Doctoral Dissertation
博 士 論 文

Analytical Framework of Optimal Total Emission Control Policy Based on Cooperation and Input-Output Structure in Environmental-Economic Systems

（環境経済システムにおける提携と
産業連関構造を考慮した
最適総量規制政策の分析フレームワーク）

WAN Yi
万　毅

東京大学
THE UNIVERSITY OF TOKYO

Doctoral Dissertation
博 士 論 文

Analytical Framework of Optimal Total Emission Control Policy Based on Cooperation and Input-Output Structure in Environmental-Economic Systems

（環境経済システムにおける提携と
産業連関構造を考慮した
最適総量規制政策の分析フレームワーク）

WAN Yi
万　毅

Department of International Studies
国際協力学専攻

Graduate School of Frontier Sciences
大学院新領域創成科学研究科

The University of Tokyo
東京大学

Abstract

In managing regional environmental-economic systems, it is significant to design a comprehensive total emission control (TEC) policy. In this study, a methodology (model) is established as an analytical framework to develop and analyse, quantitatively, the TEC policy schemes in decision-making that could create an incentive for the full cooperative structure. Using the model from a viewpoint of policy design, the resulting effective impacts of different TEC policy schemes can be simulated by modifying policy factors such as the environmental emission charges (taxes), the total emission control target and some environmental emission coefficients.

As a theoretical framework, the model is based on a cooperative game with characteristic function, in which one player is the TEC policy maker (or regional environmental administrator) who aims at maximizing the social benefit defined as an index considering not only the economic profits but also the regional environmental damage; and the other players are all the polluters who are assumed to be independent decision makers individually interested in only their own economical gains (final profits). It is clear that only if all the polluters select the decision to cooperate with the policy maker (administrator), could a maximum social benefit be produced from the cooperative case where all the players participate together. But which option each polluter will take depends on how much it can obtain more profit from the cooperation than that from the not-cooperative choice. This actually means that there should be an incentive given to each polluter in the fully cooperative case. As the interactions among all players are described mathematically in an input-output approach, an optimally stable policy scheme can be designed quantitatively to provide an increment in final profit for each player with which the overall decision-making could be realized in the cooperation to optimize the social benefit and reach the environmental total emission control target as well.

With a simple decision structure, the model deals emphatically with such a mechanism so as to solve the two problems. The first one is how to allocate optimally the total emission among all the polluters in the region, which is studied by a non-linear programming to maximize the social benefit. And the other is, then, how to redistribute rationally the resulting maximum social benefit to make the scheme stable, which is transferred to a multi-objective decision-making problem solved by

introducing the concept of "equal acceptance degree". In the model, the environmental target of TEC is reached in the cooperation of all the polluters, while the optimal allocation of the regional total emission and the fair distribution of the corresponding social benefit are realized through an economic means such as emission charges or environmental taxes and subsidies.

Based on the model, an application for a regional system is then studied on water quality planning to abate wastewater (pollutant COD) emissions from plants (factories) in the upper reaches of Huangpu river in Shanghai. After calculating the optimal value of the natural absorption capacity as well as identifying the shapes of the basic functions, the model is specifically formulated to compute the quantities of final emission, tax or subsidy for each plant. Finally given by the simulation results, a stable policy scheme is suggested in details, and the related problems such as stability for the alternative scheme are also analysed from the perspective of environmental emission charges policy design.

Furtherly, the analytical framework considering an input-output structure is established with the background of another application in an environmental-economic system with industries. The above optimal allocation model is modified to be suitable also for a multisectoral system by using input-output analysis. The extended model mainly proposes a methodology which could be an innovation on how to design a better policy with total emission control among all those economic sectors. Based on the direct input coefficients of input-output table of multisectors and the sectors' environmental emission (intensity) coefficients, the approach is established to decide an optimal set of emission allocations to maximize the whole profits (defined as the social benefit here) among all sectors under the total emission control policy.

Also, with the extended model, an empirical application is studied in details on reducing the CO_2 total emission of all the economic sectors in China. An optimal TEC policy scheme is approximately computed by using the national account data of the input-output table with 17 sectors to give optimal solutions respectively for total production, final use and the corresponding CO_2 emission of each sector. According to the simulated results, the key sectors most responsible for the total emission reduction can be identified for policy suggestion.

In addition, using the model in terms of policy design, two more aspects of the application are furtherly discussed on policy analysis. Specifically, the data of the sector (Production and Supply of Electric Power, Heat Power and Water) with the highest emission share are used as an example to investigate the impact of the key sector's technological innovation on all the sectors' emissions in a multisectoral

system. Based on the model, especially this study also explores what ripple effects would be expected by the ETS's initial operation in the power sector from a perspective of total emission control.

And finally, by changing the policy factors such as the TEC target value, different policy schemes are calculated in details to give comparisons in decision-making on policy instruments for reducing total CO_2 emission in China.

Key Words: analytical framework, policy design, total emission control, cooperative model, acceptance degree, input-output analysis, multisectoral systems.

Content

Part Two: Policy Design for a Regional System
The Basic TEC Model and Its Application on Water Quality Planning

Part Three: Policy Design for a Multisectoral System
The Extended TEC Model and Its Application for Reducing CO_2 Emission in China

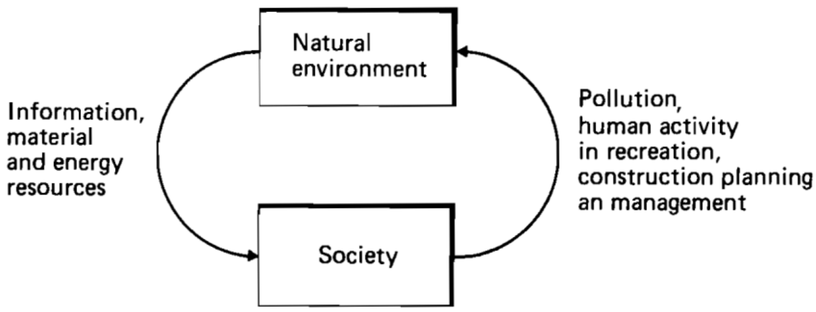
Part One: Introduction

1. Introduction

1.1 Background and objective

The natural environment provides the basis of the resources and energy needed for life on earth, but the throughput of society produces waste and emissions that could result in serious environmental problems (Bringezu S. & Bleischwitz R., 2009). There exist such relationships between the society and the natural environment, which are shown in the Figure 1-1-1 below (Ikeda S., 1987).

Generally speaking, the environmental problems are mainly caused by the process of production and consumption. Environmental management is an important part of economic operations in the present society (Clement A., 1991; Erhun K., 1992; Ross R.M., 2011). Because there are not better managing policies effective enough to manage the environment-economic issues, the market mechanism has been causing more and more serious environmental damages, even now in many developed or developing countries (Charles D.K., 2000; Ekko C., 1993; Ekko I. et al., 2001; Frank J.D., et al., 1991; Harvey H., et al., 2018).



Source: Economic-Ecological Modeling by Braatj L.C. & W.F.J. van Lierop (Editors), Elsevier Science Publishers B.V. (North-Holland) , 1987, Chapter 12, pp185-202.

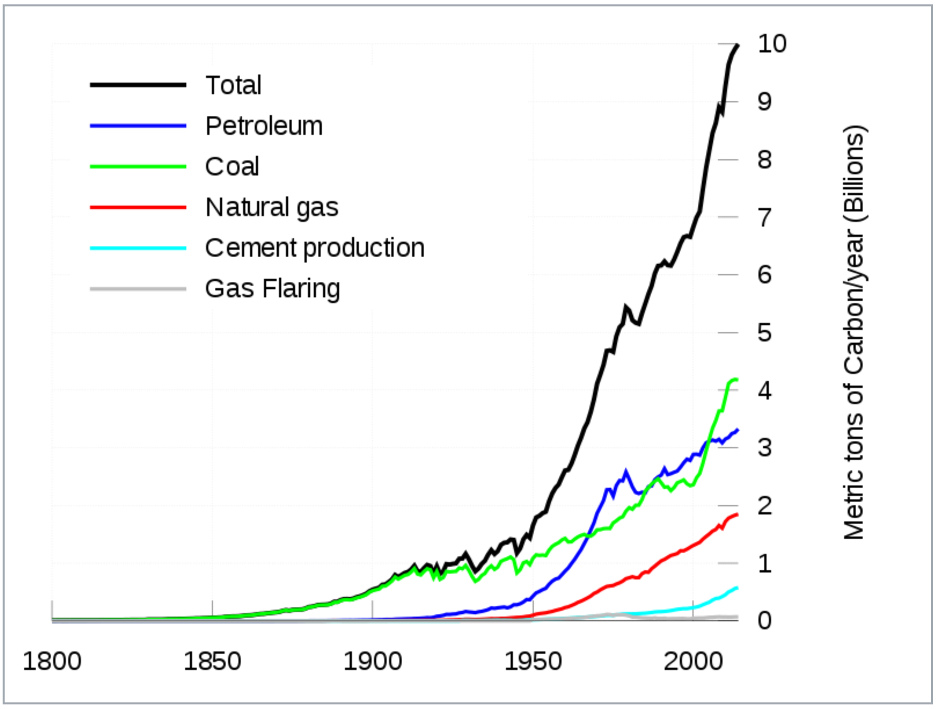
Fig.1-1-1 Relationship between society and the natural environment

Recently, the global warming has been becoming a widely concerned problem. It is actually a big challenge for economic development and human survival (Feasta, 2008; PECoP-Asia, 2018; Matthews L., 2010). Climate change is mainly resulted from combustion of fossil fuel and other human living activities, which make a great increase in emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2), specifically (Peter B., 2008).

Nowadays, it can be said that carbon is inextricably linked to human life. Carbon is circulating in nature, and is widely found in the atmosphere, minerals and organisms in many forms, from scarce and expensive diamonds to coal of huge reserves. However, the greenhouse gases (GHG) produced mainly from the mankind's uncontrolled consumption of carbon resources have gone far beyond human imagination and this has begun to endanger the global ecological environment and stable climate system (Fridolin K., et al., 2009; IPCC, 2013).

The main sources of greenhouse gases due to human activity are burning of fossil fuels and deforestation leading to higher carbon dioxide concentrations in the air. Since about 1750, human activity has increased the concentrations of carbon dioxide and other greenhouse gases (IPCC, 2001). Recent researches have shown that carbon dioxide emissions have increased dramatically on a global level since 1900 (Crippa M., et al., 2019; Krausmann et al., 2009; World Bank, 2015).

Figure 1-1-2 shows the modern global CO_2 emissions from the burning of fossil fuels, which have quickly increased in the last two centuries.



Original Data citation:"Marland, G., T.A. Boden, and R. J. Andres. 2007, Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, United States Department of Energy, Oak Ridge, Tenn., U.S.A"
Source: https://en.wikipedia.org/wiki/Greenhouse_gas#cite_note-80 (accessed on Nov.03, 2019)

Fig.1-1-2 Modern global CO_2 emissions from the burning of fossil fuels

In 18th century, Watt invented the industrial steam engine by huge heat and kinetic energy based on coal combustion and brought about a steam revolution. After more than two centuries, however, the by-products of the engine that drives the transformation of the world's industry make the planet unbearable. In fact, as a result of the steam innovation, presently the industrial boilers produce 2.6 tons of carbon dioxide, 8.5 kilograms of sulphur dioxide and 7.4 kilograms of nitrogen oxides per ton of standard coal burned. According to The Global Carbon Budget Report (GCBR, 2017), written by 76 scientists from 15 countries and 57 research institutions, the global annual emissions of fossil fuels and industrial CO_2 would reach about 37 billion tons by the end of 2017 and are expected to rise 2% from the previous year (Ju C., 2018). China, the United States, the European Union and India remain the top four countries and regions with the world's largest carbon emissions (see Table1-1-1).

Table 1-1-1 Top-10 annual energy-related CO_2 emitters for the year 2009

Country	% of global total annual emissions	Tonnes of GHG per capita
China	23.6	5.1
United States	17.9	16.9
India	5.5	1.4
Russia	5.3	10.8
Japan	3.8	8.6
Germany	2.6	9.2
Iran	1.8	7.3
Canada	1.8	15.4
South Korea	1.8	10.6
United Kingdom	1.6	7.5

Data Source: CO_2 Emissions from Fuel Combustion: Highlights (2011 edition), Paris, France: International Energy Agency (IEA), 2011, p. 9, archived from the original on 17 March 2017.

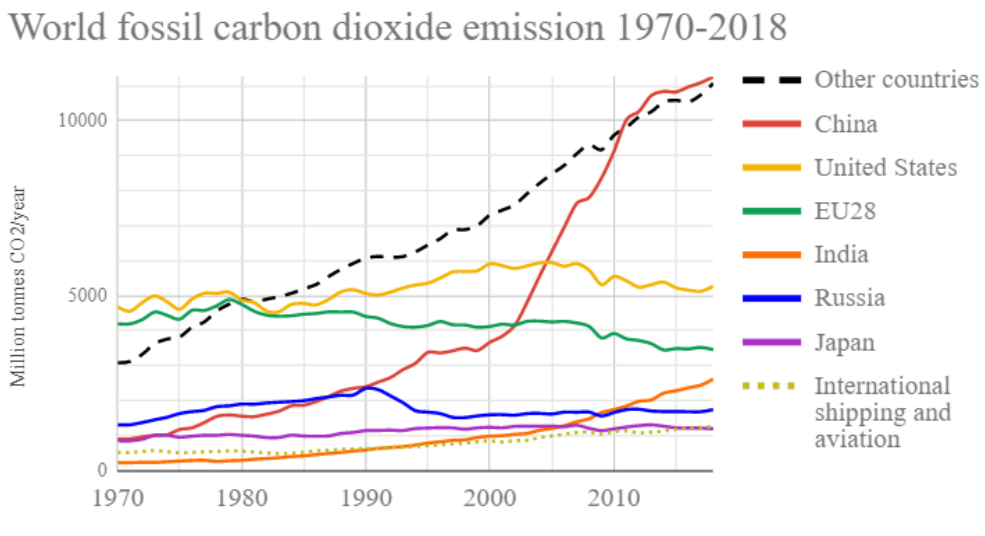
(1) CO_2 emissions in China

In the past decades, particularly, China has experienced energy and environmental problems. China has become the largest CO_2 emitter and energy consumer in the world since 2009. According to the statistics released at the 2015 Paris Conference on Climate Change, China's greenhouse gas emissions account for about 20% of world emissions (UNFCCC, 2016). The total emissions of CO_2 in China reached the level of 7.57 billion tons, roughly accounting for 24% of the global emission (Zhou S. et al., 2012), and recently it is considered to rise up to 27% of the world's total emission (Olivier & Peters, 2018).

Although there are, to some extent, differences in the statistics for different years and with different ways, it is believable that the percentage of China's annual total emission to global total emissions has been over 20% in the last decade. Furthermore, the total CO_2 emission in China has been continuously increasing in the long term trend (Li N., Zhang X., et al., 2017).

For example, in the past the total emission had increased from 1.46 billion tons in 1980 to 8.72 billion tons in 2011 (Wang X., et al., 2014). Based on the latest data shown in the Figure 1-1-3, the China's total CO_2 emission has already been more than 11.0 billion tons in 2018.

Facing to such a situation, early in 2009, Chinese government made the CO_2 emission intensity reduction commitment that during the period of years 2005-2020, the emission intensity per GDP in China must be decreased by 40-45% of the value based on year 2005 (Yi W., et al., 2011). Later on November 12, 2014, China and the United States jointly issued the "Joint Statement on Climate Change between China and the United States", in which the Chinese government proposed that the CO_2 emissions should be at peak around 2030 and China would make every effort to reach the peak as soon as possible (Tao X., et al., 2016). Also, this target of controlling CO_2 emission is promised by China at the Paris Climate Conference in 2015.



Data source: EDGAR - Emissions database for Global Atmospheric Research. Published in: Crippa, M., Oreggioni, G., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J.G.J., Vignati, E., Fossil CO_2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-11100-9, doi:10.2760/687800, JRC117610, September 2019.

Fig.1-1-3 Historical annual CO_2 emissions for the top 6 countries and confederations

As the time period of reaching the emission peak has been determined by Chinese government, the key topic is becoming the question: how to make it realized actually (Chai Q., et al., 2014; Wang J., et al., 2010). In order to achieve these emission reduction targets, adequate environmental-economic policies are required at a regional, national or international level (Baumol W.J. & Oates W.E., 1975; Gibbons R., 1992; James D.E., et al., 1978).

As a regional or national policy, China has stepped up to build a nationwide carbon trading market which would be expected to start in 2017 (NDRC, 2015). During the last ten years, China has pushed positively a comprehensive policy to reduce CO_2 emission, which is based primarily on administrative penalties and market trading of emission allowances, i.e., the cap-and-trade (C&T) system (He Y., et al, 2012; Jiang J. et al., 2016). Specifically, the big city Shenzhen was authorized as one of the pilot regions and launched the first regional C&T system in 2013. There are 635 generating companies (GCs) which were covered in the first stage and their emissions were totally up to 40% of Shenzhen's total CO_2 emissions (Jiang J., et al., 2014). Based on experiences of operating such a regional C&T system, China planned in 2015 to establish a national emission trading system (ETS) from 2017 to 2020 (Chang K. & Chang H., 2016). Actually at the end of 2017, China has started a national ETS system with a trial operation within the power industry.

Indeed, China is just beginning the ETS program and the emissions allocation is still a critical topic. There are mainly two levels of the emissions allocation. At the first level the central authority allocates the China CO_2 allowances (CHAs) to each province (sector), and at the second level each province (sector) allocates its own CHAs to specific emitters. How to process the emissions allocation in different levels has been becoming one of the key issues to which the policy designers have to face (Donald H., et al., 2015; Zhu B., et al., 2018).

In fact, however, implementations of the both regional C&T system and national ETS markets are fundamentally based on a Total Emission Control (TEC) policy at first (Zhou Z., et al., 2018). In other words, in order to reach the environmental target either for the emission intensity reduction per unit of GDP or for the emission peak control on the total CO_2 emission in China, it is essentially significant to control the total emission among all regions or sectors/industries in China (Hu Q., et al., 2018; Wang J., et al., 2010).

Particularly, according to the Work Plan for Construction of the National Emissions Trading System (Power Sector) released in December 2017 by the Chinese government, the national ETS is actually expected to start after 2020 and the power industry should be the first sector covered by the ETS at its initial operation. It is, therefore, also meaningful and valuable to investigate what ripple effects will be expected by the ETS's initial operation in the power sector, from a perspective of total emission control.

(2) TEC policy on the water pollution

As an environmental-economic policy at a regional scale (city, country, etc.), the total emission control (TEC) has been becoming a remarkable option recently because it is generally an effective means in both making a full use of the natural absorption capability and protecting the environmental quality in the region as well (Ge C., et al., 2009; Hu Q., et al., 2018).

As mentioned in the above, the TEC policy is recently considered to become more and more important for reducing the CO_2 emissions in China, but it actually has been used since 1980s in China, particularly in controlling the water pollutions.

A few of researches were carried out on distribution of total pollution load and quantitative evaluation of environmental capacity in some river areas, such as Minjiang River (1981-1985), Yangtze, Yellow and Huaihe rivers and the waters of Baiyangdian, Jiaozhou Bay and Quanzhou Bay (1986-1990). By the mid-1980s, China had made further explorations on self-purification capacity in China's offshore water regions. In 1985, Shanghai local government firstly decided by legislation to implement a TEC policy to reduce wastewater emission in the upper reaches of Huangpu River (Shanghai Gov., 1985). In March 1988, the Interim Measures for the Management of Water Pollution Emission Permits, issued by the former State Environmental Protection Bureau (SEPB), marked a new stage in China's total emission control on water pollutions (Song G.J., 2000).

Before 1980s, pollution control policies in China focused on emission concentration standards which were set by governments at all levels. In 1988 the State Environmental Protection Administration (SEPA) proposed a TEC approach in combination with emission concentration standards. The TEC policy set the maximum levels of total emissions of regulated pollutants (Song G., 2005).

In 1996, the implementation of the TEC policy was formally decided by the "Ninth Five Year Plan for Environmental Protection and Environmental Targets for 2000". From the plan, in the Ninth Five Year Plan period (1996-2000), there were 12 pollutants subject to the policy nationwide, namely sulfur dioxide (SO_2), chemical oxygen demand (COD) of discharge water, mineral oil (in sewage), smoke, particulates (industrial sources), cyanide, arsenic, mercury, lead, hexavalent chromium, cadmium and solid waste (industrial sources). See Table 1-1-2.

However, the number of controlled pollutants dropped to six in the Tenth Five Year Plan period (2001-2005) and only two in the Eleventh Five Year Plan period

(2006-2010). There are two explanations for removing some of the other pollutants from the national TEC pollutants list: (1) some pollutants are well controlled and then no longer are considered as a nationwide problem; (2) for some pollutants, it is very difficult to obtain accurate statistics needed for a better TEC policy. Regulating fewer pollutants may make it easier to implement the TEC policy (Ge C., et al, 2009).

Taking water discharges as an example, there are two types of discharges that were historically included in the TEC policy: COD discharges and specific pollutants (e.g. NH3-N, cyanide, arsenic and heavy metals). For the latter, these special water pollutants are only released from the operation of specific processes and there are few statistical data for them. Thus, as for water pollution, only COD discharges have been remained on the list of pollutants which are controlled by the TEC policy in the Eleventh Five Year Plan period (2006-2010).

Table 1-1-2 Targets of TEC for the Ninth Five Year Plan period (1996-2000)

No.	Pollutants	Targets of the TEC policy			Actual emission	
		Year 1995	Year 2000	Increase rate (%)	Year 2000	Achieve the target?
1	Smoke (1000 metric tons)	17 440	17 500	0.37	16 500	Yes
2	Industrial particle (1000 tons)	17 310	17 000	–1.80	16 200	Yes
3	SO_2 (1000 tons)	23 700	24 600	3.82	19 950	Yes
4	COD (1000 tons)	22 330	22 000	–1.49	14 450	Yes
5	Mineral oil in Sewage (ton)	84 370	83 100	–1.5		
6	Cyanide (ton)	3 495	3 263	–6.4		
7	Arsenic (ton)	1 446	1 376	–4.8		
8	Mercury (ton)	27	26	–3.7		
9	Lead (ton)	1 700	1 670	–1.9		
10	Cadmium (ton)	285	270	–5.4		
11	Hexavalent chromium (ton)	670	618	–7.7		
12	Industrial solid waste (1000 tons)	6 170	5 995	–2.9	32 000	Yes

Data Source: the Ninth Five Year Plan for National Economy and Social Development and Compendium for Long-term Objective in 2010.

According to China's Environment Annual Report (2000–2005), the targets of the TEC policy for the Tenth Five Year Plan period (2001-2005) were not achieved generally. Particularly, the SO_2 emissions and COD discharges showed the worst results: SO_2 emissions increased 28% while COD discharges had been reduced by only 2%. But the both pollutant targets were set a 10% reduction from the levels of year 2000. During the Eleventh Five Year Plan Period (2006-2010), the National Plan for Total Emissions Control of Major Pollutants clarified the details of the implementation of the National Total Pollutant Emissions Control and stipulated that only two pollutants, i.e., SO_2 and COD, were subject to the TEC policy during the Eleventh Five-Year Plan period. With regard to the COD discharge target, it would need to be reduced from 14.14 million tons (the level of year 2005) to 12.73 million tons (10 percent lower than that in 2005). The TEC policy included a very detailed allocation plan for each province or metropolitan city (see Table 1-1-3).

After the Eleventh Five Year Plan period (2006-2010), the TEC policy has kept focusing on the COD discharges in water pollutions. In March 2007, after the SEPA set up a special office with the responsibility to implement and oversee the TEC policy for the whole country, many local Environmental Protection Bureaus also respectively established the corresponding offices to be responsible for the TEC policy in their administrative areas.

Table 1-1-3 Allocations of TEC for the Eleventh Five Year Plan period (2006-2010)

No.	Provinces/municipals	COD Discharges (1000 metric tons)		
		Total discharges in 2005	Discharge target for 2010	Reduction rate (%)
1	Beijing	116	99	–14.7
2	Tianjing	146	132	–9.6
3	Shanxi	387	336	–13.2
4	Shanghai	304	259	–14.8
5	Jiangsu	966	820	–15.1
6	Shandong	770	655	–14.9
7	Guangdong	1058	899	–15.0
8	Hainan	95	95	0
9	Chongqing	269	239	–11.2
10	Sichuan	783	744	–5.0
11	Xizang (Tibet)	14	14	0
12	Qinghai	72	72	0
13	Xinjiang	271	271	0

Data Source: Ge C., et al (2009). Notes: 1.For information of other areas, see National Plan for Total Emissions Control of Major Pollutants during the Eleventh Five Year Plan period. 2.Target for COD discharge reductions is 12.728 million tons. The aggregate of the allocations is 12.639 million tons. The remaining 89 000 tons is withheld for use in a pilot program of tradable permits.

However, there are still a few of challenges for the existing TEC policy on water pollution. The scope and the effectiveness of the TEC policy should be more emphasized and as one of the national pollution control strategies the TEC allocation should be carefully improved by an effective and efficient process (Hu Q., et al, 2018).

In addition, as one of the design issues regarding the TEC policy, the current allocation system in TEC is based on historical emission data. Indeed, this allocation means is simpler than many other methods, but most importantly, it obstructs the emission reduction more than that required or the installation of more effective pollution control equipment. As an unexpected result, a better performance possibly results in lower allocations for subsequent periods, and then, greater costs to meet the target. Additionally, there is lack of clear and rational allocation methods, especially in the process from local governments to polluting enterprises. This could cause many implementing problems (Ge C, et al, 2009).

Therefore, it is necessary and significant to comprehensively design a rational and effective TEC policy with an incentive to polluting enterprises for controlling the water pollution, especially COD wastewater.

(3) The objective of the study

With the above background of realistic problems to which China has been facing now, this study is to establish a methodology (model) as the analytical framework for a TEC policy and then discuss its practical applications on these issues.

More precisely, the TEC policy considered in this study is, firstly, to set an allowed maximum value as a TEC target on the total emission of some kind of pollutants discharged into a given region, and then, secondly, to take some measures (policy instruments) to control the total emission under the allowed maximum level to reach the environmental goal in the region.

It is therefore obvious that for a TEC policy scheme the key points are on these two questions:

(1) How to decide the allowed maximum value of total emission, and
(2) What kind of environmental policy instruments, and to what extent, the instruments should be executed to achieve the environmental emission target (goal).

The process of finding better solutions to the both questions is exactly what it means here by the environmental-economic policy design of total emission control. In more detail, in other words, the TEC policy design here is thought as a simulating process to compute, analyse and/or compare quantitatively the TEC schemes for decision making on some policy instruments by using the model (methodology) established in this study.

Therefore, the objective of this study, specifically, is to solve and analyse the two questions, quantitatively, by developing a methodology or a model (a set of models) of total emission control and discussing its applications both in a regional (multiregional) system and a multisectoral system.

More specifically, as for the first question, it would not be considered as a key point and not discussed in details from the viewpoint of designing a policy in this study. For the second question, however, it seems to be rather difficult, but as a main topic in this study, it will be discussed in much more details in the following chapters.

Finally, in regard to the applications, first, a case study is briefly discussed on managing regional water quality (COD) in a given river area to better understand the TEC model, and then, an empirical application is discussed in more detail for reducing the total CO_2 emission in China, which is considered as the core application in this study.

1.2 The structure of this study

This study is organized into four parts including 11 chapters, the inter-related structure of which is simply shown in Fig.1-2-1.

Part One includes three chapters, Chapters 1-3, as an overall introduction.

Chapter 1 first introduces briefly the background, the objective and the content structure of this study.

The detailed literature review is given as Chapter 2, on the TEC policy, the methods of allocation for total emission control, and the TEC model with input-output analysis.

And then Chapter 3 simply describes the methodology blocks and the main features of the TEC policy design in this study.

Part Two consists of three chapters, Chapters 4-6, which cover the basic model and its application in a regional system.

Chapter 4 gives a brief description of the model concerning the theoretical framework and the functions used in the model.

Chapter 5 describes the model mathematically. This chapter begins to explore the emission allocation model and the maximum benefit redistribution model. At the end of the chapter, the interaction in the model is drawn by the Analytical Blocks of the TEC model shown in Fig.5-3-1.

Chapter 6 deals briefly with an empirical application as a case study on the TEC policy for reduction scheme on wastewater (COD) discharges in a given river region.

Part Three contains four chapters, Chapters 7-10, which are concerned with the extended model and its application in a multisectoral system.

Chapter 7 refers mathematically to the model extended for a multisectoral system by using an input-output analysis. Basically based on the optimal allocation model in Part Two, the allocation model is modified newly to be applicable in a multisectoral system with input-output tables and then the redistribution model of the maximum social benefit is also extended to consider the practical system with input-output structure.

Chapter 8 deals with an empirical application in details on the TEC policy scheme for reducing the total CO_2 emission among all the 17 economic sectors in China. The optimal TEC policy schemes are quantitatively identified and analysed by simulating computation. The results data are shown in details in this chapter with policy design analysis.

Chapter 9 furtherly investigates the impacts analysis of technology innovation or technology transfer on the CO_2 emissions of all the sectors. The impacts of changes of environmental emission coefficients in the power sector are analysed by using the TEC model. Also the chapter analyses the power sector's effects expected in the initial operation of the emission trading system (ETS) in China.

Chapter 10 computes and compares respectively the different alternative policy schemes by modifying policy factors such as the TEC targets or emission charges in terms of the policy design, and finally gives the block diagram of simulating process.

Finally, as Part Four, Chapter 11 concludes with characteristics of the model, the conclusions (results) and policy implications (suggestions) from the applications as well as the possible further researches.

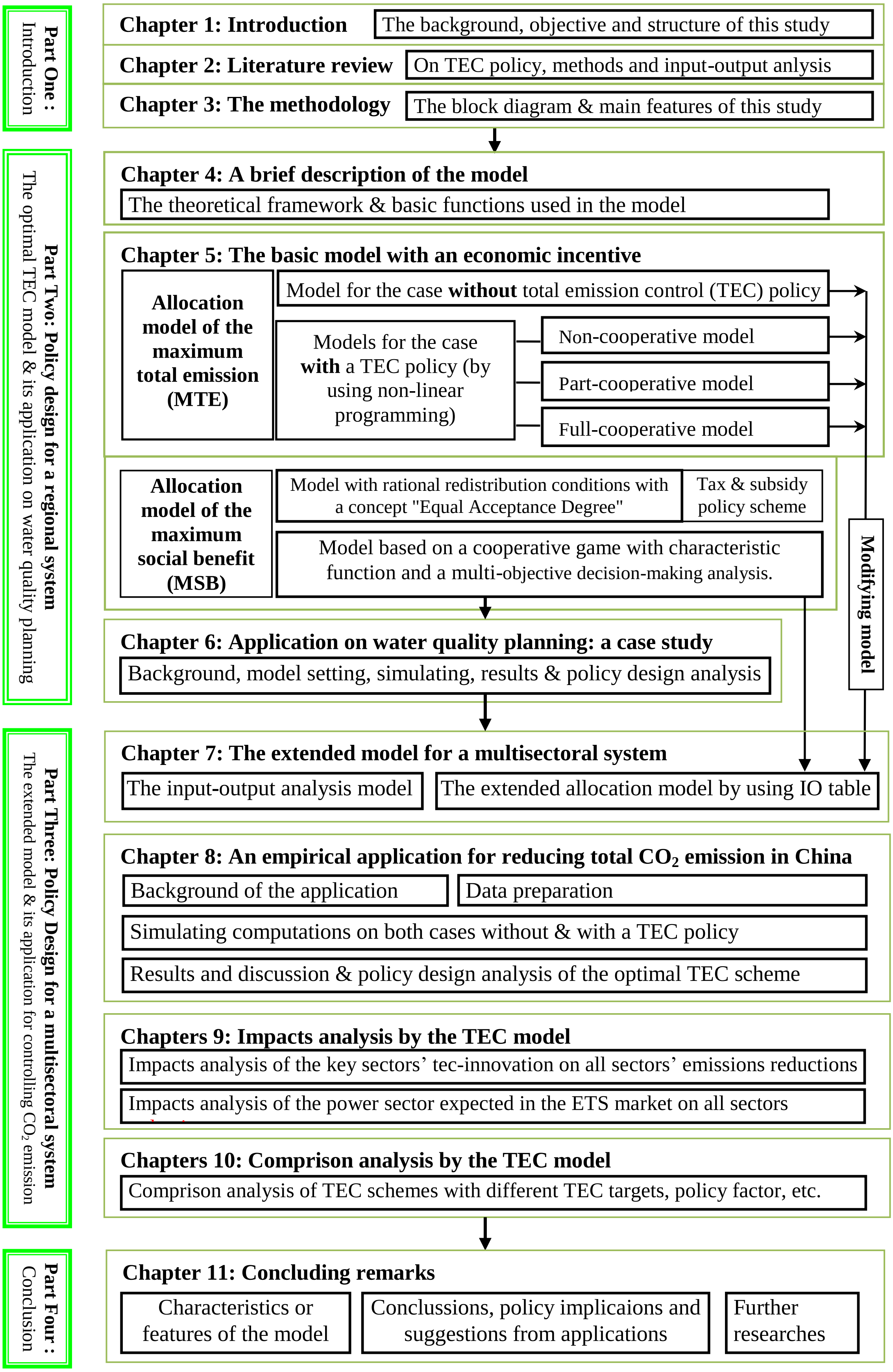


Fig.1-2-1 Structural blocks of the content in this study

2. Literature Review

This chapter is to review briefly the experiences of the TEC policy and its implementation and also review in detail the researches of the methods and techniques used for modeling and simulating the TEC policy design process in this study.

[In order to find relevant researches literatures, this study relied mainly on Science Direct, Google Scholar and Scopus, and used the keywords: "total emission control or TEC policy design", "incentive", "cooperative game", "allocation model", "input-output anaysis","CO_2 emission reduction in China".]

2.1 The TEC policy and its experience of implementation

2.1.1 The concepts of TEC policy

According to the opinions of Baumol W.J. and Oatesl W.E. (1975; 1979), the policy instruments for managing environmental quality can be classified as follows: moral situation (publicity, social pressure, etc.), direct controls (effluent standards), market processes (emission charge or tax on polluters) and government investment (e.g., waste treatment plants at public expense). Earlier environmental policies had focused on the direct control instrument, i.e., some concentration-based or amount-based standards. However, the environment quality is closely related to the total loads of pollutants, not a function of emission concentrations. The direct control by concentration standards may be ineffective in managing environmental quality.

In the end of 1960s, in Japan, so-called "Total Emission Control (TEC)" was considered to control the total amount of pollutants discharged from all the polluters in a region (Takawo T., 1980). The allowable total emission in a given region is defined as the environmental carrying capacity. The total emission control could obviously be an effective means to improve the environmental quality even if in a region where it is polluted seriously. The total emission control can make the polluters reduce the amount of emissions. (http://www.env.go.jp/en/water/wq/wemj/promot.html).

