high emissions and higher environment management expenses. In one world, the environmental management cost largely depends on the parameters like technology improvement rate. Luckily, we could find the percentages of environment management cost in all conditions keep declining, shows that the situation is improving every day and the problem is more about the speed of improvement.

6.1.6 Validation of the parameter settings

In this section, we will compare the simulation results with the real situation and some other related studies to validate the choices of the parameters in the model.

The macroeconomic indicator of the GDP data is one of the most important indexes that the CGE models aim to simulate, and most non-energy-related parameters are calibrated to fit the GDP assumptions in SSP socio-economic conditions and the real situation. Since the model simulates from the year of 2012, Figure 6-5 compares the GDP in the simulation socio-economic conditions to China’s GDP data between 2012 and 2018, where the data of 2012 to 2017 is from the World Bank dataset and the 2018 data is calculated based on the real GDP growth rate of 6.6% published by China’s NBS. The simulated results are close to the real values, and the largest discrepancy between the simulated result and the real data is about 5%, which is acceptable in most CGE studies.



Source (real GDP data, billion RMB): World Bank (WB, 2019), National Bureau of Statistics (NBS, 2019)

Figure 6-5 GDP in simulated conditions compared to real GDP data

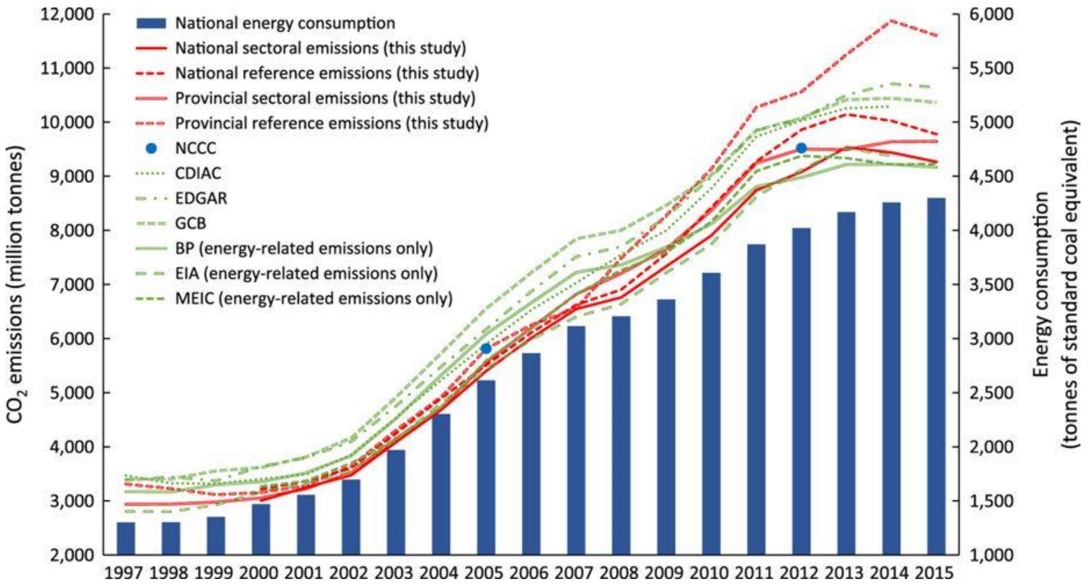
As for the energy-related parameters, they are mostly set to represent the different levels of low-carbon transition in the power sector. Table 6-5 shows the electricity generation mixes in the three situation in the report of China's Low Carbon Development Pathways (Dai et al., 2009), in contrast to the three condition in this thesis. The comparison shows that the basic structures are similar between the energy saving situation and S3, between the low-carbon situation and S2, and between deep decarbonization situation and S1. As China largely rely on the coal-fired power plants while promoting renewable energies, this thesis focuses most on the shares of these two types of generation technologies when considering the parameter settings. The simulation results show that the share of coal-fired electricity will range from 40% to 60%, and the share of renewable energies will range from 10% to 20% in different socio-economic conditions.

For CO_2 emissions, it is difficult to give an exact reference number for validation, since the results of different studies vary from each other, as shown in Figure 6-6. From the figure, most studies conclude that the emissions of 2012-15 will be in the range of 9-11Gt. The result of this thesis is 9.4 Gt (in 2012) to 10.6 Gt (in 2015), which is consistent with the other studies.

Table 6-5: Compare electricity generation mixes in 2030 in different situations

	Energy-saving situation	S3	Low-carbon situation	S2	Deep decarbonization situation	S1
Hydro	15.2%	21.6%	17.9%	20.7%	18.1%	27.1%
Coal Ele.	58.3%	57.2%	44.7%	49.8%	35.9%	36.2%
Oil Ele.	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%
Gas Ele.	7.2%	5.3%	8.1%	6.8%	8.2%	9.1%
Nuclear	12.0%	5.6%	18.8%	8.1%	22.7%	10.0%
Renewables	7.3%	10.2%	10.5%	14.4%	15.1%	17.5%

Source: Energy-saving situation, low-carbon situation, and deep decarbonization situation are from China's Low Carbon Development Pathways (Dai et al., 2009).



Source: Shan et al. (2018)

Figure 6-6 Comparisons of studies on China's carbon emissions inventories

To conclude, the parameter settings could basically replicate the major indicators in real situations and conform to the main arguments in other related studies. As for some specific parameters in the model, this thesis also discusses the sensitivity of these parameters to further explain their influences on the results.

6.2 Environmental tax policy in the middle road socio-economic condition

As explained in Section 5.2, this thesis constructs four policy scenarios based on the baseline BaU scenario, introducing the different tax levels in Environmental Protection Tax Law and the assumptive carbon tax levels. The four policy scenarios include the low environmental tax scenario LowET, the high environmental tax scenario HighET, and the carbon-constrained scenarios LowETC and HighETC which add the assumptive low and carbon taxes to the LowET and HighET scenarios, respectively. In Section 6.2, the middle road scenario S2 is chosen as the BaU scenario.

The scenario settings could be recalled in Table 5-2 in Section 5.2. In the BaU scenario, the taxes per normalized unit of gas pollutant, water pollutant, and industrial solid waste are 0.6, 0.7, and 5 RMB. In the LowET and LowETC scenarios, the tax levels are increased to 6, 7, and 10 RMB per normalized unit. In the HighET and HighETC scenarios, the tax levels are further increased to 12, 14, and 15 RMB per normalized unit. Moreover, a carbon tax of 40 RMB per tonne is levied in the LowETC scenario, and a carbon tax of 80 RMB per tonne is levied in the HighETC scenario.

6.2.1 Macroeconomic indicators

Table 6-6 shows the simulation results of the policy impacts on the macroeconomic indicators, including GDP, household consumption, government consumption, export, and import. The numbers in the brackets are the percentage changes compared to the BaU scenario.

The results show that the policies have adverse effects on all the indicators decrease except the government consumption, which increases due to the additional income from environmental tax revenue and carbon tax revenue. The negative economic impact is weakest in the LowET scenario, moderate in both the HighET and LowETC, and highest in the HighETC scenario. The negative effect of environmental tax and carbon tax could be explained by the distortion effects of tax. Environmental and carbon tax is a kind of indirect tax, and as the tax level rises, the production cost will also increase. The increased cost will finally be reflected in the price of commodities, and lead to a decrease in the households’ demands. On the other hand, since the government’s tax revenue will be largely increased in the policy scenario, the increased tax revenue will then stimulate the government’s consumption demand. However, the overall demand in the market will still be reduced despite the increase in the government’s consumption and finally leads to a decrease in the overall GDP.

Table 6-6: Policy impacts on macroeconomic indicators in 2030 (S2 as BaU)

	BaU (S2)	LowET	HighET	LowETC	HighETC
GDP	137031.8	136987.5	136947.7	136806.7	136564.0
		(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
Household consumption	84412.5	83963.2	83495.8	83327.4	82270.2
		(-0.53%)	(-1.09%)	(-1.29%)	(-2.54%)
Government consumption	11174.9	11579.8	12007.6	12034.9	12849.4
		(3.62%)	(7.45%)	(7.70%)	(14.98%)
Export	30476.0	30374.2	30275.5	30013.6	29575.6
		(-0.33%)	(-0.66%)	(-1.52%)	(-2.95%)
Import	29012.1	28910.3	28811.6	28549.8	28111.7
		(-0.35%)	(-0.69%)	(-1.59%)	(-3.10%)

Unit: billion RMB; numbers in parentheses are the changes compared to S2 BaU.

However, some other studies on environmental taxes show that imposing the taxes will not necessarily lead to the GDP loss, which is called the double dividend (Goulder, 1995). It assumes if the government carefully adjusts the tax policy and use the environmental tax to replace other existing taxes which also have distortion effects, the overall GDP might not be reduced. Nevertheless, there are still many debates on the double dividend, since it requires the tax policy to be very accurate and deliberate. Xiao et al. (2015) discuss different tax refund mechanisms after the environmental tax is imposed, and the results show that if the environmental tax revenue will be refunded to the enterprises or households, the GDP loss will be reduced, but the emission reduction effect on pollutants will also be reduced. Though this thesis does not consider the double dividend effect, future research could be done in this field.

As for the policy implications, since the Environmental Protection Tax Law gives the local governments a lot of authority and freedom in implementing the environmental taxes, it is suggested that local governments should design the tax scheme systematically and adjust it to their specific situations. For example, regions like Beijing which have a good economic condition, but heavy pollution could consider higher tax levels, while regions in western China which have great demand for economic development could start from lower tax levels. There are some other ways for the local governments to balance environmental protection and economic development. For example, it is regulated that the local governments could receive all the environmental tax revenue in its region and determine how to use the tax revenue for environmental protection and pollution management. Thus, the GDP loss might be lower if the local governments refund some of the tax revenue to award companies with lower emissions or invest in clean technologies. These specific policy scenarios could be studied in future research.

6.2.2 Sectoral output

Figure 6-7 presents the sectoral output changes in the policy scenarios compared to the BaU scenario in 2030. In each policy scenario, most sectors will suffer from an output loss, except the environmental management sectors and the less polluting sectors, like the service sector and the agriculture sector, and the clean energy sectors which include the hydroelectricity, nuclear power, and renewable energy sectors. For example, in the LowET scenario, the coal-fired electricity sector, the mining sector, and the non-metal processing sector will suffer from an output loss of around or more than 1 %. These sectors are either highly polluting or energy-intensive. For the highly polluting sectors, the environmental tax will directly increase their production costs and lead to a decrease in their demands. As for the energy-intensive sectors, since the energy sector itself is highly polluting and the energy price will rise after levying the environmental tax, the production costs in the energy-intensive sectors will also increase. If we calculate the environmental tax payable in each sector and divide by the output of each sector in the base year, we can find one of the most polluting commodities is the electricity. Thus, when the environmental tax is levied, the energy-intensive sector also suffers from a considerable output loss due to the indirect impacts of increased energy prices.