Then, how to control the total emission in the region? This is exactly the topic of the environmental-economic policy design discussed in this study. The optimal TEC model proposed here can be considered as a mix of direct control and market process in the above classification by Baumol W.J. et al (1979).

Total emission control (TEC) is short for controlling total emission of some kind of environmental pollutants, and it is also referred as total amount control, regulation of total emission, total pollutant load control, pollutant cap control, regulations on total allowable volumes of pollutants, etc.

Total emission control is to make the total amount of pollutant loads in a given region controlled within the carrying capacity of the natural environment according to environmental quality standards, based on the natural environment and its self-purification capacity.

Total emission control consists of three elements: (1) the total amount of pollutant emissions, (2) the region into which pollutants are discharged, and (3) the time when pollutants are discharged (Ministry of Environment of Japan (MOEJP), 1984; Song G., 2005; 孟伟, 2008).

Moreover, from the Environmental Restoration and Conservation Agency in Japan (ERCA, 2019), the TEC policy means a regulation method for managing the quality of environment in a given region where factories and workplaces are gathered and air pollution or water pollution is progressing, whose objective is to reduce the total amount of pollutants in the entire region when it is difficult to secure environmental standards by concentration regulations or emission regulations for each facility in the region. First of all, it needs to specify the region, make the reduction plan of the total amount of pollutants, and set up a standard for each individual facility (MOEJP, 1984; ERCA, 2019, https://www.erca.go.jp/yobou/taiki/yougo/kw74.html).

In a word, the TEC policy refers to an environmental managing system with the core of controlling the total amount of discharged pollutants under the allowed maximum value of the total emission based on the environmental carrying capacity in a given region.

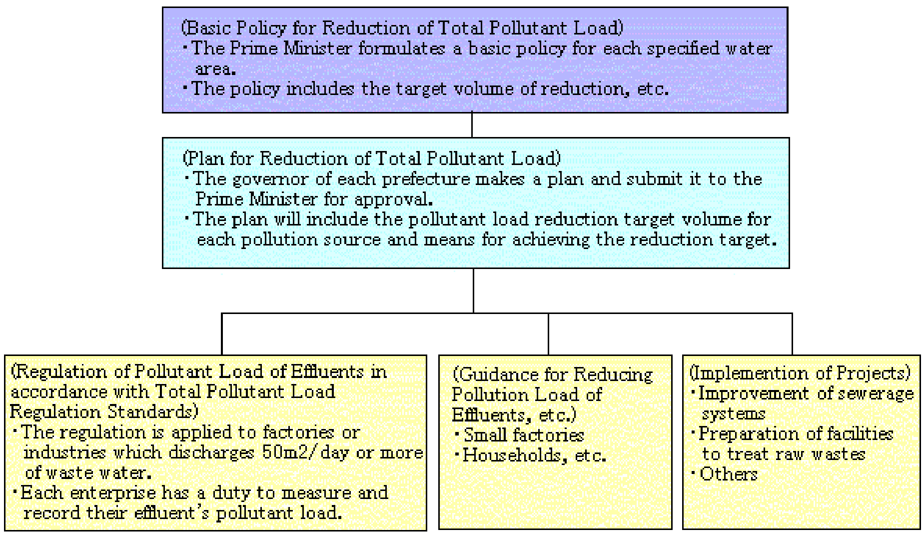
2.1.2 The experience of the TEC policy and its implementation

At the initial period of environmental management, the fundamentally used method was only concentration control. The concentration regulation refers to mainly concentration emission standards which control only the concentration of pollutants discharged from the source of pollution. The emission charges systems are based on concentration emission standards as the main evaluation criteria (Ge C., 2009). For most of countries over the world, the environmental management system has gone through the process from "concentration control" to “total emission control” (Hu Q., et al., 2018; Jang Y. K., et al, 1986; Takawo T., 1980; 宋国君, 2000).

Japan

In order to improve the water and atmospheric environment, Japanese scholars first put forward the concept of total pollutant emission control for water pollution in the late 1960s, that is, to control the total amount of pollutants in a given area or in the atmosphere under some certain limits (Tsuchiya T., 1980). The "certain limits" were later used as the main basis for determining the concept of environmental capacity. Then, in the Interim Law for Conservation of the Environment of the Seto Inland Sea, enacted in 1973, Japan first cited the concept of total emission control in the waste water discharge management, and issued emission permits for discharging wastewater (COD). Years later in June 1978, The Law and The Water Pollution Control Law were revised, and comprehensive measures have been taken under this permanent statute to protect the beautiful Seto Inland Sea. Also in 1978, a legal system limiting total allowable pollutant loads into the designated water bodies was established to improve organic marine pollution in bays and inland seas, and water quality total amount regulations were introduced first as a formal TEC policy in Japan (MOEJP, 2019).

Japanese efforts had been focused on reducing pollutant loads in populated and industrialized areas around large enclosed water bodies to improve water quality. The Water Pollution Control Law and the related legislation were amended in 1978 to implement a system of Areawide Total Pollutant Load Control System for such large enclosed water bodies. The Control System is being applied to some large watersheds for which current concentration-based effluent standards, including prefectural stringent effluent standards, were insufficient to meet COD Environmental Quality Standards (MOEJP, 2019). Fig. 2-1-1 shows the schematic diagram of total pollutant load control system in Japan.



Sources: MOE of Japan website (http://www.env.go.jp/en/water/wq/wemj/promot.html)

Fig. 2-1-1 Schematic diagram of total pollutant load control system

USA

The U.S. Environmental Protection Agency (EPA) introduced the concept of the TMDL (Total Maximum Daily Loads) program in 1972 under the Water Cleansing Act, which calculates the maximum load allowable for a water body or a given region and the distribution of the total amount of pollutant load between the sources of pollution (USEPA, 1986). At the same time, the United States began in 1972 to implement a nationwide water pollutant emission permit system, and make it in the technical routes and methods of continuous improvement and development (Robert W. H. & Gordon L. H., 1989). In 1983, legislation was enacted to implement total emission control based on water quality regulations (USEPA, 1999). In recent years, the EPA has also been making changes to the TMDL program, shifting U.S. water conservation from simple pollution source control to pollution control based on ecological health and functionality, creating new challenges for scientists working on environmental management issues (Evelyn H. & Abby W., 2004).

EU

After the federal Germany and the EU countries adopted the management method of total emission control on water pollutant discharge, more than 60% of the industrial wastewater and domestic sewage discharged into the Rhine River were treated, and the water quality of the Rhine River was improved significantly (Liu W., et al, 2011; 王卫平, 2007). Other countries such as Sweden, the former Soviet Union, Romania and Poland, have also implemented the total emission control as the core of water environmental management policies, and achieved an effective result. In 1991, Sweden introduced early the carbon taxes (Stanislav E. S., et al., 2018) and in recent years, has implemented an extensive total emission control program on nitrogen reduction and reduced nitrogen emissions by 40% from 1985 to 2000 (徐树媛, 2006). Austria has developed environmental protection ordinances and systems with total emission control policy, and has achieved good results in pollution control and environmental quality (Banks P.A, 1988).

In December 2000, the European Parliament and the European Commission jointly issued the Directive establishing a framework for action on community water policy (2000/60/EC Directive, referred to as the Water Framework Directive). The Directive requires member states to develop watershed management plans for water bodies such as rivers, lakes, oceans and groundwater, in particular for watersheds across administrative regions, and to ensure that the water environment continues to be improved for the ultimate purpose (Tietenberg T H., 1991). To date, some 20 directives on water environmental standards have been issued, which play a vital role in protecting and improving the water quality of the member states, effectively preventing and controlling water pollution, implementing the common EU environmental policy and achieving common water environmental goals (European Union, 2000; Grubb M., et al., 2005; [英]格里菲斯, 2008). According to the study by Jordi T. et al. (2019), The EU Emissions Trading System (EU ETS) imposes a cap on total emissions of carbon dioxide, nitrous oxide and perfluorocarbons from over 11,000 heavy energy using and electricity-generating installations and aircrafts, covering about 45% of the EU's overall GHG emissions (Christian E., 2007; Christian S., et al., 2016).

Moreover, in fighting against climate change for over two decades, the EU, as a leader, is committed to achieving carbon neutrality by 2050 (Cames M. & Weidlich A., 2006; Michael H., et al., 2013).

China

China has been facing serious environmental problems as a consequence of rapid economic growth of the past three decades. To curb increased levels of environmental pollution, China piloted a TEC system in 1988 and implemented the TEC policy nationwide in 1996 (Hu Q., et al., 2018; Jiu W., et al., 2011).

In the late 1970s, China began the trial research on total emission control for water pollution, with an exploration of the first Songhua River total control standard (BOD) as the earliest TEC policy practice (包存宽 et al., 2000). Then, during the Sixth Five-Year Plan period (1980-1985), the research was carried out on the distribution of total pollution load and the quantitative evaluation of the water environment capacity in Minjiang River area (冯金鹏, et al., 2014). Later during the "Seventh Five-Year Plan" period (1986-1990), based on the total emission control plans, the water environment functional zoning and the issuance of sewage permits system had explored in some sections of the Yangtze, Yellow and Huaihe rivers and the waters of Baiyangdian, Jiaozhou Bay and Quanzhou Bay (王卫平, 2007). By the mid-1980s, China had made some further explorations on the self-purification capacity and the environmental capacity of environmental pollutants in China's offshore water regions (孟伟, 2008). Particularly in 1985, Shanghai metropolitan government had decided by legislation to implement the total emission control policy to reduce wastewater emission in the upper reaches of Huangpu River as one of important water resources for the whole city. It was first trial for a local government to implement the TEC policy by legislation (SESRI, 1986b). The Regulations on Water Sources Protection in the Upper Reaches of Huangpu River in Shanghai, issued in 1985, required district- and county-level environmental protection departments to issue emission permits to all units that discharge wastewater (Shanghai Gov., 1985).

In March 1988, the former State Environmental Protection Bureau (SEPB) issued the Interim Measures for the Management of Water Pollution Emission Permits with total emission control as the core policy and then the implementation of the pilot project on emission permits marked the beginning of a new stage in China's total emission control for water environmental management (宋国君, 2000).

The TEC approach was first introduced at the Third National Conference for Environmental Protection in 1988 when the State Environmental Protection Agency (SEPA) proposed implementing a TEC approach. In 1996, eight years later, in the Ninth Five-Year Plan for National Economic and Social Development and the Outline of Vision Goals for 2010, which were adopted by the National People's Congress in 1996, the total emission control of a pollutant officially became a major measure for environmental protection in China. Also, the TEC policy was included in the Ninth Five Year Plan for Environmental Protection and Environmental Targets for 2000 in 1996. According to the plan, the discharges of 12 pollutants, namely sulfur dioxide (SO_2), chemical oxygen demand (COD) of discharge water, mineral oil (in sewage), smoke, particulates (industrial sources), cyanide, arsenic, mercury, lead, hexavalent chromium, cadmium and solid waste (industrial sources), were regulated by using the TEC policies (Ge Chazhong, et al., 2009). The TEC policy had been implemented nationwide in 1996, allotting emission quotas to its provincial governments with a target of 10% reduction in pollutants emissions over a five-year period since then (Hu Q., 2018).

Since then for more than 20 years, the TEC policy has been practiced in China as an effective option of environmental policy tool kit and has become the foundation for managing approach in controlling pollution in China (JiuW., et al., 2011; 包存宽, et al, 2000; 程纪华, 2016; 刘子刚, et al, 1997; 刘娜, et al, 2007; 肖伟华, 2011 & 2019; 熊小平, 2015; 张天柱, 1990). It was claimed that the TEC policy played a critical role in cutting annual emission of targeted pollutants and improving the quality of the environment (范英英, 2012; 王金南, et al., 2011; 王毅, 2015).

However, Hu Q., et al., (2018) pointed out that the scope and the effectiveness of the TEC policy should be more focused and the TEC as one of the national pollution control strategies should be carefully reviewed. Yet acquiring reliable and accountable pollution data has been a technical challenge.

In order to improve the scope and the effectiveness of the TEC policy, specifically in reducing the national total CO_2 emission, for example, China has been positively pushing a project for reducing carbon emission based primarily on market trading of emission allowances, i.e. the cap-and-trade (C&T) system (Fuss S., et al., 2018). For instance, Shenzhen, which was authorized as one of the pilot regions, launched the first regional C&T system in 2013 (Jiang J., et al., 2014). Actually at the end of 2017, China has already implemented a national emission trading system with a trial operation (NDRC, 2018; Pan Y., et al., 2019; Zhou J., et al., 2019).

2.1.3 Total emission control and emissions trading system

Total emission control (TEC) is the basis for implementation of emissions trading system (ETS). At meantime, the ETS is recognized widely as an environmental-economic management policy to achieve the TEC targets with effectiveness and efficiency.

The economist John H. D. first proposed the theory of emissions trading in his classic book originally published in 1968, and put forward a new policy instrument for tackling pollution problems, namely “markets in pollution rights” (John H. D., 1968). In subsequent years, a system of emissions trading has gradually evolved and it is now one of the environmental economic policies which have attracted wide attention from all over the world, particularly in international discussion on how to address the problem of global climate change (John H.D., 2002; Michael H., et al., 2014; Tietenberg T.H., 1991).

Emission trading, as an environmental-economic policy that seeks reducing pollution efficiently, is to put a limit on emissions, give polluters a certain number of allowances consistent with those limits, and then permit the polluters to buy and sell the allowances. The trading of a finite number of allowances results in a market price, which enables polluters to work out the most cost-effective means of reaching the required reduction. Emissions trading had been used with notable success to reduce emissions that cause acid rain, and it is currently being used in various attempts around the world (https://www.britannica.com/technology/emissions-trading).

Emission trading originated in the United States. In the face of the reality that sulfur dioxide pollution had been increasing, in order to resolve the contradiction between the economy’s development and environmental protection through new enterprises, the U.S. Federal Environmental Protection Agency (EPA) put forward the idea of emissions trading, and introduced the concept of "emission reduction credit", in realization of air quality targets by the Clean Air Act. Later since 1977, regarding the emission reduction credit, the US EPA has developed a series of policies and regulations, which allow the transfer and exchange of emissions between different factories, and also provide enterprises with a new option for the least cost of pollution reduction (Portney P.R. & Stavins R.N., 2000). Then Germany, UK, Australia and other countries have begun the practice of emissions trading. At present, the global carbon emissions trading market has been improved recently. There are international markets including The European Climate Exchange in Amsterdam, The European Energy Exchange in Germany, and The Future Power Exchange in France. In addition, Japan, Canada, Russia and Australia also have their own emissions trading markets (Tokyo, 2010). The Chicago Climate Change Exchange is the world's first domestic climate exchange. The European Climate Exchange is the largest market in the world, accounting for 82% of all carbon transactions globally settled through exchanges in 2006. In 2005, the EU ETS has been the cornerstone of the EU strategy for decarbonizing the economy and EU climate policy. The EU ETS is thus expected to have a central role in inducing low-carbon technological change as needed (Fuss S., et al., 2018; Fontini F., Pavan G., 2014). (https://baike.baidu.com/item/排污权交易制度).

As for ETS in China, based on the experiences of years from the seven pilot carbon markets, including Beijing, Tianjin, Shanghai, Guangdong, Shenzhen, Hubei and Chongqing, operated by the respective local governments, the Chinese central government planned in 2015 to establish a national emission trading system from 2017 to 2020 (Chang K. & Chang H., 2016; NDRC, 2015). At the end of 2017, in fact, China has already begun the trial implementation of a national emission trading system and the power sector initially proceeded into the market in the trial period (NDRC, 2018).

Generally considered, the emissions trading system (ETS) consists of the main content below. The environmental quality targets of a given region are first determined and the environmental capacity is evaluated accordingly. The maximum allowable emissions of pollutants are then deduced and divided into a number of prescribed emissions, i.e., “emissions rights”. There are different ways to allocate the right to exclusive, mainly including public auction, pricing sale and free distribution, and such rights can be legally traded through the establishment of emission rights trading market. In the emission rights market, the polluters can independently make their own decision on the degree of emitting pollutants, thereby buying or selling the emission rights to pursue their interests (马中&(美)杜丹德(Daniel Dudek),1999).

The theoretical background of the ETS comes from the famous "Coase Theorem", which could imply that as long as the right is clearly defined, spontaneous market transactions can guarantee achieving the optimal state of resource allocation. (https://en.wikipedia.org/wiki/Coase_theorem).

The techniques of implementing the ETS, however, are based on the total emission control (TEC) policy. As a core component of the ETS, the initial allocation of emission quotas to participants is extremely important and certainly dependent of the allocation methods of the TEC policy (Gagelmann F., 2008, 2017; Li L., et al, 2018; 段茂盛, 2014).

As a cost-effective means to deal with the global climate change, carbon market can reduce CO_2 emissions at the lowest costs. CO_2 allowance allocation is one of the key issues to build an effective carbon market (Jiang J., et al., 2016). European Union Emissions Trading System (EU ETS) allocated the European Union allowances (EUAs) in three phases. In phase I and phase II the EUAs were allocated by national allocation plan (NAP), which can be called “down-top”. In phase III (2013–2020), EUAs allocation was handled uniformly, that is no longer national allocation plans with different targets but an almost fully harmonized European instrument. Thus EUAs allocation in phase III is processed by “top-down” approach, which composes of two stages: in the first stage, European Union commission allocates the EUAs to the member states, and in the second stage, each state allocates its own EUAs to emitters (Zhu B., et al., 2018).

China, however, is just beginning the ETS program with a trial operation only in the power sector. How to process the emissions allocation in both the stages has been becoming one of the key topics which the policy designers have to face to.

2.2 The methods and techniques of the TEC policy design

The following literature review focuses on these topics included in Fig.2-2-1 below, which shows the diagram of relations among the core theoretical methods and techniques used in the TEC policy design in this study (Braat L.C. & W.F.J. van Lierop, 1987).

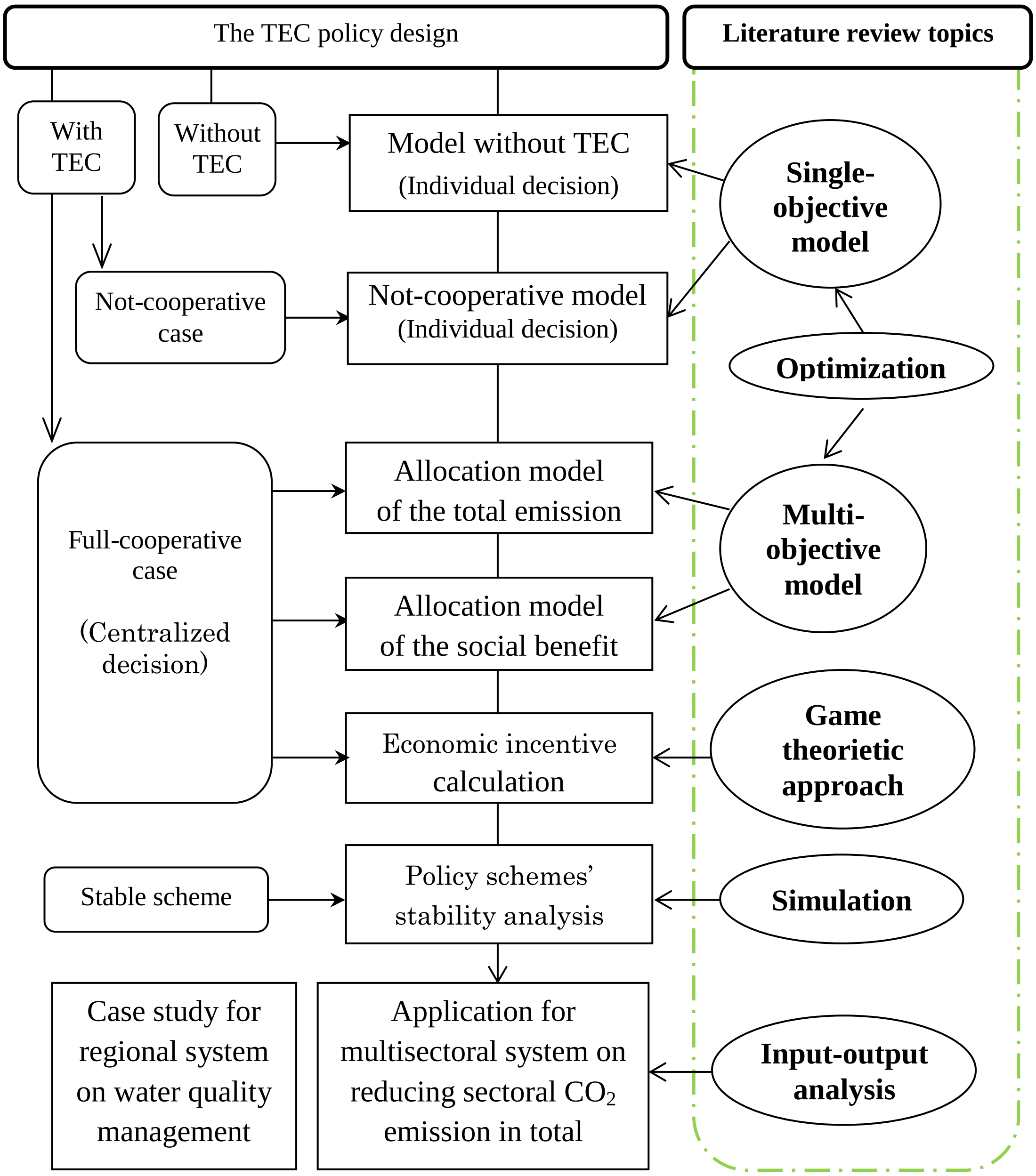


Fig. 2-2-1 The core theoretical methods and techniques used in the TEC policy design

Simply, the methodology of the TEC policy is considered to calculate the allowable total emission of pollutants and then allocate the total emission reasonably among all the polluters so as to achieve the environmental quality target in a given region during a certain period. The core techniques, therefore, are the allocation methods of the environmental resources (Donald H., et al, 2015).

As for the application levels, a number of literatures discussed the allocation schemes in different ranges that could be grouped into three categories i.e. the international level, the interregional level and among industrial sectors (Feng Z., et al. 2018). But for any level of them, most of researches on the allocation topic in recent years have concentrated on the allocation “principles” and “methods” (Zhou P. & Wang M., 2016; James K. B., 2018).

In respect to the allocation “principles”, the emissions allocations are usually discussed from different perspectives of fairness. But there is not yet a unified understanding of fairness. Several scholars argued that efficiency should be treated as one type of fairness, while others have different opinions (Dommen E., 1993; Hamilton C., 2001; Zhou L., et al., 2014). In spite of this situation, the allocation principles can be generally classified into a number of criteria such as “fairness”, “efficiency” and “feasibility” (Zhu B., et al., 2018). The three principals have played a major role in designing methods to allocate CO_2 emissions quotas (Bothe M., 1993; Yang et al., 2012).

In regard to the “methods”, the allocation methods can be roughly classified into three types including “indicator”, “optimization” and “game theory” (Zhu B., et al., 2018). Besides the three main methods, there is also the “hybrid approach” proposed as the fourth major method for the allocation of CO_2 emissions. Each approach has its strengths and weaknesses, and none is superior in all respects (Zhou P. & Wang M., 2016).

From the above, thus, this study here reviews allocation principles of “fairness”, “efficiency” and “feasibility” as well as the allocation methods of “indicator”, “optimization” “game theoretic” and “hybrid” approaches

2.2.1 Allocation principles

Firstly, regarding the “fairness” criteria, Ringius L., et al. (1998; 2002) have once summarized the fairness criteria that mainly include “sovereignty”, “egalitarianism”, “horizontal equity”, “vertical equity”, and “polluter-pays”. There are different implications for the criteria (Aaditya M. & Arvind S., 2012). Sovereignty means that all nations (firms) have equal right to pollute and to be protected from pollution the permits are allocated in proportion to historical emissions. Egalitarianism means that anyone has the equal rights of Human beings to use the atmospheric resources and permits are allocated in proportion to population. Horizontal equity means that the countries should be treated with equal net welfare changes and permits allocation should make that net cost of abatement as a proportion of GDP is the same for each country. Vertical equity means that greater emissions reduction burden to be carried by richer countries and permits should be progressively distribute in terms of per capita GDP. Polluter pays means that greater abatement burden to be carried by the larger polluter and the abatement burden is allocated in proportion to historical emissions (Feng Z., et al. 2018; Zhu B., et al., 2018).

There are many research papers related to the fairness principle, specifically. From some meaning of the fairness, Ringius L., et al. (1998) discussed a number of concepts of equity, examined three specific burden sharing rules and formulae, and presented cost calculations on the burden sharing rules (Grtibler A. and Nakicenovic N., 1994).

Hakon S., et al., (2019) discussed the question asking "Does the relationship between fairness and ambition vary across the three fairness principles: responsibility, capability, and rights (needs)?". Harry G. and David G. (2016) examined four ethical principles that speak to different notions of fairness in the way this burden can and should be shared, and used them to produce three normative criteria for pursuing fairness in the clean energy fiscal policy context. Brick K. and Visser M. (2015) examined the strategic use of burden-sharing principles by the experiment of a multi-country public-good game with the use of the historical and future polluter-pays rules. Groh D. E. & Ziegler A. (2018) gave an econometric analysis for the costs of energy policy measures on self-interested preferences for burden sharing rules.

Zhu B., et al. (2018) pointed out that the conception of fairness in carbon permits allocation is philosophically debated, and so far, there has been no consensus on the best fairness principle in the literature. Some major allocation principles, including equality and contribution (Tornblom Y. K., Jonsson R.D., 1985; Tornblom Y.K. & Foa G.U., 1983) have been examined in the area of distributive justice evaluation.

Secondly, the "efficiency" principle reflects the emission control technology and emission reduction potential and focuses on achieving environmental targets with high efficiency, usually aiming at the maximum economic profits or the lowest abatement costs (Yang et al., 2012; Gupta S. and Bhandari P.M., 1999).

Lennox A.J. and Nieuwkoop v.R. (2010) used a computable general equilibrium model to analyse the impacts of output-based allocation for achieving the maximum economic profits.

Feng C., et al. (2015) proposed a new two-step method for carbon emissions abatement (CEA) allocation and compensation schemes based on data envelopment analysis (DEA) to optimize the social benefit. Some researches applied the efficiency principle to save abatement cost.

DeCara S. and Jayet P.A. (2011) studied the marginal abatement costs of greenhouse gas emissions from European agriculture, cost-effectiveness, and the EU non-ETS burden-sharing agreement and used the efficiency principle of sharing abatement burden with the lowest costs. Cui L.B. et al., (2014) proposed the emissions trading scheme with lowest cost for achieving China's 2020 carbon intensity reduction target.

In addition, some researchers also considered a number of indicators as the efficiency principles. For instances, the same unit of GDP emissions or per capita GDP emission is considered to be an efficient allocation indicator reflecting the efficiency principle (Carlsson F., et al., 2013; Zhou P. & Wang M., 2016). Energy intensity and emissions reduction costs are other indicators related to the efficiency principle. Energy consumption per unit of an industrial added value is used to represent the reduction potential (Yi W., et al., 2011). On the basis of benchmarking criterion, CO_2 emissions per unit of product are used to allocate CO_2 emissions quotas at firm level (Zetterberg L., et al., 2012). Ian A.M., et al. (2009) suggested using contests to allocate pollution rights. In macroeconomic modelling for energy and environmental analyses, Bye B. (2008) established integrated economy-energy- environment models as efficient tools.

Thirdly, in addition, the “feasibility” principle is also proposed in the existing allocation researches. The principle originally comes from operational requirements that the burden sharing formula or calculation should be more easily accepted by different participants and easily implemented in practice, and so the allocation needs to take account of the different economic developments and living standards (Amheka A., et al., 2014; Zhou P. & Wang M., 2016).

Fang J., et al. (2009) assumed four GHG emissions scenarios to analyse equity and feasibility of the global abatement goal announced by the Group of Eight (G8), and pointed out that CO_2 emissions volume is a good indicator reflecting the feasibility principle. The grandfathering criterion and benchmarking criterion are the two common allocation criterions widely used as easily acceptable ones although they are criticized with inefficiency (Faure M., et al, 2003).

Zetterberg L., et al. (2012) used an economic analysis to evaluate grandfathering, auctioning, and benchmarking approaches for allocation of emissions allowances and then discuss practical experience from European and American schemes. And they concluded that in principle, auctions are superior from the viewpoints of efficiency, fairness, transparency, and simplicity.

Ji J., et al. (2017) considered that the total emissions volume and emissions volume per unit of product were the indicators with feasibility for reducing CO_2 emissions. Arif F. and Dissou Y. (2016) analysed the implications of burden sharing rules in a decentralized federation, assessed the impacts of traditional entitlement-based permit allocation rules, and introduced the “no prior entitlement” (NPE) allocation rule of emissions.

Finally, in addition to the above, there are a number of studies about the allocation principles in some respective topics, using justice (Chukwumerije O. & Kate D., 2010); responsibility (Nathan R., et al., 2006); equity (Valerie C., et al., 2015; Asami M., et al., 2006); effort-sharing rules (Fredrik C, et al., 2011); mutual recognition (Arild U., et al., 2015), etc.

2.2.2 Indicator methods

The indicator approach is the most commonly used method which is simple and easy to be understood (Zhou P. & Wang M., 2016). The indicator methods can be divided into the ones of a single indicator and comprehensive indicators or multi-objectives (Zhu B., et al., 2018; Odu G.O, et al., 2013; Mardania A., et al., 2017).

(1) The single indicator methods

Many scholars have often used the single indicator approach to solve the allocation problems of emissions quotas because of its simplicity and ease of use (Miketa A. & Schrattenholzer L., 2006).

The single indicator methods can be used in terms of a measurable indicator, such as: GDP (Rose A. & Stevens B., 1993; Rose A., et al., 1998), carbon intensity (Gupta & Bhandari, 1999; Miketa A.,et al., 2006), population (Niklas H., et al., 2006; Meyer A, 2000), outputs (Markus A.E. et al., 2005; Christoph B., et al., 2014), historical emissions (Böhringer & Lange, 2005; Robert C. Schmidt & Jobst Heitzig, 2014), and others.

The frequently used indicators are the per capita emission (Zhou P., et al., 2013) and the per capita cumulative emissions (Christoph B., et al., 2009). Besides, the CO_2 volume annually emitted by each individual is also proposed as an indicator (Wei Y.M., et al., 2014).

Moreover, the logarithmic mean divisia index (LMDI) method is commonly presented to analyse CO_2 emissions for some sector in China (Wang W.W., et al., 2011; Xu J., Fleiter T., et al., 2012). The method is generally adopted to decompose emission factors into energy structure, energy intensity, industrial structure, economic output and population scale (Shen L., et al., 2018; Chong C. H., et al., 2019).

(2) The comprehensive indicators methods

If compared with the single indicator, the comprehensive indicators methods have the merit of integrating multiple criteria and so received increasing attention. Although the single indicator method is simple and easy to use in practice, the selection of different indicator often leads to different or even contradictive allocation results and so reaching a consensus among the parties is usually difficult only by one indicator (Zhou P. & Wang M., 2016).

In practice, as a result, the sharing policy with comprehensive indicators would be easier for polluters to accept. The comprehensive indicators lead to relatively “balanced” and less discrepancy allocations results by providing better and more integrated representation for multiple indicators (Zhou P. & Wang M., 2016).

There are two main comprehensive indicators approaches, i.e., Triptych and multi-criteria decision analysis (MCDA).

The Triptych approach divides the national economic sectors into three groups: domestic sector, energy-intensive and power sector. This approach needs to specify the functions of CO_2 emissions of three sectors, and the CO_2 emission allowances for each sector can be calculated based on the estimation of economic growth, demographic change, and CO_2 emissions allowance increment (Michel D.E., et al., 2008; Phylipsen G.J.M. et al., 1998).

The MCDA approach is an analysis procedure on how to decide the best from alternative options (Mardania A., et al., 2017; Fang K., et al., 2019; Kaya I., et al., 2019; Konidari P., et al., 2007; Leimbach M., et al., 2010; Manuel B., et al., 2019; Odu G.O., et al, 2013; Ringius L., et al., 1998; Vaillancourt K., et al., 2004, 2006; Yi W., et al., 2011). Particularly, Mardania A., et al., (2017) gave a review of multi-criteria decision-making applications to solve energy management problems from 1995 to 2015. Kumara A. et al., (2017) have reviewed the multicriteria decision making towards sustainable renewable energy development.

In addition, Zhang Y.J., et al. (2016) constructed a comprehensive index based on equity and efficiency principles to allocate carbon emission quotas among 39 sectors of China's industry. To explore the optimal emission quota allocation, their paper draws on a different theoretical framework of achieving a given total emission reduction target in a least-cost manner.

Dong F., et al. (2018) considered both equity and efficiency on how to allocate CO2 reduction targets at the provincial level in China. Their study employs a modified Fixed Cost Allocation Model (FCAM) to determine permitted emissions of each province in China based on provincial carbon allocation results following Equity principle, which contain historical egalitarian, population egalitarian and pays ability egalitarian.

In the comprehensive indicators approach, it can be seen that the determination of the weights of different indicators are very important, and the selection of different methods has a significant impact on the allocation results (Zhou P., et al., 2016).

2.2.3 Optimization and simulation

The optimization is defined as finding universal solutions of a function that minimizes or maximizes its value while being subjected to constraints. In the optimization models, it is absolutely required to establish the objective functions and set the related constraints which the objective function is being subjected to (Banos R., et al., 2011; Li H. & Scott K., et al., 2019).

As for optimization methods, there are the single-objective model (SOM) and multi-objective model (MOM). An optimization model of multiple objective problems is sometimes called a multi-criteria optimization model (MCOD) in some cases where the model is likely used to deals with two or more conflicting objectives (Odu G.O. & Charles-Owaba O.E., 2013). As seen in studies of economic environmental management policies, minimizing the total reduction costs, minimizing carbon emissions, and maximizing economic growth, maximizing economic profits, are the most commonly used optimizing objectives but they are obviously the conflicted objectives (Ning C., 2015). For example, Lennox J.A. and Nieuwkoop V. R. (2010); Feng C. et al. (2015) set the maximum economic profits, and DeCara S. and Jayet P.A (2011); Cui L.B. et al. (2014) set the lowest cost of carbon intensity reduction, as the objective targets.

For the constraints, there are some ones identified as constraints across different research themes, including, energy demand, energy resource availability, emission control targets, and manufacturing budgets, etc. For example, Zhang et al. (2012) took three distinct carbon tax policies as constrains for scenario analysis to find the best carbon mitigation policy.