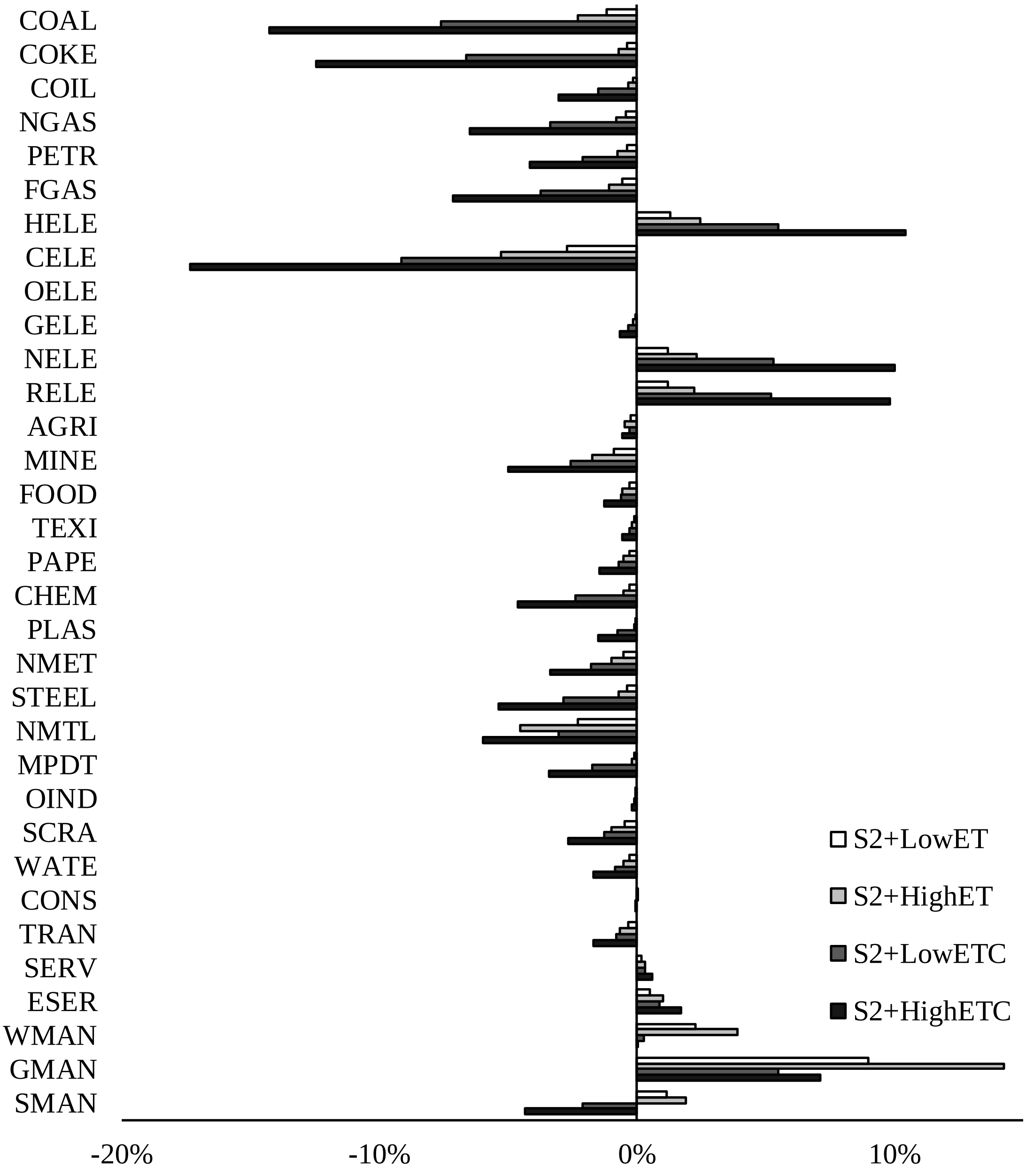


Figure 6-7: Policy impacts on sectoral output compared to S2 BaU scenario in 2030

Comparing among different policy scenarios, the results show that when the tax rate is higher, the negative or positive impacts on sectoral outputs will also be more apparent. According to the parameter setting in Table 5-2, the tax levels in the HighET scenario is as twice as that in the LowET scenario. The output changes of most sectors in the HighET scenario are slightly higher than twice as that in the LowET scenario, and this is also consistent with the changes on the macroeconomic indicators as shown in Table 6-6.

It can be observed that the environmental and carbon taxes have a significant influence on the electricity production sectors. The aggregated electricity sector will suffer from an output loss of 0.81%, 1.61%, 2.24% and 4.28% in the LowET, HighET, LowETC and HighETC scenarios, respectively. Within the electricity sector, the production structure will be changed significantly. The output share of coal power in the aggregated electricity sector is 49.8% in the BaU scenario but will be reduced to 48.9%, 48.0%, 46.3% and 43.0% in the LowET, HighET, LowETC and HighETC scenarios, respectively. In the meantime, the output share of other clean electricity technology will increase. For example, the share of renewable energies will be increased from 14.4% in the BaU scenario to 16.6% in the HighETC scenario.

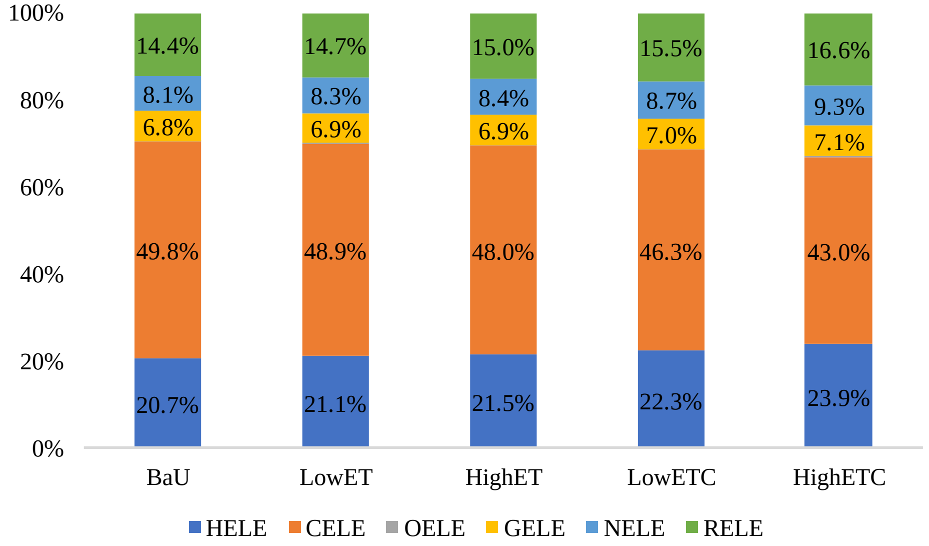


Figure 6-8: Policy impacts on the structure of generation mixes in 2030

These changes are basically consistent with the results in the studies of China's Low Carbon Development Pathways by 2050 (Dai et al., 2009), that the share of coal fire electricity might range from 35.4 % to 58.3 % in different policy situations. It should be noticed that this study does not consider other policy constraints or natural resource constraints in the energy sectors. For example, the output of hydroelectricity relies not only on the market price comparison but also on the construction of hydropower station, which will take a long time and may face many other problems. These constraints are not included in the model but should be considered when facing real situations.

6.2.3 Pollutant emission

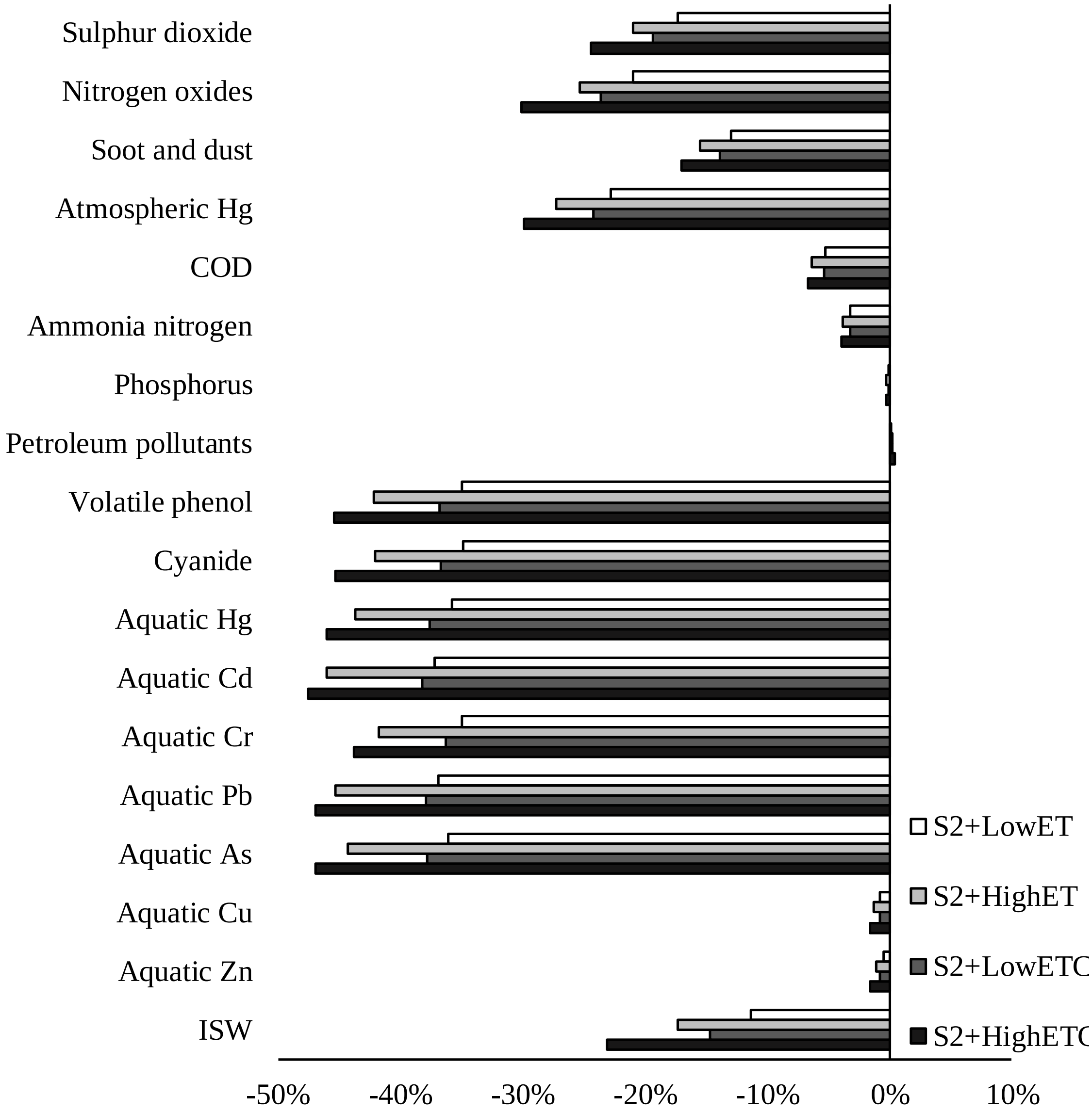


Figure 6-9: Policy impacts on emissions compared to S2 BaU scenario in 2030

Figure 6-9 shows the policy impacts on pollutant emission compared to the BaU scenario. Among the policy scenarios, the results show that when the tax level increases, the emission of most kinds of pollutants will reduce more. Other studies that mainly focus on the air pollutants give similar results in terms of the reduction effects. According to Xiao et al. (2015), the SO_2 will be reduced from 4.55 % to 13.06 % under different tax levels, whose reduction effects are lower than the simulation results in this thesis. The main reason is that after introducing the environmental management sectors in the models of this thesis, the production sectors could reduce the emissions by adding up the inputs of environmental management services, but this mechanism is not considered in Xiao's model.

The results also show that, in each policy scenario, the reduction effects vary a lot among different kinds of pollutants. The emission of gas pollutants, including the SO_2, NOx, soot and dust, and atmospheric Hg, will be largely reduced in each scenario. However, the reduction effects of some water pollutants are not very apparent. The emission of petroleum pollutants will even increase a little. This is because these pollutants are mainly emitted from the service industry, while the service industry experiences an output growth in the policy scenarios, so the emission of these pollutants will also be increased. It shows that some extra efforts are needed if we want to decrease the specific emissions which mainly comes from the service industry, like introducing new technology to treat these pollutants or improve the production processes and reduce emission factors of these pollutants.

6.2.4 Carbon emission

Figure 6-10 shows the carbon emission in the BaU scenario and the policy scenarios from 2012 to 2030.

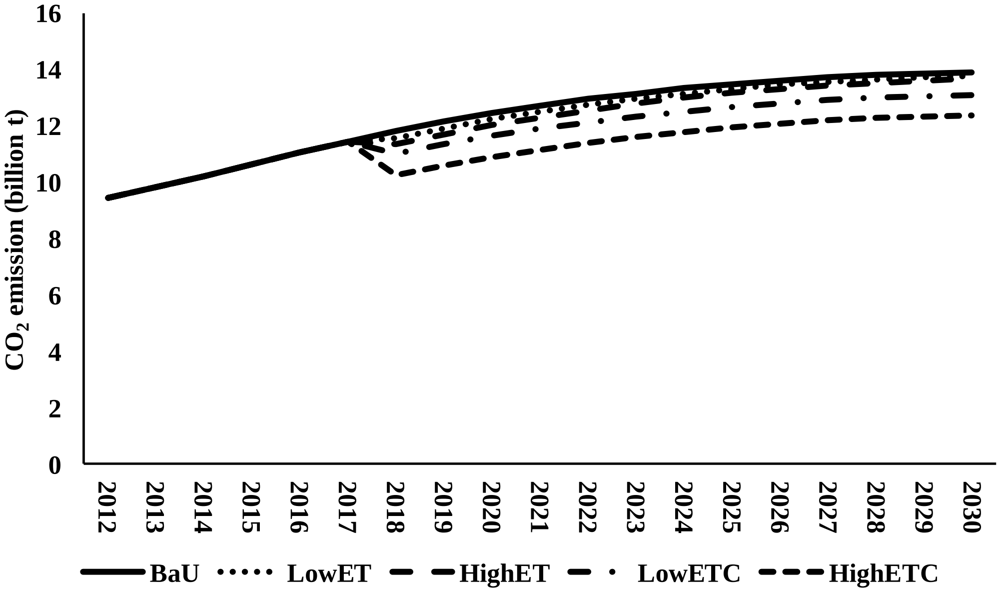


Figure 6-10: CO_2 emission in different policy scenarios

As discussed in Section 6.1.3, the BaU scenario of S2 will fulfill China's NDC goal, that the CO_2 emission will peak or reach a plateau before 2030. In the policy scenarios, when the policy shock is exerted in the year of 2018, a sharp decrease will happen in that year and then the carbon emission will gradually bounce back, but still lower than the BaU level. This is because sectors will experience the biggest shock in the first year, and as the market gradually adjusts its structure to adapt to the new policy and absorb the policy's influence.

The results show that environmental taxes have a synergy effect of reducing carbon emissions. As shown in the LowET and HighET scenarios, the carbon emission also decreases compared to the BaU scenario. By 2030, the carbon emissions in the LowET and HighET are 0.9 % and 1.7 % lower than the BaU scenario, respectively. Despite this co-benefit effect, the carbon emission could be reduced more rapidly in carbon tax scenarios. The carbon reduction rate in the LowETC scenario is 5.8 % and will increase to 11.0 % in the HighETC scenario. This shows that the carbon tax has more direct and significant impacts on reducing the carbon emission, and it is still a necessary measure if China wants to achieve a higher goal of carbon reduction.

6.2.5 Comparison with models not separating pollution treatment sectors

In this Section, we will discuss the benefits of disaggregating pollution treatment sectors. In the first step, we build a CGE model without disaggregating pollution treatment sectors (naming as Model 2, as shown in Figure 6-11), and all the other input data and model settings are the same as the original model (naming as Model 1).

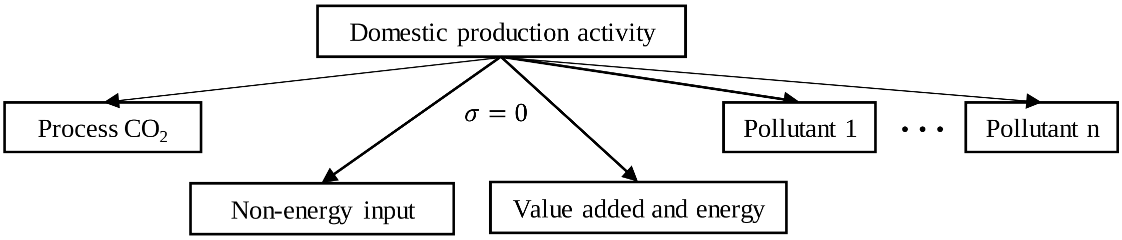


Figure 6-11: Production structure of the comparison model 2 (not disaggregating pollution treatment sectors)

Then, we choose the middle road scenario S2 BaU as the baseline scenario and conduct the policy shocks to the baseline scenario when high environmental tax and carbon tax are levied (the HighETC policy setting). The results are shown in the following tables, in contrast to the results in the original model settings.

Table 6-7 shows the changes in macroeconomic indicators and Figure 6-12 shows in the changes on sectoral outputs. After imposing pollution tax on the emissions from all the production sectors, the results show that the negative impacts in Model 2 (without disaggregating pollution treatment sectors) are a little larger than those in Model 1 (disaggregating pollution treatment sectors), but the difference is not large in the economic indicators. This could be explained by the fact that Model 2 only relates pollution information to the CGE model via emission coefficients, and the only way to reduce pollution is to reduce output levels. Therefore, faced with the rising pollution tax and carbon tax, the economic losses in Mode 2 is larger. However, as the environmental tax only accounts for a small part of the total production cost, the negative impacts on overall economic performance are still limited.

Table 6-7: Comparison of policy impacts in different types of models

	Original Model 1 (disaggregating pollution treatment sectors)	Comparison Model 2 (not disaggregating pollution treatment sectors)
GDP	-0.34%	-0.35%
Household consumption	-2.54%	-2.69%
Government consumption	14.98%	16.05%
Export	-2.95%	-3.23%
Import	-3.10%	-3.40%

Note: policy impacts on macroeconomic indicators in 2030 (compare S2 HighETC to S2 BaU)

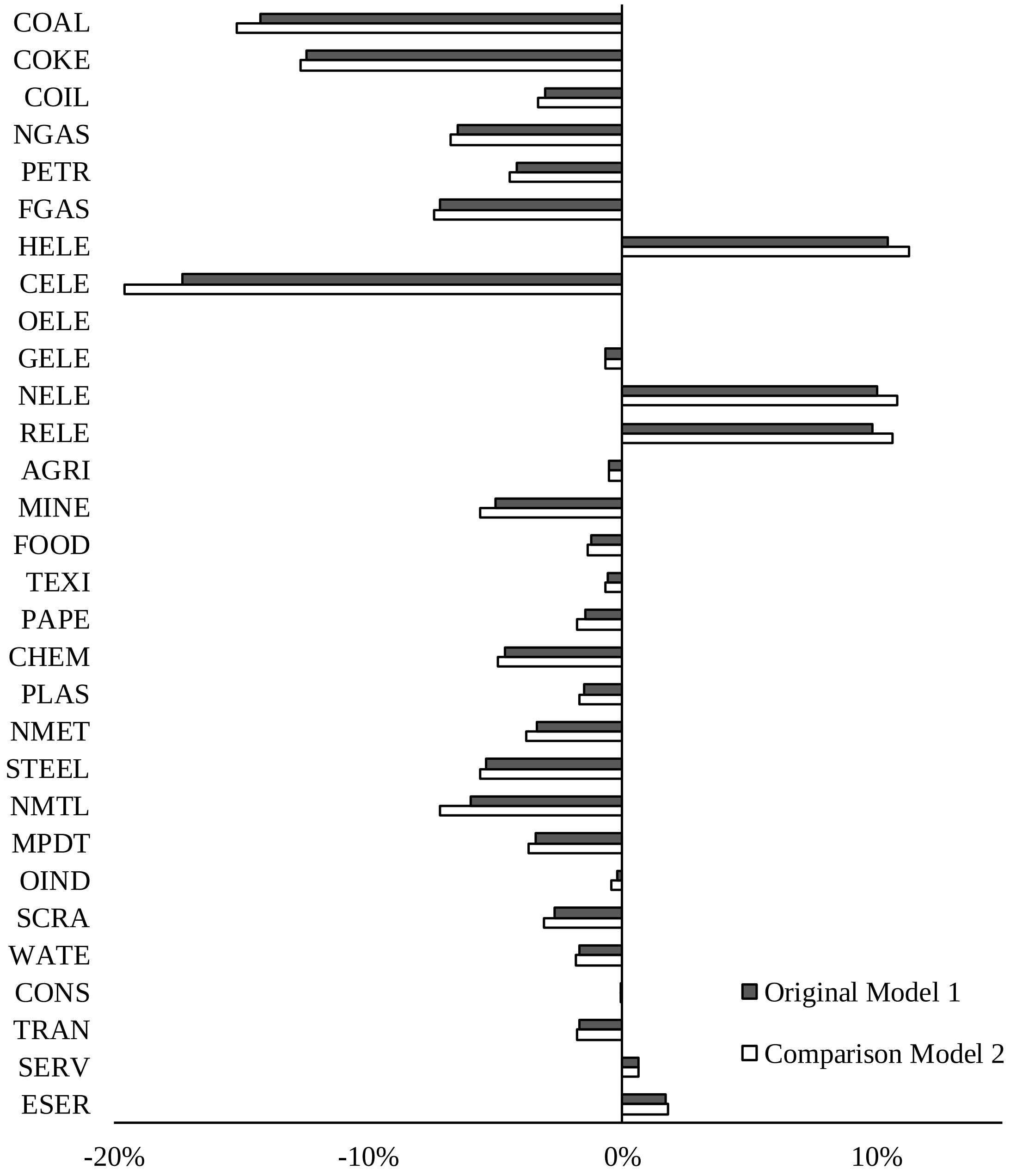


Figure 6-12: Comparison of policy impacts on sectoral outputs in 2030 in different types of models (compare S2 HighETC to S2 BaU)

Figure 6-13 shows the changes in pollutant emissions between the two models. It clearly shows the reduction impacts in Model 1 (disaggregating pollution treatment sectors) much larger than those in Model 2 (without disaggregating pollution treatment sectors). This is because when the tax levels are raised, the production sectors could choose to invest more on the pollution treatment other than only reduce the overall production levels in Model 2. The results show that the environmental benefits of environmental tax will be much larger if we take into consideration the investment particularly on pollution treatment in CGE models, which is also more reasonable in the real case.