As techniques to solve optimization problems, various operational research models (Bloemhof-Ruwaarda J.M., et al., 1995) are used mostly including nonlinear programming (Nordhaus W.D and Yang Z., 1996; Xu G., 2019), data envelopment analysis (DEA) (Feng et al., 2015; Guo X.Y., et al., 2017; Lu B. et al., 2013; Wang Y., et al., 2017; Zhou et al., 2014), index decomposition analysis (IDA) (Ang B.W, 2004; Xu X.Y & Ang B.W., 2013), etc. By the way, from Li H. and Scott K., et al., (2019), there were a total of 80 papers reviewed using index decomposition analysis (IDA), and the data envelopment analysis (DEA) was reviewed by Meng F. et al. (2016) who compared five widely used DEA efficiency methods. A computable general equilibrium model is developed to deal with detailed energy end-use technology (Fujimori S., Masui T., et al., 2014b) and analyse the different impacts of fine mechanisms in ETS (Lin B. & Jia Z., 2019). The bi-level optimization approach is used to taxing strategies for carbon emissions (Wei W., et al., 2014). The Pareto optimization method, as a well-known method to solve a multi-objective function problem, is suitable in a regulated market (Sarjiya, et al., 2019).

During the more than two decades of research from 1995, the multi-criteria optimization model (MCOD) has been widely applied in decision-making to solve energy management problems (Mardania A., et al., 2017) and recently the multi-criteria decision making (MCDM) methods have been also developed towards sustainable renewable energy development (Kumara A., et al., 2017). Particularly in controlling the CO_2 emission, the methods are frequently used to discuss topics such as: carbon mitigation policies (Chang Z., et al., 2017), tax, emission trading, the mixed policy (Li W. & Jia Z., 2017), carbon trading systems, taxing strategies (Wei W., Liang Y., et al., 2014), industrial infrastructure (Chen S., et al., 2016), the mechanisms of inter-regional carbon emissions transfer (Sun L., et al., 2017; Zhou P., et al., 2016), a top-down and bottom-up merging energy policy (Christoph W. F., et al., 2003), and the effectiveness of energy service (Fujimori S, et al., 2014a).

Also, the multicriteria (multiobjective) optimization methods are generally applied to allocate the CO_2 allowances and investigate an optimal pathway with the maximum total production profit while achieving carbon emission reduction targets under different sets of constraints (Wan Y., et al.,2019). Mori S. (1996) discussed in detail the resources and industry allocation model and its first simulations by a multiregional approach. Zhang L., et al. (2018) established a computable general equilibrium (CGE) model to analyse the impact of different ETS quota allocation scheme on the electricity industry and determine the best choice of quota allocation scheme for the electricity industry in China.

In addition, specifically, there are many studies on allocation methods by using optimization techniques with various constraints in different cases (Gacitua L., et al., 2018).

Aqeel A.B. et al. (2011) discussed the optimization modeling techniques in power generation and supply. Athanasios I.T., et al. (2010) studied the simulation of electricity energy markets and assessment of CO_2 trading on their structure (a stochastic analysis of the Greek Power sector).

Zhang S. and Zhao T. (2019) analysed the regional disparities based on STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model from 1996 to 2015 to identify major influencing factors of CO_2 emissions in China.

Augusto S. S., et al. (2018) applied parametric and semiparametric analysis using panel data to discuss the flexible-fuel automobiles and CO_2 emissions in Brazil. Benjamin F. H. (1995) discussed optimization methods for electric utility resource planning in European.

Reynolds J., et al. (2018) used the Holistic modelling techniques for the operational simulation of multi-vector energy systems. Peter T.J. (2017) analysed a comparation of renewable energy simulation tools: performance simulation model vs. system optimization.

Pang R.Z, et al. (2015) presented a methodology that discusses a reallocation of carbon emission quotas based on the ZSG-DEA model to reach Pareto improvement. Jaruwan C. (2018) proposed an extended IPAT model (IPAT/Kaya approach combined with Variance analysis technique) on decomposition analysis of CO_2 emission in ASEAN.

Oliveira T., et al. (2019) studied on econometric modeling of CO_2 emissions abatement. They compared different econometric models that estimate the amount of carbon abated due to renewable energy (RE) in terms of their results and their inherent methodological benefits and drawbacks.

Li L., et al., (2019) pointed out that currently, most allocation methods mainly focus on the realization of a single performance goal, which will result in conflicts between different levels of participants. To overcome this limitation, a bi-objective programming model (BPM) with two sub-objective functions of abatement costs and carbon assets is proposed. Meanwhile, cost-oriented model (CM) and asset-oriented model (AM) are implemented as comparison approaches that represent the minimization of regional abatement costs and the maximization of individual interests, respectively. Also, Li L., et al. (2018) studied on the evidence from the maximum deviation method for carbon dioxide emissions quotas allocation in the Pearl River Delta (PRD) region in China. They used the maximum deviation method (MDM) to allocate CO_2 emissions quotas in the PRD region by taking the imbalanced development of different cities into consideration. Three principles including equality (represented by a population indicator), efficiency (represented by a GDP indicator) and feasibility (represented by a historical CO_2 emissions indicator) are considered in the method.

Feng Z., et al. (2018) proposed an allocation model based upon weighted voting to consider the scheme preference of each region in China. In this model, three allocation schemes (historical emission based, GDP based and population based) are taken into account to be selected by each region. The voting rights of each region are quantified by the comprehensive carbon emission indices, which are weighted indices of four indicators (emission reduction pressure, capacity, responsibility and potential).

Ye F., et al. (2019) innovatively applied the 3E system to the carbon dioxide quota allocation issue and developed a dual-objective programming model that considered both the economic goal and the energy goal, while the environmental goal was contained in constraints.

Liu Z., et al. (2018) proposed an allocation method at the city level by combining a data envelop analysis method, an entropy weight method and a clustering analysis method using the Yangtze River Delta region as a case study.

Kong Y., et al. (2019) combined DEA and entropy method to offer an improved approach for the nationwide provincial allocation in 2030 instead of using a single research method. Compared with previous studies that emphasize the efficiency and equality principles separately, they used the environmental Gini coefficient (Dai et al., 2018; Fabrizi & Trivisano, 2016) to examine the equality of allocation results.

Zhao S., et al. (2018) studied on the carbon emissions quota allocation based equilibrium strategy toward carbon reduction and economic benefits in China’s building materials industry. Their study seeks to reach a trade-off between economic benefits and carbon emissions in the building materials industry by integrating a carbon emissions quota allocation (CEQA) based equilibrium strategy under a carbon emissions trading

(CET) mechanism that fully considers the stakeholder relationships between the regional authority and the building materials suppliers. An interactive solution approach with fuzzy random variables (FRVs) is designed to determine the trade-off between these decision makers.

Liao Z., et al. (2015) investigated the comparison of the initial allocation methods of several main carbon markets. The initial allocation is fundamental, but it proposes difficulty in the mechanism design of the carbon emission trading system. Benchmark, grandfathering and the Shapley value have been employed to simulate a specific case, which consists of the initial allocation of carbon emission allowances of three power plants in Shanghai, China.

Liu H. and Lin B. (2017) proposed a novel nonlinear programming approach to obtain an optimal emission quota allocation in a least-cost way among multiple decision-making units under administration. Marginal emission abatement cost curves are simulated based on the environmental performance and marginal emission abatement costs measured in a set of parametric directional output distance functions with multi-inputs and multi-outputs. In addition, the proposed model is applied to empirically investigate the optimal carbon emission quota allocation for China's building construction industry among thirty-three provinces in three different regions.

Yuan Y.N., et al. (2012) analysed the intensity allocation criteria of carbon emission permits based on a 30-province-autonomous region computable equilibrium model.

Chen Z.M., et al (2010) used a systems input-output simulation for embodied carbon dioxide emissions of the world economy.

Fang G., et al. (2018) explored the optimization of carbon emission rights allocation based on energy justice. The justice-based model is built with the aid of Gini coefficient to optimize allocation scheme with constraints of population, ecological productive land, fossil energy resources and GDP.

Zhou M., et al., (2016) discussed the multi-agent-based simulation for policy valuation of carbon emissions. They have selected the total actual annual emissions as the statistical output indicator and evaluated how the relevant policies of carbon emission reduction affect it.

2.2.4 Game theoretical approach

(1) The economic incentives

Since 1970s, the design of policy instruments making use of economic incentives for environmental management has been widely discussed, for example, in the book named as "The Theory of Environmental Policy" by Baumol W.J. and Oatesl W.E. (1975; 1988; 1979). The knowledge about economic incentive approaches to pollution control has grown rapidly in the two decades in which they have received serious analytical attention (Anna Creti et al., 2017; Bower B.T., et al., 1977). Not only have the theoretical models become more focused and the empirical work more detailed, but also environmental policies have been experiencing for over a decade with emission charges and emissions trading (Tietenberg T.H., 1990).

As a policy instrument with economic incentives, the effective taxation might work well on the total emission regulation in a region. Pigou A. (1918) proposed taxation as a means of internalizing the externalities generated by an activity. The Pigouvian solution seeks to add the external costs to the market price, through taxation. As the social result, it will be optimal to consider the benefits and drawbacks which some productive activity brings to society. Taxation is an important instrument for achieving socio-environmental sustainability and can also be placed to offset the losses or gains generated by the indirect effects of the activity, the so-called negative externalities (Dresner S, et al., 2006).

Tax schemes have been widely considered for the water quality management and other environmental policies.

Sweden offers a useful example as a country where fuel taxes were introduced as early as 1920s, energy and natural gas tax in 1957 and carbon tax was introduced in 1991 (Stanislav E. S. & Stefan U. S., 2018).

Carlin A. (1992) released such a report named as "United States Experience with Economic Incentives to Control Environmental Pollution" (published by The EPA of United States,1992) and demonstrated that a policy based on economic incentives would be an effective or useful tool in controlling pollution and improving the environmental quality.

Soumya B. and Dennis W. (2012) pointed out that economic incentives can enhance policy efforts to improve the water quality in Asia. Robert G. C. (2002) considered that the economic incentives would be a standard tool on the design of agricultural policies. Boyd R. and Krutilla K., et al. (1995) researched the energy taxation as a policy instrument to reduce CO_2 emissions by a net benefit analysis.

Incentive policies for renewable energy sources (RES) development are strategies used in many locations, and international treaties, regulatory mechanisms, and incentives for investment are among their attributes (Solangi K.H, et al., 2011).

Tamura H. and Kimura T. (2001) dealt with how to evaluate the effectiveness of carbon tax (environmental tax) for regulating the carbon dioxide emissions. Zhou Y., Wang L. and McCalley JD (2011) discussed on designing effective and efficient incentive policies for renewable energy in generation expansion planning.

Cavalcanti M., et al. (2012) studied the taxation of automobile fuels in Brazil: Does ethanol need tax incentives to be competitive and if so, to what extent can they be justified by the balance of GHG emissions? They indicated that part of the tax revenue currently forgone because of tax incentives on ethanol in Brazil could be recovered without affecting its competitiveness.

Giancarlo A., et al., (2017) overviewed and discussed long-term incentive policies such as feed-in tariffs, shares with commercialization of certificates, auctions, and net metering. They described different strategies for incentivizing investments in renewable energy generation and emphasized their advantages and disadvantages, with a focus on their relevance and compatibility with the Brazilian renewable energy market.

Zhang X. and Bai X. (2016) proposed a policy dependency mapping (PDM) method to uncover the important paths in which government intentions and priorities are implemented from national to regional and local governments, which helps understand the key role that these policies play in the promotion of new energy vehicles (NEVs) in China. They then decoded the policy systems along the dependency paths using the PDM method and reveal how incentive policies in the last ten years drove new energy vehicle (NEV) adoption and built the world's largest electric vehicle market from scratch.

Megan C. E. (2018) studied the effective incentives on Australia's carbon farming policies for reforestation, and pointed out that well-designed incentives can encourage landholder adoption of reforestation within production landscapes, while delivering social, economic and biodiversity co-benefits.

Black G. et al., (2014) made the research that focuses on measures undertaken at the state level in the western region of the United States. Several of these states have implemented legislation in the form of financial incentives and renewable portfolio standards to support wind development. It is shown that state tax incentives and physical drivers have a significant positive impact on wind energy growth. At the federal level, one of the most important incentives is the renewable energy production tax credit (PTC), initially authorized by the Energy Policy Act of 1992. The PTC has a volatile history, having been allowed to expire twice and being renewed for only short periods during the past decade.

Hitaj C. (2013) showed that the variability in the presence and amount of this federal incentive is an important determinant of the number of new wind power facilities in the US. In addition to federal incentives, several studies to date have concluded that state-level incentives for wind energy producers are important drivers behind wind energy development. Elijah I.O. (2013) reviewed the Nigerian policy and incentives and found some policy conflicts, gaps and inconsistencies.

Based on the development status of power industry and electricity market in China, Zeng M., et al. (2013) have reviewed the three key development stages of traditional demand side management (DSM), including management content, operation mode and results assessment. In their studies, however, since the 1990s, DSM has been introduced by local governments and enterprises in China to improve terminal power efficiency and optimize resources allocation, and certain breakthrough have already been achieved. Demand Side Management (DSM) safeguard system and incentive mechanism, including political, economic, technical and managerial measures, are further discussed to achieve the aim of energy conservation and emission reduction.

Laesa E., et al. (2018) pointed out that "most of the reviewed quantitative studies find that financial incentives and subsidies have a positive impact on the probability of energy efficiency improvements being undertaken. However, when evaluating the energy efficiency improvements or CO_2 reductions induced by the incentives and therefore their effectiveness, the presence of free riding turns out to be a problem.

Jordi T., Stefano F. V. and Francesco N. (2019) analysed the recent reforms of the EU ETS and pointed out that "the incentives for innovation and adoption of low-carbon technologies are probably stronger today than ever before." Flues F. and van Dender K. (2017) studied on permit allocation rules and investment incentives in emissions trading systems. Mahdiloo M., et al. (2018) developed a set of decision models to support public managers in analysing performance compliance with CO_2 abatement incentive schemes. The models are based on data envelopment analysis (DEA) and the theory of incentive contracts (Joseph E. S., 1975; Harris M. & Raviv A., 1979).

(2) Game theoretical approach and simulation

Furthermore, Li H. and Scott K., et al. (2019) described that taking allowance allocation as a process of the multi-stage dynamic game, game theory has been introduced to exploring the optimal allocation mechanism (Eyckmans J. & Tulkens H., 2003; Helm D., 2003; MacKenzie I.A., et al., 2009; Zhang Y., et al., 2014). Imma C. (1997) described cooperative games arising from combinatorial optimization problems in his book published in 1997. Negotiations among the participants in allocation can be fully embodied in the game theory models, but the models are usually complicated and the results are less transparent (Zhu B., et al., 2018).

As an extension and concrete realization of the game theory of taxation described by Rinaldi S, SonciniSessa R. and Wbimton A.B. (1979), Tamura H. and Suzuki H. (1981) developed a simple game theoretical model for realizing total emission control in managing regional water quality. In their paper, they proposed a way of allocating the allowable total emission (environmental carrying capacity) among all the polluters to maximize the social benefit in the region. As a game theoretic decision process, specifically, the model is based on the concept of a characteristic function game (von Neumann J. & Morgenstem, 1953).

In order to simulate the cooperative game theoretic aspects of global climate negotiations, Eyckmans J. and Tulkens H. (2003) introduced the CLIMNEG world simulation (CWS) model which is derived from the seminal RICE model by Nordhaus W.D and Yang Z. (1996). In simulating coalitionally stable burden sharing agreements, they first state the necessary conditions that determine Pareto efficient investment and emission abatement paths under alternative regimes of cooperation between the regions, and then show with a numerical version of the CWS model that the transfer scheme advocated by Germain M., et al. (1997) induces an allocation in the (“gamma”) core of the world carbon emission abatement cooperative game.

Liu Z., Zhang X. and Lieu J. (2010) discussed the design of the incentive mechanism in electricity auction market based on the signaling game theory. Xu X., Pan S. & Ballot E. (2012) studied the allocation of transportation cost and CO_2 emission in pooled supply chains by using cooperative game theory. They used cooperative game theory as the cooperative mechanism for the implementation of the horizontal pooling of supply chains to reduce the costs and the transport CO_2 emissions.

Wu P., et al. (2014) simulated the saving in terms of the total abatement cost of CO_2 emission reductions for different trading games reflecting the potential cooperation among organizations including the European Union (EU), the Asia-Pacific Economic Cooperation (APEC) countries, the Union of South American Nations (USAN), and the Indian Ocean Rim Association for Regional Cooperation (IOR-ARC). A game approach is conducted to determine if the cooperation will come into existence among the organizations stated above. A similar idea is applied to the four largest emission countries, China, the United States, Russia, and India, as four individual players in the trading game. The results show that the design and selection of policy instruments for increasing the incentive for each country to participate are normally the keys to the success of agreements such as that to reduce emissions of carbon dioxide internationally. Theoretically, the incentive can be based on a comparison of the costs and benefits of a specific policy instrument. The highest incentive will be the one that generates the highest net benefit for achieving the committed target.

LoPrete C. and Hobbs B. F. (2016) also studied a cooperative game theoretic analysis of incentives for electricity markets. Specifically they developed a model of the economic incentives for market participants to cooperate in the development of a microgrid in a small electricity network served by a regulated utility. Using the framework of cooperative game theory and assuming exchangeable utility and full public information, they quantified how microgrid development affects prices, costs and benefits for parties in the network under alternative sets of assumptions.

Pan Y., et al., (2019) studied on game analysis of carbon emission verification with a case study from Shenzhen's cap-and-trade system in China. They has devised a three-player game model to analyse the behaviors among the emission generating companies (GCs), third-party verifiers (3PVs) and government, based on actual practice of Shenzhen's cap-and-trade (C&T) system, and proposed policy for proper implementation of a C&T system.

Sarjiya, et al., (2019) put forward a model to optimize generation expansion planning (GEP) in the deregulated markets, which usually depends on several factors such as economic, reliability, and CO_2 emissions. To solve the deregulated markets problems, their research combines bi-level optimization method and multi-period framework into game theory.

To overcome the ineffectiveness and high cost of the independent emission reduction model (IER model), Wang Q., et al. (2019) established a generalized Nash equilibrium game model for removing regional air pollutant and then performed a sensitivity analysis to simulate the effects of changes in the State-set SO_2 reduction targets and the upper and lower bounds on the optimal pollutant removal rate and the removal cost of each province in China.

Zhang M. and Li H. (2018) constructed an evolutionary game model of the regional governance of haze pollution cooperative control between the heterogeneity governments in China. The model is used to analyse the dynamic evolution path of game system as well as evolutionarily stable strategy under the three different conditions: no constraint, the introduction of compensation mechanisms and the introduction of punishment mechanism.

Yan J., et al. (2012) studied on the effects of CO_2 emissions control on electricity by using a swarm simulation model based on multiagent game theory. Zhang H., et al.(2017) built an evolutionary game to model three parties including the government, biofuel enterprises and restaurants under incomplete information and bounded entity rationality, and investigated supply chain policy options.

Cui H., et al. (2018) explored the CO_2 emissions from China’s power industry: Policy implications from both macro and micro perspectives. They selected seven socio-economic and technological factors involved in the whole power industry to investigate the mechanism driving CO_2 emissions based on the extended STIRPAT model, and established the evolutionary game model between power enterprise and government.

Chen F., et al. (2018) analysed how to achieve a cooperative mechanism of municipal solid waste (MSW) source separation among individuals based on evolutionary game theory.

(3) Hybrid approach

Wang X., et al. (2014) studied on the optimal strategies for carbon reduction at dual levels in China based on a hybrid nonlinear grey-prediction and quota-allocation model. They developed a hybrid nonlinear grey-prediction and quota allocation model (HNGP-QAM) for supporting optimal planning of China's carbon intensity reduction at both departmental and provincial levels in 2020. At such dual levels, HNGP-QAM can not only help forecast carbon intensity and its fluctuations over the concerned period, but also facilitate the identification of China's carbon intensity reduction target in 2020 and the corresponding quotas for minimizing the total abatement cost.

Hong Z., et al. (2017) studied on "Optimizing an emission trading scheme for local governments: A Stackelberg game model and hybrid algorithm", whose study investigates a policy-making problem for a local government to implement an emission trading scheme by considering the interactive production decisions of firms in its administrative region. The market-based allowance trading price formed freely among the firms in the region is investigated by taking into account regional environmental bearing capacities. Under the scheme, the government sets the emission reduction target of the region and allocates tradable initial allowances to firms, and firms plan their production according to their allowances on hand.

Tamura H. and Teraoka R. (2011) used a method of decision analysis called Prospect Theory under Uncertainty to show the effectiveness of a hybrid policy of carbon tax and emissions trading under uncertainty compared with the use of each policy independently. A mathematical model is described for assessing quantitatively how the hybrid policy of carbon tax and emissions trading would be effective to achieve the targeted reduction of the post-Kyoto target.

Gambhir A. et al., (2013) discussed a hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050. Nagashima S., et al, (2017) applied the hybrid input-output table method for socioeconomic and environmental assessment of a wind power generation system.

Hybrid approaches are increasingly being used to estimate the changes in carbon emissions performance and to identify the driving forces at the industry and whole economy levels. The meta-frontier nonradial Malmquist CO_2 emissions performance index model is a good example of this kind of methods (Lin B. & Tan R., 2017; Zhou P., et al., 2010).

In addition to the above, there are also many studies about simulation methods applied for energy-environmental problems, for instance, a simulation analysis for the UK's carbon taxes, consumer demand and carbon dioxide Emissions (Elizabeth S., et al., 1994) and simulations of the macroeconomic level for clean energy in Europe (Astrid D. et al., 2008).

2.3 The TEC model with input-output analysis

For input-output analysis, the topic searches have used with terms (key words): "TEC" OR "total emission control" with "IO" OR "input-output" OR "structural decomposition" OR "SDA" , "sector-", mainly on the Web of Science database and found numerous researches articles related to the field.

Measuring and controlling China's sectoral carbon emissions (CSCE) can be extremely important for climate change mitigation in the world. A number of empirical methods have been developed to research the emissions (Li H. & Scott K., et al., 2019). Some studies involve examining allowance allocation or evaluating the allocation options at industry or sector level via different methodologies (Ekholm et al., 2010; Jensen J. & Rasmussen T.N, 2000; Stenqvist C. & Ahman M., 2016). According to a systematic review on empirical methods for modelling sectoral carbon emissions in China (Li H. & Scott K., et al., 2019), there are five common groups of methods which can be identified as: environmentally-extended input-output analysis (EE-IOA), index decomposition analysis (IDA), econometrics, carbon emission control efficiency evaluation, and simulation. However, here in this study, the following review just focuses on the input-output analysis (IOA).

2.3.1 Topics frequently studied with IOA

Input-output analysis (IOA), which was originally developed by W. Leontief, is a form of quantitative economic analysis based on the interdependencies between different sectors of a national economy or different regional economies. The IOA method has been commonly used to calculate approximately the impacts of positive or negative economic shocks and analyse the flow effects throughout an economy (Sohn I., 1986; Maurizio C., 1988; Joy M. & Richard W., 2010; Yoshioka K., et al., 2013; 夏明, 2013; ThijsTen Raa, 2017).

Since 1970s, the input-output analysis has been used for the assessment of environmental emissions from both a production and a consumption perspective (Leontief, 1970). The method known as environmentally-extended input-output analysis (EE-IOA) was reviewed by Hoekstra R. (2010) and updated by Hawkins J., et al. (2015). In the two decades, IOA has been increasingly applied to investigate the regional and sectoral effects of carbon emissions. Particularly, IOA is useful for examining the embodied carbon flows of industries both interregionally (Yang J., et al, 2016; 吉岡完治, 2003) and internationally (Nansai K., et al, 2009; Kagawa S., et al, 2005), and so it provides a better understanding for "common but differentiated" responsibilities in tackling carbon abatement in China and globally (Liu X.L, 2012; Su B. & Ang B.W., 2014; Oscar D., et al., 2017).

By making a good use of input-output analysis, both the direct and indirect effects of economic production activities on the environment in a given region (city, country or industry or sector) can be analysed in the entire supply chain and production process of products. The impacts analysis of changes of production, technology, industrial structure and final consumption (demand) on the carbon emissions is one of the most frequently studied topics now, particularly in China. For instance, the influences on China's carbon emissions were examined through multiplier effect analysis (Su B. & Thomson, 2016; Zhang W. et al., 2015) and structural decomposition analysis (SDA) (Isabela B., et al., 2011; Su B. & Ang B.W., 2012; Wang Y., et al., 2013; Liu L., et al, 2017; Shan Y. et al., 2017).

Also as a significantly useful tool, input output analysis is widely used for policy maker to analyse policy schemes in an inter-regional system (White J.D., et al., 2017; Tamura H. & Ishida T., 1985) or a multi-regional system (Kagawa S., et al, 2004; Peter G.M., et al 2008; Surugiu S.C, et al., 2012; Hasegawa R., et al., 2015; Zhang W., et al., 2015; Zhang W., 2016; Llop M., 2017; Liu Q., et al., 2019) or a multisectoral system (Ju L. & Chen B., 2010; Zuhdi U., et al., 2014; Ahmad N., 2017). Besides, input-output techniques have been applied to trace the direct and indirect CO_2 emissions related with energy consumption in production processes (Yuan R., et al., 2016; Lin B., et al., 2015; Tarancon M.A & Rio P.D, 2012; Nagashima S., et al., 2017). The most applications are usually focused on investigating methodological instruments for identifying the economic factors responsible for the increase of environmental emissions (Lenzen M., et al., 2004; Chen Z, et al., 2010; Kagaw S., et al., 2015; Qi T., et al., 2016; Li J., et al., 2016; Ali Y., et al., 2017; Liu L, et al., 2017; Nagashima F., et al., 2017; Hanaka T., Kagawa S., et al., 2017).

Additionally, there are special topics, such as carbon trading schemes in the sector carbon emissions. For instance, Wu J., et al. (2019) put forward an integrated approach for allocating carbon emission quotas in China's emissions trading system, and Kagawa S., et al. (2005) explored the relationship between Kyoto Protocol and efficient resource uses by using the international input-output programming model: an application to the Japanese and Chinese economies. Fosten J. (2019) looked at the short-to-medium run impact of economic activity on CO_2 emissions in the United States, shifting the existing focus away from the long-run Environmental Kuznets Curve (EKC). The novel methodological approach combines discrete wavelet transforms with dynamic factor models.

In order to provide more solutions to research problems in the sectoral carbon emissions control field, the environmentally-extended input-output analysis (EE-IOA) are frequently integrated with other methods such as life cycle assessment (LCA). For instance, the integration of IOA with LCA will make it possible to enables in a more detailed way an account of total life-cycle carbon emissions and adopt subsequently a policy instrument like a cradle-to-grave approach for economic regions and sectors (Bilec M.M. et al., 2010; Janire P.G., et al. 2016; Lamnatou C. & Chemisana D, 2017; Nansai K., et al., 2012; Reutter B., et al., 2017; Thiesen J. et al., 2008).

2.3.2 Emissions inventory, impact analysis and predictions for emission trends

The IOA method has been basically conducted from the residential sector to international trade and applied to the three common topics: the emissions inventory, impact analysis, and predictions for carbon emission trends (Li H. & Scott K., et al., 2019).

At first, as for the carbon emissions inventory topic, the frequently used IOA methods include single-region input-output models (SRIO), bi-regional input-output models (BRIO), as well as multiregional input-output models (MRIO) and their integration with life-cycle assessment models (MRIO-LCA). Emissions inventories have been constructed at the household, industry, city, province, country and international trade levels. Input-output analysis, more specifically, the databases of MRIO, SRIO and MSIO, are used to calculate the embodied carbon emissions of industry sectors and regions (Liang Q.M., et al., 2007, 2014; Wilting H.C., 2012; Acquaye A. et al., 2017).

In addition, the IOA is frequently used in conjunction with other methods, such as life-cycle assessment, computable general equilibrium, and network analysis. The IOA could also be used to make decisions on how to allocate the initial quotas of certificates for an emissions trading scheme (ETS) in China. Discrepancies may result from the different assumptions that are associated with the different methods (Fan J., et al, 2017). In order to note the large fluctuation in both production-based emissions (PBE) and consumption-based (CBE) emissions, Zhang Z., et al. (2017) compared ten PBE and CBE results for 1995, 2000, 2002 and 2005. They found significant differences in the quantities of carbon emissions and the differences tended to increase over time. The different data sources on which these models are based also contribute to differences in results. For example, there was a gigatonne gap between the national carbon dioxide inventory and the summation of provincial inventory data between 1997 and 2010 in China (Guan D, et al., 2012).

Secondly, regarding the impact analysis, there are useful methods, such as input-output analysis (IOA), index decomposition analysis (IDA) and econometrics (Li H. & Scott K., et al., 2019). The main advantage of IOA techniques lies in the examination of system-wide effects, including the direct and indirect effects on the entire supply chain.

However, techniques of input-output analysis were used generally in carbon emissions researches at the national and international trade levels (Ang B.W. & Wang H., 2015). Daniel R.S., et al. (2019) used a multi-objective extended input-output model for a regional economy. Fernando S.P. et al. (2015) studied on the increase in Brazilian household income and its impact on CO_2 emissions: evidence for 2003 and 2009 from input-output tables.

In assessing impacts of the factors which affect carbon emission levels, there are usually two approaches. The first one is based on the assumption of a stable technological structure. As the outputs flow in any part of the system is changed, this will change the input requirements in all sectors in fixed proportions, leading to a multiplier effect across the economy (Jaume F.G, et al, 2017; Su B. & Ang B.W., 2014; Zhang W. et al., 2015). The second one, known as structural decomposition analysis (SDA), is based on the assumption of fixed technology coefficients and allows the sensitivity of changes to technical coefficients to be explored to assess their relative impacts (Goto N., 1996; Ning C., 2015; Tarancon M.A. & Rio P.D., 2012; Yan J., et al., 2016 & 2017; Yuan R. & Zhao T., et al., 2016).

Thirdly, for the prediction of carbon emissions, it is an active research topic in national, sectoral, regional, and residential carbon emissions. More models and techniques within IOA/ IDA have been developed for forecasting.

As an example, they focus more on the simulation or prediction of carbon emissions under different scenarios, including GM (1, 1) grey model (Tang D., et al., 2016), autoregressive integrated moving average model (ARIMA) (Liu L. et al., 2014), the vector error correction model (Zheng Y. & Luo D., 2013), the uncertainty analysis for multi-region input-output models (Lenzen M., et al., 2010) and the model for next generation energy systems (Nakano S. and Washizu A., 2017).

Li H. and Scott K. et al. (2019) have identified the top 10 papers with the strongest citation in the development of researching multisectoral carbon emission control in China. Among these important milestone papers, there are three ones using IOA approach.

Glen P. P. (2008) proposed a model with IOA on the national emission inventories from production-based to consumption-based perspective. Under the United National Framework Convention of Climate Change (UNFCCC) countries are required to submit National Emission Inventories (NEI) to benchmark reductions in greenhouse gas emissions. Several alternative options for incorporating consumption- based inventories into climate policy are discussed.

Zhu Q., et al. (2012) studied on the calculation and decomposition of indirect carbon emissions from residential consumption in China. Based on the IOA model and the comparable price input-output tables, their paper investigates the indirect carbon emissions from residential consumption in China in 1992–2005, and examines the impacts on the emissions using the structural decomposition method. The results indicate that the change in the consumption structure showed a weak positive effect on the emissions, and that China's population size is no longer the main reason for the growth of the emissions.

Peters G. P., et al. (2007) used IOA/SDA to analyse how the changes in China’s technology, economic structure, urbanization, and lifestyles affect CO_2 emissions. They found that infrastructure construction and urban household consumption, both in turn driven by urbanization and lifestyle changes, have outpaced efficiency improvements in the growth of CO_2 emissions.

2.3.3 Researches on China's carbon emissions by using IOA

In addition, there are many studies else using IOA to deal with environmental emission problem, particularly in China.

Wiedmann T. (2009) reviewed on recent multi-region input-output models used for consumption-based emission and resource accounting (Supasa T., et al., 2017). Zhao R. et al. (2017) used an integrated method based on input-output analysis and entropy weightings (Liu G., et al. 2018; Wang H., et al. 2018) to allocate carbon emissions among industries or sectors in China.

Wang K., et al. (2011; 2013) studied the regional allocation of CO_2 emissions allowance over provinces in China by 2020. Zhang J., et al. (2016) explored the comprehensive evaluation of energy intensity change for 1997-2012 based on input-output analysis with evidence from Beijing China. Zhang Y.J., et al (2017) used an analysis based on the input-output method on the indirect energy consumption and CO_2 emission caused by household consumption in China.

Wang Z., et al. (2018) developed a consumption-based framework to identify key sectors and paths along supply chains play a critical role in climate change mitigation, which combines input–output analysis (IOA), a power-of-pull approach (PoP) and structural path analysis (SPA), and they applied it to supply chain networks derived from 2010 and 2012 Jing-Jin-Ji interregional input-output tables.

Hawkins J., et al. (2015) investigated the promises and pitfalls in environmentally extended input-output analysis for China (a survey of the literature). Ang Y., et al. (2019) made an analysis of driving factors and allocation of carbon emission allowance in China. Liao C., et al. (2019) explored the driving forces of provincial-level CO_2 emissions in China's power sector based on LMDI method. Glen P. P., et al. (2011) constructed an environmentally extended multi-regional input-output table using the GTAP Database.

Gao J., et al. (2018) explored the greenhouse gas emission reduction in different economic sectors from the aspects of mitigation measures, health co-benefits, knowledge gaps, and policy implications.

Finally, although input-output analysis has a number of advantages in analysing an interregional or multisectoral system, it also has several disadvantages. The table data of IOA is changeable, which is usually renewable in every five years for the national IO table of a country, for example. And usually there is a significant time lag between each new release of input-output tables. Besides, the data of IOA table depends, to a great extent, on the used assumptions, accounting and collecting methods. Different methods could be easily resulting in different outcomes. For example, estimates of consumption-based carbon emissions for China varied from 1841 Mt to 4030 Mt in 2012 with a 54% difference rate (Zhang Z. et al., 2017).

2.4 Summary of the literature review

The TEC policy has been widely used since 1970s, and is proved to be an effective means for improving environmental pollution totally in a given region. Presently, it has been concerned greatly because it provides a basis for the emission trading systems to reduce efficiently GHG (mainly CO_2) emissions in the world, especially in China, which has been resulting in the global warming problem.

The key step of designing a TEC policy is to establish the total emission allocation model. Many studies have been conducted to determine how to allocate environmental emissions in different regions (countries, sectors) by using different allocation principles (such as fairness, efficiency and feasibility) and various methods (such as indicator, optimization, simulation, game theoretic and hybrid approaches). Specifically, most researchers used the allocation principles including historical emissions, population, GDP, per capita GDP, burden sharing, energy intensity, the lowest abatement costs, the maximum economic profits, justice, responsibility, effort-sharing rules, mutual recognition, etc. This study, however, adopts the concept of "equal acceptance degree" as the allocation criteria, which can be calculated based on the contribution of polluters.