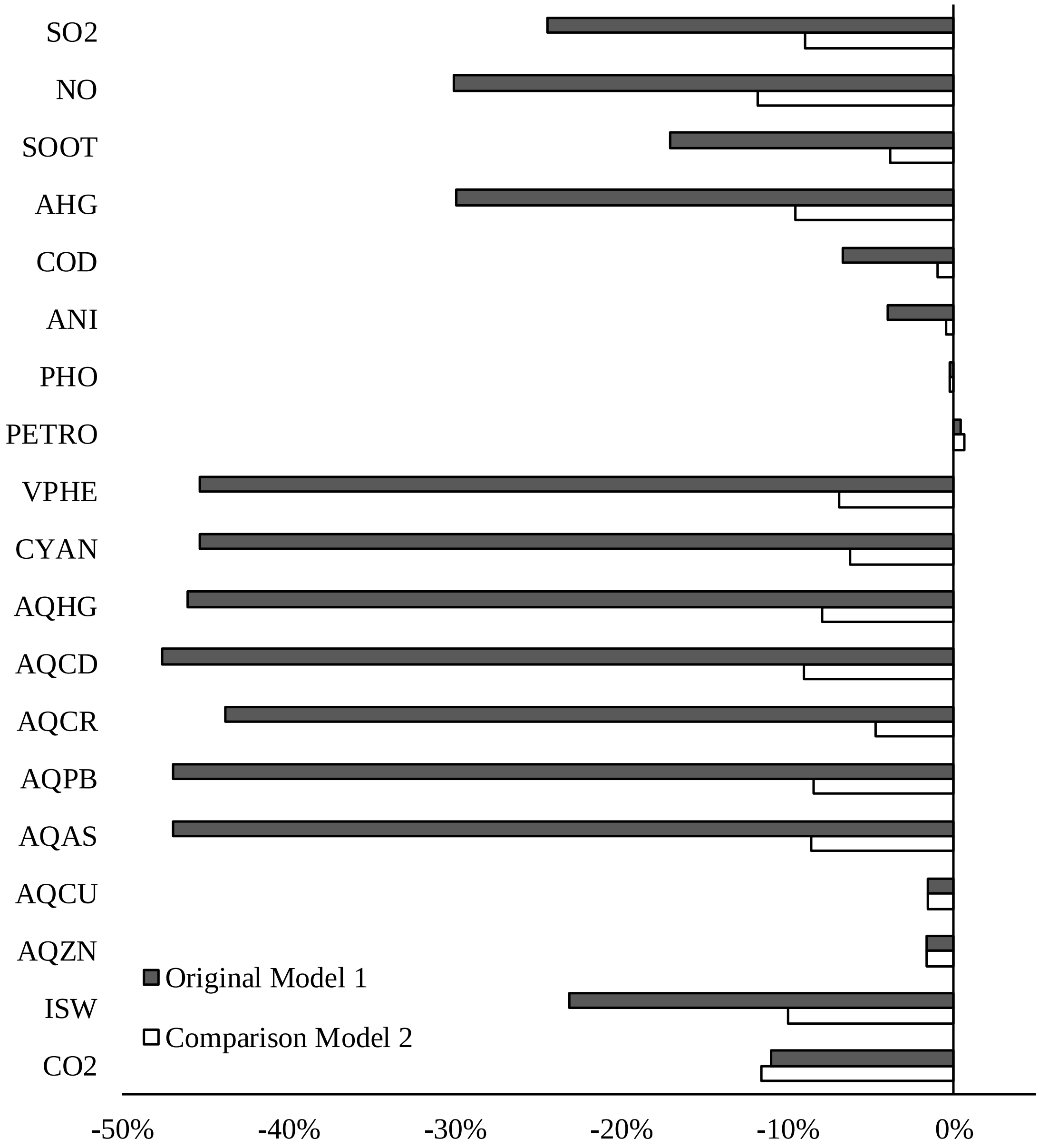


Figure 6-13: Comparison of policy impacts on carbon and pollutant emissions in 2030 in different types of models (compare S2 HighETC to S2 BaU)

6.3 Environmental policies in the sustainable socio-economic condition

While Section 6.2 simulates the policy effects in the middle road scenario of S2, this section will analyze the policy influence in the sustainable scenario of S1. There are mainly two reasons for repeating similar simulations. Firstly, though the middle road scenario seems to be the “expected” or “average” scenario in the future, the sustainable development scenario is what the governments are working hard for. Secondly, the policy effects large rely on the macro socioeconomic environment, and by comparing the policy effects in S1 and S2, we could better understand how the policy effects would change along with the general economic situation and provide tailored policy implications in different scenarios.

In Section 6.3.1, the simulation results are presented as the same framework and order as that in Section 6.2.1. In Section 6.3.2, we compare the simulation results in Section 6.2.1 and Section 6.3.1 by the absolute values and the relative changes. The aim is to gain a deep understanding of how the outside environment affects the policy effects.

6.3.1 Simulation results

Table 6-8 presents the policy impacts on the major macroeconomic impacts in 2030 when S1 is chosen as the BaU scenario. The results show similar trends as in Section 6.2.1 that more stringent environmental policies will bring negative effects on almost all the macroeconomic indicators, except on the government consumption. Because the government will gain more tax income and its expenditure will increase if it will not save more or transfer more to other accounts. On the other hand, the economic impacts here are not very huge. This is partly because the GDP in S1 is the highest in the three baseline scenarios and the relative changes compared to such a huge base is smaller than in other scenarios, and partly because the pollutant emissions in S1 are indeed lower than in other scenarios and the impacts of environmental policies are thus also limited.

Table 6-8: Policy impacts on macroeconomic indicators in 2030 (S1 as BaU)

	BaU (S1)	LowET (S1)	HighET (S1)	LowETC (S1)	HighETC (S1)
GDP	154,508.44	154,480.68	154,458.02	154,335.66	154,162.34
		(-0.02%)	(-0.03%)	(-0.11%)	(-0.22%)
Household consumption	91,509.95	91,172.07	90,820.91	90,629.42	89,784.60
		(-0.37%)	(-0.75%)	(-0.96%)	(-1.89%)
Government consumption	12,026.11	12,336.22	12,664.73	12,733.86	13,405.35
		(2.58%)	(5.31%)	(5.89%)	(11.47%)
Export	34,900.21	34,808.33	34,718.90	34,454.59	34,035.97
		(-0.26%)	(-0.52%)	(-1.28%)	(-2.48%)
Import	33,436.32	33,344.44	33,255.01	32,990.69	32,572.08
		(-0.27%)	(-0.54%)	(-1.33%)	(-2.58%)

Unit: billion RMB; numbers in parentheses are the changes compared to S1 BaU.

Figure 6-14 presents the policy impacts on sectoral outputs in 2030 when S1 is chosen as the BaU scenario. The industries most affected are the fossil fuel sectors, the mining sector, the chemical sector, the energy-intensive and high-emission sector like the steel making sector, and so on. The less polluted sectors like the clean energy sectors, the service sector, and the environmental management sectors will gain output growth.

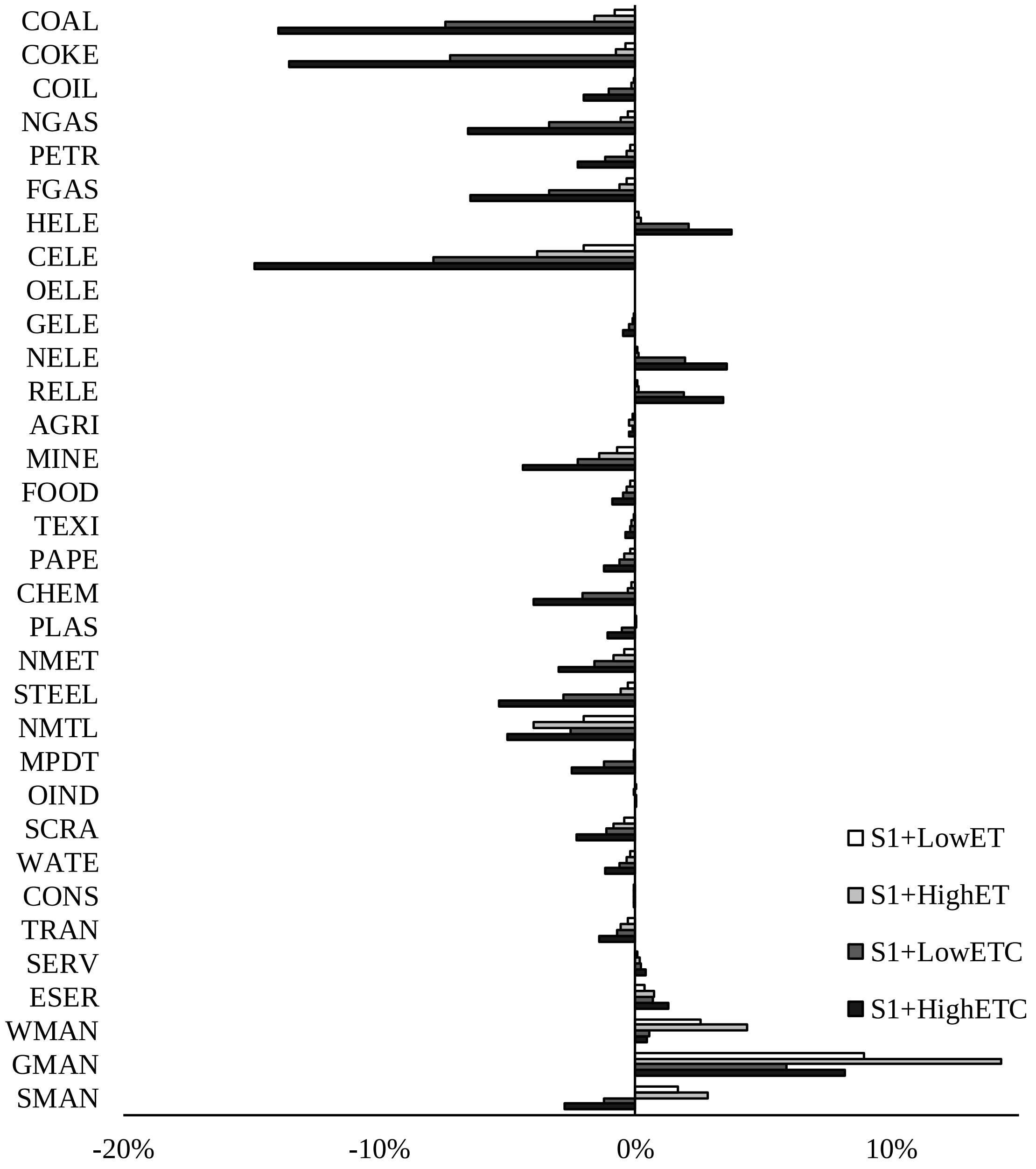


Figure 6-14: Policy impacts on sectoral output compared to S1BaU scenario in 2030

Figure 6-15 shows the change in generation mix in 2030. The environmental policies, especially the carbon tax, will drive the low-carbon transition in the power sector. The share of the coal-fired sector will decrease to 31.9% in the HighETC scenario when it is only about half of its current share. On the other hand, the percentage of renewable energies will boost into 18.7%, almost six times as the 2012 share of 2.8%. This change of generation mix will profoundly shape China's energy structure, and influence all energy-related consumptions, productions, and emissions.

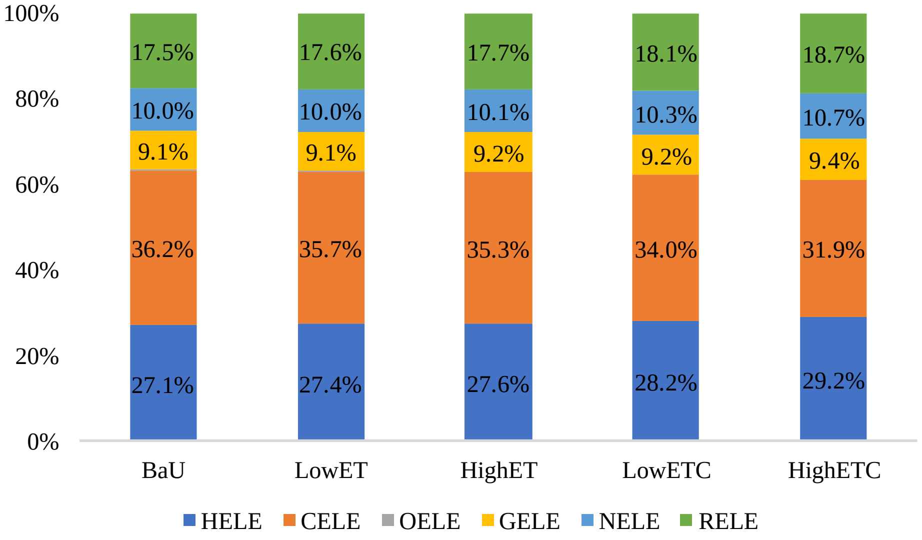


Figure 6-15: Policy impacts on generation mixes in 2030 (S1 as BaU)

Figure 6-16 presents the CO_2 emission curve when S1 chosen as the BaU scenario. All the scenarios presented in the graph will peak carbon emissions around 2022 and mainly differ in the magnitude of the peak value. The peak value could be reduced by about 1.5 Gt from the BaU scenario to the HighETC scenario. If compared with the S3 BaU scenario where the carbon emission could be as high as 15.4 Gt by 2030, a considerable amount of 4.4 Gt of CO_2 could be reduced in the S1 HighETC scenario.

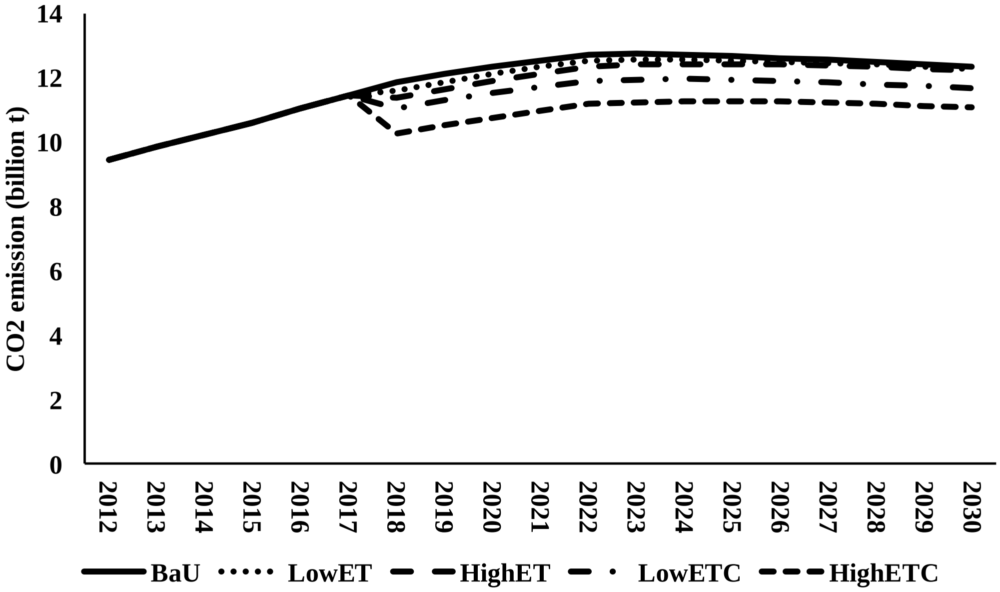


Figure 6-16: CO_2 emission in different policy scenarios (S1 as BaU)

Figure 6-17 presents the policy impacts on pollutant emissions in 2030 when S1 chosen as the BaU scenario. Generally, most pollutants will be reduced by more than 10% in different policy scenarios. However, the policies seem to be ineffective to reduce some pollutants like the phosphorus and petroleum pollutants, mainly since they mainly stem from the emissions in the service sector. This situation is similar as in Section 6.3.1 because the output of the service sector will increase in the policies scenarios and thus has little help to reduce these specific pollutants. It means that special efforts need to be put in to tackle these pollutants.

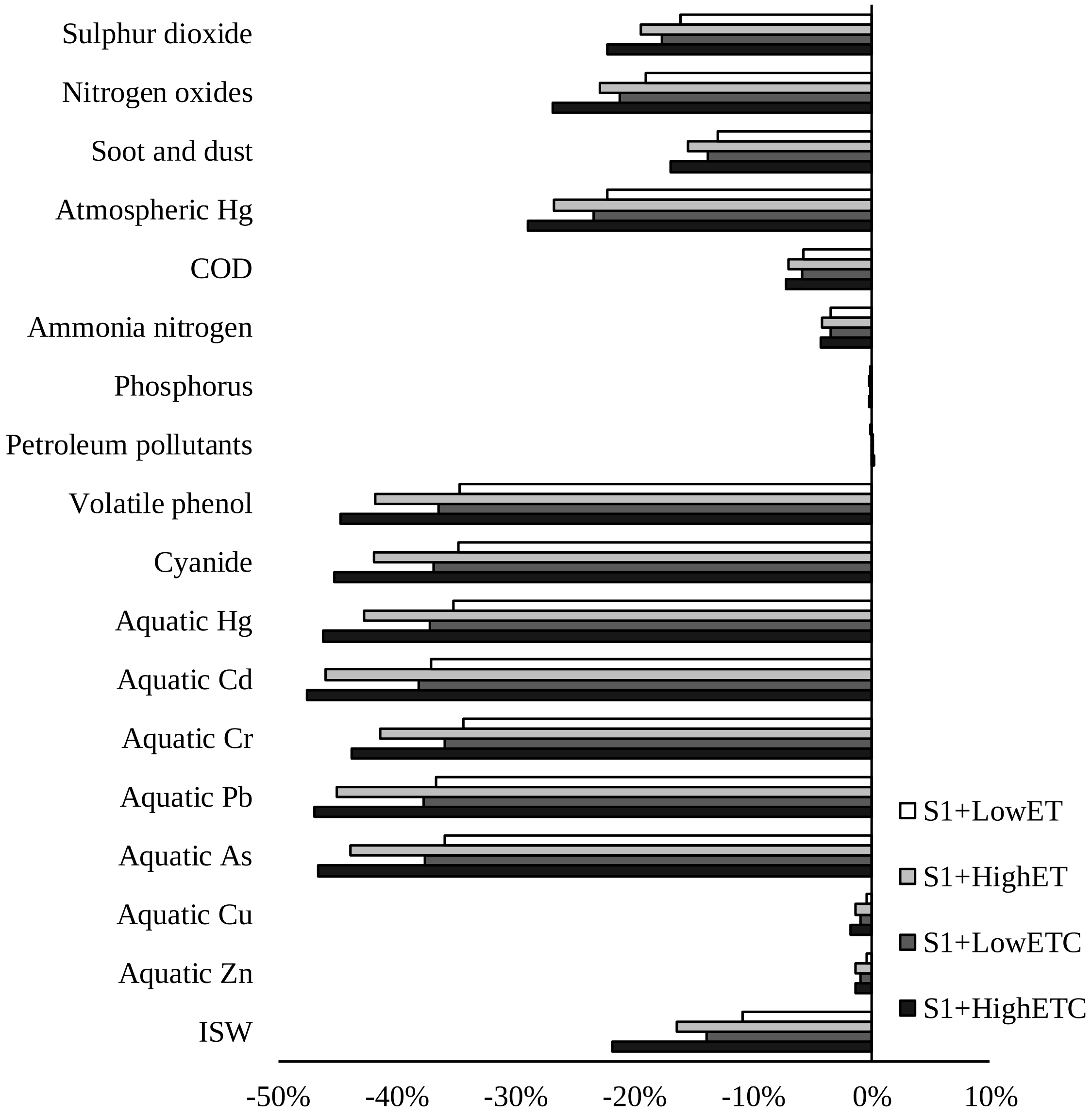


Figure 6-17: Policy impacts on pollutant emissions in 2030 (S1 as BaU)

6.3.2 Comparison with simulation results in the middle road condition

There are two main features of the policy effects when comparing S1 or S2 is chosen as the BaU scenario. The first feature is that no matter which baseline scenario is chosen as the BaU scenario, there are negative impacts on the economic indicators, but the degree of influence is different. Take the change of GDP for example. As shown in Table 6-6 and Table 6-8, if the highest level of pollutant tax and carbon tax are levied, the GDP loss is 0.22 % when S1 is the BaU scenario and rises to 0.34 % when S2 is chosen as the BaU scenario. It is shown that the relative changes on the economic indicators are smaller when S2 serves as the BaU scenario. This could explain by the high baseline value in S1 and the fact that the emission levels in S1 are lower thus environmental policies are less influential. The changes in sectoral output also show similar characteristics. The negative impacts on sectoral outputs in HighET and HighETC are almost twice as large as in LowET and LowETC scenarios, respectively. The level of impacts in S2 scenarios is slightly smaller than that in S1 scenarios.

The second feature is that in absolute values, S1 scenarios are much more economically developed and environmentally sustainable than all the S2 scenarios. For example, the GDP value by 2030 in S2 is 11.31% lower than that in S1, much larger than the GDP loss caused by environmental policies. It means that the negative economic impact could be negligible compared to the existing huge gap between different baseline scenario. Another example is CO_2 emissions. As shown in Figure 6-18, the lowest carbon emission in 2030 in S2 scenarios is about 12.4 Gt in the “S2+HighETC” scenario, which is higher than the level in S1 BaU scenario already. This shows that even without carbon policies, all S1 scenarios are more low-carbon than any S2 scenario.

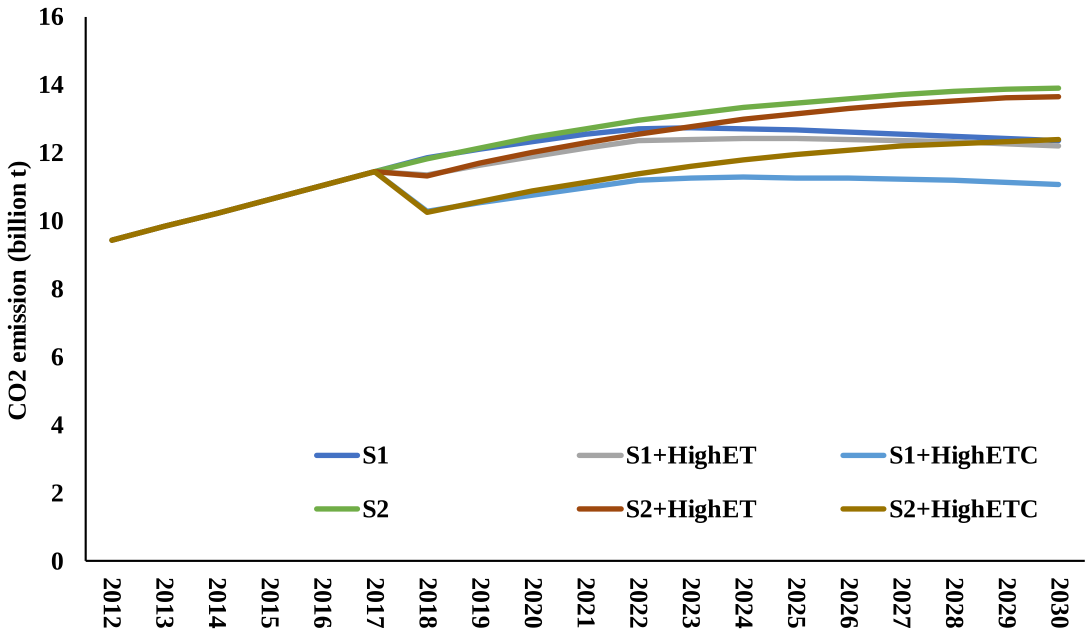


Figure 6-18: CO_2 emission in different policy scenarios

An important lesson we could learn from the comparisons is that pursuing the sustainable pathway maybe is more effective than implementing the environmental policies. Recalling from the scenario setting in Section 5.1, the significant differences between S1 and S2 are productivity improvement rates for factors, technologies, and pollutant emission reductions. However, these improvements, especially technology improvements, partly depend on governmental policies and partially rely on the technology evolution, and partly depend on the development of market competition, and so on. Though how to most effectively pursue the S1 scenario is not the focus of this thesis, the settings of scenario parameters indicate that higher productivity and better technology, the environmental problems could be tackled with less environmental impacts.

Another important takeaway concerning the carbon emissions is that the carbon tax policy matters. Though it might be difficult to pursue the S1 scenario, it is possible to reduce the carbon emission to the S1 level with a GDP loss of 0.34% in the S2 setting. Given the severe challenge in climate change, it is a feasible solution if the situation continues to deteriorate. Of course, no matter in which scenario, China’s carbon emission will still be more than 10 Gt by 2030, and a deep decarbonization pathway still needs to be pursued in a longer time horizon.

6.4 Sensitivity analysis

The results of CGE rely on the parameter assumptions in the modelling structures and scenario settings, and sensitivity analysis is needed to test the robustness of the model. For this study, since we focus on the environment and carbon policies, we will focus on the sensitivity analysis of the most related parameters. Therefore, the sensitivity analysis is conducted on the elasticity of substitution between capital and energy inputs, the substitution elasticity between pollution treatment and pollution discharge, and the sectoral pollutant emission factors. Based on S2 BaU and four policy scenarios, we assume a 10% increase or decrease of the elasticity parameter σ_{ke} and the elasticity parameter σ_{env} and examine the changes in GDP and CO_2 emissions. Besides, we also suppose the sectoral emission factors of all kinds of pollutants decrease by 10% since 2018 and examine the emission amounts of SO_2, COD, and ISW. The results are displayed in Table 6-9 to Table 6-11.