In regard to the allocation methods, most previous studies adopted the modelling techniques including entropy method, clustering analysis, data envelopment analysis (DEA), and logarithmic mean divisia index (LMDI) model, operational research models (including nonlinear programming), index decomposition analysis (IDA), multi-criteria (multi-objective) optimization, bilevel optimization, Pareto optimization, and computable general equilibrium model, etc. Also, a few of researchers studied the emission allocation models with economic incentives based on the game theoretic approaches, such as a generalized Nash equilibrium game model, evolutionary game and cooperative game model. But there are few literatures concerning about an optimization model for simulating a TEC process, and to date, few studies have attempted to mix the above different allocation methods in a TEC model with incentives.

This study, however, combines the multi-objective optimization, simulation and cooperative game theoretical approach and establishes an optimal TEC model to simulate the policy-making process for an incentive-based policy scheme maximizing the social benefit while achieving the TEC goal as well.

The literatures about input-output analysis (IOA) are also reviewed with the realistic topic of reducing the CO_2 total emissions among all the sectors in China. The IOA method has been basically applied to the three common topics: the emissions inventory, impact analysis, and predictions for carbon emission trends. The frequently used IOA methods include single-region input-output models (SRIO), bi-regional input-output models (BRIO), as well as multiregional input-output models (MRIO) and their integration with life-cycle assessment models (MRIO-LCA). Also, input-output analysis is frequently used as a structural decomposition analysis (SDA) tool for an impacts analysis. For the prediction of carbon emissions, IOA is an active research topic in regional, national, sectoral, and residential carbon emissions. There are many research articles and reports on the impacts analysis---one of the most frequently studied topics now, particularly in China. In addition, there are special topics, such as carbon trading schemes in the sector carbon emissions, especially in power industry. But there are few literatures applying IOA from the viewpoint of an optimal TEC model. Also, there are few literatures on a TEC model based on input-output analysis among all the sectors in China, even though some scholars have studied on TEC among multi-regions (provinces in China). In particular, so far there are limited researches on the realistic application of the optimal TEC model among all economic sectors in China.

Finally, in a word, compared with the previous researches, this study enriches a methodology (model) as an analytical framework to design, quantitatively, a TEC policy scheme with an incentive in decision-making by combining the different allocation techniques of multiobjective optimization and cooperative game theoretical approach so as to realize an optimal balance between production economic profits and total emission control target, and for the first time, this study also discusses its practical application in detail based on input-output analysis for reducing the CO_2 total emission of all the 17 economic sectors in China.

3. Methodology and features

3.1 Blocks of the methodology

The total emission control proposed in this study can also be regarded as a decision process with a simple structure in which the first level decision is centralized to allocate optimally environmental resource and redistribute rationally social benefit among all the polluters in the region with incentives through taxation or subsidy schemes, while the second level decision is individually decided by each polluter to optimize its own production profit.

The methodology block diagram for the TEC policy design in this study is briefly described in Fig.3-1-1 below.

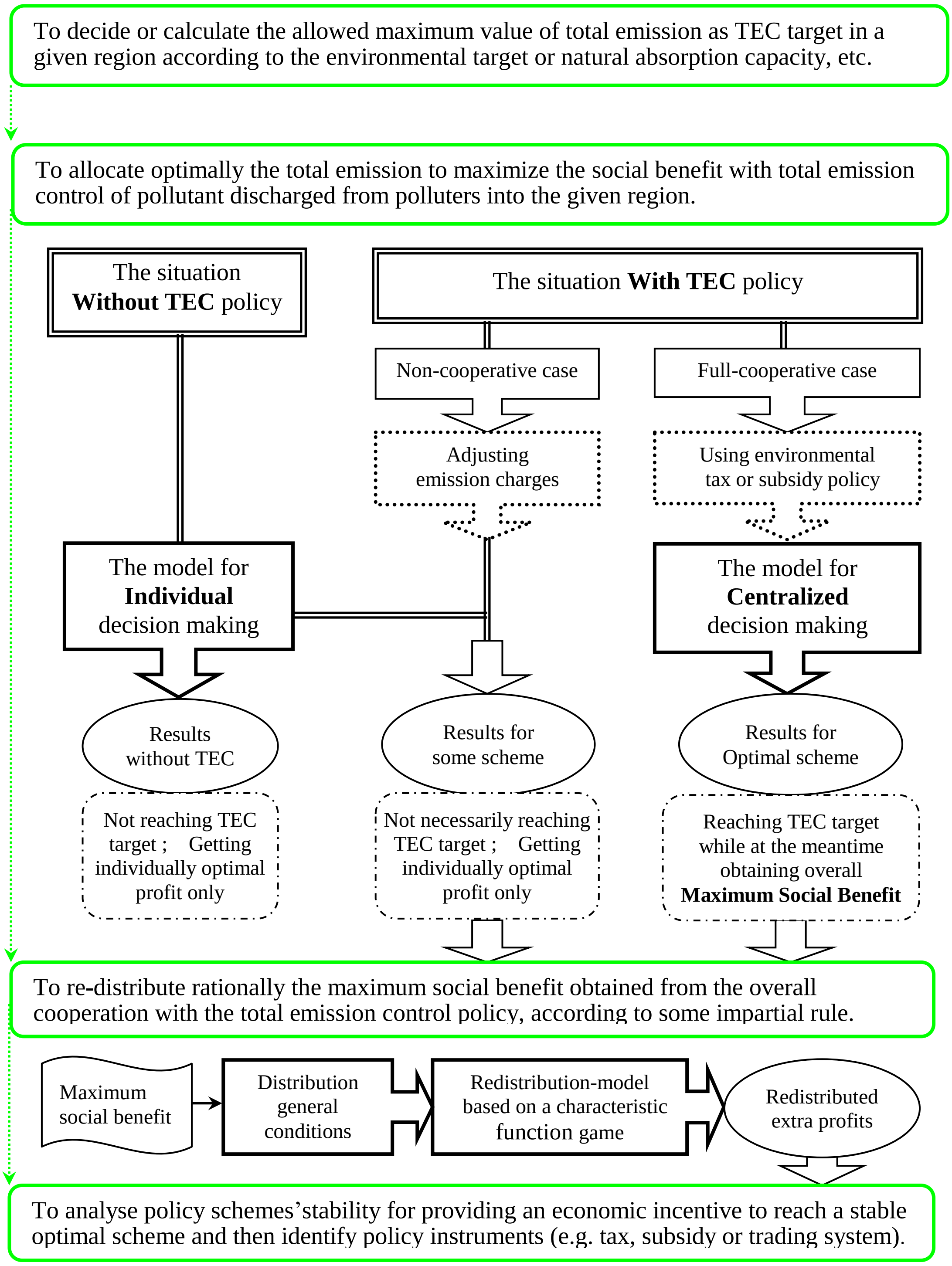


Fig.3-1-1 Blocks of the analytical framework for the TEC policy design in this study

3.2 Main features and creations

This study takes the maximum total emission (MTE) allocation as a game process and adopts the cooperative game in a characteristic function form as the theoretical framework of the TEC policy design approach.

From the previous literature review, it is understood that among researches using the same concept of the cooperative game theory to develop allocation model with an incentive, there are two literatures below which the model in this study is most closely related to.

One is the paper by LoPrete C. & Hobbs B.F., (2016) who used a cooperative game theoretic analysis to create incentives for microgrids in regulated electricity markets, but they did not concern with the aspect of the TEC in a region or for all sectors. The other is the paper by Tamura H. and Suzuki H. (1981) who indeed proposed an optimal TEC model based on a cooperative game for managing water quality in a given region. In their paper, however, they just conducted theoretically the model as an extension and concrete realization of the game theory of taxation described by Rinaldi S. et al (1979), and did not study its application to any realistic problem. Besides, their model was developed only for a regional system and was not directly suitable for a multisectoral case. Thus, in order to improve the shortage, although the TEC model in this study is based on the same theoretical approach as in their model, this study’s main emphasis is surely on establishing an analytical framework (methodology) to simulate and optimize a TEC policy scheme, rather than only on quantifying the scheme. Additionally this study modifies the model and also discusses its practical application, and specifically formulates the concrete basic functions used in the model as a case study of water pollution control in Shanghai, China. In particular, by using an input-output analysis, this study furtherly extends the basic model to be applicable for a multisectoral system and newly develops an optimal TEC model (or a set of models) with an economic incentive. Also, for the first time, this study discusses in details the practical application of the new extended TEC model based on the national input-output table for reducing the CO_2 total emission of all the 17 economic sectors in China.

Regarding the techniques or methods in multiobjective input-output model, Janire P.G., et al. (2016) presented a decision-support tool that minimizes the impact at a global macroeconomic scale by performing changes in the economic sectors of an economy and combines multi-objective optimization, environmentally extended input-output tables and life cycle assessment within a unified framework. Similar to the literature, this study enriches a methodology to design a TEC policy by combining the different allocation techniques of multiobjective optimization and cooperative game theoretical approach.

Specifically, compared with previous researches, the main contributions of this study are:

(1) An optimal TEC model is firstly established as analytical framework to simulate the policy-making process for a stable policy scheme pursuing a maximum social profit while achieving the TEC target. The methodology can be applied to other similar TEC policy design problems also for different levels of application in regional, international systems, and for different environmental pollutants.

(2) With a cooperative game theoretic approach, an optimal stable TEC policy scheme with incentives is reached by employing and quantifying a new concept of acceptance degree, which is adopted as an indicator on each polluter's contribution to achieving the TEC policy target.

(3) The policy design process with instability and complexity is handled through simulating computation with the integration of multi-objective optimization model, fairness allocation methods, game theoretic approach and input-output analysis.

(4) More notably, by using input-output analysis, an optimal TEC model is newly developed (extended) for a multisectoral system to reach the optimal allocations among all sectors and a realistic application of the TEC model is firstly studied in detail for a trade-off between environmental emissions and economic profits among all the 17 sectors in China.

(5) Also, for the first time, an empirical application is studied in detail on reducing the CO_2 total emission of all the 17 sectors in China, and an optimal TEC policy scheme is approximately calculated by using the national account data of the input-output table to give optimal solutions respectively for total production, final use and the corresponding CO_2 emission of each sector. Based on the simulated results, the key sectors most responsible for total emission reduction can be identified for policy suggestion. The data of the power sector with the highest emission share are used as an example to investigate the impact of the key sector's technological innovation on all other sectors' emissions in a multisectoral system. Finally, as a more meaningful impact analysis, the model is applied especially to estimate the ripple effects expected by the national ETS market with the initial phase only covering the power sector in China.

Part Two: Policy Design for a Regional System
The Basic TEC Model and Its Application on Water Quality Planning

4. Brief description of the model

According to Portney P.R. and Stavins R.N. (2000), it is recognized that nearly all environmental policies consist of two components: the identification of an overall goal and some means to achieve that goal.

In this study it is mainly concerned with the second component: the means, i.e., the instrument of environmental policy, especially, the economic-incentive policy instrument. More specifically, the policy instrument proposed in this study is mixed between direct control and market process defined by Baumol's classification (Baumol W.J., et al., 1995).

From the researches on how to reduce CO_2 emission by international cooperation, it is understood that the design and selection of policy instruments for increasing the incentive for each country to participate are normally the keys to the success of agreements such as that to reduce emissions of carbon dioxide internationally. Theoretically, the incentive can be based on a comparison of the costs and benefits of a specific policy instrument. The highest incentive will be the one that generates the highest net benefit for achieving the committed target (Wu P.I. et al, 2014).

With such a conception for the environmental-economic policy, this study considers the total emission allocation as a process of the cooperative game (Imma C., 1997), and specifically, adopts the cooperative game with characteristic function form as the theoretical framework of the TEC policy design approach to reach a policy scheme with an incentive.

4.1 The theoretical framework of the model

As its theoretical background, the total emission control model can be interpreted in the theoretical framework of a cooperative game in characteristic function form as follows

The total emission control model in this study is based on the game theory, specifically, an *n*-person cooperative game in characteristic function form (Jones A.J., 1980; Tamura H. & Suzuki H., 1981; Ichiishi T., 1993; 今井晴雄等, 2002). Although the game theory itself has been improved gradually (Fudenberg D. & Tirole J., 1991), it has been used widely in political, economic, and environmental systems (Paul R.K., 1985; Friedman J.W.,1985; William F.L., 1981; マケケル・テーラー著, 松原望訳, 1995; 松原望, 2001; 柳川範之, 1998).

Here just give some basic concepts about a characteristic function game (Imma C., 1997).

For *n*-person cooperative game, let *N* stand for the set of *n* persons (players), i.e.

$$N = \{1,2,\cdots,n\} \quad (4\text{-}1\text{-}1)$$

For any set S, if

$S \subseteq N$ (including $S = N$ and $S = \{i\}$, $i=1, 2, \ldots, n$)

then the set S is called a "coalition". (Friedman, J. W., 1985)

For any S, define a real function v. If v meets the super additivity conditions:

(i) $v(\emptyset) = 0$; (4-1-2)

(ii) $v(S \cup Q) \geq v(S) + v(Q),\ \ S, Q \in N\ \ \&\ \ S \cap Q = \emptyset$ (4-1-3)

then the function v is the characteristic function of n-person cooperative game. This means that the value of a union of disjoint coalitions is no less than the sum of the coalitions' separate values (Owen G., 1995).

Actually, the $v(S)$ can imply the "total gain" obtained under the coalition S.

Let α_i be the i-th person's value of a distribution from the total gain, if

(a) $\alpha_i \geq v(\{i\})$ (4-1-4)

(b) $\sum \alpha_i = v(N)$ (4-1-5)

then the vector

$$\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_n) \quad (4\text{-}1\text{-}6)$$

is considered as an imputation (or a solution) of the cooperative game.

The expression (a) is the "individual rationality" condition which means that no person (player) receives less than what he could get on his own. And the (b) is the "group rationality (or efficiency)" condition and means that the sum of each player's gain is exactly as the same as the total gain obtained in the coalition N.

In other words, here $\boldsymbol{\alpha}$ may have such an implication that the i-th person's gain α_i is a part of the total gain $v(N)$ due to the n-person cooperation and no less than that obtained while the i-th person is not participating any cooperation.

Now, let's give a brief description of the model as follows.

For situations where a group of (more than one) decision-makers are involved and they try to undertake a project together in order to increase the total gain (profit) or decrease the total costs, there will be two problems arising in their decision-making practice. One is how to execute the project optimally so as to get the maximum gain, and the other is how to distribute the gain attained collectively among the participants. It is with such problems that the cooperative game theory can be helpful to solve. The solution concepts from cooperative game theory can be applied to arrive at the gain (profit) allocation schemes.

In executing a total emission control policy in a regional system, the "the maximum total emission value" can be considered as some kind of rare resource which needs to be allocated among all the polluters in the region. How to implement the policy in an optimal way is essentially an allocation optimization problem on which cooperative game theory can be applied.

The process of designing a total emission control policy in an environmental-economic system can be actually interpreted in the theoretical framework of a cooperative game.

In the game, one player can be defined as the regional environmental administrator or policy maker who aims to maximize the social benefit, based on not only the polluters' economic profits but also the environmental damage; and the other players can be considered as all the polluters who are supposed to be independent decision makers individually interested in only their own final economic profits as much as possible from the game.

Also it is assumed that

(1) In the existing situation without total emission control policy, each polluter makes the decision independently to get his own maximum profit.
(2) If implementing the total emission control policy, each polluter will be given two choices in modifying his final emission by an economic means rather than a direct regulation.

(a) The cooperative choice: Participating in the grand coalition in which all polluters cooperate with the policy to realize the centralized decision-making (For the case, the concept of environmental tax or subsidy is used to adjust the each cooperator's final gain or profit);

(b) The not-cooperative choice: Making decision only by himself with the individual decision-making (For the case, the concept of emission charges or fines policy is used to control the each not-cooperative polluter's final gain or profit expected separately).

It is clearly understood that only if all the polluters select the option (a), a maximum total profit could be produced from the grand coalition where all polluters cooperate with the policy to form the overall cooperation.

But which option each polluter will select depends on how much it can obtain more profit from the cooperation than that from the not-cooperative choice (b).

This is, essentially, the maximum gain (profit) allocation problem in a cooperative game.

With the solution concepts in cooperative game theory, the model in this study will focus on establishing such a mechanism so as to solve these two allocation problems:

+ how to allocate in an optimal way the total emission in the region to maximize the "social benefit", and then,

+ how to divide with a rational rule the maximum social benefit which is attained collectively among the cooperative polluters to keep the optimal overall cooperation scheme in a stable state.

4.2 The basic functions used in the model

Before giving the model mathematically, first it would be better to discuss the essential data and the necessary functions needed in the model.

Here just the main characteristics are described for each of these basic functions necessary for the model. The detailed shapes for them usually can be identified in practical applications.

In all the following discussions,

X : stands for the amount of waste or pollutant produced from the production process;

x: stands for the amount of waste or pollutant discharged into the regional environmental system after waste treatment.

t: represent time (time can also be a variable of all the functions discussed below, but to be simple here it is omitted in the expressions.)

(1) The profit function: $\boldsymbol{P(X)}$

It is assumed that the production profit depends only on the production scale, which is relevant to the amount of waste. The more waste means the larger scale, and furthermore, the greater profit.

The profit function is defined to indicate the relation between the production profit and the quantity of waste. If $P(X)$ is the production profit taking no account of the waste treatment cost, it is considered generally to meet the following conditions (John A.D., et al., 1990; 塩田尚樹, 2001) and the relation is demonstrated in Fig.4-2-1.

(a). $P(X) = 0$, when $X = 0$; (4-2-1)

(b). $d\,P(X)/d\,X > 0$, when $X > 0$; (4-2-2)

(c). $d^2P(X)/d\,X^2 > 0$, when $0 < X < X^{Max}$. (4-2-3)

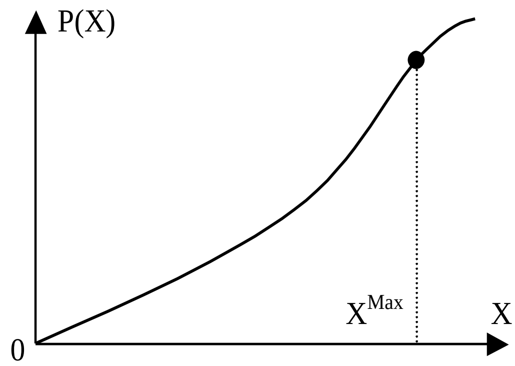


Fig.4-2-1 The profit function $P(X)$

(2) The cost function of waste treatment: $\boldsymbol{C(X,x)}$

The treatment cost varies generally in treatment technologies and kinds of waste. But it mostly be a function of the flow Q and the treatment efficiency η (John A.D., et al., 1990; 塩田尚樹, 2001) . That is

$$C(\,,) = f(Q,\ \eta) \qquad (4\text{-}2\text{-}4)$$

$$\because \quad Q = X/C_X \quad \text{and} \quad \eta = (X-x)/X,$$

where C_X is the concentration.

$$\therefore \quad C(\,,) = f(X,x) \qquad (4\text{-}2\text{-}5)$$

Based on the empirical data, when η > 40%, $C(X,x)$ is usually needed to satisfy the conditions below (D.A. Morley, 1979) and visually shown in Fig.4-2-2

(a). $\partial C(X,x) / \partial x < 0,\ and\ \partial^2 C(X,x) / \partial x^2 \geq 0$; (4-2-6)

(b). $\partial C(X,x) / \partial X > 0,\ and\ \partial^2 C(X,x) / \partial X^2 \geq 0$; (4-2-7)

(c). $\partial C(X,\beta X) / \partial X > 0,\ and\ \partial^2 C(X,\beta X) / \partial X^2 \leq 0$; (4-2-8)

where β is a constant between 0 and 1 .

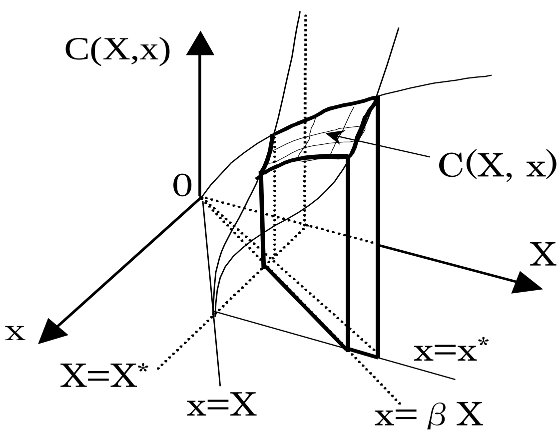


Fig.4-2-2 The treatment cost function $C(X,x)$

(3) The emission charges function: $\boldsymbol{T(X,x)}$

The emission charges, similar to emission fines, can be explained as a kind of emission cost. As a compensation for the environmental damage resulted from the waste or pollutant discharge, it is also considered as an economic instrument to control indirectly the environmental pollution. Here in this study, it is used for the case without total emission control (TEC) policy and the non-cooperative case of the individual decision-making under the TEC policy (see Chapter 5 for details).

In the policy analysis of later applications, it will be discussed that at what level, the emission charges should be set as an adjustable economic means in designing the total emission control policy.

The function is completely based on the direct regulations or the standards of emission charges or fines that could be quite variable in different areas, and for various kinds of waste or pollutant. It may be researched from a viewpoint of taxes theory (Ekko C., 1993; Boyd R., et al., 1995; 呉錫畢等, 1999; 淡路剛久等, 2001), but the characteristics of the function are not discussed in detail here and a specific form will be given later in the chapter of application.

Use $T(X,x)$ to stand for the function, define

$$T(X,x) = 0, \quad \text{for} \quad X * x = 0. \tag{4-2-9}$$

(4) The environmental damage function: $D(\sum x)$

It is really not easy to estimate the environmental damage by a monetary form. Until now, therefore, there is hardly a successful research method suitable for general uses (Ekko C., 1993). Here just from the point of solving the problem in the total emission control, some characteristics of the damage function are discussed below.

First, since it is the total emission that results in the environmental damage, the damage is certainly expressed as a function of the total emission. Using $D(\,,\,)$ to stand for it, then

$$D(\,,\,) = D(\Sigma\, x)\,. \tag{4-2-10}$$

Secondly, the regional damage is also related to the natural absorption capacity or the allowed maximum value of the total emission x^T. This relation can be described mathematically as

$$D(\,,\,) = D(\textstyle\sum x\,,\ x^T) = \begin{cases} 0, & \text{when} \quad x^T \longrightarrow \infty \\ D(\sum x), & \text{when} \quad 0 < x^T < \infty \\ \infty, & \text{when} \quad x^T \longrightarrow 0 \end{cases} \tag{4-2-11}$$

Notice that generally, x^T is an invariable value ($0 < x^T < \infty$) specified in advance for the total emission control. Therefore x^T may also be considered as a coefficient rather than a variable of the damage function. Thus in general,

$$D(\,,\,) = D(\sum x\ , x^T) = D(\sum x), \quad where\ 0 < x^T < \infty \qquad (4\text{-}2\text{-}12)$$

Finally, the damage is proved to be relevant to the congestion effect (Ekko C., 1993; 塩田尚樹, 2001) of the waste or pollutant. This means that the environmental damage increases as the total emission increases, but the increasing rate is dependent of the level of total emission. In other words, for a unit of increment on the total emission, the corresponding increment on the damage (i.e., the marginal environmental damage) with a higher level of the total emission is greater than that with a lower level (Orlob G. T., 1983).

The congestion effect is described in the mathematical expression and in Fig.4-2-4 below.

Let $x^H > x^L$ and $\varepsilon \geq 0$, then

$$\Delta D^H = D\,(x^H + \varepsilon) - D\,(x^H) \geq \Delta D^L = D(x^L + \varepsilon) - D(x^L) \qquad (4\text{-}2\text{-}13)$$

or

$$\partial^2 D(x) / \partial x^2 \ \geq\ 0 \qquad (4\text{-}2\text{-}14)$$

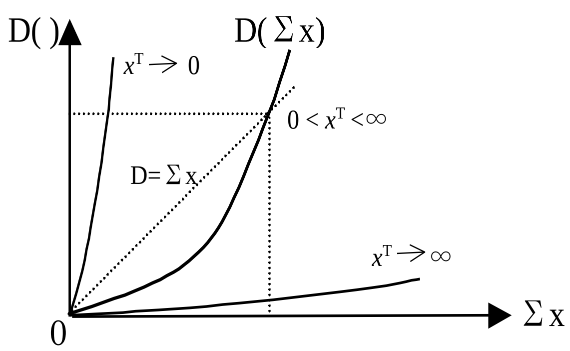


Fig.4-2-4 The environmental damage function $D(\sum x)$

5. The basic model with economic incentives

The first step of the total emission control method is to decide the allowed maximum value for the total emission in a given region, which is usually considered as the environmental target specified in advance for the total emission control policy.

Generally, as a long-term emission goal, the total emission volume is estimated according to the natural or environmental absorption capacity in the regional environmental system (Portney P.R. & Stavins R.N., 2000). There have been a number of models and methods on how to calculate it scientifically (Morley D.A., 1979; Li W.J., et al., 1982; 塩田尚樹, 2001). For example, in this study with an application for planning water quality in a river region, the proper quantity of the environmental absorption capacity will be calculated by a dynamic model of river water quality in the next chapter.

In this chapter, therefore, the mathematical model will not be concerned with how to determine the allowed maximum value of the total emission. The model will deal with only how to allocate the maximum total emission which is defined as an invariable value (or a coefficient) rather than a variable in the model.

5.1 The model for optimal allocation of the total emission

In the following, use the symbols like this: the under bar "_" represents a vector, and the " ^{T} " represents the transpose of a vector.

5.1.1 The model without total emission control

As shown in Fig.5-1-1, it is assumed that the environmental-economical system considered here consists of

(1) A regional economic-environmental system in which a certain amount of total emission of waste or pollutant may be allowed. For example, a river area;
(2) An administrator or a policy-maker, somewhere also called "controller", whose responsibility is to make the regional environmental plans or policies (including the emission charges policies) and enforce a total

emission control scheme. For example, an environmental protection bureau of the given regional government;

(3) A number of pollution sources, here called "polluters", who earn production profits from their production process and meanwhile produce some kind of waste or pollutant. For example, firms, plants or factories.

Also, it is assumed that there are *n* polluters in the regional system, and each one has his own waste treatment plant which just treats the waste produced in its own production process. Each polluter has to pay all the cost relevant to the waste treatment and also has to submit some emission charges or fines to the controller if the polluter still discharges a certain amount of waste into the region after its treatment.

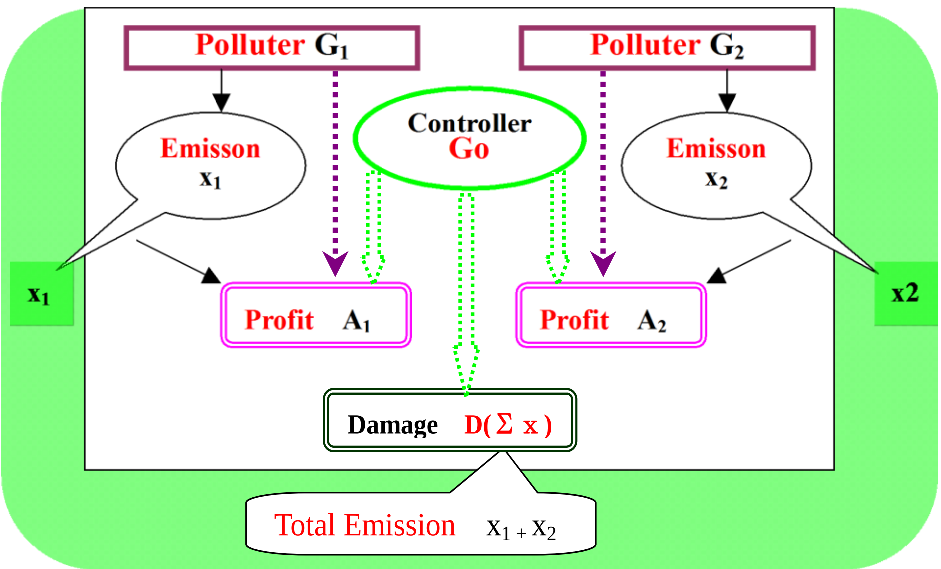


Fig.5-1-1 The environmental-economical system in this study

Let G_0 represent the controller;

G_i represent the *i*-th polluter, (where i = 1, 2, …, n)

and

X_i : stands for the quantity of waste that is derived from G_i's production process;

x_i : stands for the quantity of waste that is not purified (treated) and then discharged finally from G_i into the given region after treatment;

By the way, $(X_i - x_i)$ is the quantity of waste that is purified or treated by G_i.

$P_i(X_i)$: Production function, stands for gross production profit of G_i , which is obtained by taking no account of treatment cost and emission charges (emission cost).

$C_i(X_i, x_i)$: Cost function of treatment, stands for the waste treatment cost of G_i ;

$T_i(X_i, x_i)$: Emission charges function, stands for the G_i's cost of discharging waste x_i (the emission charges or fines paid to controller G_0).

Based on the above, for the existing situation with only the emission charges policy where there is no implementation of total emission control, then the "initial profit" of G_i can be defined as:

$$A_i(X_i, x_i) = P_i(X_i) - C_i(X_i, x_i) \quad (5\text{-}1\text{-}1a)$$

and the "net profit" of G_i can be defined as:

$$B_i(X_i, x_i) = P_i(X_i) - C_i(X_i, x_i) - T_i(X_i, x_i) \quad (5\text{-}1\text{-}1b)$$

In this case without total emission control, each polluter can make a decision independently. Therefore, G_i will try to get the maximum net profit as possible. i.e.,

$$\boldsymbol{G_i}^0\textbf{:} \quad Max.\ B_i(X_i, x_i) \quad (5\text{-}1\text{-}2a)$$

$$\text{s.t. } \boldsymbol{g_i}(X_i, x_i) \leq \mathbf{0} \quad (5\text{-}1\text{-}2b)$$

where

$\boldsymbol{g_i}(X_i, x_i)$ is a function vector, which is dependent on production process, characteristics of waste, treatment technology and other factors. (In the application, a detailed form will be defined for it in the next chapter.)

Let $(X_i{}^0, x_i{}^0)$ be the optimal solution for the above model (5-1-2), then the *i*-th polluter's maximum net profit is

$$B_i(X_i{}^0, x_i{}^0) = P_i(X_i{}^0) - C_i(X_i{}^0, x_i{}^0) - T_i(X_i{}^0, x_i{}^0) \quad (5\text{-}1\text{-}3)$$

In addition, the actual total emission of waste in the region is given as

$$x^0 = \sum_{i=1}^{n} x_i{}^0 \quad (5\text{-}1\text{-}4)$$

then,

$$D^0 = D(x^0) \quad (5\text{-}1\text{-}5)$$

is considered as the regional environmental damage, where, $D(x)$ stands for the function of damage on the regional environment system. (In the application, a detailed form will be defined for it.)

Usually, even if there is the existing emission charges $T_i(X_i\ ,\ x_i)$ on the polluters' final emission, it can be possibly supposed that $x^0 = \sum x_i{}^0$ could be higher than x^{Total}, the maximum value of total emission that is set as the target by G_0 when the total emission control policy is imposed in the given region.

5.1.2 The model with total emission control

When the controller G_0 implements a total emission control, the G_0 is supposed to set a target of the maximum total emission x^{Total} and impose a policy for reducing the total emission x^0 to meet the target. Here, it is assumed that G_0 implements the policy by an economic instrument rather than direct regulation so that a role of the controller is to determine the proper form of the function $T_i(X_i\ ,\ x_i)$. However, even if under the total emission control policy, the polluter G_i will not be forced to cooperate with the policy and therefore, there are three possible cases to be discussed below.

(1) All of the G_i, $_{i=1,2,\dots,n}$ do not take an attitude to cooperate with G_0; that is, none of the G_i does cooperate with G_0, i.e., the case where there are only individual coalitions $\{G_0\}$ or $\{G_i\}$ in the game; here it is also referred to as the non-cooperative case (or the non cooperation) in the following discussion.
(2) All of the G_i, $_{i=1,2,\dots,n}$ take an attitude to cooperate with G_0; that is the case of the grand coalition in the cooperative game; here is also referred to as the full-cooperative case (or the overall cooperation).
(3) Some of the G_i, $_{i=1,2,\dots,n}$ are willing to cooperate with G_0, but the others are not; that is the case of the partial coalition in the cooperative game; here it is also referred to as the part-cooperative case (or the partial cooperation).

Here it is also assumed that G_i will never cooperate with G_j ($i \neq j$) in any case. Otherwise, there are 2^n -1 possibilities of cooperative coalition. For instance, in the application of Chapter 6, there is such a case where n=39 and the number of possible coalitions is 2^{39}-1. Clearly, it is in fact neither easy nor necessary to cope with it in applications.

With these assumptions, the following discussion is concentrated on developing an optimal model to allocate the maximum total emission set by the total emission control policy for the three cases, respectively. Since the total emission control model is processed in the framework of a cooperative game with characteristic function form, the related characteristic function value is specified correspondingly for each case.

1) Non-cooperative case

For the situation of non-cooperation, in order to reach the target of total emission control policy, G_0 is supposed to take an economic means, which, here, could be considered as an adjustment on the existing policy for emission charges.

This means that in this case, a role of the controller G_0 is to determine a better form of the function $T_i(X_i\ ,\ x_i)$ for reducing the total emission x^0 to meet the target amount of total emission which is no more than x^{Total}, the allowed maximum value of total emission.

Specifically, it can be possibly assumed that G_0 is to modulate the emission charges function from $T_i(X_i\ ,\ x_i)$ to $Tt_i(X_i\ ,\ x_i)$, letting it satisfy:

$$Tt_i(X_i\ ,\ x_i) \geq T_i(X_i\ ,\ x_i), \quad \text{where } X_i \geq x_i \geq 0\,. \qquad (5\text{-}1\text{-}6)$$

For this case, the structure of the system with total emission control can be depicted as in Fig.5-1-2.

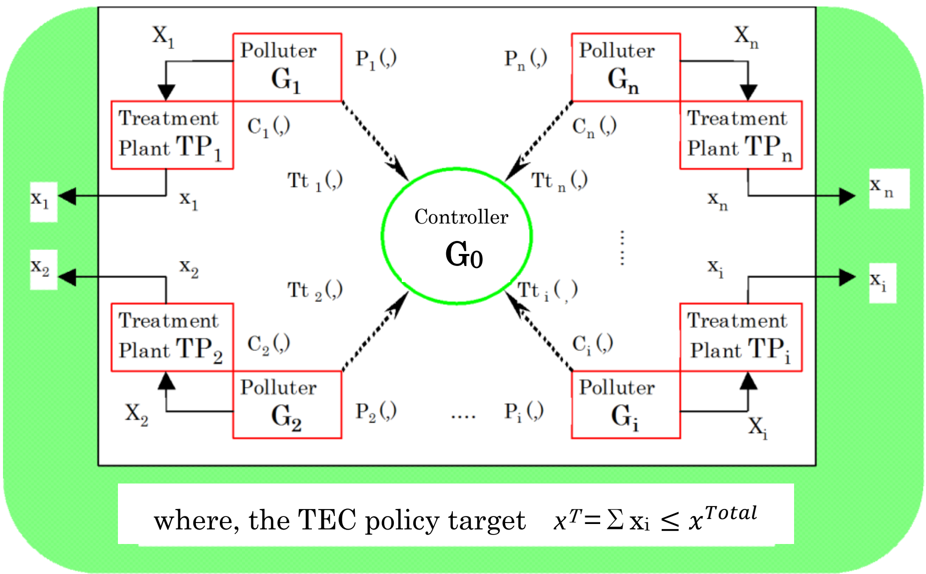


Fig.5-1-2 The structure of the system with TEC policy in the non-cooperative case

Because there is not any cooperative coalition between G_0 and G_i, $_{i=1, 2, \ldots, n}$, all of G_i still make their decisions individually. The model should not be, substantially, quite different from that in the case without a total emission control policy. The difference is just on the G_i's net profit. Under the total emission control policy, the net profit may decrease to:

$$Bt_i(X_i\ ,\ x_i)\ =\ P_i(X_i\ ) - C_i(X_i\ ,\ x_i) - Tt_i(X_i\ ,\ x_i) \qquad (5\text{-}1\text{-}7)$$

Similarly, each G_i can make decision individually and optimally as follows:

$$\boldsymbol{G_i}^{\boldsymbol{t}}\ :\quad Max.\ Bt_i(X_i\ ,\ x_i) \qquad (5\text{-}1\text{-}8a)$$

$$\text{s.t. } \boldsymbol{g_i}(X_i\ ,\ x_i)\ \leq\ \boldsymbol{0} \qquad (5\text{-}1\text{-}8b)$$

where, the function vector $\boldsymbol{g_i}(X_i\ ,\ x_i)$ is the same one as in the previous model by expression (5-1-2).

Let $({X_i}^{t*}, {x_i}^{t*})$ be the optimal solution for the above model (5-1-8), then the *i*-th polluter's maximum initial profit under this case is

$$A_i({X_i}^{t*}, {x_i}^{t*})\ =\ P_{\boldsymbol{i}}({X_i}^{t*}) - C_{\boldsymbol{i}}({X_i}^{t*}, {x_i}^{t*}) \qquad (5\text{-}1\text{-}9a)$$

and the maximum net profit is

$$Bt_i({X_i}^{t*}, {x_i}^{t*})\ =\ A_i({X_i}^{t*}, {x_i}^{t*}) - Tt_i({X_i}^{t*}, {x_i}^{t*}) \qquad (5\text{-}1\text{-}9b)$$

Also, it can be defined here as the corresponding value of the characteristic function, i.e.

$$v\ (\mathrm{G_i})\ =\ v(\{i\})\ =\ Bt_i\ ({X_i}^{t*}, {x_i}^{t*}) \qquad (5\text{-}1\text{-}10)$$

Note that the value of $v(\{i\})$ will be also used as "the reference or contrastive value" of the G_i's final profit in the full-cooperative model described later.

In addition, let Bt_0 indicate the G_0's "net profit (or revenue)" in the case, then the corresponding value of the characteristic function for G_0 is defined as:

$$v\ (G_0) = v\ (\{0\}) = Bt_0 = \sum_{i=1}^{n} Tt_i({X_i}^{t*},\ {x_i}^{t*}) - D(x^{t*}\ ) \qquad (5\text{-}1\text{-}10)$$

where, x^{t*} is the actual total emission of waste in the region, obtained by

$$x^{t*} = \sum_{i=1}^{n} x_i{}^{t*} \tag{5-1-11}$$

and $D(x^{t*})$ is the damage to the regional environmental system.

$$D^{t*} = D(x^{t*}) \tag{5-1-12}$$

Then, the "Social Benefit" in the case is defined as the sum of net profit among G_0 and $G_{i,\ i=1,2,\ldots,n}$, that is

$$SB^t\ (\boldsymbol{X^{t*}},\ \boldsymbol{x^{t*}}) = \sum_{i=0}^{n} v\ (\{i\})$$

$$= \sum_{i=1}^{n}\ [P_{\boldsymbol{i}}(X_i{}^{t*}) - C_{\boldsymbol{i}}(X_i{}^{t*}, x_i{}^{t*})] - D\ (x^{t*}) \tag{5-1-13}$$

where

$$\boldsymbol{X^{t*}} = [X_1{}^{t*},\ X_2{}^{t*},\ \ldots,\ X_n{}^{t*}]^T$$

$$\boldsymbol{x^{t*}} = [x_1{}^{t*},\ x_2{}^{t*},\ \ldots,\ x_n{}^{t*}]^{\mathrm{T}}$$

From the expression (5-1-6), it is easy to get

$$Tt_i\ (X_i\ ,\ x_i{}^0) \ \geq\ T_i\ (X_i\ ,\ x_i{}^0) \tag{5-1-14}$$

Also, if selecting a proper form of the function $Tt_i\ (X_i\ ,\ x_i)$, generally it is possible to get:

$$x_i{}^{t*} \leq x_i{}^0 \tag{5-1-15}$$

i.e.

$$D^{t*} = D(x^{t*}) \ \leq\ D^0 = D\ (x^0) \tag{5-1-16}$$

where, $D(x)$, the function of damage to the regional environment, is a convex function (see Section 4.2).

Now note that, from the above model, it is possible to reduce the actual quantity of total emission by increasing the emission charges standard (or fines per unit of waste discharged), but it is not sure that the actual total emission x^{t*} is absolutely no more than the allowed maximum value x^{Total} in the non-cooperative case.

2) Full-cooperative case

For this case where all the polluters G_i cooperate with the controller G_0, there exists one and only one "cooperative relation" with G_0 for anyone in the system, which is defined here as "fully cooperative set", i.e., the grand coalition in the game:

$$\tilde{N} = \{G_0, G_1, G_2, \dots, G_n\} = \{0, 1, 2, \dots, n\}$$

In the case, based on the cooperation by all the polluters G_i, the controller G_0 can make a centralized decision in the overall region to achieve the target of total emission control and meanwhile obtain the maximum social benefit by allocating optimally the total emission among all the polluters.

For the non-cooperative case where each polluter G_i does not cooperate with the controller G_0, if the G_i discharges waste x_i after waste treatment, the G_i has to pay the emission charges to G_0 as a fine for the discharged waste x_i. However, for the full-cooperative case here, it is assumed that when all the polluters G_i cooperate with G_0, the G_i does not need to pay the emission charges for the untreated amount discharged into the regional environment but should have a responsibility to submit an emission tax (or receive subsidy) to share the social benefit loss resulted from the environmental damage due to the total emission of waste x_i from all G_i.

Thus, the emission charges function is no longer used in the full-cooperative model. Instead of it, the emission taxes (subsidies) function is introduced as an adjustment on the final profit of each polluter G_i in the full-cooperative case.

Here let $t_i(X_i, x_i)$ be the amount of the emission tax (subsidy) applied to G_i, then the G_i's final profit in this case is

$$\begin{aligned} B_i(X_i, x_i) &= A_i(X_i, x_i) - t_i(X_i, x_i) \\ &= P_i(X_i) - C_i(X_i, x_i) - t_i(X_i, x_i) \end{aligned} \quad (5\text{-}1\text{-}17)$$

and with consideration of the environmental damage, the G_0's "net profit" in the case is defined as:

$$B_0(\boldsymbol{X}, \boldsymbol{x}) = \sum_{i=1}^{n} t_i(X_i, x_i) - D\left(\sum_{i=1}^{n} x_i\right) \quad (5\text{-}1\text{-}18)$$

And then, the "Social Benefit" in this case can be also defined as the sum of profits among all polluters and controller, i.e.

$$\begin{aligned} SB(\boldsymbol{X}, \boldsymbol{x}) &= B_0(\boldsymbol{X}, \boldsymbol{x}) + \sum_{i=1}^{n} B_i(X_i, x_i) \\ &= \sum_{i=1}^{n} A_i(X_i, x_i) - D\left(\sum_{i=1}^{n} x_i\right) \end{aligned} \quad (5\text{-}1\text{-}19)$$

where

$$\boldsymbol{X} = [X_1, X_2, \dots, X_n]^T$$

$$\boldsymbol{x} = [x_1, x_2, \dots, x_n]^T$$

and

$$A_i(X_i\,,\,x_i) \;=\; P_i(\,X_i) \;-\; C_i(X_i,\,x_i) \qquad (5\text{-}1\text{-}20)$$

Note that here $A_i(X_i,\,x_i)$ is the initial profit of G_i without payment of the emission charges; and the environmental damage $D(\sum x_i\,)$ could be considered as the G_0's "negative profit", for only G_0 is responsible for controlling the environmental damage.

Here, it is obviously seen that the emission charges function $Tt_i\,(X_i\,,\,x_i)$ is not used actually in the above full-cooperative model. Also, the emission tax (subsidy) function $t_i(X_i\,,\,x_i)$ can not be seen directly in the model, because the maximum social benefit is independent of $t_i(X_i\,,\,x_i)$ in the full-cooperative case.

Based on the above, the controller G_0 is supposed to aim at making a decision to reach the target of total emission control as well as obtain a socially optimal solution on the allocation of the total emission among the polluters.

Thus the optimal allocation model of the maximum total emission can be described as follows.

$$\boldsymbol{G_0:} \qquad Max.\ SB\,(\,\boldsymbol{X},\boldsymbol{x}\,) \qquad (5\text{-}1\text{-}21a)$$

$$\text{s.t} \begin{cases} \boldsymbol{G}\,(\,\boldsymbol{X},\boldsymbol{x}\,) \le \mathbf{O} \\ \sum_{i=1}^{n} x_i \le x^{Total} \end{cases} \qquad (5\text{-}1\text{-}21b)$$

where

$$\boldsymbol{X} \;=\; [X_1, X_2, \dots, X_n]^{\mathrm{T}}$$

$$\boldsymbol{x} \;=\; [x_1, x_2, \dots, x_n]^{\mathrm{T}}$$

and

$\boldsymbol{G}(\,\boldsymbol{X},\boldsymbol{x}\,)$ is a function vector whose form is defined as:

$$\boldsymbol{G}(\,\boldsymbol{X},\boldsymbol{x}\,) = \begin{bmatrix} \boldsymbol{g_1}(X_1, x_1) \\ \boldsymbol{g_2}(X_2, x_2) \\ \vdots \\ \boldsymbol{g_n}(X_n, x_n) \end{bmatrix} \qquad (5\text{-}1\text{-}22)$$

and here the function vector $\boldsymbol{g_i}(X_i, x_i)$, $i=1, 2, \dots, n$ is the same as in the previous model expression (5-1-2).

Let the optimal solution for the above model (5-1-21) be $(\boldsymbol{X}^*,\ \mathbf{x}^*)$, i.e.,

$$\boldsymbol{X}^* = [X_1{}^*, X_2{}^*, \dots, X_n{}^*]^{\mathrm{T}};$$

$$\boldsymbol{x}^* = [x_1{}^*, x_2{}^*, \dots, x_n{}^*]^{\mathrm{T}}.$$

Then, the "maximum social benefit" under a total emission control policy with the full-cooperation is:

$$SB(\boldsymbol{X}^*, \boldsymbol{x}^*) = \sum_{i=1}^{n} A_i(X_i{}^*, x_i{}^*) - D(\sum_{i=1}^{n} x_i{}^*) \tag{5-1-22}$$

$$= \sum_{i=1}^{n}\{P_i(x_i{}^*) - C_i(X_i{}^*, x_i{}^*)\} - D(\sum_{i=1}^{n} x_i{}^*) \tag{5-1-23}$$

Also, here define it as the corresponding value of the characteristic function, i.e.

$$v(\tilde{\mathrm{N}}) = v(\{0, 1, 2, \dots, n\}) = SB(\boldsymbol{X}^*, \boldsymbol{x}^*) \tag{5-1-24}$$

In this case, the actual total emission can be controlled to reach the target:

$$x^* = \sum_{i=1}^{n} x_i{}^* \leq x^{Total} \tag{5-1-25}$$

The regional environmental damage is

$$D^* = D(\sum_{i=1}^{n} x_i{}^*) \tag{5-1-26}$$

And the i-th polluter's initial profit after waste treatment before the final redistribution of the maximum social benefit is

$$A_i(X_i{}^*, x_i{}^*) = P_i(X_i{}^*) - C_i(X_i{}^*, x_i{}^*) \tag{5-1-27}$$

Note that the G_i's final profit in this case is finally calculated based on the redistribution of the maximum social benefit. Actually, because all the G_i's cooperation makes it possible to form the overall cooperation, i.e., the grand coalition in the game, G_0 can make a centralized decision to get the maximum social benefit which should be divided in a rational way to provide the G_i with an extra profit, i.e., an incentive. Thus, the final profit of each G_i in the case is needed to be adjusted by computing the emission tax (subsidy) $t_i(X_i{}^*, x_i{}^*)$ based on the incentive (see Section 5.2.3 for details).

3) Part-cooperative case

As mentioned in the full-cooperative case, with all G_i's cooperation G_0 can make decision for all G_i to maximize the social benefit which should be finally allocated among all the G_i to generate an additional profit , i.e., an incentive. But the incentive should be based on how it makes a difference on the social benefit if the polluter G_i does not cooperate with G_0. It is required, therefore, to discuss the part-cooperative model for such a situation where some polluters like to be in cooperation with the controller and the others do not.

First of all, it is assumed that among all the polluters $G_{i,\ i=1,2,\ldots,n}$, here expressed as a set: $N = \{1, 2, 3, \ldots , n \}$, there are k polluters to cooperate with the controller, but (n-k) polluters not to cooperate. When $k = 0$, it is the non-cooperative case. When $k = n$, it is the full-cooperative case.

And when k = 1, 2, …, or, n-1, it indicates the part-cooperative case where k is defined as follows:

$$k \in N_k = \{1, 2, 3, \ldots , n-1 \}$$

Then, generally, all the "cooperative relations" between G_0 and G_i can be expressed as such a set called a "partially cooperative coalition":

$$S_k = \{0, 1, 2, \ldots , k \}, \quad \text{where} \quad k \in N_k \ .$$

Similarly, use $Q_{(n-k)}$ to stand for the set of (*n*-*k*) polluters not to cooperate, i.e.

$$Q_{(n-k)} = \{k+1, k+2, \ldots , n \}, \quad \text{where} \quad k \in N_k \ .$$

It is understood that $Q_{(n-k)}$ is not a "coalition", so it is not necessary to define a value of characteristic function for $Q_{(n-k)}$, because G_{k+1}, G_{k+2}, …, G_n are supposed not to cooperate with each other. In this case, each G_i only forms the "individual coalition" {i}, here $i \in Q_{(n-k)}$. Thus it is only needed to give a value of characteristic function respectively for each $G_{i,\ i \in Q_{(n-k)}}$.

For the case, all the $G_{i,\ i \in Q_{(n-k)}}$ make their own decisions independently by the non-cooperative model (5-1-8) described previously. That is:

$$\underset{i \in Q_{(n-k)}}{G_i^{\ t}}: \quad Max.\ B_i(X_i\,,\ x_i) = P_i(X_i) - C_i(X_i\,,\ x_i) - Tt_i(X_i\,,\ x_i) \qquad \text{(5-1-28a)}$$

$$\text{s.t.} \quad \boldsymbol{g_i}(X_i\,,\ x_i) \ \leq\ \mathbf{0} \qquad \text{(5-1-28b)}$$

where the function vector $\boldsymbol{g_i}(X_i\,,\ x_i)$ is the same as in the model (5-1-2) of the previous section.

Let $(X_i^{\ Q*}, x_i^{\ Q*})$ be the optimal solution for the above model (5-1-28), then the *i*-th polluter's maximum initial profit and the maximum net profit is as the same as in the non-cooperative model.

Also, the sum of the initial profits for all G_i, $i \in Q_{(n-k)}$ in this case is

$$A_Q = \sum_{i=k+1}^{n}[P_i\left(X_i^{Q*}\right) - C_i(X_i^{Q*}, x_i^{Q*})\,] \tag{5-1-29}$$

and the sub total emission of waste discharged from all the G_i, $i \in Q_{(n-k)}$ is obtained by

$$x^{Q*} = \sum_{i=k+1}^{n} x_i^{Q*} \tag{5-1-30}$$

And the value of characteristic function correspondingly for each $G_{i,\ i \in Q(n\text{-}k)}$ is still given as the same as in expression (5-1-10), i.e., for $i \in Q_{(n-k)}$

$$\begin{aligned} v(\{i\}) &= Bt_i(X_i^{Q*}, x_i^{Q*}) \\ &= P_i(X_i^{Q*}) - C_i(X_i^{Q*}, x_i^{Q*}) - Tt_i(X_i^{Q*}, x_i^{Q*}) \end{aligned} \tag{5-1-31}$$

Now, discuss the cooperative coalition S_k. At this time, S_k makes a decision to get the maximum total profit within the cooperative coalition S_k by the following model.

Here, $BS^k(\boldsymbol{X^k}, \boldsymbol{x^k})$ is defined as the sum of intial profit of G_i, $i \in S_k$, taking an account for the environmental damage resulted from all $G_{i,\ i=1,2,\ldots,n}$.

$\boldsymbol{G_0}$: $i \in S_k$

$$Max.\ \ BS^k(\boldsymbol{X^k}, \boldsymbol{x^k}) = \sum_{i=1}^{k} A_i(X_i\,,\ x_i) - D((\sum_{i=1}^{k} x_i) + x^{Q*}) \tag{5-1-32a}$$

s.t.

$$\begin{cases} \boldsymbol{G^k}(\,\boldsymbol{X^k}, \boldsymbol{x^k}\,) \le \mathbf{O} \\ \sum_{i=1}^{k} x_i \le x^{Total} - x^{Q*} \end{cases} \tag{5-1-32b}$$

where, $\boldsymbol{X^k} = [\,X_1, X_2, \ldots, X_k]^{\mathrm{T}}$;

$\boldsymbol{x^k} = [\,x_1, x_2, \ldots, x_k]^{\mathrm{T}}$.

and

$$A_i(X_i\,,\ x_i) = P_i(X_i) - C_i(X_i\,,\ x_i) \tag{5-1-32c}$$

And also

$\boldsymbol{G^k}(\boldsymbol{X^k}, \boldsymbol{x^k})$ is a function vector whose form is defined as:

$$\boldsymbol{G^k}\ (\boldsymbol{X^k}, \boldsymbol{x^k}) = \begin{bmatrix} \boldsymbol{g_1}(X_1, x_1) \\ \boldsymbol{g_2}(X_2, x_2) \\ \vdots \\ \boldsymbol{g_k}(X_k, x_k) \end{bmatrix} \qquad (5\text{-}1\text{-}32d)$$

and here the function vector $\boldsymbol{g_i}(X_i\ ,\ x_i)$, i=1, 2, … , k is the same one as in the previous model (5-1-2).

Let the optimal solution of the model (5-1-32) be $(\boldsymbol{X^{S*}},\ \boldsymbol{x^{S*}})$, i.e.

$$\boldsymbol{X^{S*}} = [X_1{}^{S*}, X_2{}^{S*}, \dots, X_k{}^{S*}]^{\mathrm{T}};$$

$$\boldsymbol{x^{S*}} = [x_1{}^{S*}, x_2{}^{S*}, \dots, x_k{}^{S*}]^{\mathrm{T}}.$$

then the sum of initial profits for all G_i, $(i \in S_k)$ in this case is defined as:

$$A_S = \sum_{i=1}^{k}[P_i(X_i{}^{S*}) - C_i(X_i{}^{S*}, x_i{}^{S*})] \qquad (5\text{-}1\text{-}33)$$

For the circumstance, the environmental damage can be identified as:

$$D_{S\&Q} = D(\sum_{i=1}^{k} x_i{}^{S*} + \sum_{j=k+1}^{n} x_j{}^{Q*}) \qquad (5\text{-}1\text{-}34)$$

and, the social benefit is:

$$SB^*{}_{S\&Q} = A_S + A_Q - D_{S\&Q} \qquad (5\text{-}1\text{-}35)$$

Finally the value of characteristic function for the coalition S_k is correspondingly given as follows:

$$\begin{aligned} v\,(S_k) &= SB^*{}_{S\&Q} - \sum_{j=k+1}^{n} Bt_j(X_j{}^{Q*}, x_j{}^{Q*}) \\ &= SB^*{}_{S\&Q} - [A_Q - \sum_{j=k+1}^{n} Tt_j(X_j{}^{Q*}, x_j{}^{Q*}) \\ &= A_S - D^*{}_{S\&Q} + \sum_{j=k+1}^{n} Tt_j(X_j{}^{Q*}, x_j{}^{Q*}) \\ &= \sum_{i=1}^{k}\big[P_i(X_i{}^{S*}) - C_i(X_i{}^{S*}, x_i{}^{S*})\big] + \sum_{j=k+1}^{n} Tt_j(X_j{}^{Q*}, x_j{}^{Q*}) - \\ &\quad - D(\sum_{i=1}^{k} x_i{}^{S*} + \sum_{j=k+1}^{n} x_j{}^{Q*}) \end{aligned} \qquad (5\text{-}1\text{-}36)$$

Actually, in the applications of this study, the part-cooperative model is only used for calculating the incentive on each polluter G_j's final profit which is based on how much contribution G_j makes to the maximum social benefit if G_j cooperates with G_0, or how much loss G_j makes to the maximum social benefit if G_j does not cooperate with G_0.

Therefore, it is just needed to concern about such an instance with k = (n-1) and get the value only for $v\ (S_k) = v\ (N - \{ j \})$.

Specifically, that is the case where all polluters $G_{i,\ i \in N}$ cooperate with the controller G_0 except for only one polluter $G_{j,}$ (j=1, or 2, …, or n , & $j \neq i$) .

5.2 The model for rational redistribution of the maximum social benefit

As mentioned previously, with all G_i's cooperation in the full-cooperative case, G_0 can make a decision on the overall region to maximize the social benefit which should be redistributed among all the G_i in a rational way to offer an extra profit as an incentive. In fact, the allocation of the maximum social benefit is essentially significant to keep the cooperation stable.

In this section, a model is discussed to allocate the maximum social benefit with an incentive for each G_i by calculating the emission tax (subsidy).

5.2.1 General conditions for rational redistribution

It is assumed that the controller G_0 aims at the maximum social benefit with consideration of the environmental damage over the whole region, and all the polluters $G_{i,\ i=1,\ 2,\ \ldots,\ n,}$ try to obtain their own final profits individually as much as possible even in the full-cooperative case.

From the viewpoint of redistribution of the maximum social benefit, G_0 is really not considered as a player or competitor to take part in the competition that takes place only among all the polluters $G_{i,\ i=1,\ 2,\ \ldots,\ n}$.

Therefore G_0 can be supposed to get a profit (gain) from the maximum social benefit before redistributing it to $G_{i,\ i=1,\ 2,\ \ldots,\ n}$. The G_0's gain may be explained as a management cost to operate the total emission control policy.

Let α_0 , α_i , $i \in N$ be respectively the G_0's gain and the G_i's final profit in the overall cooperation, then, here is the sum of actual benefit to be redistributed among all $G_{i,\, i \in N}$.

$$v(N) = v(\tilde{N}) - \alpha_0 = SB(\boldsymbol{X}^*, \boldsymbol{x}^*) - \alpha_0 \qquad (5\text{-}2\text{-}1)$$

where v is the characteristic function defined previously in the model for allocating the total emission; and $N = \{G_1, G_2, .., G_n\}$, $\tilde{N} = \{G_0, G_1, G_2, .., G_n\}$.

From the cooperative game theory in a characteristic function form, the α_i , as an imputation (solution of the game), is required to meet the conditions:

$$\sum_{i=0}^{n} \alpha_i = v(\tilde{N}) \qquad (5\text{-}2\text{-}2)$$

i.e.

$$\sum_{i=1}^{n} \alpha_i = v(N) \qquad (5\text{-}2\text{-}3)$$

and also,

$$\alpha_i \geq v(\{i\}) . \qquad (5\text{-}2\text{-}4)$$

The above expression (5-2-3) is called as the "group rationality" condition or "efficiency" condition (the Pareto optimal condition). This implies that the sum of each G_i's net profit obtained under the full-cooperative case is equal to the maximum social benefit excluding α_0. And the expression (5-2-4) is called as the "individual rationality" condition which means that each G_i's final profit obtained under the full-cooperative case is no less than that obtained from the non-cooperative case.

Generally, as the general conditions for rational redistribution, the polluter G_i's final profit $\alpha_{i,\, i=1,2,\dots,n}$ should satisfy the above two expressions at least.

5.2.2 The model with equal acceptance degree

In addition to the expressions (5-2-3) and (5-2-4), obviously, it is still needed to find some other conditions to identify a solution of

$$\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \dots, \alpha_n)$$

From the expression (5-2-3), it is known that an increase or a decrease in the polluter's profit α_i will result in a decrease or an increase on the other polluter's profit α_j (j ≠ i). Meanwhile, each G_i aims at making α_i as much as possible. The controller G_0 has to set each α_i according to some rational or optimal rule. The rule, in this study, is introduced with the concept of "Equal Acceptance Degree" (EAD) which is computed based on how much the G_i makes contribution to the total emission control policy in the full-cooperative case.

For estimating the each G_i's contribution, it is first required to give the value of characteristic function respectively for the following three coalitions, which is defined in the allocation model in the previous section.

① $v(\{i\}),\quad i = 1, 2, \ldots, or\ n$;
② $v(N),\quad N = \{1, 2, \ldots, n\}$;
③ $v(N - \{i\})$.

The coalition for the ③ is the part-cooperative case with k = (n-1) where all the polluters cooperate with G_0 except only one polluter G_i (i = 1, 2, …, or n).

Based on the superadditivity condition in the cooperative game with the characteristic function:

$$v(S \cup Q) \geq v(S) + v(Q),\ S, Q \in N \ \&\ S \cap Q = \emptyset \ \&\ v(\emptyset) = 0. \qquad (5\text{-}2\text{-}5)$$

it can be concluded that the following condition is satisfied:

$$v(N) \geq v(N - \{i\}) + v(\{i\}). \qquad (5\text{-}2\text{-}6)$$

Actually, as mentioned previously in the non- or part-cooperative model in Section 5.1, the G_0 aims at designing such a proper form of the emission charges function $Tt_i(X_i, x_i)$ so as to adjust the G_i's net profit $v(\{i\})$ as follows.

$$v(\{i\}) = Bt_i(X_i{}^{t*}, x_i{}^{t*}) = A_i(X_i{}^{t*}, x_i{}^{t*}) - Tt_i(X_i{}^{t*}, x_i{}^{t*}) \qquad (5\text{-}2\text{-}7)$$

Thus, here it can be possibly assumed that there exists the emission charges function (policy) which makes the condition (5-2-6) be satisfied in enforcing the total emission control policy. In fact, this means that with such a proper emission charges policy, the G_i's cooperation with G_0 not only makes the actual total emission controlled under the allowed maximum value, but also brings an increase on the total profit over the whole region. Here the increment is defined as

$$\Delta\alpha_i{}^{Tinc} = v(N) - [\, v(N - \{i\}) + v(\{i\}) \,]. \qquad (5\text{-}2\text{-}8)$$

In this situation, the G_i is considered to be capable of contributing to the full-cooperative decision making. In order to let the G_i keep cooperating stably with the total emission control policy, G_0 should guarantee the G_i for such a profit α_i that, at least, never be less than that obtained when taking not-cooperative attitude, as required by the individual rationality condition in (5-2-4), i.e.,

$$Min.\ \alpha_i = v(\{i\}), \quad \text{i.e.,} \quad v(\{i\}) \leq \alpha_i \qquad (5\text{-}2\text{-}9)$$

On the other hand, certainly, the G_i's final profit increment given by G_0 in the full-cooperative case, i.e.,

$$\Delta\alpha_i = \alpha_i - v(\{i\}) \qquad (5\text{-}2\text{-}10)$$

is not possibly more than the total profit increment resulted from the G_i's cooperation.

That is,

$$Max.\,\Delta\alpha_i = \Delta\alpha_i^{Tinc}\ . \qquad (5\text{-}2\text{-}11)$$

or

$$Max.\ \alpha_i = v(\{i\}) + \Delta\alpha_i^{Tinc}\ . \qquad (5\text{-}2\text{-}12)$$

Therefore, if

$$v(N) \geq v(N-\{i\}) + v(\{i\} \qquad (5\text{-}2\text{-}13)$$

then can get

$$v(\{i\}) \leq \alpha_i \leq v(\{i\}) + \Delta\alpha_i^{Tinc} \qquad (5\text{-}2\text{-}14)$$

Now, based on the above, the redistribution problem can be clearly described as the following multiobjective decision-making model (Nemhauser G.L. et al, 1989):

Obj.

$$\begin{cases} G_1: & Max.\ \alpha_1 \\ G_2: & Max.\ \alpha_2 \\ \vdots & \vdots \\ G_n: & Max.\ \alpha_n \end{cases} \qquad (5\text{-}2\text{-}15a)$$

s.t.

$$\begin{cases} G_1: & \alpha_1^{L} \leq \alpha_1 \leq \alpha_1^{H} \\ G_2: & \alpha_2^{L} \leq \alpha_2 \leq \alpha_2^{H} \\ \vdots & \vdots \\ G_n: & \alpha_n^{L} \leq \alpha_n \leq \alpha_n^{H} \\ G_0: & \sum_{i=1}^{n} \alpha_i = v(N) \end{cases} \qquad (5\text{-}2\text{-}15b)$$

where, for i = 1, 2, …, n , the corresponding α_i^{L} and α_i^{H} are obtained respectively from,:

$$\alpha_i^{L} = v(\{i\}) \qquad (5\text{-}2\text{-}16)$$

and

$$\alpha_i^{H} = v(\{i\}) + \Delta\alpha_i^{Tinc} \qquad (5\text{-}2\text{-}17)$$

In fact, solving the above multi-objective decision-making problem is not as complicated as it seems. Usually, the model can be simplified by using the methods like "possibility degree and satisfaction degree" (Nagasse Y. & Emilson C.D.S, 2000; Tamura H. & Suzuki H., 1981; Zhang Y., et al., 2014) and the concepts of the propensity to disrupt (Gately D., 1974), the Shapley value (Shapley L.S., 1971) and nucleolus (Schmeidler D., 1969).

By referring to the above methods, this study here introduces and adopts the following concept of "Equal Acceptance Degree" (EAD) to find an optimal solution with an impartial and rational rule (Gately D., 1974; 塩田尚樹, 2001; 植田和弘等, 1997).

Let $\gamma(i)$ express the "Acceptance Degree" of the *i*-th polluter G_i regarding the distributed final net profit α_i , and then define:

$$\gamma(i) = \frac{\alpha_i - \alpha_i^{L}}{\alpha_i^{H} - \alpha_i^{L}} \tag{5-2-18}$$

where, generally,

$$0 \le \gamma(i) \le 1 \tag{5-2-19}$$

From the expressions (5-2-8), (5-2-16), (5-2-17) and (5-2-18), can get

$$\gamma(i) = \frac{\Delta\alpha_i}{\Delta\alpha_i^{Tinc}} = \frac{\alpha_i - v(\{i\})}{v(N) - v(N - \{i\}) - v(\{i\})} \tag{5-2-20}$$

where, when $v(N) = v(N - \{i\}) + v(\{i\})$, define it as:

$$\gamma(i) = \gamma, \qquad 0 \le \gamma \le 1. \tag{5-2-21}$$

From the expression (5-2-20), the acceptance degree $\gamma(i)$ is the ratio of the increment of the *i*-th polluter's net profit and the increment of the regional total profit. This is based on the profits from both the cases with and without the G_i's cooperation with the total emission control policy. It is most acceptable when $\gamma(i) = 1$; and completely indifferent when $\gamma(i) = 0$.

Now the rational redistribution rule can be determined with such a sense: the "Equal Acceptance Degree (EAD)". That is to set

$$\gamma(1) = \gamma(2) = \cdots = \gamma(n) = \gamma \quad . \tag{5-2-22}$$

i.e.

$$\frac{\alpha_1 - \alpha_1{}^L}{\alpha_1{}^H - \alpha_1{}^L} = \frac{\alpha_2 - \alpha_2{}^L}{\alpha_2{}^H - \alpha_2{}^L} = \cdots = \frac{\alpha_n - \alpha_n{}^L}{\alpha_n{}^H - \alpha_n{}^L} = \gamma \, . \tag{5-2-23}$$

Therefore, with the condition expressions (5-2-3) and (5-2-23), the multi-objective model (5-2-15) is transferred to a simple single-objective one shown as follows:

$$\boldsymbol{G_0}^{\gamma}\textbf{:} \quad \text{Max.} \ \ \gamma \tag{5-2-24a}$$

$$\text{s.t.} \begin{cases} \alpha_i - \alpha_i{}^L = \gamma\,(\alpha_i{}^H - \alpha_i{}^L)\,, \quad i = 1, 2, \ldots, n\,; & \text{(5-2-24b)} \\ \sum_{i=1}^{n} \alpha_i = v(\,N\,)\,. & \text{(5-2-24c)} \end{cases}$$

It is obviously easy to obtain the solution of the above model. Let γ^* be the solution, then get the rational redistribution, finally:

$$\alpha_i = \alpha_i{}^L + \gamma^*(\alpha_i{}^H - \alpha_i{}^L), \quad i = 1, 2, \ldots, n; \tag{5-2-25}$$

and the extra profit, correspondingly,

$$\Delta\alpha_i = \alpha_i - v\,(\{\,i\,\})\,, \qquad i = 1, 2, \ldots, n\,. \tag{5-2-26}$$

Finally, note that as a rational distribution, the final profit α_i is indeed solved to meet the "individual rationality" condition in the expression (5-2-4).

But this condition is not guaranteed if the G_0 cannot find such a kind of emission charges function (policy) so that it can play an effective role in regulating the each polluter's net profit $v\,(\{\,i\,\})$ expected individually to get in the non-cooperative case. The situation where a proper emission charges function cannot be found is furtherly discussed in Section 7.3 later.

5.2.3 Calculation for the environmental tax and subsidy policy

After the value of each α_i is decided, the rising question is how to make it realized practically.

For the situation without the total emission control policy, if G_i discharges waste x_i after waste treatment, the polluter G_i has to pay the emission charges (fines) to the controller G_0 as compensation to the environmental damage resulted from waste x_i. The emission charges concept, however, is not still suitable for the cooperative case under the total emission control policy. Note that actually the emission charges function has not used in the full-cooperative model.

Instead of the emission charges (fines), here tax and subsidy policy could be used as an economic means to adjust the profits and realize the rational redistribution of the maximum social benefit obtained collectively among all cooperative polluters (Rinaldi S, et al., 1979).