Table 6-9: Sensitivity analysis on substitution elasticity of capital and energy

	σ_{ke}	BaU	LowET	HighET	LowETC	HighETC
GDP	+10%	137,104.01	137,059.14	137,018.77	136,877.34	136,632.95
(billion yuan)			(-0.03%)	(-0.06%)	(-0.17%)	(-0.34%)
	0	137,031.79	136,987.50	136,947.75	136,806.73	136,563.96
			(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
	-10%	136,962.60	136,918.87	136,879.71	136,739.04	136,497.78
			(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
CO_2	+10%	138,998.56	137,764.96	136,577.34	130,846.10	123,582.05
(million t)			(-0.89%)	(-1.74%)	(-5.87%)	(-11.09%)
	0	139,142.14	137,920.52	136,742.06	131,076.96	123,870.74
			(-0.88%)	(-1.72%)	(-5.80%)	(-10.98%)
	-10%	139,302.59	138,092.98	136,923.56	131,324.74	124,175.66
			(-0.87%)	(-1.71%)	(-5.73%)	(-10.86%)

Note: numbers in the syntheses are the changes compared to the S2 BaU in 2030; "+10%" or "-10%" means how the parameter changes compared to the level used in the thesis.

The elasticity of substitution between capital and energy inputs determines to what extent the capital input could replace energy inputs. In the original model, the value of substitution elasticity of capital and energy is 0.3 (Xiao et al., 2015) in all the sectors. The results show that the relative changes among different scenarios do not change much as σ_{ke} varies. Within each scenario, if σ_{ke} increases by 10%, the GDP will increase by about 0.05%, and the CO_2 emission will decrease by 0.10% to 0.25% in different situations.

Table 6-10: Sensitivity analysis on elasticity of pollution treatment and discharge

	σ_{env}	BaU	LowET	HighET	LowETC	HighETC
GDP	+10%	137,031.76	136,987.56	136,949.02	136,807.03	136,566.09
(billion yuan)			(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
	0	137,031.79	136,987.50	136,947.75	136,806.73	136,563.96
			(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
	-10%	137,031.82	136,987.45	136,946.43	136,806.44	136,561.77
			(-0.03%)	(-0.06%)	(-0.16%)	(-0.34%)
CO_2	+10%	139,142.99	137,961.87	136,836.99	131,115.81	123,954.71
(million t)			(-0.85%)	(-1.66%)	(-5.77%)	(-10.92%)
	0	139,142.14	137,920.52	136,742.06	131,076.96	123,870.74
			(-0.88%)	(-1.72%)	(-5.80%)	(-10.98%)
	-10%	139,141.29	137,877.92	136,643.94	131,036.94	123,783.94
			(-0.91%)	(-1.79%)	(-5.82%)	(-11.04%)

Note: numbers in the syntheses are the changes compared to the S2 BaU in 2030; "+10%" or "-10%" means how the parameter changes compared to the level used in the thesis.

The substitution elasticity between pollution treatment and pollution discharge relates to the effectiveness of pollution treatment. If the elasticity is higher, the same amount of treatment could more emissions. In a policy scenario, the model will choose to apply more inputs pollution treatment to reduce the policy impacts, and the GDP loss will be lower. In the original model, the value of substitution elasticity of pollution treatment and discharge is 0.2 in all the sectors. In the results, the GDP in the BaU scenarios are almost the same when the elasticity changes by 10%, and we can observe that in the policy scenario with higher σ_{env}, the GDP is a little bit higher, though the difference in percentages is too small to distinguish.

Table 6-11: Sensitivity analysis on sectoral pollutant emission factors

	Relative changes	BaU	LowET	HighET	LowETC	HighETC
SO_2	0	141.87	117.24	112.11	114.48	107.17
			(-17.36%)	(-20.98%)	(-19.31%)	(-24.46%)
	-10%	127.66	105.24	100.64	102.78	96.23
			(-17.56%)	(-21.16%)	(-19.49%)	(-24.62%)
COD	0	167.49	158.74	156.82	158.52	156.34
			(-5.23%)	(-6.37%)	(-5.35%)	(-6.66%)
	-10%	150.73	142.81	141.09	142.62	140.67
			(-5.25%)	(-6.40%)	(-5.38%)	(-6.68%)
ISW	0	7.22	6.40	5.97	6.17	5.56
			(-11.38%)	(-17.33%)	(-14.64%)	(-23.10%)
	-10%	6.49	5.75	5.36	5.53	4.98
			(-11.45%)	(-17.42%)	(-14.72%)	(-23.20%)

Unit: 100 million standard unit; numbers in the syntheses are the changes compared to the S2 BaU scenario in 2030; "+10%" or "-10%" means how the parameter changes compared to the level used in the thesis.

As for the sectoral emission factors, the relative changes in pollutant emissions among different scenarios also do not change much. Within each scenario, if all the emission factors decrease by 10%, the emission of pollutants will decrease by about 10%. The sensitivity analysis shows that the relative changes among different policy scenarios of the CGE model are stable, but the absolute values in each scenario rely on the parameter assumptions.

7. Findings, conclusions, and future work

This thesis builds a dynamic environmental CGE model with detailed sectoral emission data and disaggregated electricity sectors to analyze the policy impacts of the latest China's environmental tax regulations in different socio-economic scenarios. It has re-confirmed that the CGE models are useful analytical tools for environmental policies, which combines the perspectives of environment, economy, and energy. Extended from the standard CGE framework, this thesis compiles and adds pollution treatment sectors to adequately represent the interactive mechanisms among different sectors and the pollution treatment activities, which is an improvement in modeling technique compared to the many previous models that only introduce pollution via the exogenous emission factors without any impact mechanism on the production structure.

7.1 Findings

The simulations on different socioeconomic conditions show that:

- the expected GDP by 2030 could reach about 154.5 trillion RMB in the most sustainable condition S1, almost 20% higher than that in the least sustainable condition S3. The other main indicators also show similar trends that the economic situation in S1 is the best among three baseline conditions, and the S3 is the worst, and the S2 is in the middle.
- the electricity generation mix will change to a green structure in all socio-economic conditions but at a much fast pace in the case of S1. The share of coal-fired electricity will be reduced from 75% in 2012 to 35% ~ 60% in 2030 in various socioeconomic conditions. In the meantime, the share of renewable energies will quickly increase from 3% in 2012 to 10% ~ 18% in 2030 in different conditions.
- the carbon emissions will peak by 2030 in both S1 and S2 situations but whether peaking at the level of 12.7 Gt or at 14.0 Gt makes a big difference to the global carbon budget. However, the carbon emission will continue to grow in S3 which doesn't fulfill China's promise in the NDC and reach an annual emission of about 15.5 Gt in 2030.

- most kinds of pollutant emissions in all three socioeconomic conditions will decrease a lot compared to the baseline situation of the 2012 level, like the SO_2 emissions will be 40% ~ 60% lower than the 2012 level. However, the emissions of some pollutants will not necessarily decrease a lot, like the soot and dust, atmospheric Hg, petroleum pollutants, volatile phenol, and aquatic Cr. This could be explained by the major sources of different pollutants and shows that extra efforts need to be put to tackle the pollutants mainly from the service sector and agriculture sector.
- in the high sustainable condition S1, the total waste management cost will rise to 585.0 bil CNY and the percentage of GDP will decrease to 0.38% by 2030. While in the least sustainable condition S3, the total waste management cost will rise to 700.1 bil CNY with a percentage of 0.57% of GDP by 2030.

Based on the middle road socioeconomic scenario S2, this thesis constructs four policy scenarios with different levels of pollution tax and carbon tax. The results show that:

- the additional pollution and carbon tax would lead to a GDP loss of 0.03%, 0.06%, 0.16%, and 0.34% in the LowET (low pollution tax), HighET (high pollution tax), LowETC (low pollution tax and low carbon tax), HighETC (high pollution tax and high carbon tax) scenarios, respectively.
- heavy polluted or energy-intensive sectors will suffer more loss in the environmental tax scenarios, but the agriculture, service and pollution treatment sectors will experience output growth. For example, the coal-fired electricity sector’s output will reduce by 17.3% in the high pollution tax and high carbon tax scenario.
- in the policy scenarios, the emissions of CO_2 and many types of pollutants will be reduced significantly. The SO_2 emissions will be reduced by 17.4%, 21.0%, 19.3%, and 24.5% in the LowET, HighET, LowETC, HighETC scenarios, respectively. However, as for some pollutants like phosphorus and aquatic Cu which are mainly emitted from the agriculture and service sectors, their emissions will not necessarily be reduced.

An important feature of the CGE model in this thesis is to disaggregate the pollution treatment sectors. When comparing the simulation results with CGE models not disaggregating pollution treatment sectors, the results show that the GDP loss or sectoral output losses are similar in the policy scenarios, but the policy effects on reducing pollution emissions are quite different. For example, in the high pollution tax and high carbon tax scenario, the SO_2 emission will decrease by 24.5% in this thesis's model, much higher than 8.95% in a CGE model not disaggregating pollution treatment sectors. This is because if not separating pollution treatment sectors, pollution information is related to the production sectors only via emission coefficients, and the only way to reduce pollution is to reduce output levels but not to increase the pollution treatment input in the original production structure.

Lastly, since simulation results would vary among different socioeconomic conditions, this thesis compares the policy effects of environmental and carbon tax in S1 and S2. The results show that no matter which baseline socioeconomic condition is chosen as the BaU scenario, there are negative impacts on the economic indicators, but the degree of influence is different. The relative changes on the economic indicators are smaller when S1 serves as the BaU scenario compared to S2, which could be explained by the high baseline value in S1, and the fact that S1 condition is more sustainable with lower emission levels.

7.2 Conclusions

This thesis develops a CGE model with disaggregated pollution treatment sectors to fully assess the pollution tax and carbon tax policies. Based on the numerical simulation results, the key conclusions are summarized from various aspects as follows.

From the perspective of pollution tax policies, the simulation results show that additional environmental tax will bring negative but limited impacts on economic performance. Compared to China's real GDP growth rate in 2018 of 6.6% (NBS, 2019), the largest GDP loss in the highest pollution tax and carbon tax (HighETC) scenario is only 0.34% when the middle road socioeconomic situation S2 is taken as the baseline scenario. This is a very important message for policymakers, since most concerns in environmental policies are about its negative economic influence. However, the real impacts of environmental policies also rely on a lot of internal and external factors, like the general socioeconomic situation and the specific implementation procedures of certain policies.

In general, good macroeconomic environment and appropriate deployment is essential to the successful implementation of environmental policies. For example, as the share coal-fired electricity goes down in the policy scenarios, policymakers should be aware of many potential problems are not reflected in the model, like the massive layoff of mining workers and the urgency of steady reply of electricity to households and enterprises.

From the perspective of carbon tax policies, though not levied yet, the simulation results find the necessity to introduce the carbon tax if China aims to reduce the carbon emission at a high ratio. A synergy effect has been observed that levying the environment tax could also help the carbon emission, but the positive impact is limited. In the middle road socioeconomic situation S2, the carbon emissions in the LowET and HighET scenarios are 0.9 % and 1.7 % lower than the BaU scenario but will be about 10% even lower after high carbon tax is levied. Besides, the environmental tax and carbon tax could accelerate the green transitions within the electricity sector that coal electricity and gas electricity will gradually transform into other clean electricity generation technologies.

From the perspective of CGE modeling, this thesis confirms the importance of disaggregating pollution treatment sectors when studying environmental tax in CGE modeling. The comparison between different types of models shows that if the impact of environmental policies on the production structure is not considered, the simulation results will underestimate the policy effects in reducing emission levels. The real production structure should be more flexible towards environmental policies and it is important to understand the reaction mechanism within it.