Let t_i stand for the amount of tax submitted to G_0 by G_i, i=1, 2, …, n, then

$$t_i = A_i(X_i^*, x_i^*) - \alpha_i \quad (5\text{-}2\text{-}27)$$

$$= [P_i(X_i^*) - C_i(X_i^*, x_i^*)] - \alpha_i \quad (5\text{-}2\text{-}28)$$

where, as for $A_i(X_i^*, x_i^*)$, see the expression (5-1-27).

If t_i is less than zero, it means that G_i should receive a subsidy from G_0 with the amount of $|t_i|$.

Finally, note here that t_i is not a function in the model. It is only a value for adjusting the G_i's final profit obtained in the full-cooperative case.

5.3 The analytical blocks diagram

Finally, after modeling mathematically, in order to show the structure and interaction in the total emission control model, the analytical blocks diagram is drawn in Fig.5-3-1, as the summary of this chapter.

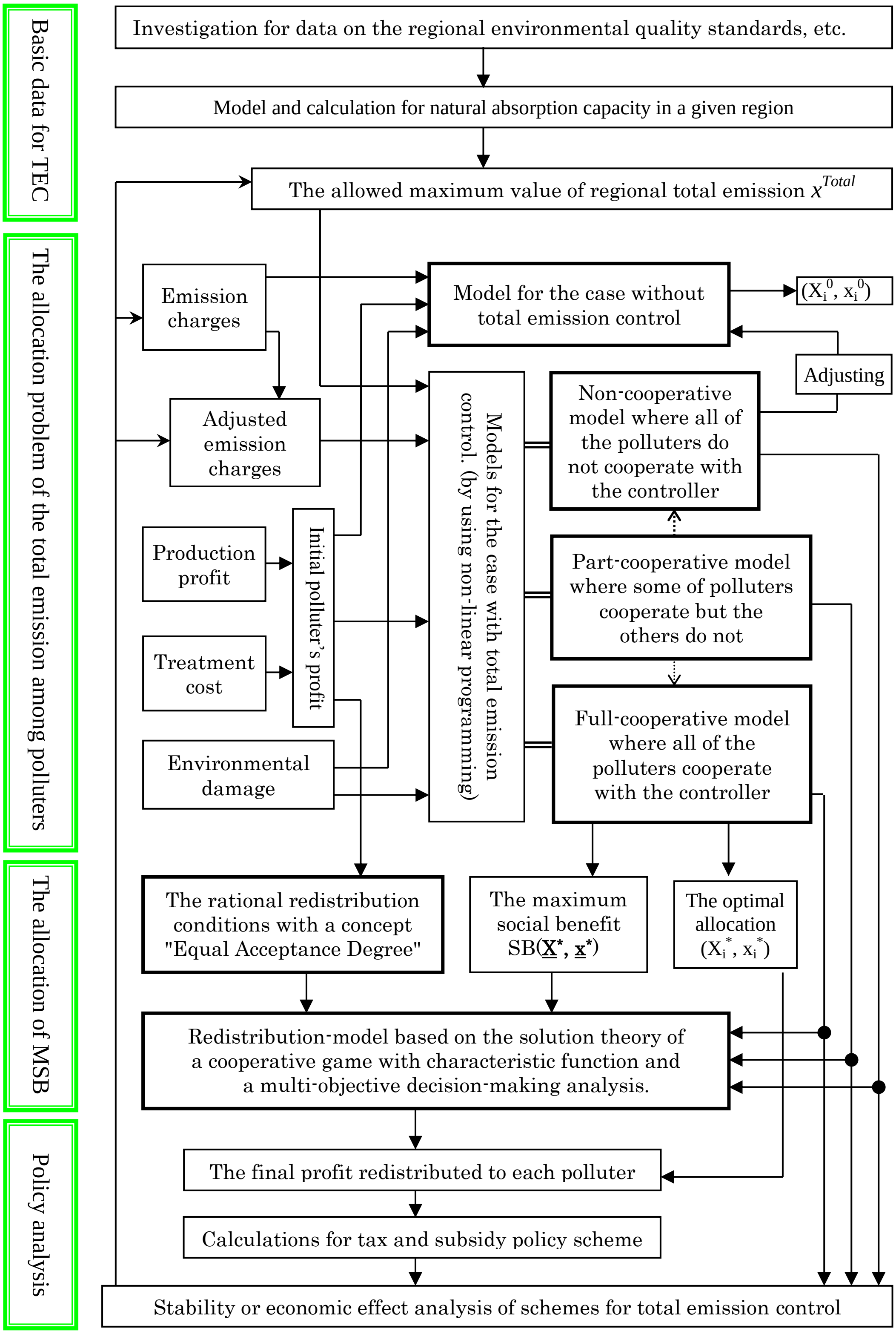


Fig.5-3-1 Analytical Blocks of the TEC model in this study

6. An empirical application on water quality planning: A case study

In this chapter, a case study of the total emission control (TEC) model's application on water quality planning in a river region is briefly discussed so as to solve a realistic problem as well as better understand the TEC model for a regional system.

6.1 Background of the application

Since the early 1960s, water quality management models have become increasingly sophisticated and complex (Loucks D.P., 1987; Orlob G. T., 1983). Instead of discussing a water quality planning model itself, this study would prefer applying the established model to find an optimal TEC policy scheme with an economic incentive for a practical issue. Thus, the case study in this chapter can be discussed also as an example to give a better understanding on how to reach an optimal TEC policy scheme by a simulating process.

With an actual application background, in the following a TEC policy scheme is discussed to reduce the total emission of COD wastewater in a given region along the upper reaches of Huangpu River in Shanghai, China.

By the way, all the original data used here in Chapter 6, except for some data given with the data sources, come from the research reports "Investigation Data in Shongjiang Industrial District (1-21)", and "Economic Analysis on Emissions Standards of Industrial Wastewater at Upper Reaches of Huangpu River in Shanghai", provided by Shanghai Environmental Science Research Institute (SESRI, 1986a).

Huangpu River in Shanghai, as one of important water resources for the whole metropolitan city, had actually been polluted by wastewater, particularly, on the upper reaches of the river where a typical area called as Songjiang district is a key one in improving water quality of the river.

In the district, there were more than 100 plants or factories, most of which discharged mainly the COD wastewater totally up to 30,000m^3/day, i.e. the actual COD total emission of about 9,400Kg/day (SESRI, 1986a). It is certainly much over the maximum value allowed by the national environmental standards for the river region. Therefore, Shanghai metropolitan government has decided by legislation to implement the total emission control policy to reduce wastewater emission in the region (Shanghai Gov., 1985).

With such a background in the application study, the purpose of the application in this chapter is to develop and analyse, quantitatively, the feasible alternative policy schemes of total emission control in the district on the pollutant, here, COD.

According to the actual situation in pollution and the data collected possibly, it is thought useful and suitable to finally pick up 39 plants or factories (see Appendix A-1 for the list). It means that in the model, there are 39 polluters, i.e. n=39.

6.2 Model setting

6.2.1 The environmental absorption capacity

Under the conditional constraints from water quality standards in the river region, it is possible to obtain the maximum natural absorption capacity (程声通, 2003; 张玉清, 2001) in the chosen segment of the river by means of a dynamic model of river water quality. Then the natural absorption capacity could be considered as the allowed maximum value of total emission.

To calculate it, the Auto-Qual-ss model in one dimension (Robert L. C. and Norman L. L., 1985; Yang Z., 1985) is applied here.

Let the vector of the concentration of COD be

$$\boldsymbol{C} = [C_1, C_2, \ldots, C_n]^T \qquad (6\text{-}2\text{-}1)$$

and the vector of the emission of COD be

$$\boldsymbol{W} = [W_1,\ W_2, \ldots, W_n]^T \qquad (6\text{-}2\text{-}2)$$

Then from the Auto-Qual-ss model, there is the expression below

$$\mathbf{MC} + \boldsymbol{W} = \mathbf{0} \qquad (6\text{-}2\text{-}3)$$

where $\mathbf{M}$ is a constant matrix of the coefficients known.

In fact, the model can be described as a mathematical programming model:

$$Max.\ Z = \sum_{i=1}^{n} W_i \qquad (6\text{-}2\text{-}4a)$$

. s.t.

$$\begin{cases} \boldsymbol{C} = -\boldsymbol{M}^{-1}\boldsymbol{W} \leq \boldsymbol{C}^s \\ \qquad\qquad \boldsymbol{W} \geq \mathbf{0} \end{cases} \qquad (6\text{-}2\text{-}4b)$$

where $\boldsymbol{C}^s$ is the vector of the water quality standards for the chosen segments of the river.

By solving the above programming model, it is simple to obtain the allowed maximum values for $\boldsymbol{W}$, by which the maximum value of the allowed total emission as the TEC policy target is defined as follows.

$$x^{Total} = \sum_{i=1}^{n} W_i \qquad (6\text{-}2\text{-}5)$$

Actually, the result is calculated by using the Auto-Qual model's software on the computer (Yang Z., 1985), which is selected to study in the later discussion. That is, to set

$$x^{Total} = 2{,}260 \quad \text{(kg/day)} \qquad (6\text{-}2\text{-}6)$$

6.2.2 Shapes of the used basic functions

Before setting model completely, it is required to establish the basic functions and estimate their corresponding parameters or coefficients based on the data for the COD wastewater. (For the general discussion on these functions, see Section 4.2)

Here are the essential data for each plant.

P_{i0} : the production profit, with a unit of (10,000 CNY) per year ;
Q_{Xi0} : the flow of COD wastewater, with a unit of m^3 per day ;
C_{Xi0} : the concentration of COD wastewater before treatment, with a unit of mg per litre.

In all the following discussions, use

X_i : stands for the amount of waste produced from the *i*-th plant's production process before waste treatment, with a weight unit (kg or ton);

x_i : stands for the amount of waste discharged from the *i*-th plant into the regional environmental system after waste treatment, with a weight unit (kg or ton);

(1) The production profit function

It is assumed that the production profit depends only on the amount of waste before treatment. The more the waste, the greater the profit, but the increasing rates are different.

Assuming that the increasing rate of the waste is as μ times as that of the profit at any scale of production, then

$$\frac{\Delta X_i / X_i}{\Delta P_i / P_i} = \mu$$

then

$$\frac{d\,P_i}{d\,X_i} = Limit \frac{\Delta\,P_i}{\Delta\,X_i} \approx \frac{1}{\mu} * \frac{P_i}{X_i} \qquad (6\text{-}2\text{-}7)$$

∵ $Ln\,P_i = \left(\frac{1}{\mu}\right) * LnX_i + C_{i0}$, where C_{i0} is a constant.

∴ $P_i = p_{i0} X_i^{(1/\mu)}$, where p_{i0} is a constant. (6-2-8)

Now, let's identify μ and p_{i0}.

First, regarding μ, from the empirical data (Li W.J., et al, 1982), when the production grows by 100%, the waste increases by 60%.

That is

$$P = p_{i0} X^{(1/\mu)} \qquad (6\text{ -2-9})$$

and

$$2P = p_{i0} (1.6X)^{(1/\mu)} \qquad (6\text{-}2\text{-}10)$$

From the two equations, get

$$(1/\mu) = (Ln2) / (Ln1.6) \approx 1.474 \qquad (6\text{-}2\text{-}11)$$

Then, as for p_{i0} , with the essential data P_{i0} , Q_{Xi0} , C_{Xi0} and X_{i0} , the equation (6-2-8) should be satisfied, i.e.

$$P_{i0} = p_{i0} X_{i0}^{(1/\mu)} , \qquad (6\text{-}2\text{-}12)$$

$$\therefore \quad p_{i0} = \frac{P_{i0}}{X_{i0}^{(1/\mu)}} = \frac{P_{i0}}{(C_{Xi0} * Q_{Xi0})^{1.474}} \qquad (6\text{-}2\text{-}13)$$

Therefore, finally get

$$P_i(X_i) = p_{i0} X_i^{1.474}. \qquad (6\text{-}2\text{-}14)$$

(2) The treatment cost function

In general, the treatment cost is a function of the flow Q_i and the treatment efficiency η_i. (Morley D.A., 1979; 塩田尚樹, 2001). That is

$$C_i = C_i(Q_i, \eta_i) \quad (6\text{-}2\text{-}15)$$

From the empirical data, there are various kinds of form for the treatment function (Robert W.H., 1989; 植田和弘等, 1997). Here, choose the shape below:

$$C_i = a_1 Q_i^{\,q1} + a_2 Q_i^{\,q2} \eta_i^{\,p} \quad (6\text{-}2\text{-}16)$$

where a_1, a_2, q_1, q_2 and p are all parameters specified. In general (Li W.J., et al, 1982), it is proper to set

$$q_1 = q_2 \quad (6\text{-}2\text{-}17)$$

Based on the original data shown in Table 6-2-1, the parameters are estimated with the least square method by minimizing

$$J = \sum_{i=1}^{39}[C_i - (a_1 Q_i^{\,q_1} + a_2 Q_i^{\,q_2} \eta_i^{\,p})]^2 = \sum_{i=1}^{39}[C_i - C_i^{\wedge}]^2 \quad (6\text{-}2\text{-}18)$$

Table 6-2-1 The data for estimating the parameters in *C(,)*

i	K(i)	Qi (kl/day)	η i (%)	Ci (CNY/day)
4	4	206	75.61	47.342
5	5	82	93.75	47.342
6	6	280	89.69	255.732
7	7	4	63.87	14.003
9	9	967	72.81	705.984
10	10	10	77.28	33.534
11	11	7910	88.33	929.315
12	12	40	63.03	48.288
13	13	100	97.75	133.375
14	14	5	85.88	54.795
15	15	370	97.16	381.37
16	16	80	95.51	66.959
17	17	1.5	87.98	0.822
18	18	3	86.91	6.088
19	19	20	66.67	49.877
20	20	4	83.97	8.129
22	22	2221	74.94	375.521
25	25	20	90.42	40.66
26	27	2	62.31	0.907
27	29	10	52.77	7.019
28	30	15	79.81	64.735
29	31	24	71.6	48.736
30	32	5	95.1	4.914
31	33	6	95.36	52.74
32	35	120	76.18	65.436
34	37	2400	96.16	460.997
37	40	20	97.19	6.55
38	41	100	87.24	127.321
39	42	275	69.57	36.73

Source: (SESRI, 1986a) Investigation Data in Shongjiang Industrial District (1-21) [W], Research Reports, Shanghai Environmental Science Research Institute, Shanghai. China

By estimating the parameters the results are obtained as follows:

$$a_1 = 0.996532,\ a_2 = 4.992307,\ q_1 = q_2 = 0.5921632,\ p = 1.994352$$

Practically in computations, roughly use

$$a_1 = 1.0\,,\quad a_2 = 5.0\,,\quad q_1 = q_2 = 0.6\,,\quad p = 2.0$$

then, the function can be expressed as

$$C_i = C_i(Q_i, \eta_i) = 1.0{Q_i}^{0.6} + 5.0{Q_i}^{0.6}{\eta_i}^{2.0} \qquad (6\text{-}2\text{-}19)$$

Furthermore, from

$$Q_i = X_i / C_{Xi0} \quad \text{and} \quad \eta_i = (X_i - x_i)/X_i\ , \qquad (6\text{-}2\text{-}20)$$

where C_{Xi0} is the concentration before treatment, known from the essential data, the treatment cost function can be obtained in the final form as:

$$C_i(X_i, x_i) = \left(\frac{1.0}{{C_{Xi0}}^{0.6}}\right) * {X_i}^{0.6} + \left(\frac{5.0}{{C_{Xi0}}^{0.6}}\right) * {X_i}^{-1.4} * (X_i - x_i)^2 \qquad (6\text{-}2\text{-}21)$$

(3) The emission charges function

The emission charges can be explained as a compensation of the environmental damage resulted from the waste discharge.

The existing emission charges standards is based on a segmented fines (penalty) system shown in Table 6-2-2, which has been decided by Environmental Protection Bureau of the local government.

In order to establish easily the emission charges function according to the data in the table, it is conceivably feasible to convert the segmented fines system to the segmented linearization function below.

Table 6-2-2 The existing emission charges standards for calculating the values of (N_j , M_j) in the function

No. j	N_j (C_{COD}=50mg/l)	M_j (CNY/ton)
1	[0 -1)	0
2	[1 -2)	0.05
3	[2 -5)	0.10
4	[5 -10)	0.20
5	[10 -20)	0.35
6	[20 -50)	0.55
7	[50 -100)	0.80
8	[100 -200)	1.10
9	[200 -500)	1.45
10	[500 -1000)	1.85
11	[1000 - N)	2.30
12	[N -)	2.30

Source: (SESRI, 1986a) Investigation Data in Shongjiang Industrial District (1-21) [W], Research Reports, Shanghai Environmental Science Research Institute, Shanghai. China

$$T_i(X_i, x_i) = \left(\frac{K_j}{C^s}\right) * x_i + \left(\frac{B_j}{C_{Xi0}}\right) * X_i ,$$

$$if\ N_j \le (C_{Xi0}/C^s) * (x_i/X_i) < N_j + 1 . \qquad (6\text{-}2\text{-}22)$$

where, $K_j = (M_{j+1} - M_j) / (N_{j+1} - N_j)$;

$B_j = M_j - K_j * N_j$;

and (N_j , M_j) is obtained from the existing standard data for the emission charges or emission fines shown in Table 6-2-2.

C^s is the value of standard for COD, here C^s = 50 mg/l.

(4) The environmental damage function

According to its characteristics discussed in Section 4.2 (see the expressions (4-2-11) to (4-2-14)), the damage function is given in the form below:

$$D(x) = d * x^k \qquad (6\text{-}2\text{-}23)$$

Here for discussing the model behavior and possible implications from the results, $k = 2$ is assumed for simplifying the calculation. And then, it is just needed to identify the coefficient d.

Considering the expression (6-2-23) and the characteristic of the $D(x)$ discussed in Section 4.2 (see the expression (4-2-11)), define

$$d = C_T\,(x^{Total}) / (x^{Total})^2 \qquad (6\text{-}2\text{-}24)$$

where, x^{Total} is the environmental absorption capacity or the maximum of the allowed total emission set as the policy target (see Section 6.2.1); and $C_T\,(x^{Total})$ can be computed by the treatment cost function $C(,)$.

This means that $C_T\,(x^{Total})$ is to be equal to the cost that is required to treat or abate the same amount of waste as x^{Total} .

6.3 Equilibrium computation procedure

(1) Formulating the objective functions

Specifically given the basic functions, the objective functions for each case can be established respectively from the expressions (5-1-2a), (5-1-8a), (5-1-21a) and (5-1-32a).

(2) Formulating the s.t. function vector $\boldsymbol{g_i}(X_i\ ,\ x_i\ )$

a) Production scale

It is assumed that the production scale should be limited at a certain level. In other words, the variable X_i has an upper limit expressed as $X_i{}^{Max}$, i.e.

$$X_i \leq X_i{}^{Max}\ ,\ \text{or}\quad X_i - X_i{}^{Max} \leq 0 \qquad (6\text{-}3\text{-}1)$$

where, $X_i{}^{Max}$ is usually determined by the policy-maker based on the limited economic development scale (see the example in Section 6.4.1).

b) Treatment efficiency

Usually the efficiency of wastewater treatment has an upper limit because of technological problems (Morley D.A., 1979). Let the highest efficiency be $\eta_i{}^{Max}$,

then

$$(X_i - x_i\ )\ /X_i\ \leq \eta_i{}^{Max} \qquad (6\text{-}3\text{-}2a)$$

or

$$(1 - \eta_i{}^{Max}\ )X_i - x_i \leq\ 0 \qquad (6\text{-}3\text{-}2b)$$

c) Obviously,

$$x_i \leq X_i\ ,\ or\quad - X_i + x_i\ \leq\ 0 \qquad (6\text{-}3\text{-}3)$$

d) The non-negative condition

$$X_i \geq\ 0\ ;\quad x_i \geq\ 0\ . \qquad (6\text{-}3\text{-}4)$$

e) Treatment scale

There is usually a limitation on the total amount of the treatment, i.e.

$$X_i - x_i \leq \Delta X_i{}^{Max}$$

It is not necessary, however, to consider this condition here, because the conditions a) and c) are considered already in use.

Now, the vector of function $\boldsymbol{g_i}(X_i\ , x_i\ )$ can be given as follows:

$$\boldsymbol{g}_i(\ X_i,\ x_i) = \begin{bmatrix} X_i - X_i{}^{Max} \\ (1 - \eta_i{}^{Max}\ )X_i - x_i \\ -X_i + x_i \\ -X_i \\ -x_i \end{bmatrix} \qquad (6\text{-}3\text{-}5)$$

(3) Formulating the s.t. conditons in the model

With the $\boldsymbol{g_i}(X_i\,, x_i\,)$, the model (5-1-2b) or (5-1-8b) is:

$$s.t.\begin{cases} \boldsymbol{A}_i\,\boldsymbol{X}^{(i)} \;\le\; \boldsymbol{B}_i \\ \qquad \boldsymbol{X}^{(i)} \;\ge\; \boldsymbol{0} \end{cases} \tag{6-3-6a}$$

where,

$$\boldsymbol{A}_i = \begin{bmatrix} 1 & 0 \\ (1-\eta_i{}^{Max}\;) & -1 \\ -1 & 1 \end{bmatrix},\ \boldsymbol{B}_i = \begin{bmatrix} X_i{}^{Max} \\ 0 \\ 0 \end{bmatrix},\ \boldsymbol{X}^{(i)} = \begin{bmatrix} X_i \\ x_i \end{bmatrix} \tag{6-3-6b}$$

And the s.t. condition of the full-cooperative model (5-1-21) is

$$s.t.\begin{cases} \boldsymbol{A}_T\;\boldsymbol{X_T} \le\; \boldsymbol{B}_T \\ \qquad \boldsymbol{X_T} \;\ge\; \boldsymbol{0} \end{cases} \tag{6-3-7a}$$

where, $\boldsymbol{A_T}$ is defined below, called as the "interaction coefficients matrix" among all polluters.

$$\boldsymbol{A}_T = \begin{bmatrix} \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} & \boldsymbol{0} \\ \begin{pmatrix} 1-\eta_i{}^{Max} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1-\eta_i{}^{Max} \end{pmatrix} & \begin{pmatrix} -1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -1 \end{pmatrix} \\ \begin{pmatrix} -1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -1 \end{pmatrix} & \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} \\ \boldsymbol{0} & 1 \quad 1 \ldots \quad 1 \end{bmatrix} \tag{6-3-7b}$$

$$\boldsymbol{B}_T = \begin{bmatrix} X_1{}^{Max} \\ X_2{}^{Max} \\ \vdots \\ X_n{}^{Max} \\ \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{x}^{Total} \end{bmatrix},\qquad \boldsymbol{X}_T = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \\ x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{6-3-7c}$$

From the above, it is seen that model (5-1-2), (5-1-8), (5-1-21) or (5-1-32) is a non-linear programming model. Particularly, for the full-cooperative model (5-1-21), there are 2n variables and (3n+1) constraints. In the application with n=39, the model has 78 variables and a set of 198 constraints (including the non-zero ones).

To solve the above model, it is easy to use the non-linear programming methods (Nemhauser G.L., 1989; Li W.J., et al., 1982; 奈良宏一, 2000; 矢部博, 2001), and the related software to calculate the results on the computer.

At last, based on the results data, it is also simple to calculate the equal acceptance degree, the distributions of the maximum social benefit and environmental taxes or subsidies according to the expressions (5-2-23), (5-2-26) and (5-2-28).

6.4 Results and discussion

In this section, the results are computed and then discussed for the following cases.

(1) Based on the individual decision making model, the each plant's waste emission and final profit are computed for the situation without the TEC policy and the non-cooperative case with TEC policy, respectively, See Table 6-4-1 and Table 6-4-2;

(2) In the full-cooperative case, the optimal solution for the each plant's final emission is decided by the allocation model of total emission and the each plant's final profit is determined based on the redistribution model of the maximum social benefit. See Table 6-4-3;

(3) Also, the each plant's extra profit is calculated as an incentive based on the part-cooperative case in which all the plants cooperate with the TEC policy except one plant. See Table 6-4-3 and Table 6-4-4;

(4) As a result, the optimal TEC policy scheme with an incentive is specified and discussed finally.

6.4.1 Simulating results

At first, in simulating computation, the relevant conditions are specifically set as follows:

1) The maximum amount of the allowed total emission in the region is set as x^{Total} =2,260 Kg/day, which is actually decided by the city's local

government from the environmental absorption capacity in the river region (see Section 6.2.1) ;

2) The production scale $P_i(X_i)$ for each plant is set as a limited value under 4 times (twice of twice) of the present level according to the city's economic development plan (Shanghai, 1986). According to what discussed in Section 6.2.2 (1) and expression (6-3-1), the limited production scale means that the each plant's waste load from the producing process is allowed to increase by 1.6^2=2.56 times, i.e. setting $X_i^{Max} = 2.56\, X_{i0}$.

3) As for the highest treatment efficiency, it is not possible to remove all the waste completely because of the usual technology of waste treatment. In this application, based on the practical treatment capacity of each plant (SESRI, 1986), the highest treatment efficiency is possibly set to 95%, i.e. setting η_i^{Max} = 0.95.

4) The gain of the administrator (controller) G_0 under total emission control is considered as zero for simple calculation, i.e. setting $\alpha_0 = 0$, which implies that there is no cost for operating the total emission control policy.

5) For the situation without the TEC policy, the existing emission charges standard is set as the same as shown in Table 6-2-2, i.e., the function $T_i(\,,\,)$ is expressed by the expression (6-2-22) in Section 6.2.2 (3).

6) And finally for the non-cooperative case of the individual decision-making under the TEC policy, the adjusted emission charges standard is adjusted up to twice of the existing one, that is, the adjusted emission charges function $Tt_i(\,,\,)$ is defined as $Tt_i(\,,\,)$ = $2{*}T_i(\,,\,)$. (See Section 6.2.2 for details). By the way, the reasons for setting $Tt_i(\,,\,)$ = $2{*}T_i(\,,\,)$ here is just for simpler calculation as an easier example to demonstrate the methodology in this study. Of course, it is possible to set any $Tt_i(\,,\,)$ as long as it can be suitable for adjusting the each plant's net profit in the non-cooperative model so as to form fully a stable cooperation with the TEC policy. How to adjust the function $Tt_i(\,,\,)$ is exactly one of the topics for designing the TEC policy in this study. See the later Section 6.5.2.

The following Table 6-4-1 and Table 6-4-2 show the results based on the individual decision making model. The former is for the situation without the TEC policy, and the later for the non-cooperative case with the TEC policy.

Table 6-4-1 and Table 6-4-2 Results based on the individual decision making model

Table 6-4-1 For the case Without TEC policy based on the existing function T_i (,)						Table 6-4-2 Non-cooperative case With TEC based on the function Tt_i (,) = 2 T_i (,)				
i	K(i)	xi (g/d)	ηi (%)	Bi (cny/d)		i	K(i)	xi (g/d)	ηi (%)	Bti (cny/d)
1	1	15,187.20	0.00	28,658.20		1	1	15,187.20	0.00	28,643.02
2	2	1,035.24	0.00	12,267.27		2	2	1,035.24	0.00	12,266.24
3	3	8,488.45	0.00	12,161.42		3	3	8,488.45	0.00	12,159.12
4	4	68,488.24	0.00	13,044.45		4	4	68,488.24	0.00	12,981.21
5	5	83,170.31	0.00	19,640.90		5	5	83,170.31	0.00	19,580.50
6	6	16,070.66	0.00	2,124.04		6	6	16,070.66	0.00	2,107.97
7	7	2,352.74	0.00	651.59		7	7	2,352.74	0.00	649.68
8	8	1,920.77	0.00	13,135.22		8	8	1,920.77	0.00	13,133.33
9	9	443,118.10	0.00	16,346.25		9	9	443,118.10	0.00	15,968.33
10	10	27,750.40	0.00	2,170.34		10	10	27,750.40	0.00	2,155.90
11	11	99,830.52	0.00	76,228.93		11	11	99,830.52	0.00	76,129.09
12	12	5,431.30	0.00	2,827.81		12	12	5,431.30	0.00	2,822.38
13	13	45,816.32	0.00	2,124.85		13	13	45,816.32	0.00	2,085.77
14	14	3,237.76	0.00	1,636.63		14	14	3,237.76	0.00	1,634.05
15	15	422,604.80	0.00	21,721.42		15	15	21,130.24	95.00	21,722.01
16	16	228,556.80	0.00	23,968.62		16	16	11,427.84	95.00	23,952.41
17	17	1,597.56	0.00	873.32		17	17	1,597.56	0.00	872.17
18	18	583.83	0.00	872.73		18	18	583.83	0.00	872.15
19	19	7,680.00	0.00	267.50		19	19	7,680.00	0.00	260.67
20	20	525.72	0.00	50.23		20	20	525.72	0.00	49.70
21	21	2,050.38	0.00	2,161.71		21	21	2,050.38	0.00	2,159.66
22	22	613,550.40	0.00	25,414.25		22	22	613,550.40	0.00	24,815.69
23	23	87,040.00	0.00	2,973.08		23	23	87,040.00	0.00	2,897.99
24	24	103,441.90	0.00	5,228.06		24	24	103,441.90	0.00	5,202.84
25	25	4,754.94	0.00	1,847.65		25	25	4,754.94	0.00	1,842.90
26	27	28.36	0.00	348.00		26	27	28.36	0.00	347.96
27	29	188.93	0.00	7,116.10		27	29	188.93	0.00	7,115.91
28	30	3,338.11	0.00	1,598.70		28	30	3,338.11	0.00	1,595.36
29	31	4,894.93	0.00	914.78		29	31	4,894.93	0.00	909.88
30	32	7,834.88	0.00	51.07		30	32	7,834.88	0.00	46.65
31	33	4,010.04	0.00	3,827.28		31	33	4,010.04	0.00	3,824.11
32	35	811.01	0.00	42,861.26		32	35	811.01	0.00	42,860.45
33	36	10,831.87	0.00	1,496.58		33	36	10,831.87	0.00	1,485.92
34	37	1,074,342.00	95.00	3,395.92		34	37	1,074,342.00	95.00	2,321.58
35	38	81,715.20	0.00	11,428.92		35	38	81,715.20	0.00	11,347.21
36	39	172.03	0.00	180.01		36	39	172.03	0.00	179.84
37	40	16,007.17	0.00	59.42		37	40	16,007.17	0.00	47.26
38	41	9,344.00	0.00	11,031.29		38	41	9,344.00	0.00	11,021.95
39	42	127,888.60	0.00	7,686.74		39	42	127,888.60	0.00	7,578.01
sum		3,635,691.47		380,392.54		sum		3,017,087.95		377,646.87

Furtherly the following Table 6-4-3 and Table 6-4-4 show the results based on the centralized decision making model for the full-cooperative case under TEC policy. The former Table 6-4-3 is for allocating the allowed total emission and the later Table 6-4-4 is for the redistributing the maximum social benefit among all the cooperative plants.

Table 6-4-3 and Table 6-4-4 Results based on the full-cooperative model with TEC policy

Table 6-4-3
Optimal allocation of the allowed total emission

i	K(i)	Xi (g/d)	xi (g/d)	ηi (%)
1	1	15,187.20	15,187.20	0.00
2	2	1,035.24	1,035.24	0.00
3	3	8,488.45	424.41	95.00
4	4	68,488.24	68,488.24	0.00
5	5	83,170.31	83,170.31	0.00
6	6	16,070.66	16,070.66	0.00
7	7	2,352.74	2,352.74	0.00
8	8	1,920.77	1,920.77	0.00
9	9	443,118.08	22,155.90	95.00
10	10	27,750.40	1,387.52	95.00
11	11	99,830.52	99,830.52	0.00
12	12	5,431.30	5,431.30	0.00
13	13	45,816.32	45,816.32	0.00
14	14	3,237.76	3,237.76	0.00
15	15	422,604.80	21,130.24	95.00
16	16	228,556.80	11,427.84	95.00
17	17	1,597.56	1,597.56	0.00
18	18	583.83	583.83	0.00
19	19	7,680.00	7,680.00	0.00
20	20	525.72	525.72	0.00
21	21	2,050.38	2,050.38	0.00
22	22	613,550.35	410,120.98	33.16
23	23	87,040.00	87,040.00	0.00
24	24	103,441.92	5,172.10	95.00
25	25	4,754.94	4,754.94	0.00
26	27	28.36	28.36	0.00
27	29	188.93	188.93	0.00
28	30	3,338.11	3,338.11	0.00
29	31	4,894.93	4,894.93	0.00
30	32	7,834.88	7,834.88	0.00
31	33	4,010.04	4,010.04	0.00
32	35	811.01	811.01	0.00
33	36	10,831.87	10,831.87	0.00
34	37	21,486,847.50	1,074,342.39	95.00
35	38	81,715.20	81,715.20	0.00
36	39	172.03	172.03	0.00
37	40	16,007.17	16,007.17	0.00
38	41	9,344.00	9,344.00	0.00
39	42	127,888.60	127,888.60	0.00
sum		24,048,196.92	2,260,000.00	

Table 6-4-4
Rational redistribution of the social benefit

i	K(i)	ti (cny/d)	αi (cny/d)	△αi (cny/d)
1	1	26.55	28,646.81	3.79
2	2	1.82	12,266.50	0.26
3	3	-3.91	12,159.70	0.58
4	4	111.68	12,997.02	15.81
5	5	105.70	19,595.60	15.10
6	6	28.12	2,111.99	4.02
7	7	2.62	650.87	1.19
8	8	3.34	13,133.81	0.48
9	9	139.73	16,094.03	125.70
10	10	-5.75	2,158.96	3.06
11	11	174.71	76,154.05	24.96
12	12	9.49	2,823.74	1.36
13	13	68.38	2,095.54	9.77
14	14	4.51	1,634.71	0.66
15	15	136.95	21,727.29	5.28
16	16	10.00	23,955.27	2.86
17	17	2.01	872.46	0.29
18	18	1.01	872.30	0.15
19	19	11.94	262.38	1.71
20	20	4.92	49.83	0.13
21	21	3.60	2,160.16	0.50
22	22	825.80	25,088.58	272.89
23	23	133.92	2,924.27	26.28
24	24	1.75	5,219.95	17.11
25	25	8.31	1,844.09	1.19
26	27	0.06	347.96	0.00
27	29	0.35	7,115.95	0.04
28	30	8.84	1,596.63	1.27
29	31	8.57	911.11	1.23
30	32	8.84	47.92	1.27
31	33	5.13	3,825.34	1.25
32	35	1.42	42,860.65	0.20
33	36	18.63	1,488.58	2.66
34	37	1,881.10	2,590.17	268.59
35	38	143.02	11,367.64	20.43
36	39	0.30	179.88	0.04
37	40	21.28	50.03	2.77
38	41	16.34	11,024.29	2.34
39	42	190.28	7,605.19	27.18
sum		4,111.36	378,511.25	864.40

6.4.2 Discussion and policy implication

Table 6-4-1 shows the result for the existing state, i.e., the case of individual decision-making without total emission control. Here, x_i is the amount of pollutant finally discharged into the regional environment; η_i is the treatment percentage; and the B_i is the profit for each plant (polluter). Also, the emission charges standard is kept as the existing level, i.e. $Tt_i(\,,\,) = T_i(\,,\,)$.

It is observed that in this situation, the total emission is 3,635,691.47 g/day, i.e. 3,635.69 Kg/day, which is much over 2,260.00 Kg/day, the maximum value of the allowed total emission in the region. The sum of each plant's profit is 380,392.54 CNY/day (here "CNY" or "cny" stands for RMB CNY, the Chinese currency unit "yuan". It is the same afterwards).

Table 6-4-2 presents the results for the case of individual decision-making under total emission control. In this situation, the emission charges standard is adjusted up to twice as the existing level, i.e., $Tt_i(\,,\,) = 2T_i(\,,\,)$. Because the emission charges amount is doubled for any not-cooperative plant, the total emission decreases slightly down to 3,017,087.95 g/day, i.e., 3017.09 Kg/day. It is still, however, much more than the maximum value of the allowed total emission, 2,260.00 Kg/day. The sum value of all the plants' profits is 377,646.87 CNY/day.

The net profit of each plant in the non-cooperative case, $Bt_i(X_i, x_i)$, can be considered as the comparative value to the final profit α_i in the full-cooperative case, i.e., $v(\{i\}) = Bt_i(X_i, x_i)$.

From Table 6-4-3 and Table 6-4-4, the results data can be seen for the full-cooperative case of the centralized decision-making under total emission control.

In Table 6-4-3, it indicates the optimal allocation of the maximum total emission in the region, where, X_i is the amount of pollutant load resulted from the production process; x_i is the amount of pollutant finally discharged into the regional environment; η_i is the treatment percentage.

Also, Table 6-4-4 shows the fair redistribution of the maximum social benefit among all the cooperative plants (the administrator's profit is set to be zero), where t_i is the value of "the environmental tax or subsidy" (a definition formally similar to, but, conceptually different from, "the emission charges" in the individual decision-making case, see Section 5.1); α_i is the final profit for each plant; and $\Delta\alpha_i$ is an increment in each plant's final profit which could be considered as an extra-gain (incentive) obtained from the overall cooperation with the total emission control policy.

In the situation, because the total emission control instrument is enforced by the centralized decision-making approach, the total emission in the region is controlled under the allowed maximum amount, 2,260.00 Kg/day. Also, the social benefit is maximized up to the value of 378,511.25 CNY/day, which is more than 377,646.87 CNY/day, the sum value of all the plants' profits expected separately in the non-cooperative case, and this makes it possible that each plant can gain an increment in its own final profit due to its cooperation.

As a conclusion, therefore, the results data in Table 6-4-3 and Table 6-4-4 show a stable scheme of total emission control policy. The details are discussed as follows:

(1) The stable scheme in Table 6-4-3 shows that the production scale $P_i(X_i)$ for each plant is allowed to grow up to the double and redouble level from the existing state, that is, the produced waste X_i is allowed to increase up to 2.56 times of the present value. Among all the plants, however, there are 8 plants (the 3rd, 9th, 10th, 15th, 16th, 22nd, 24th, and 34th ones) which should reduce their final pollutant discharges to a certain extent. Given as examples, the 9th, 15th and 34th plants (for the correspondent names, see List of Plants in the Appendix) are supposed to treat the wastewater by the highest percentage up to 95%, and also the 22nd plant needs to decrease its final emission by 33.16%. It is understood from Table 6-4-3 that these plants are the key ones in controlling the regional total emission and should take the greatest responsibility to treat the wastewater first.

(2) As shown in Table 6-4-4 for the final profit of each plant, it is quite clear that all the plants can respectively gain no less profit than that in their individual (or independent) decision-making situation, i.e., the non-cooperative case (Table 6-4-1). Actually, there is a profit increment for each of them except for the 26th plant whose profit increment is just zero. Based on Table 6-4-4, it is obvious from $\Delta\alpha_i$ that the greater beneficiary in the scheme is such a plant whose amount of wastewater load is relatively more. For example, the 22nd, 34th and 9th plants have to treat more wastewater loads, and on the other hand, they are expected to get relatively more profit increment than other plants (they can get more profits as much as, respectively, 272.89 CNY/day, 268.59 CNY/day and 125.70 CNY/day). In other words, the more a plant reduces the pollutant emission, the more the plant obtains the profit increment. This is exactly an incentive or motivation for those

bigger polluters to take a positive attitude to cooperate with the TEC policy in realizing the centralized decision-making over the whole region.

(3) Instead of the emission charges or fines, the environmental tax or subsidy concept is used in the computation for the full-cooperative case. As a result shown in Table 6-4-4, most of the plants should submit a certain amount of tax to the administrator, but inversely, a few of plants are supposed to receive some amount of subsidy from the administrator. Specifically, the 3^{rd} and 10^{th} plants should obtain the subsidies, 3.91 CNY/day and 5.75 CNY/day, respectively. In the scheme, the sum amount of taxes and subsidies is 4,111.36 CNY/day, which is exactly equal to the corresponding value of the environmental damage compensation.

6.5 Policy design analysis

6.5.1 Stability of policy schemes with an economic incentive

In general, the environmental administrative authorities have several instruments available for managing or protecting the regional environmental system, including direct regulation, economic instruments and educational propaganda, etc. (Charles D. K., 2000; Clement A., et al., 1991; Robert W. H., 1989).

The economic instruments usually refer to environmental emission charges (fines), or environmental taxes (subsidies), and tradeable pollution permits, etc. (Hepburn C., 2006; 寺西俊一, 2002; 長谷川弘訳, 1993). In most cases economic instruments will be more efficient than direct regulations, at least in providing an incentive to innovate and improve technologies (Richard M.H., 1985; Varian R. H., 1992; Boyd R., et al., 1995; Harland W. W., & Armonk Jr., 1999).

Furthermore, if a policy instrument of environmental management, for example, setting emission charges, is adopted, still the raised problem is that at what level it should be set as to reach a socially optimal solution or a comprehensively rational option (Verbruggen H., 1991; 植田和弘等, 1997; 寺西俊一, 2002). In choosing policy instruments, the fundamental principle (basic idea) is how to design and analyse an appropriate policy scheme to take into consideration of not only the environmental quality but also an economic incentive or a motivation.

In this section, specifically based on the calculated results, the TEC policy scheme is analysed from a viewpoint of designing regional environmental-economic policy. By using the model to simulate the process for a better policy scheme, some concepts are introduced to discuss about how to decide and measure the TEC policy scheme.

Firstly, the first one is about the stability of the total emission control policy scheme.

What does it mean by "stable" here? It implies that

(1) it makes the total emission reduced or controlled under the allowed maximum value to meet the regional environmental target or standards; and meanwhile

(2) it ensures a gain distributed for each plant more than the profit which may be expected (or obtained) by the individual decision-making.

In the model discussed previously, the above condition (2) is actually the individual rationality condition defined in a cooperative game. As in Section 5.2, it is assumed that there exists such an emission charges function $Tt_i(,)$ or an emission charges standard policy so that it can adjust the G_i's net profit in the non-cooperative case and then makes the above condition (2) be satisfied, that is $\alpha_i \geq v(\{i\})$. In the application, when $Tt_i(,)$ is designed by increasing the emission charges by 100%, that is to set $Tt_i(,) = 2T_i(,)$, indeed the final redistribution is “stable” scheme.

However, it has not been guaranteed that the above condition (2) is absolutely satisfied for any case. Because the condition $\alpha_i \geq v(\{i\})$ is not set in the model, it is possible that there is not a "stable" solution for the total emission control policy, which is based on how to form the emission charges function $Tt_i(,)$.

When, for example, the emission charges function is kept as the same as the existing one, i.e., $Tt_i(,) = T_i(,)$, it can not reach a stable scheme for the total emission control policy because in the situation the maximum total profit by the centralized decision-making model is totally only 378511.25 CNY/day which is less than 380392.54 CNY/day, the sum value of all the plants' profits gained by individual decision-making model, and this makes it impossible to distribute more profit for *all* of the plants.

In such a situation, if the emission charges standard (function) keeps unchangeable, i.e., $Tt_i(,) = T_i(,)$, the total emission control policy could possibly be realized only by one direct administrative order or mandatory regulation. If the emission charges standard (function) is allowed to change as to reach a stable scheme, usually it can be possible to find a stable policy scheme by amending the emission charges standard to let each plant's profit $Bt_i(,)$ be decreased to such an extent so that the condition below is satisfied.

$$\alpha_i \geq v(\{i\} = Bt_i(,) \qquad (6\text{-}5\text{-}1)$$

As one example, when increasing the emissions charges by 100%, i.e., setting $Tt_i(,) = 2T_i(,)$, indeed there exists a stable scheme of the total emission control policy shown previously in Table 6-4-3 and Table 6-4-4. Specifically, if comparing the simulated results for the case without TEC policy and the case with TEC policy, it can be clearly understood that the TEC policy scheme is a stable one because it makes the TEC target achieved and at meantime the each plant's final profit increased. See Table 6-5-1 and Table 6-5-2 for comparison of the both cases.

Then, the second one is about how to reach a stable solution?

A stable solution for total emission control policy by adjusting the emission charges function surely depends to a great extent on whether the emission charges function $Tt_i(,)$ can effectively be established according to the characteristic in shape as shown in Fig.6-5-1. That is, $Tt_i(,)$ should be a single increasing function of the final emission x_i and so should the marginal emission charges (or marginal emission fines) that can be calculated by $\partial Tt_i(,)/\partial x_i$.

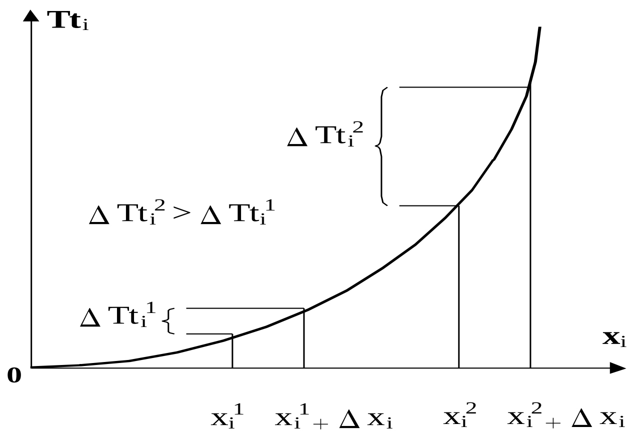


Fig.6-5-1 The characteristic in shape for $\boldsymbol{Tt_i}(,)$

That is, $Tt_i(,)$ is needed to meet the following conditions:

(a). $Tt_i(,) = 0$, when $x_i = 0$; (6-5-2)

(b). $\partial Tt_i(,)/\partial x_i > 0$, when $x_i > 0$; (6-5-3)

(c). $\partial^2 Tt_i(,)/\partial {x_i}^2 > 0$, when $x_i > 0$. (6-5-4)

Finally, the third one is about the evaluation of the alternative policy scheme.

From the results and discussion in the above, it is understood that there are different alternative schemes of total emission control policy if they are computed under different emission charges standards corresponding to different functions of Tt_i (,).

Then, the rising question is how to choose the best one or which scheme is more rational one, which will be analysed in the next section.

Table 6-5-1

Comparison analysis for emissions x_i

i	xi.0 (g/d)	xi.t (g/d)	xi* (g/d)
1	15,187.20	15,187.20	15,187.20
2	1,035.24	1,035.24	1,035.24
3	8,488.45	8,488.45	424.41
4	68,488.24	68,488.24	68,488.24
5	83,170.31	83,170.31	83,170.31
6	16,070.66	16,070.66	16,070.66
7	2,352.74	2,352.74	2,352.74
8	1,920.77	1,920.77	1,920.77
9	443,118.10	443,118.10	22,155.90
10	27,750.40	27,750.40	1,387.52
11	99,830.52	99,830.52	99,830.52
12	5,431.30	5,431.30	5,431.30
13	45,816.32	45,816.32	45,816.32
14	3,237.76	3,237.76	3,237.76
15	422,604.80	21,130.24	21,130.24
16	228,556.80	11,427.84	11,427.84
17	1,597.56	1,597.56	1,597.56
18	583.83	583.83	583.83
19	7,680.00	7,680.00	7,680.00
20	525.72	525.72	525.72
21	2,050.38	2,050.38	2,050.38
22	613,550.40	613,550.40	410,120.98
23	87,040.00	87,040.00	87,040.00
24	103,441.90	103,441.90	5,172.10
25	4,754.94	4,754.94	4,754.94
26	28.36	28.36	28.36
27	188.93	188.93	188.93
28	3,338.11	3,338.11	3,338.11
29	4,894.93	4,894.93	4,894.93
30	7,834.88	7,834.88	7,834.88
31	4,010.04	4,010.04	4,010.04
32	811.01	811.01	811.01
33	10,831.87	10,831.87	10,831.87
34	1,074,342.00	1,074,342.00	1,074,342.39
35	81,715.20	81,715.20	81,715.20
36	172.03	172.03	172.03
37	16,007.17	16,007.17	16,007.17
38	9,344.00	9,344.00	9,344.00
39	127,888.60	127,888.60	127,888.60
sum	3,635,691.47	3,017,087.95	2,260,000.00

Table 6-5-2

Comparison analysis for profits B_i

i	Bi.0 (cny/d)	Bi.t (cny/d)	αi (cny/d)
1	28,658.20	28,643.02	28,646.81
2	12,267.27	12,266.24	12,266.50
3	12,161.42	12,159.12	12,159.70
4	13,044.45	12,981.21	12,997.02
5	19,640.90	19,580.50	19,595.60
6	2,124.04	2,107.97	2,111.99
7	651.59	649.68	650.87
8	13,135.22	13,133.33	13,133.81
9	16,346.25	15,968.33	16,094.03
10	2,170.34	2,155.90	2,158.96
11	76,228.93	76,129.09	76,154.05
12	2,827.81	2,822.38	2,823.74
13	2,124.85	2,085.77	2,095.54
14	1,636.63	1,634.05	1,634.71
15	21,721.42	21,722.01	21,727.29
16	23,968.62	23,952.41	23,955.27
17	873.32	872.17	872.46
18	872.73	872.15	872.30
19	267.50	260.67	262.38
20	50.23	49.70	49.83
21	2,161.71	2,159.66	2,160.16
22	25,414.25	24,815.69	25,088.58
23	2,973.08	2,897.99	2,924.27
24	5,228.06	5,202.84	5,219.95
25	1,847.65	1,842.90	1,844.09
26	348.00	347.96	347.96
27	7,116.10	7,115.91	7,115.95
28	1,598.70	1,595.36	1,596.63
29	914.78	909.88	911.11
30	51.07	46.65	47.92
31	3,827.28	3,824.11	3,825.34
32	42,861.26	42,860.45	42,860.65
33	1,496.58	1,485.92	1,488.58
34	3,395.92	2,321.58	2,590.17
35	11,428.92	11,347.21	11,367.64
36	180.01	179.84	179.88
37	59.42	47.26	50.03
38	11,031.29	11,021.95	11,024.29
39	7,686.74	7,578.01	7,605.19
sum	380,392.54	377,646.87	378,511.25

6.5.2 The simulating process of an optimal policy design

To be simple in discussion, as an example, select $Tt_i(,) = t{*}T_i(,)$, where t is a constant coefficient.

So the question is how many times the emission charges standard should be increased if compared with the existing emission charges standard, i.e. how to decide the value of *t*. Answering this question, it generally needs to consider, at least, the following three hints:

1st point: if it results in a stable scheme for total emission control policy in a given region;

2nd point: if it makes the sum amount of emission charges from all the plants equal to, or slightly more than the value of the environmental damage in the region;

3rd point: if it keeps the actual total emission in the individual decision-making situation equal to, or slightly less than the allowed maximum value of the total emission in the region.

Based on the previous results in Section 6.4, when $t=2$, a stable scheme can be obtained to meet the 1st point, but it does not satisfy the other two points. From the view of the above 2nd and 3rd points, the scheme with the condition of setting $t=2$ may not be the best option.

In general, it is quite difficult to meet the three points at the same time if modifying only the emission charges standard (function) as an uncertainty factor.

With the above analysis, it is natural to ask such a question: how to decide the value of the coefficient *t* ?

In fact, this is essentially the problem of optimizing the emission charges standard, which can be solved just by using the model developed in Chapter 5 to repeat the computation for the alternative schemes until the expected one is reached. This simulating process is shown in the Fig.6-5-2.

However, it will not be discussed any more here because it would be expected to be studied in detail as a further research topic.

Finally, note that in the application, only the instrument of emission charges or taxes is selected as an economically adjustable policy factor. But it may be more effective if practicing it in combination with other environmental-economic policy such as tradable pollution permit system, etc. (Jensen J., et al., 2000; 中澤幸壽, 1999).

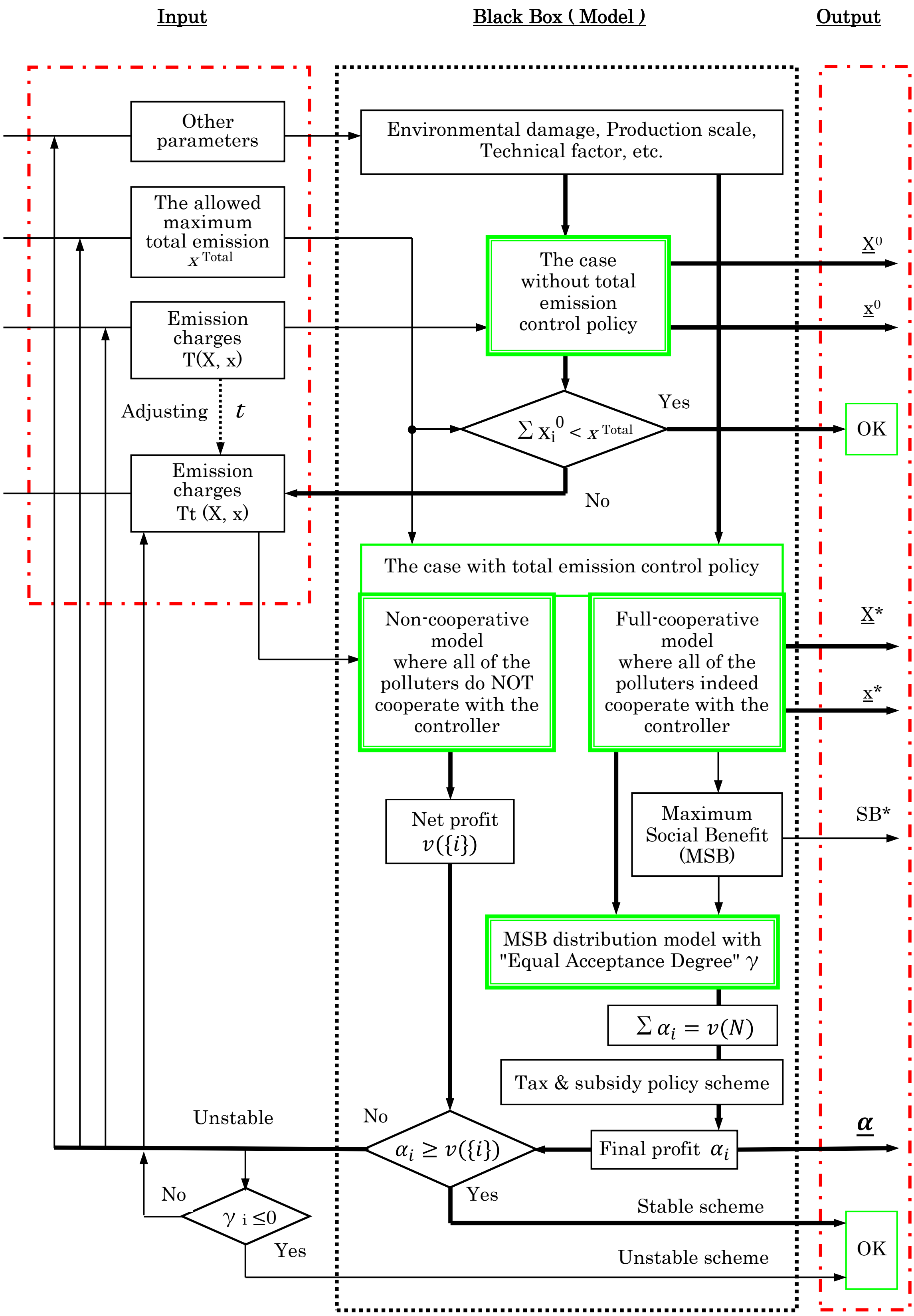


Fig.6-5-2 Simulating process for an optimal TEC policy in a regional system

Part Three: Policy Design for a Multisectoral System
The Extended TEC Model and Its Application for Reducing CO_2 Emission in China

The aim of this part is to explore furtherly the analytical framework to design and analyse an optimal TEC policy based on an input-output structure for a multisectoral system. As a methodological extension of the optimal TEC model established previously in Part Two, the multisectoral model is set up by incorporating an input-output analysis to maximize the whole production profit among all the sectors and meanwhile achieve the TEC policy’s target. And then, based on the extended model, the specific empirical application is discussed in more detail to develop, design and analyse an optimal TEC policy scheme for reducing CO_2 total emission over all the economic sectors in China. Besides, given an input and output structure, it is meaningful to analyse the ripple effects expected by ETS's initial operation in power sector.

7. The extended TEC model with input-output analysis

Concerning the model usable in a multisectoral system, however, it is required to find another way for setting up the interaction coefficients among all sectors and re-build a new optimal model for allocating the total emission to all sectors. This topic is absolutely much more complicated because all sectors have to be interrelated with each other in production and so one sector cannot really make decision independently from others on how many (much) the final products should be produced. This is what different from that in the regional system model in which it is assumed that one of polluters (eg., plants in the same sector) can be independent of each other in decision making to reach his own maximum net profit in the not-cooperative case.

Fortunately it is possible to solve the complicated problem by making a use of an input-output analysis. With the input-output table, actually, it is just needed to extend (or modify) the previous model to be also suitable for a multisectoral system. In modelling the detailed formulas of the model, as the same as most of the embodied environmental emission researches, it could be modified within the environmental input-output framework introduced first by Leontief (1972).

As in Chapter 5, the model for multisectoral system can be also described in the framework of a characteristic function game where there are (n+1) players, G_0, G_1, G_2, …, G_i, .., G_n. And so the basic concept is methodologically similar to that of the previous model for a regional system.

Here also let G_0 represent the "controller" (here in the application, specifically, the policy maker or the corresponding central governmental administrator) of a given country that is supposed to be responsible for reducing the total emission, and G_i represent the *i*-th polluter, specifically, the *i*-th sector in the application in the next chapter.

By the way, in the following, use the symbols: the underbar "**_**" means a vector, and the " ^{T} " represents the transpose of a vector.

7.1 The basic representation of the input-output approach

Also it is assumed that there are n sectors in a given environmental-economic system and each sector i produces product i (goods and services) as total output (production) P_i in monetary units to meet the final use (demand) F_i in monetary units and thus generates the environmental emission X_i in weight units.

Then the basic input-output equation can be given as follows (Miller E. R., et al, 2009; Yoshioka K., et al., 2013; 夏明, 2013).

$$P_i = \sum_{j=1}^{n} a_{ij} P_j + F_i , \ for \ i = 1, 2, \dots, n \qquad (7\text{-}1\text{-}1)$$

where a_{ij} represents the direct input coefficients (technical coefficients), i.e., requirement on sector i per unit output of sector j.

Actually by using matrix notation, the above expression (7-1-1) can be described in the following form (Yoshioka K., et al., 2013).

$$(\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\, \underline{\boldsymbol{P}} = \underline{\boldsymbol{F}} \qquad (7\text{-}1\text{-}2)$$

or

$$\underline{\boldsymbol{P}} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-1} \underline{\boldsymbol{F}} \qquad (7\text{-}1\text{-}3)$$

let

$$\underline{\boldsymbol{L}} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-\boldsymbol{1}} \qquad (7\text{-}1\text{-}4)$$

where

$\underline{\boldsymbol{P}}$ = $[P_1, P_2, \dots, P_n]^T$ stands for the column vector of total production (output), with element P_i representing the total production (output) of sector i;

$\underline{\boldsymbol{F}} = [F_1, F_2, \ldots, F_n]^{\mathrm{T}}$ stands for the vector of final use, with element F_i representing the final use of sector i;

$\underline{\boldsymbol{A}} = \{a_{ij}\}$ stands for an n×n matrix of input-output coefficients, in which an element a_{ij} denotes the direct input coefficients, i.e., requirement on sector i per unit output of sector j;

$\underline{\boldsymbol{I}}$ stands for the identity matrix; and

$\underline{\boldsymbol{L}} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-1}$ is the n×n matrix of input-output multipliers or Leontief inverse matrix (Leontief, 1970; Miller E. R., et al, 2009) determined by the structure of intermediate input and its elements represent the total amount of sector i's output required both directly and indirectly to produce one unit for final use of sector j. (Shimoda M. & Fujikawa K., 2012; Yoshioka K, et al., 2013).

In addition, define $\beta_i\ (i = 1, 2, \ldots, n)$ as the environmental emission (intensity) coefficient of sector i, (i.e., the amount of the environmental emission generated from the per unit output of sector i). Then, X_i the emission of each sector i can be calculated by P_i as follows:

$$X_i = \beta_i P_i, \quad (i = 1, 2, \ldots, n) \qquad (7\text{-}1\text{-}6)$$

or

$$P_i = X_i/\beta_i, \quad (i = 1, 2, \ldots, n) \qquad (7\text{-}1\text{-}7)$$

Also, the above expressions can be described in matrix notation as follows (吉岡完治 et al, 2003).

$$\underline{\boldsymbol{X}} = \underline{\boldsymbol{\beta}}\,\underline{\boldsymbol{P}} \qquad (7\text{-}1\text{-}8)$$

or

$$\underline{\boldsymbol{P}} = \underline{\boldsymbol{\beta}}^{-1}\,\underline{\boldsymbol{X}} \qquad (7\text{-}1\text{-}9)$$

where,

$\underline{\boldsymbol{X}} = [X_1, X_2, \ldots, X_n]^{\mathrm{T}}$ is the column vector of total environmental emissions, and its elements X_i denote the total amount of the environmental emission driven both directly and indirectly by the final use of product in sector i; and

$\underline{\boldsymbol{\beta}} = \{\beta_{ij}\}$ is the n×n diagonal matrix of environmental emission coefficients, with an element β_i on its main diagonal and zeros elsewhere, i.e.

$$\beta_{ij} = \beta_i, \text{ for } i = j; \quad \beta_{ij} = 0, \text{ for } i \neq j. \qquad (7\text{-}1\text{-}10)$$

Now, from the expressions (7-1-2) and (7-1-9) the basic input-output model in matrix notation can be described as follows.

$$(\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\,\underline{\boldsymbol{\beta}}^{-1}\,\underline{\boldsymbol{X}} = \underline{\boldsymbol{F}} \qquad (7\text{-}1\text{-}11)$$

7.2 The optimal allocation model of the total emission

In the model established in Chapter 5, the "net profit" of the i-th polluter G_i is defined as follows.

$$B_i(X_i\,,\ x_i)\ =\ P_i(X_i)\ -\ C_i(X_i\,,\ x_i)\ -\ T_i(X_i\,,\ x_i) \qquad (7\text{-}2\text{-}1)$$

where,

X_i : stands for the quantity of waste derived from the G_i's production process;

x_i : stands for the quantity of waste discharged from G_i into the given region after treatment;

$P_i(X_i)$: Production function, standing for the gross production profit of G_i, obtained by production taking no account of waste treatment cost and emission charges (emission cost);

$C_i(X_i, x_i)$: Cost function of treatment, standing for the waste treatment cost of G_i for reducing the amount of the waste ($X_i - x_i$);

$T_i(X_i, x_i)$: Emission charges function, standing for the G_i's cost of discharging waste x_i (the emission charges or fines submitted to controller G_0).

Else, let $A_i(X_i\,,\ x_i)$ be the initial profit before waste treatment, define:

$$A_i(X_i\,,\ x_i)\ =\ P_i(X_i) - C_i(X_i\,,\ x_i) \qquad (7\text{-}2\text{-}2)$$

and

$$B_i(X_i\,,\ x_i)\ =\ A_i(X_i\,,\ x_i) -\ T_i(X_i\,,\ x_i) \qquad (7\text{-}2\text{-}3)$$

However here, in the following multisectoral allocation model, it is realistically reasonable not to consider directly the waste treatment cost for G_i to reduce the emission from X_i to x_i , that is, it can be assumed that the G_i does not treat any amount waste resulted from G_i's production $P_i(X_i)$, i.e., $C_i(X_i\,,\ x_i) = 0$.

There are two reasons for the assumption.

One is because it is hardly to find the practically usable data for establishing the waste treatment cost function, respectively, for all the economic sectors in the realistic situation. As an example, actually, in the application discussed in next chapters for reducing the carbon total emission of China, the necessary data have not been found for the cost of treating (reducing) the carbon before the final emission from each sector.

The other reason is for making the computation simpler in accordance with the realistic TEC policy considering the input-output structure in a multisectoral system. As seen in the following model for any case, for instance, in the model (7-2-6) below,

$C_i(X_i,\ x_i)$ is just included in the objective function instead of the constraint's condition expressions. As long as there are data for $C_i(X_i,\ x_i)$, it can be easily dealt with by including it in the net profit $B_i(X_i,\ x_i)$ as a new objective function considering the treatment cost. Even if in this sense the objective function is changed, the model's formation is not essentially different from that not considering the treatment cost. In other words, as the analytical framework provided in this study, the methodology is the same no matter how to cope with the waste treatment cost function.

Thus, with the assumption of $C_i(X_i,\ x_i) = 0$, it can be possible to set

$$X_i = x_i$$

in the following model for every case for simplifying the expressions discussed in this section. Then, the function expression (7-2-3) can be simplified to the following:

$$B_i(X_i) = A_i(X_i) - T_i(X_i) \tag{7-2-4}$$

or

$$B_i(X_i) = P_i(X_i) - T_i(X_i) \tag{7-2-5}$$

7.2.1 The model based on input-output table

At first, let's define here that:

SB expresses the social benefit considering both the total production profit of all the sectors G_i (i=1, 2, .., n) and the environmental damage in a given region or country, when all G_i cooperate with G_0;

SB_i expresses the social benefit considering both the production total profit of all the sectors G_i (i=1, 2, .., n) and the environmental damage in a given region or country, when only G_i does not cooperate with G_0, but all the other sectors cooperate with G_0;

$B_i(X_i)$ represents the net profit from the sector i's production, which is dependent on the environmental emission X_i;

F_i^{Min} is the minimum value set as the initial value for F_i and F_i^{Max} is the maximum one, which means the sector i's final use is allowed to be variable between F_i^{Min} and F_i^{Max}, generally decided by the sector i's economic development goal (see the application example for setting them in Section 8.3 of the next chapter).

P_i^{Min} is the minimum value set as the initial value for P_i and P_i^{Max} is the maximum one, which means the sector i's production scale is fixed to change between P_i^{Min} and P_i^{Max}, generally decided by the sector i's economic development goal).

x^{Total} denotes the allowed maximum total emission which is decided by the policy maker G_0 and is also considered as the target value of the TEC policy.

Based on the above, here is given the basic allocation model of the total emission using the input-output table $\underline{\boldsymbol{A}}$.

***G₀* :**

$$Max.\ SB(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} B_i(X_i) \tag{7-2-6a}$$

s.t.

$$\begin{cases} \underline{\boldsymbol{F}}^{Min} \le (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{P}} \le \underline{\boldsymbol{F}}^{Max} \\ \sum_{i=1}^{n} X_i \le x^{Total} \end{cases} \tag{7-2-6b}$$

where,

$$\begin{aligned} \underline{\boldsymbol{F}}^{Min} &= \underline{\boldsymbol{L}}\,\underline{\boldsymbol{P}}^{Min} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-1}\underline{\boldsymbol{P}}^{Min} \\ \underline{\boldsymbol{F}}^{Max} &= \underline{\boldsymbol{L}}\,\underline{\boldsymbol{P}}^{Max} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-1}\underline{\boldsymbol{P}}^{Max} \end{aligned} \tag{7-2-7}$$

and

$$\begin{aligned} \underline{\boldsymbol{F}}^{Min} &= [F_1{}^{Min}, F_2{}^{Min}, \cdots, F_n{}^{Min}]^T \\ \underline{\boldsymbol{F}}^{Max} &= [F_1{}^{Max}, F_2{}^{Max}, \cdots, F_n{}^{Max}]^T \\ \underline{\boldsymbol{P}}^{Min} &= [P_1{}^{Min}, P_2{}^{Min}, \cdots, P_n{}^{Min}]^T \\ \underline{\boldsymbol{P}}^{Max} &= [P_1{}^{Max}, P_2{}^{Max}, \cdots, P_n{}^{Max}]^T \end{aligned} \tag{7-2-8}$$

Also, the above basic model can be described in another form as follows

***G₀* :**

$$Max.\ SB = \sum_{i=1}^{n} B_i(X_i) \tag{7-2-9a}$$

s.t.

$$\begin{cases} (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1}\underline{\boldsymbol{X}} \le \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \le x^{Total} \end{cases} \tag{7-2-9b}$$

where,

$$\underline{\boldsymbol{X}}^{Min} = [X_1{}^{Min}, X_2{}^{Min}, \cdots, X_n{}^{Min}]^T = \underline{\boldsymbol{\beta}}\,\underline{\boldsymbol{P}}^{Min} \tag{7-2-10}$$

In order to describe the model easily, here let's define

$$\underline{\boldsymbol{H}} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\,\underline{\boldsymbol{\beta}}^{-1} \tag{7-2-11}$$

where, $\underline{\boldsymbol{H}}$ is an n×n matrix with elements h_{ij}, that is

$$\underline{\boldsymbol{H}} = (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1n} \\ h_{21} & h_{22} & \cdots & h_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ h_{n1} & h_{n1} & \cdots & h_{nn} \end{bmatrix} \quad (7\text{-}2\text{-}12)$$

Also, the vector $\underline{\boldsymbol{h}}_i$ is defined as:

$$\underline{\boldsymbol{h}}_i = [\, h_{i1},\ h_{i2}, \dots, h_{ii}, \dots, h_{in} \,] \quad (7\text{-}2\text{-}13)$$

and the vector $\underline{\boldsymbol{H}}$ is expressed as:

$$\underline{\boldsymbol{H}} = [\, \underline{\boldsymbol{h}}_{\boldsymbol{1}},\ \underline{\boldsymbol{h}}_{\boldsymbol{2}}, \dots,\ \underline{\boldsymbol{h}}_{\boldsymbol{i}}, \dots,\ \underline{\boldsymbol{h}}_{\boldsymbol{n}} \,]^T \quad (7\text{-}2\text{-}14)$$

The final use of sector i is

$$F_i = \underline{\boldsymbol{h}}_i \underline{\boldsymbol{X}} = \sum_{j=1}^{n} h_{ij} X_j\ ,\ i = 1,2, \dots, n \quad (7\text{-}2\text{-}15)$$

Then, the basic model with input-output table can be described as:

$\boldsymbol{G_0}$ **:**

$$Max.\ SB = \sum_{i=1}^{n} B_i(X_i) \quad (7\text{-}2\text{-}16a)$$

s.t.

$$\begin{cases} \underline{\boldsymbol{H}}\,\underline{\boldsymbol{X}} \le \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \le x^{Total} \end{cases} \quad (7\text{-}2\text{-}16b)$$

7.2.2 The model without total emission control

Here, in the situation, each G_i is assumed to make a decision independently on the production scale. Therefore G_i will try to get the maximum net profit as possible, i.e.