Lastly, this thesis highlights the importance of modeling research in policy assessments, but also emphasizes its limits. The real situation is much more complicated than modeling settings, and scenario studies could only represent certain possible pathways of future development in strict assumptions. In this thesis, we have reviewed the progressive improvement of China’s environmental policy system and stressed the importance of patience and prudence in designing public policies. China’s environmental situation is resulted by various development problems, not only in the environment, but also in the development. When designing and assessing environmental policies, full-rounded integrated assessments of the socioeconomic factors are crucial to the responsible policymaking process.

7.3 Future work

There is still some further work that could be done in the future.

- Firstly, we could look deeper into the pollution generation mechanisms in production. Currently, pollutant emissions are calculated based on the overall sectoral output, but the result would be more accurate if the pollutant emissions are calculated based on the different production stages.
- Secondly, it will be very helpful to further disaggregate the environmental management sectors according to various pollution treatment technologies. For example, the solid waste management sector could be disaggregated into landfilling, waste-to-energy, recycling, and so on.
- Thirdly, different production technologies could be introduced. After levying the environmental tax, companies will be motivated to turn to cleaner production technologies with a higher cost but lower emissions, and it will be interesting to see the impacts of technology transition.
- Fourthly, we could further discuss how to treat the collected environmental tax revenue and if the double-dividend effect would take place. The current tax reform policies in China could also be included.
- Lastly, we could expand the one-country model into the multiregional model, adding more foreign country accounts other than simply one account of "rest of the world". We could also modify the small country assumption. In such a case, we could more data from the multiregional accounts and consider the new socio-economic situation in international trades.

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Appendix A: Input-Output Table of 2012

Sector/Commodity/Account code	Explanation
COA	Coal mining and processing
COK	Coking
COI	Crude petroleum extraction
NGA	Natural gas extraction
PET	Petroleum refining and nuclear fuel
FGA	Fuel Gas production and supply
ELE	Electricity
HEL	Hydroelectricity
CEL	Coal-fired electricity
OEL	Oil-fired electricity
GEL	Gas-fired electricity
NEL	Nuclear electricity
REL	Renewable energies
AGR	Agriculture
MIN	Mining
FOO	Food
TEX	Textile
PAP	Paper industry
CHE	Chemical industry
PLA	Plastic industry
NME	Non-metallic production
STE	Steel and iron production
NMT	Nonferrous metal production
MPD	Metal product industry
OIN	Other industries
SCR	Scrap and waste recycling products
WAT	Water production and supply
CON	Construction
TRA	Transport
SER	Service
ESE	Environmental governance service
WMA	Waste water management
GMA	Waste gas management
SMA	Solid waste management
LAB	Labor
CAP	Capital
TAX	Production taxes
HH	Households
GOV	Government
INV	Investment/savings
STK	Stock
EXP	Export
IMP	Import
TOT	Total

China’s Input-Output Table of 2012

	COA	COK	COI	NGA	PET	FGA	HEL	CEL	OEL	GEL	NEL	REL	AGR	MIN	FOO	TEX	PAP	CHE	PLA	NME	STE	NMT	MPD	OIN	SCR	WAT	CON	TRA	SER	ESE	WMA	GMA	SMA	HH	GOV	INV	STK	EXP	IMP	TOT
COA	3,595.6	2,157.9	27.6	4.0	138.6	204.8	0.0	8,852.5	0.0	0.0	0.0	0.0	4.7	139.8	183.9	237.4	248.2	2,074.7	93.9	2,368.8	2,590.8	342.8	135.7	280.2	9.8	2.1	36.6	55.0	154.0	8.6	0.6	4.3	0.2	163.2	0.0	0.0	114.0	91.3	1,813.1	22,508.2
COK	1.1	105.5	0.1	0.0	0.0	13.5	0.0	2.7	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0	649.2	5.5	169.2	3,918.3	98.3	27.5	4.3	5.3	0.0	106.2	0.7	0.1	0.0	0.6	4.2	0.2	0.0	0.0	0.0	-114.0	48.1	5.2	5,064.4
COI	5.2	57.3	72.6	10.5	22,368.0	0.0	0.0	283.6	13.8	98.1	0.0	0.0	0.0	14.7	0.0	0.0	0.0	1,136.9	3.1	59.9	13.7	21.9	17.2	38.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.6	0.1	0.0	0.0	0.0	325.3	140.5	13,972.1	10,711.5
NGA	1.1	12.5	15.8	2.3	0.0	1,417.1	0.0	0.0	0.0	86.2	0.0	0.0	0.0	3.2	0.0	0.0	0.0	247.8	0.7	13.1	3.0	4.8	3.7	8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0.0	46.8	314.7	1,552.4
PET	148.2	19.4	339.7	49.2	2,713.2	32.4	0.0	1,375.2	67.1	475.7	0.0	0.0	1,380.8	979.3	138.0	254.7	33.6	6,671.3	112.0	1,599.9	352.6	713.2	197.6	898.3	17.1	3.8	1,651.0	8,922.4	4,685.8	9.2	3.5	23.9	1.1	2,318.2	0.0	0.0	511.8	1,126.4	2,876.5	34,948.8
FGA	0.4	3.0	1.2	0.2	33.1	324.4	0.0	0.0	0.0	62.6	0.0	0.0	0.5	0.3	3.1	1.8	1.4	127.2	0.1	7.9	30.3	0.9	21.4	62.4	0.5	0.3	1.1	675.3	303.7	0.0	0.3	1.9	0.1	1,375.2	0.0	0.0	82.2	0.0	0.0	3,122.8
ELE	890.5	134.8	484.5	70.2	511.7	68.1	3,615.7	11,165.4	10.9	102.3	403.8	594.7	871.3	1,647.0	721.5	1,465.4	398.7	4,648.8	425.0	2,653.3	2,426.8	2,247.6	1,460.4	2,928.0	43.8	268.1	1,796.4	561.7	3,119.5	13.2	13.3	89.6	4.3	2,852.2	0.0	0.0	-70.6	77.8	22.2	48,693.3
AGR	15.4	0.5	0.4	0.1	1.4	0.1	1.1	3.4	0.0	0.0	0.1	0.2	10,839.9	9.2	31,822.3	8,291.4	981.4	4,416.7	2.3	17.5	9.3	3.0	15.4	149.2	1.0	0.8	1,093.1	5.6	5,024.9	5.3	0.0	0.1	0.0	20,586.1	0.0	3,094.4	4,228.5	781.6	5,118.7	86,282.9
MIN	75.4	0.0	1,113.6	161.4	8.8	8.2	4.1	12.6	0.0	0.1	0.5	0.7	0.3	1,917.3	36.9	53.0	1.7	1,414.3	2.6	3,555.2	12,765.7	5,138.0	227.6	130.4	6.0	0.0	775.3	1.0	12.1	0.1	4.8	32.2	1.5	0.0	0.0	0.0	-25.6	187.6	8,797.1	18,826.0
FOO	74.9	13.8	44.6	6.5	218.1	10.1	35.9	110.9	0.1	1.0	4.0	5.9	9,168.0	107.8	20,020.6	1,521.2	55.1	2,726.3	93.9	212.1	256.9	168.5	145.6	1,018.2	20.4	20.2	347.1	565.4	11,248.9	13.9	1.7	11.1	0.5	37,621.0	0.0	0.0	2,668.6	2,802.0	3,381.0	87,959.6
TEX	496.6	6.2	27.6	4.0	40.1	7.9	15.2	47.0	0.1	0.4	1.7	2.5	25.4	147.3	442.7	39,501.1	296.9	1,221.5	918.9	647.1	149.1	132.8	469.0	3,075.0	30.8	13.0	4,194.5	333.7	10,553.0	27.7	1.4	9.4	0.5	13,944.9	0.0	1,764.5	1,993.9	24,553.4	3,130.2	101,966.4
PAP	5.0	0.2	1.3	0.2	6.7	0.2	7.1	21.9	0.0	0.2	0.8	1.2	2.6	4.7	842.1	3,055.7	3,722.3	435.0	95.4	635.3	13.5	22.2	90.8	1,100.4	7.1	0.2	56.4	32.3	2,431.3	0.7	0.7	4.8	0.2	159.4	0.0	0.0	-28.4	591.1	902.8	12,417.5
CHE	461.8	23.7	267.8	38.8	920.5	11.4	11.3	35.0	0.0	0.3	1.3	1.9	6,808.4	1,049.9	554.8	7,396.9	1,426.7	37,614.5	8,236.2	3,309.0	436.5	1,116.5	1,439.2	9,526.1	80.7	78.4	4,414.1	526.3	12,342.1	55.6	5.6	37.5	1.8	5,652.9	0.0	0.0	-20.1	7,804.9	11,293.1	100,375.0
PLA	18.2	1.4	2.0	0.3	48.8	3.0	1.7	5.4	0.0	0.1	0.2	0.3	659.7	67.5	1,193.5	1,727.5	179.5	2,464.6	4,047.1	344.8	39.3	39.0	313.9	5,751.2	65.1	37.6	1,651.7	24.6	532.3	7.5	1.4	9.1	0.4	307.4	0.0	0.0	36.5	2,080.8	1,013.6	20,649.6
NME	98.0	264.1	8.5	1.2	25.1	0.9	8.2	25.2	0.0	0.2	0.9	1.3	23.6	226.1	396.7	241.1	17.1	610.4	134.8	9,247.8	1,230.0	540.6	342.5	3,301.9	12.8	1.5	26,963.3	26.1	532.2	4.9	21.5	145.2	6.9	506.1	0.0	0.0	-333.0	2,673.4	702.6	46,604.6
STE	974.2	2.3	409.4	59.3	4.1	5.8	4.5	13.8	0.0	0.1	0.5	0.7	2.0	274.7	11.7	364.1	8.1	189.5	39.8	765.4	20,253.9	399.3	8,279.4	16,536.2	25.3	2.3	19,953.3	180.6	124.7	1.5	1.9	13.1	0.6	0.0	0.0	0.0	-567.5	3,065.1	1,285.3	70,114.4
NMT	8.7	0.0	0.1	0.0	1.1	0.6	0.9	2.7	0.0	0.0	0.1	0.1	0.0	46.5	5.2	1,787.5	12.5	617.9	42.5	349.8	1,733.1	16,551.6	2,867.8	19,995.3	73.0	0.3	1,968.4	0.7	128.1	0.3	1.0	6.6	0.3	0.0	0.0	0.0	71.6	1,392.2	7,667.6	39,998.9
MPD	449.7	6.8	54.8	7.9	15.3	2.2	3.4	10.4	0.0	0.1	0.4	0.6	26.9	460.0	260.3	895.8	52.6	586.4	169.3	1,254.0	582.3	69.2	4,275.8	6,446.8	10.6	40.3	5,775.5	192.4	2,553.0	3.9	144.4	974.1	46.3	490.9	0.0	2,856.8	31.7	4,288.2	812.2	32,226.5
OIN	1,003.5	135.2	602.9	87.4	274.3	17.7	821.9	1,554.3	-0.6	-2.1	91.8	135.2	688.4	1,122.4	173.6	1,086.2	-34.7	925.8	178.8	1,192.8	1,185.0	5.6	1,529.7	103,749.0	117.2	23.2	7,148.4	5,041.8	19,515.7	84.8	139.5	941.3	44.8	14,888.4	0.0	76,059.3	2,079.6	59,565.9	45,887.8	256,286.2
SCR	4.9	1.0	0.4	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.6	12.3	7.9	689.0	98.1	67.2	215.1	2,500.4	2,158.6	402.5	121.0	192.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	47.9	2,300.1	4,222.6
WAT	10.7	1.9	2.2	0.3	2.7	1.0	16.4	50.8	0.1	0.5	1.8	2.7	1.6	23.4	61.6	41.4	11.5	67.9	8.2	41.8	26.4	10.3	16.1	94.5	5.9	74.5	100.6	13.0	270.7	1.1	0.5	3.3	0.2	741.6	0.0	0.0	-6.0	0.0	0.0	1,701.1
CON	58.1	4.1	17.2	2.5	48.5	4.5	44.3	136.9	0.1	1.3	5.0	7.3	5.8	47.7	95.3	129.2	20.0	121.7	19.6	90.1	67.0	36.6	69.6	390.5	7.3	11.3	3,735.1	380.3	3,084.7	18.4	0.2	1.4	0.1	0.0	0.0	128,912.3	494.6	773.0	228.4	138,612.6
TRA	489.6	150.7	75.7	11.0	508.0	89.5	143.7	443.9	0.4	4.1	16.1	23.6	803.7	651.7	2,579.5	2,224.3	394.1	2,720.9	473.7	1,731.5	1,698.8	544.5	865.1	6,068.6	73.4	18.8	4,328.7	5,972.5	9,504.4	28.2	12.4	83.8	4.0	6,152.0	1,942.4	1,923.7	289.9	5,656.1	3,238.2	55,464.5
SER	2,383.3	270.5	572.9	83.0	1,164.9	220.9	910.0	2,810.0	2.8	25.7	101.6	149.7	4,074.7	1,872.6	7,534.5	9,654.4	1,018.8	8,856.0	1,574.7	3,778.0	4,137.7	2,040.9	2,578.6	26,242.3	148.4	321.2	15,701.3	10,898.6	89,019.5	122.7	33.3	224.9	10.7	90,711.3	71,050.3	23,139.6	928.5	18,812.9	7,165.9	396,015.5
ESE	8.0	6.8	1.1	0.2	9.8	0.4	1.8	5.6	0.0	0.1	0.2	0.3	1.7	16.4	20.3	70.1	4.9	42.4	3.2	20.0	33.1	10.5	6.8	69.8	0.9	1.9	9.8	24.7	133.7	12.1	0.0	0.0	0.0	66.0	189.1	0.0	-0.6	59.2	98.6	731.3
WMA	60.0	4.8	16.6	2.4	32.9	0.4	0.0	55.7	0.2	1.4	0.0	0.0	0.0	99.6	104.8	107.9	149.3	174.0	4.2	21.8	462.8	38.4	16.4	41.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,396.0
GMA	13.7	10.9	7.0	1.0	74.9	1.4	0.0	832.9	2.6	21.4	0.0	0.0	0.0	23.4	38.9	30.0	25.9	158.3	9.0	519.3	677.6	133.9	21.4	69.8	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2,674.9
SMA	61.3	0.7	0.2	0.0	5.1	0.1	0.0	95.0	0.3	2.4	0.0	0.0	0.0	182.4	6.1	1.7	3.5	43.5	0.3	10.8	66.9	15.9	0.8	2.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	499.7
LAB	5,642.1	649.0	1,320.6	191.4	835.9	192.8	819.7	2,531.2	2.5	23.2	91.5	134.8	51,522.4	3,284.4	6,418.1	10,855.4	1,093.9	6,127.4	1,853.2	4,678.1	4,141.1	2,049.0	2,818.2	22,984.4	153.7	388.9	22,461.7	9,949.0	100,512.9	208.3	145.4	7.4	46.6							
CAP	3,148.8	766.6	3,251.3	471.2	1,108.1	413.8	1,570.1	4,848.6	4.7	44.4	175.4	258.2	2,196.8	2,771.6	8,044.6	7,709.3	1,134.2	10,000.3	1,351.0	4,589.7	6,421.5	4,052.0	2,511.4	17,721.3	3,054.1	305.0	9,221.6	10,425.1	90,152.6	104.2	861.7	42.6	328.3							
TAX	2,304.3	253.1	1,972.1	285.8	3,829.0	70.1	466.4	1,440.1	1.4	13.2	52.1	76.7	-2,826.6	1,609.8	6,236.8	3,254.1	471.5	3,185.9	683.5	2,505.9	1,891.2	1,292.8	1,059.2	7,480.7	57.9	87.5	5,121.5	655.7	30,075.6	-1.0	0.0	0.0	0.0							
TOT	22,508.2	5,064.4	10,711.5	1,552.4	34,948.8	3,122.8	8,503.3	36,772.2	106.6	963.1	949.6	1,398.5	86,282.9	18,826.0	87,959.6	101,966.4	12,417.5	100,375.0	20,649.6	46,604.6	70,114.4	39,998.9	32,226.5	256,286.2	4,222.6	1,701.1	138,612.6	55,464.5	396,015.5	731.3	1,396.0	2,674.9	499.7							

unit: 100 million RMB (2012 price)

Appendix B: Sectoral Pollutant Generation in 2012

	Industrial waste water (10 000 tonnes)	Industrial waste gas (100 million cu.m.)	Industrial solid waste (10 000 tonnes)
Coal mining and processing	314114	3249	38537
Coking	25034	2588	466
Crude petroleum extraction	87076	1656	111
Natural gas extraction	12620	240	16
Petroleum refining and nuclear fuel	172081	17788	3205
Fuel Gas production and supply	2040	341	59
Hydroelectricity	0	0	0
Coal-fired electricity	291389	197740	59735
Oil-fired electricity	899	610	184
Gas-fired electricity	7495	5086	1536
Nuclear electricity	0	0	0
Renewable energies	0	0	0
Mining	521062	5547	114666
Food and tobacco	548545	9238	3805
Textile	564756	7131	1050
Paper industry	781375	6146	2168
Chemical industry	910612	37588	27344
Plastic industry	21739	2143	174
Non-metallic production	114242	123285	6781
Steel and iron production	2421216	160875	42047
Nonferrous metal production	200848	31799	9978
Metal product industry	85975	5079	523
Other industries	217012	16582	1417
Scrap and waste recycling products	4335	336	246
Water production and supply	12	0	0
Total	7304477	635047	314049

Appendix C: Sectoral Pollutant Emission Data in 2012

Pollutant code	Explanation
SO2	Sulfur dioxide
NO	Nitrogen oxides
SOOT	Soot and dust
AHG	Atmospheric Hg
COD	Chemical oxygen demand
ANI	Ammonia nitrogen
PHO	Phosphorus
PETRO	Petroleum pollutants
VPHE	Volatile phenol
CYAN	Cyanide
AQHG	Aquatic Hg
AQCD	Aquatic Cd
AQCR	Aquatic Cr
AQPB	Aquatic Pb
AQAS	Aquatic As
AQCU	Aquatic Cu
AQZN	Aquatic Zn
ISW	Industrial solid wastes

Sectoral Pollutant Emission Data in 2012 (unit: tonne)

	SO_2	NO	SOOT	AHG	COD	ANI	PHO	PETRO	VPHE	CYAN	AQHG	AQCD	AQCR	AQPB	AQAS	AQCU	AQZN	ISW
COA	124,866.0	45,495.0	333,033.0	14.1	122,356.0	3,678.0	0.0	2,539.0	0.2	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	180,000.0
COK	101,515.0	47,600.1	55,910.7	0.2	10,178.5	1,875.9	0.0	240.2	156.3	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,265.7
COI	19,307.8	25,991.2	6,040.6	0.2	11,383.3	752.9	0.0	736.3	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NGA	2,798.2	3,766.8	875.4	0.0	1,649.7	109.1	0.0	106.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PET	700,536.0	328,478.9	385,829.3	1.5	70,239.5	12,945.1	0.0	1,657.8	1,078.6	32.9	0.0	0.0	0.1	0.0	0.1	0.0	0.0	8,734.3
FGA	16,561.0	11,632.0	7,477.0	0.1	1,003.0	157.0	0.0	13.0	0.9	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HEL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CEL	7,745,027.7	9,899,340.9	2,164,904.1	257.3	30,032.3	1,965.8	0.0	189.5	0.7	0.2	0.0	0.0	0.0	0.0	8.8	0.0	0.0	155,477.0
OEL	22,460.5	28,708.0	6,278.2	0.7	87.1	5.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	450.9
GEL	202,848.8	259,272.1	56,700.7	6.7	786.6	51.5	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	4,072.1
NEL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
REL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AGR	1,084,215.7	181,440.2	4,794,845.5	15.0	11,538,000.0	806,216.0	488,530.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	666.8	1,322.0	0.0
MIN	87,997.0	23,322.0	163,346.0	59.6	61,983.0	1,776.5	0.0	177.9	0.1	3.0	0.4	3.2	0.6	27.9	32.4	0.0	0.0	660,000.0
FOO	524,464.0	182,543.0	312,933.0	4.0	858,448.0	39,367.0	0.0	256.0	3.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50,000.0
TEX	365,512.0	105,116.0	274,001.0	2.9	375,909.0	27,653.0	0.0	497.0	3.4	0.5	0.0	0.8	3.6	0.0	0.0	0.0	0.0	0.0
PAP	496,904.0	207,417.0	167,286.0	2.7	623,221.0	20,699.0	0.0	72.0	59.9	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
CHE	1,494,404.1	588,949.4	657,778.3	18.8	572,072.1	95,495.3	0.0	2,958.2	95.0	54.5	0.5	1.6	0.8	8.5	44.0	0.0	0.0	50,000.0
PLA	64,341.9	20,160.6	23,955.7	0.7	9,775.9	795.7	0.0	416.8	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
NME	1,997,859.0	2,742,154.0	2,551,531.0	126.8	32,352.0	1,836.0	0.0	196.0	14.7	0.1	0.0	0.0	0.1	0.2	0.3	0.0	0.0	40,000.0
STE	2,406,154.0	971,637.0	1,812,773.0	45.7	75,473.0	6,492.0	0.0	2,642.0	48.0	31.0	0.0	0.2	3.9	1.2	4.4	0.0	0.0	130,000.0
NMT	1,144,323.0	230,046.0	319,415.0	717.0	27,792.0	15,457.0	0.0	386.0	6.3	2.3	0.2	20.4	2.4	51.4	36.0	0.0	0.0	10,000.0
MPD	76,031.0	23,909.0	82,396.0	0.5	32,422.0	2,735.0	0.0	1,203.0	3.2	33.0	0.0	0.3	44.7	1.6	0.3	0.0	0.0	0.0
OIN	154,796.0	57,541.0	172,539.0	6.2	98,183.0	7,549.0	0.0	2,967.0	6.3	6.0	0.0	0.1	13.8	6.1	0.5	0.0	0.0	0.0
SCR	4,309.0	1,000.0	4,204.0	0.0	3,311.0	182.0	0.0	9.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
WAT	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
CON	777,947.3	158,599.4	1,972,007.3	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRA	4,239,700.5	4,670,150.9	1,166,752.0	10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SER	4,107,834.1	423,413.1	3,787,412.8	15.0	7,461,982.1	1,489,850.9	383,063.8	2,010,286.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESE	7,585.1	781.8	6,993.4	0.0	13,778.5	2,751.0	707.3	3,712.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HH	2,057,000.0	393,000.0	1,427,000.0	12.8	9,128,000.0	1,446,000.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	30,027,298.7	21,631,465.4	22,714,218.0	1,320.6	31,160,428.6	3,986,396.4	872,301.1	2,031,267.7	1,481.4	171.7	1.1	26.6	70.4	97.0	127.7	666.8	1,322.0	1,290,000.0

Appendix D: Share parameters in final consumptions

α_i is the consumption share of commodity i in households' final spending.

Products	α_i
Coal products	0.08%
Petroleum refining products	1.20%
Fuel gas products	0.70%
Electricity	1.40%
Agricultural products	10.40%
Food and tobacco products	18.90%
Textile products	7.00%
Paper products	0.08%
Chemical products	2.80%
Plastic products	0.20%
Non-metallic products	0.30%
Metal products	0.20%
Other industries products	7.50%
Water	0.40%
Transport	3.10%
Service	45.70%
Environmental public service	0.03%

β_i is the consumption share of commodity i in government's final spending.

Products	β_i
Transport	2.65%
Service	97.09%
Environmental public service	0.26%

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