$\boldsymbol{G_i}$: $i = 1, 2, \dots, n$

$$Max.\ B_i\,(X_i) = P_i(X_i) - T_i(X_i) \quad (7\text{-}2\text{-}17a)$$

s.t.

$$\begin{cases} (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1}\underline{\boldsymbol{X}} \le \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \le x^{Total} \to \infty \end{cases} \quad (7\text{-}2\text{-}17b)$$

Note that the objective function is including the $T_i(X_i)$ as in the expression (7-2-5). However, for most of the practical applications, there are not any existing emission charges standards on the environmental emission usable for each sector in a multisectoral system. As an instance in the application for reducing the total carbon emission in China in these chapters below, there is indeed not yet any existing emission charges policy on the carbon emission for each sector. So if considering the model to be in accordance with the real situation in China now, it is possible to set $T_i(X_i) = 0$, i.e.,

$$B_i(X_i) = P_i(X_i) \tag{7-2-18}$$

Hence, for the circumstance under the condition (7-2-18) as assumed in the application in the next chapter, the previous model (7-2-17) can be also expressed in the following form:

$\boldsymbol{G_i}$: $i = 1, 2, \ldots, n$

$$Max.\ B_i(X_i) = P_i(X_i) \tag{7-2-19a}$$

s.t.

$$\begin{cases} (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1}\underline{\boldsymbol{X}} \leq \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \geq \underline{\boldsymbol{X}}^{Min} \end{cases} \tag{7-2-19b}$$

So for the special objective function only, the solution of $\underline{\boldsymbol{X}}$ can be simply obtained by

$$\underline{\boldsymbol{X}} = \underline{\boldsymbol{\beta}}(\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})^{-1}\underline{\boldsymbol{F}}^{Max} \tag{7-2-20}$$

Let X_i^0 be the optimal solution for the above model (7-2-17), then the *i*-th sector's maximum net profit is

$$B_i(X_i{}^0) = P_i(X_i{}^0) - T_i(X_i{}^0) \tag{7-2-21a}$$

But for the model (7-2-19) in the special situation with $T_i(X_i) = 0$, then

$$B_i(X_i{}^0) = P_i(X_i{}^0) \tag{7-2-21b}$$

And the total emission of all sectors is given as

$$x^0 = \sum_{i=1}^{n} X_i{}^0 \tag{7-2-22}$$

Generally, it can be supposed that $x^0 = \sum X_i{}^0$ could be higher than x^{Total}, the maximum total emission allowed by the policy maker G_0, even if there is the existing emission charges $T_i(X_i)$ on the each G_i's final emission. In the case without $T_i(X_i)$, the possibility is greater.

Therefore, if the total emission control policy is implemented among all sectors, x^0 is expected to decrease to some extent to meet the target of total emission control.

7.2.3 The model with total emission control

Similar to that in Part Two, in the situation where the actual total emission $\boldsymbol{x}^0$ is over the allowed maximum of total emission, the policy maker G_0 is to enforce the total emission control policy and then to make each sector G_i reduce its emission by using an economic instrument rather than direct regulation. Specifically here, G_0 is supposed to adjust the existing emission charges function $T_i(X_i)$.

In other words, even if under the total emission control policy, the sector G_i will not be forced to cooperate with the policy. With this assumption, therefore, there are only three possible cases as follows.

(1) Non-cooperative case: All of the G_i, $_{i=1, 2, \dots, n}$ do not take an attitude to cooperate with G_0; that is, none of the G_i does cooperate with G_0, i.e., the case where there are only individual coalitions $\{G_0\}$ or $\{G_i\}$ in the game.

(2) Full-cooperative case: All of the G_i, $_{i=1, 2, \dots, n}$ take an attitude to cooperate with G_0; that is the case of the overall cooperation, i.e., the grand coalition in the cooperative game.

(3) Part-cooperative case: Some of the G_i, $_{i=1, 2, \dots, n}$ are willing to cooperate with G_0, but the others are not; that is the case of the partially cooperative coalitions in the cooperative game.

Additionally here, it is also assumed that G_i will never cooperate with G_j ($i \neq j$) in any case. Otherwise, there are 2^n-1 possibilities of cooperative coalition. For instance, in the application of Chapter 8, there is such a case where n=17 and the number of possible coalitions is $2^{17}-1$. Undoubtedly, it is neither feasible nor necessary to deal with all the coalitions in an application.

1) Non-cooperative case

For the non-cooperative case, in order to reach the objective of total emission control, G_0 is supposed to take an economic means, which, here, could be considered as an adjustment on the existing policy for emission charges. In the study, that is to modify the emission charges function from $T_i(X_i)$ to $Tt_i(X_i)$, letting it satisfy:

$$Tt_i(X_i) \geq T_i(X_i) \text{ , where } X_i \geq 0. \tag{7-2-23}$$

Here, define "modifiable policy vector (MPV)" as

$$\underline{\boldsymbol{Tt}}(\underline{\boldsymbol{X}}) = [\, Tt_1(X_1), Tt_2(X_2), \ldots, Tt_n(X_n)\,]^T \tag{7-2-24}$$

In the application of next chapters, the detailed discussion will be also concerned with the topic on how to modify the policy vector in keeping stability of the optimal solutions in the full-cooperative case.

Because there is not any cooperative coalition among G_0 and G_i , $_{i=1, 2, \ldots, n}$ in the case, all of G_i still make their decisions individually. The model should not be, substantially, quite different from that in the case without total emission control policy. The difference is just on the G_i's net profit.

Under the total emission control policy, the net profit may decrease to:

$$Bt_i(X_i) = P_i(X_i) - Tt_i(X_i) \tag{7-2-25}$$

Similarly, each G_i can make decision independently and optimally as follows:

$$\boldsymbol{G_i}: \quad i = 1, 2, \ldots, n$$

$$Max.\ Bt_i(X_i) = P_i(X_i) - Tt_i(X_i)$$

$$\text{s.t.} \quad \begin{cases} (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1}\underline{\boldsymbol{X}} \leq \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \geq \underline{\boldsymbol{X}}^{Min} \end{cases} \tag{7-2-26}$$

Let X_i^{t*} be the optimal solution for the above model (7-2-26), then the *i*-th sector's maximum net profit under this case is

$$Bt_i(X_i^{t*}) = P_i(X_i^{t*}) - Tt_i(X_i^{t*}) \tag{7-2-27}$$

Aslo, it is defined as the corresponding value of the characteristic function, i.e.

$$v(\{\, i \,\}) = Bt_i(X_i^{t*}) \tag{7-2-28}$$

Note that the value $v(\{\,i\,\})$ will be also used as "the reference or contrastive value" of the G_i's net profit (final profit) in the full-cooperative model described later.

In addition, define the G_0's "net profit (gain)" as the corresponding value of the characteristic function, i.e.

$$v(\{0\}) = \sum_{i=1}^{n} Tt_i({X_i}^{t*}) - D(x^{t*}) \quad (7\text{-}2\text{-}29)$$

where, x^{t*} is the actual total emission of all sectors, obtained by

$$x^{t*} = \sum_{i=1}^{n} {X_i}^{t*} \quad (7\text{-}2\text{-}30)$$

and $D(x^{t*})$ is the value of function of damage to the regional environmental system.

Then "Social Benefit" in the case is defined as

$$SB^{t*}(\underline{\boldsymbol{X}}^{t*}) = v(\{0\}) + \sum_{i=1}^{n} v(\{i\}) = \sum_{i=0}^{n} v(\{i\}) \quad (7\text{-}2\text{-}31)$$

where

$$\underline{\boldsymbol{X}}^{t*} = [{X_1}^{t*}, {X_2}^{t*}, \cdots, {X_n}^{t*}]^T$$

From the expression (7-2-23), get

$$Tt_i({X_i}^0) \geq T_i({X_i}^0) \quad (7\text{-}2\text{-}32)$$

and if selecting a suitable form of the function $Tt_i(X_i)$, generally it can be possible to obtain:

$${X_i}^{t*} \leq {X_i}^0 \quad (7\text{-}2\text{-}33)$$

i.e.

$$x^{t*} \leq x^0 \quad or \quad D^{t*} = D(x^{t*}) \leq D^0 = D(x^0) \quad (7\text{-}2\text{-}34)$$

Now note that, from the above model, it is possible to reduce the actual quantity of total emission by increasing the emission charges standard (the level of amount on fine per unit of pollutants emitted), based on the emission charges policy, but it is not assured that the actual total emission x^{t*} in the non-cooperative case is absolutely less than the allowed maximum value x^{Total} set by the policy maker.

2) Full-cooperative case

For this case, there exists one and only one "cooperation relation", which is defined as "cooperative coalition or cooperative set":

$$\tilde{N} = \{0, 1, 2, 3, \dots, n\} \qquad (7\text{-}2\text{-}36)$$

And the social benefit in this case can be defined as the sum of the total production profit of all sectors G_i, $_{(i=1,2,\dots,n)}$ and the gain (profit) of the policy maker G_0, i.e.,

$$SB(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} B_i(X_i) + B_0(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} P_i(X_i) - D(\sum_{i=1}^{n} X_i) \qquad (7\text{-}2\text{-}37)$$

Because all the sectors $G_{i,\ i=1,2,\dots,n}$ cooperate with the policy maker G_0, the policy maker G_0 can make decision over all the sectors to achieve the target for total emission control as well as pursue a socially optimal solution for allocating the total emission among all the sectors (Jensen J., et al., 2000).

Thus, the optimal model for G_0 can be described as follows.

G₀ :

$$Max.\ SB(\underline{\boldsymbol{X}}) \qquad (7\text{-}2\text{-}38a)$$

s.t.

$$\begin{cases} \underline{\boldsymbol{H}}\,\underline{\boldsymbol{X}} \le \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \le x^{Total} \end{cases} \qquad (7\text{-}2\text{-}38b)$$

Let $\underline{\boldsymbol{X}}^*$ be the optimal solution for the above model (7-2-38), i.e.

$$\underline{\boldsymbol{X}}^* = [X_1^*, X_2^*, \cdots, X_n^*]^T \qquad (7\text{-}2\text{-}39)$$

Then, the maximum social benefit under total emission control in the full-cooperative case is:

$$SB(\underline{\boldsymbol{X}}^*) = \sum_{i=0}^{n} B_i(X_i^*) = \sum_{i=1}^{n} P_i(X_i^*) - D(\sum_{i=1}^{n} X_i^*) \qquad (7\text{-}2\text{-}40)$$

Also, define it as the corresponding value of the characteristic function, i.e.

$$v(\tilde{N}) = SB(\underline{\boldsymbol{X}}^*) \qquad (7\text{-}2\text{-}41)$$

In this case, the actual total emission can be controlled to reach the target:

$$x^{T*} = \sum_{i=1}^{n} X_i^* \le x^{Total} \qquad (7\text{-}2\text{-}42)$$

and the regional environmental damage is

$$D^{T*} = D(\sum_{i=1}^{n} X_i^*) \qquad (7\text{-}2\text{-}43)$$

The *i*-th sector's initial production profit before the redistribution of $SB(\underline{\boldsymbol{X}}^*)$ is

$$A_i(X_i^*) = P_i(X_i^*) \qquad (7\text{-}2\text{-}44)$$

Here, it is noted that the G_i's initial production profit needs to be adjusted by redistributing the maximum social benefit among all the G_i in some fair way so as to decide the each G_i's final profit in the full-cooperative case. See Section 7.3 for details.

3) Part-cooperative case

As explained in Chapter 5, in order to calculate the G_i's final profit gained in the full-cooperative case based on how much the G_i makes contribution to the total emission control policy, it is necessary to discuss the part-cooperative model for such a case in which some sectors like to be in cooperation with the TEC policy and the others do not.

Firstly, it is assumed that among all the sectors $G_{i,\ i=1,2,\ldots,n}$, there are k sectors to cooperate with the TEC policy, but the other (n-k) sectors not to cooperate. When k = 0, it indicates the non-cooperative case; and when k = n**,** the full-cooperative case; or else, when k = 1, 2 ,…, or, n-1, it is called as the part-cooperative case.

In the following model, let k be limited as

$$k \in N_k = \{1, 2, 3, \ldots, n-1\} \tag{7-2-45}$$

only for the part-cooperative case.

Then, all the "cooperative relations" between G_0 and G_i can be generally expressed as such a set called a "partially cooperative coalition":

$$S_k = \{0, 1, 2, \ldots, k\}, \text{ where } k \in N_k . \tag{7-2-46}$$

Similarly, use $Q_{(n-k)}$ to stand for the set of (n-k) sectors not to cooperate, i.e.

$$Q_{(n-k)} = \{k+1, k+2, \ldots, n\}, \text{ where } k \in N_k . \tag{7-2-47}$$

It is understood that $Q_{(n-k)}$ is not a "coalition", so it is not necessary to define a value of characteristic function for $Q_{(n-k)}$, because G_{k+1}, G_{k+2}, …, G_n are supposed not to cooperate with each other. In this case, each G_i only forms the "individual coalition" {i}, here $i \in Q_{(n-k)}$. Thus it is only needed to give a characteristic function value respectively for each $G_{i,\ i\in Q(n-k)}$.

As the same as in the previous model in Part Two, it is just required to concern about such an instance with k = (n-1) in the actual applications. That is the case where only sector $G_{i,\ i\in N}$ does not cooperate with the policy maker G_0 but all other sectors $G_{j,}$ (j=1, or 2, …,or n , & j$\neq$i) do.

For the part-cooperative case with k = (n-1) where only the i-th sector G_i is not cooperative, this $G_{i,\ i\in Q(n-1)}$ makes decision independently by the non-cooperative model to maximize the $Bt_i(X_i)$, but all other sectors $G_{j,}$ (j=1, 2, …, n , & j≠i) cooperate with G_0 on making decision to maximize the social benefit $SB_i(\underline{\boldsymbol{X}})$ under the total emission control policy, which includes all $B_i(X_i)$ and takes an account of the environmental damage. That is:

$$SB_i(\underline{\boldsymbol{X}}) = \sum_{i=0}^{n} B_i(X_i) = B_0(\underline{\boldsymbol{X}}) + Bt_i(X_i) + \sum_{j=1, j\neq \mathrm{i}}^{n-1} B_i(X_i) \qquad (7\text{-}2\text{-}48)$$

i.e.,

$$SB_i(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} P_i(X_i) - D(\sum_{i=1}^{n} X_i) \qquad (7\text{-}2\text{-}49)$$

Then, the model for the part-cooperative case with k = (n-1) can be described as:

Obj. *for i=1,2, …, n*

$$\begin{cases} \boldsymbol{G_i} : Max.\ \ B_i(X_i) \ = \ P_i(X_i) - Tt_i(X_i) \\ \boldsymbol{G_0} : Max.\ SB_i(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} P_i(X_i) - D(\sum_{i=1}^{n} X_i) \end{cases} \qquad (7\text{-}2\text{-}50a)$$

s.t.

$$\begin{cases} \underline{\boldsymbol{H}}\,\underline{\boldsymbol{X}} \leq \ \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \geq \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \leq \ x^{Total} \end{cases} \qquad (7\text{-}2\text{-}50b)$$

Let X_i^{P*} be the optimal solution for the above model (7-2-50), then net production profit for each G_i in this case is

$$B_i(X_i^{P*}) = P_i(X_i^{P*}) - Tt_i(X_i^{P*}) \qquad (7\text{-}2\text{-}51)$$

where, $Tt_i(X_i^{P*})$ is a value of the environmental emission charges (fines) function for G_i.

And the value of characteristic function correspondingly for each G_i is given as

$$v(\{\,i\,\}) \ = \ B_i(X_i^{P*}) \qquad (7\text{-}2\text{-}52)$$

Then for the circumstance, the social benefit can be identified as:

$$SB_i^{P*}(\underline{\boldsymbol{X}}^{P*}) = \sum_{i=1}^{n} P_i(X_i^{P*}) - D(x^{P*}) \qquad (7\text{-}2\text{-}53)$$

where, $D(x^{P*})$ is a value of the environmental damage function and x^{P*} is the total emission, i.e.,

$$x^{P*} = \sum_{i=1}^{n} X_i^{\ P*} \leq \ x^{Total}$$

Finally, the value of characteristic function for G_0's cooperative coliation given as follows:

$$v(S_k) = \ v(\tilde{N} - \{i\}) = SB_i^{\ P*}(\underline{X}^{P*}) - v(\{\ i\ \}) \qquad (7\text{-}2\text{-}54)$$

Now let's discuss the situation like that in the application in the next chapter.

It is noticeable that the objective function in the model (7-2-50) is including the emission charges (standards) function $Tt_i(\ X_i\ )$ as in the expression (7-2-23). However, for most of the practical applications, there is not any existing emission charges standard on the environmental emission usable for each sector in a multisectoral system. For instance, in the application for reducing the total carbon emission in China, which is discussed in the next chapter, there is actually no existing emission charges policy on the carbon emission for each sector. Thus, for making the model be in accordance with the reality in China now, it is set as $Tt_i(\ X_i\ ) = 0$.

Also, as seen in the above model, the total environmental emission $x = \sum X_i$ definitely controlled within the allowed maximum value x^{Total}, and this means that the environmental damage is considered under the allowed level. So it can be reasonably assumed that when the TEC target is reached, it could take no account of the environmental damage $D(\sum X_i)$ in the case for simple computation.

Hence, only for such a situation as in the application in the next chapter, if letting

$$Tt_i(X_i) = 0\ . \ \ \text{i.e.,} \ \ \ Bt_i(X_i) = \ P_i(X_i) \qquad (7\text{-}2\text{-}55)$$

and

$$D(\textstyle\sum_{i=1}^{n} X_i) = 0. \ \ \ \text{i.e.,} \ \ \ SB_i(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} P_i(X_i) \qquad (7\text{-}2\text{-}56)$$

then the above model (7-2-50) for the case can be transferred to the same as follows:

$\mathbf{G_0}^{\mathbf{t\,i}}$: i = 1,2, ... , n

$$Max. \ \ SB_i(\underline{\boldsymbol{X}}) = \sum_{i=1}^{n} P_i(X_i) \qquad (7\text{-}2\text{-}57a)$$

s.t.

$$\begin{cases} \underline{\boldsymbol{h}_i}\, \underline{\boldsymbol{X}} = F_i^{\ Max} \\ \underline{\boldsymbol{H}}^{(\boldsymbol{n}-\{\boldsymbol{i}\})} \underline{\boldsymbol{X}} \leq \ \underline{\boldsymbol{F}}^{\boldsymbol{Max}\,(\boldsymbol{n}-\{\boldsymbol{i}\})} \\ \underline{\boldsymbol{X}} \geq \underline{\boldsymbol{X}}^{\boldsymbol{Min}} \\ \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} X_i \leq \ x^{Total} \end{cases} \qquad (7\text{-}2\text{-}57b)$$

where $\underline{\boldsymbol{H}}^{(\boldsymbol{n}-\{\boldsymbol{i}\})}$ is an (n-1)×n matrix equal to $\underline{\boldsymbol{H}}$ excluding the row vector $\underline{\boldsymbol{h}}_{\boldsymbol{i}}$ of $\underline{\boldsymbol{H}}$, that is

$$\underline{\boldsymbol{H}}^{(\boldsymbol{n}-\{\boldsymbol{i}\})} = [\, \underline{\boldsymbol{h}}_{\boldsymbol{1}},\ \underline{\boldsymbol{h}}_{\boldsymbol{2}}, \dots ,\ \underline{\boldsymbol{h}}_{\boldsymbol{i-1}},\ \underline{\boldsymbol{h}}_{\boldsymbol{i+1}}, \dots ,\ \underline{\boldsymbol{h}}_{\boldsymbol{n}}\ ]^T \qquad (7\text{-}2\text{-}58)$$

and $\underline{\boldsymbol{F}}^{\boldsymbol{Max}(\boldsymbol{n}-\{\boldsymbol{i}\})}$ is an (n-1)×1 vector equal to $\underline{\boldsymbol{F}}^{\boldsymbol{Max}}$ excluding the row F_i^{Max} of $\underline{\boldsymbol{F}}^{\boldsymbol{Max}}$, that is

$$\underline{\boldsymbol{F}}^{\boldsymbol{Max}(\boldsymbol{n}-\{\boldsymbol{i}\})} = [\, F_1^{Max}, F_2^{Max}, \dots , F_{i-1}^{Max}, F_{i+1}^{Max}, \dots , F_n^{\ Max}\,]^T \qquad (7\text{-}2\text{-}59)$$

In addition, for better understanding, from expression (7-2-15), $\underline{\boldsymbol{h}}_{\boldsymbol{i}}\underline{\boldsymbol{X}}$ is defined as:

$$\underline{\boldsymbol{h}}_{\boldsymbol{i}}\underline{\boldsymbol{X}} = \sum_{k=1}^{n} h_{ik} X_k \ , \ i = 1, 2, \dots , n \qquad (7\text{-}2\text{-}60)$$

Then, the above model (7-2-57) can be also expressed as

$\mathbf{G_0}^{\mathbf{t\,i}}$: i = 1,2, … , n

$$Max.\ \ SB_i(\underline{X}) = \sum_{i=1}^{n} P_i(\, X_i\,) \qquad (7\text{-}2\text{-}61a)$$

s.t.

$$\begin{cases} \underline{\boldsymbol{h}}_{\boldsymbol{i}}\underline{\boldsymbol{X}} = \sum_{k=1}^{n} h_{ik} X_k \ = \ F_i^{Max} \\ \underline{\boldsymbol{h}}_{\boldsymbol{j}}\underline{\boldsymbol{X}} = \sum_{k=1}^{n} h_{jk} X_k \ \le \ F_j^{Max} \ , \ for\ all\ j = 1,2, \dots , n;\ j \ne i \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{\boldsymbol{Min}} \\ \sum_{i=1}^{n} X_i \le \ x^{Total} \end{cases} \qquad (7\text{-}2\text{-}61b)$$

Let $X_i^{\mathrm{P}*}$ be the optimal solution for the above model (7-2-61), then net production profit for each $\mathrm{G_i}$ in this case is

$$B_i(X_i^{\mathrm{P}*}) = P_i(X_i^{P*}) \qquad (7\text{-}2\text{-}62)$$

And the value of characteristic function correspondingly for each $\mathrm{G_i}$ is given as

$$v\ (\{\, i\, \})\ = P_i(X_i^{P*}) \qquad (7\text{-}2\text{-}63)$$

Then for the special situation, the social benefit can be identified as:

$$SB_i^{P*}(\underline{\boldsymbol{X}}^{P*}) = \sum_{i=1}^{n} P_i(X_i^{P*}) \tag{7-2-64}$$

Finally, the value of characteristic function for G_0 is given as follows:

$$v(S_k) = v(\tilde{N} - \{i\}) = \sum_{i=1}^{n} P_i(X_i^{P*}) - v(\{i\}) \tag{7-2-65}$$

7.3 The extended redistribution model of the maximum social benefit

As mentioned in Section 5.2, in the full-cooperative case under the TEC policy, all G_i's cooperation with G_0 can makes it realized to achieve an optimal allocation of the allowed total emission and meanwhile pursue a maximum social benefit. But the maximum social benefit is needed to redistribute rationally among all the cooperators G_i to keep the cooperation stable.

In this section, a model with an extension is discussed to divide the maximum social benefit among all the sectors in multisectoral system. As for the model for a rational redistribution of the maximum benefit, however, both the concept and the model formulas are basically as the same as those in Part Two (see Section 5.2 and Section 5.3 in Chapter 5 for details).

7.3.1 General conditions with three cases

As discussed in Section 5.2, let α_0 , α_i (i=1,2,…,n) be the G_0's gain and the G_i's final profit respectively, then, here is the sum of actual benefit to be redistributed among all $G_{i,\, i \in N}$.

$$v(N) = v(\tilde{N}) - \alpha_0 = SB(\boldsymbol{X}^*) - \alpha_0 \tag{7-3-1}$$

where v is the characteristic function defined previously in in Section 7.2.

From the cooperative game theory in a characteristic function form, the α_i as an imputation or solution of the game, is required to meet the group rationality (efficiency) condition:

$$\sum_{i=1}^{n} \alpha_i = v(N) \tag{7-3-2}$$

and also the individual rationality condition:

$$\alpha_i \geq v(\{i\}), \quad i = 1,2,\dots,n \tag{7-3-3}$$

Generally, the G_i's final profit α_i, i=1,2, …, n should satisfy the above two expressions at least as the general conditions for a rational redistribution.

However, here it is needed to mention below that the "individual rationality" condition in the cooperative game is not prerequisite in establishing the redistribution model for a sectoral system in this study. That is, the expression (7-3-3) is not always satisfied in distributing the maximum social benefit in a rational way.

In Section 5.2, for the redistribution model for a regional system, it is assumed that G_0 can design such a proper emission charges policy (function) by which the G_i's net profit $v(\{ i \})$ can be adjusted to some extent to meet the superadditivity condition in the cooperative game, i.e.,

$$v(N) > v(N - \{ i \}) + v(\{ i \}) \quad (7\text{-}3\text{-}4)$$

But it is usually not easy to find such an emission charges function that it can possibly be set up to adjust the solution to meet the (7-3-3) in the allocation model for a multisectoral system.

As shown in the allocation model in the non-cooperative case in Section 7.2.3, the G_i is not really be capable to make decision independently from the other G_j, because all their production scales should be completely decided together with each other based on the interaction relations fixed by the input-output table $\underline{\boldsymbol{A}} = \{a_{ij}\}$. Even if there possibly is such a proper function, it depends on how the function imposes a decrease of the productive scale and if a further reduction of the waste treatment cost is technologically feasible or not.

In addition, actually in coping with a practical environmental problem, it is really either difficult or unrealistic to create such an emission charges policy (function) suitable for each sector or for all sectors. For example, in the application discussed in the next chapter for reducing the CO_2 total emission in China, there is in fact no emission charges policy on the CO_2 emission for all sectors presently and so in fact it is hardly possible to find the necessary data to establish the adjusting emission charges policy (function). In order to make the model be in accordance with the true situation in China, the function $Tt_i(X_i)$ in the model is simply considered as $Tt_i(X_i) = 0$.

Thus, in establishing the redistribution model of the maximum social benefit in this study, particularly for a multisectoral system, it is not absolutely needed to emphasize that the G_i's final profit α_i would meet strictly the individual rationality condition (7-3-3).

That is, the redistribution model is needed to deal with not only the case in the expression (7-3-4) but also the opposite case, i.e., the following possible situation:

$$v(N) < v(N - \{ i \}) + v(\{ i \}) \quad (7\text{-}3\text{-}5)$$

This implies that under the total emission control policy, the sum of the G_i's final profits obtained in the full-cooperative case may be less than that in the non-cooperative case. Actually it can be understood that in implementing the total emission control policy, the G_i's cooperation with G_0 makes the actual total emission controlled under the allowed maximum value and then surely improves the environmental quality due to the reduced amount of the environmental damage, but meanwhile it would make some G_i's production scale decreased and correspondingly result in a decrease on the total production profit over the whole region. The decrement is

$$\Delta\alpha_i^{Tdec} = [v(N-\{i\}) + v(\{i\})] - v(N). \qquad (7\text{-}3\text{-}6)$$

It is then easy to understand that due to the decrement, the each G_i's final profit in the full-cooperative case is possibly less than that in the non-cooperative case, i.e., for some $G_{i,\ i=1,2,\ \ldots,\ n}$, there exists $\alpha_i < v(\{i\}$. For this situation, practically, it can be explained that the G_i makes a contribution to the environmental quality improvement at the cost of a profit decrease as:

$$\Delta\alpha_i = v(\{i\}) - \alpha_i. \qquad (7\text{-}3\text{-}7)$$

If phrased differently, the decrement on the total production profit can be also considered as a loss on the maximum social benefit. How to estimate the contribution of each G_i's cooperation with the TEC policy and finally to share the loss among all the G_i in a rational way is principally just the same concept as in the redistribution model of the maximum social benefit for the case where the condition (7-3-4) is satisfied.

Specifically the concept of "Equal Acceptance Degree (EAD)" introduced in Chapter 5 can be also applied here for the redistribution model of the maximum social benefit for a multisectoral system.

Since both the concept and the formulas in the model here are fundamentally as same as those in Section 5.2 and Section 5.3, it is just needed to directly give the united expressions. However, it should be emphasized here that there also is a difference. Instead of one situation in Chapter 5, there are three possibilities needed to be considered in this section as follows.

1) If $\boldsymbol{v(N) > v(N-\{i\}) + v(\{i\})}$

For a better understanding, the situation is discussed here again as in Section 5.2. In the situation, it means that the G_i's cooperation with G_0 in enforcing the total emission control policy brings an increase on the total profit over the whole region.

The increment is

$$\Delta\alpha_i^{Tinc} = v(N) - [v(N - \{i\}) + v(\{i\})]. \quad (7\text{-}3\text{-}8)$$

At this time G_i is considered as a contributor on the full-cooperative decision. In order to let the G_i keep cooperating stably with the total emission control policy, G_0 should promise G_i with such a profit α_i that at least never be less than the net profit obtained in the non-cooperative case, i.e.

$$Min.\ \alpha_i = v(\{i\}) \quad (7\text{-}3\text{-}9)$$

Conversely, of course, G_0 cannot possibly provide G_i with a profit increment which is more than the total benefit increment resulted from the G_i's cooperation, i.e.

$$Max.\ \Delta\alpha_i = \alpha_i - v(\{i\}) = \Delta\alpha_i^{Tinc} \quad (7\text{-}3\text{-}10)$$

or $$Max.\ \Delta\alpha_i = v(\{i\}) + \Delta\alpha_i^{Tinc} \quad (7\text{-}3\text{-}11)$$

Thus, if $v(N) > v(N - \{i\}) + v(\{i\})$, (7-3-12)

then $v(\{i\}) \le \alpha_i \le v(\{i\}) + \Delta\alpha_i^{Tinc}$ (7-3-13)

2) If $\boldsymbol{v(N) < v(N - \{i\}) + v(\{i\})}$

Regarding this situation, as discussed previously, the G_i's cooperation with G_0 makes the actual total emission controlled within the allowed maximum value, but it results in a decrease on the total profit over the whole region.

The decrement is

$$\Delta\alpha_i^{Tdec} = [v(N - \{i\}) + v(\{i\})] - v(N). \quad (7\text{-}3\text{-}14)$$

At this time, G_i is considered to bring an economical loss to the full-cooperative decision. For the G_i, the best is to take no responsibility for the loss, i.e.

$$Max.\ \Delta\alpha_i = 0$$

and the worst is to be responsible for the whole loss, i.e.

$$Min.\ \Delta\alpha_i = -\Delta\alpha_i^{Tdec}\ .$$

Thus, if $v(N) < v(N - \{i\}) + v(\{i\})$, (7-3-15)

then $v(\{i\}) - \Delta\alpha_i^{Tdec} \le \alpha_i \le v(\{i\})$ (7-3-16)

3) If $\boldsymbol{v(N) = v(N - \{i\}) + v(\{i\})}$.

For this special case (Kindler J., et al., 1980; Katayama K., et al., 1981), it implies that the G_i's cooperation with G_0 makes the actual total emission controlled within the allowed limitation, and has no influence on the total profit over the whole region (Steven C. Hackett, 1998).

Therefore, if $v(N) = v(N - \{i\}) + v(\{i\})$, (7-3-17)

then $\alpha_i = v(\{i\})$ (7-3-18)

7.3.2 The extended model with equal acceptance degree

Now, based on the above, the redistribution problem can be clearly described as the multi-objective decision-making model (G.L.Nemhauser, et al, 1989) as that in Section 5.2. Here is given the united formation below.

For all G_i at the mean time:

Obj.

$$\{ G_i : \quad Max.\ \alpha_i \ , \ for\ all\ i = 1, 2, \dots, n \qquad (7\text{-}3\text{-}19a)$$

s.t.

$$\begin{cases} G_i : & \alpha_i^L \le \alpha_i \le \alpha_i^H \ , \ for\ all\ i = 1, 2, \dots, n \\ G_0 : & \sum_{i=1}^{n} \alpha_i = v(N) \end{cases} \qquad (7\text{-}3\text{-}19b)$$

where, for i = 1, 2, …, n , the corresponding α_i^L and α_i^H are respectively obtained from:

$$\alpha_i^L = \begin{cases} v(\{i\}), & \text{if } v(N) \ge v(N - \{i\}) + v(\{i\}); \\ v(\{i\}) - \Delta\alpha_i^{Tdec}, & \text{if } v(N) < v(N - \{i\}) + v(\{i\}). \end{cases} \qquad (7\text{-}3\text{-}20)$$

$$\alpha_i^H = \begin{cases} v(\{i\}) + \Delta\alpha_i^{Tinc}, & \text{if } v(N) \ge v(N - \{i\}) + v(\{i\}); \\ v(\{i\}), & \text{if } v(N) < v(N - \{i\}) + v(\{i\}). \end{cases} \qquad (7\text{-}3\text{-}21)$$

As discussed in Section 5.2, also let $\gamma(i)$ be the “Acceptance Degree” of the *i*-th sector G_i in regards to the distributed net profit α_i , and then define:

$$\gamma(i) = \frac{\alpha_i - \alpha_i^L}{\alpha_i^H - \alpha_i^L} \qquad (7\text{-}3\text{-}22)$$

where generally, $0 \le \gamma(i) \le 1$ (7-3-23)

From the expressions (7-3-20) and (7-3-21), it can be described as

(1) when $v(N) > v(N-\{i\}) + v(\{i\})$,

$$\gamma(i) = \frac{\Delta\alpha_i}{\Delta\alpha_i^{Tinc}} = \frac{\alpha_i - v(\{i\})}{v(N) - v(N-\{i\}) - v(\{i\})} \quad (7\text{-}3\text{-}24)$$

(2) when $v(N) < v(N-\{i\}) + v(\{i\})$,

$$\gamma(i) = \frac{\alpha_i - [\, v(\{i\}) - \Delta\alpha_i^{Tdec}\,]}{\Delta\alpha_i^{Tdec}} \quad (7\text{-}3\text{-}25)$$

(3) when $v(N) = v(N-\{i\}) + v(\{i\})$, define it as:

$$\gamma(i) = \gamma \quad (7\text{-}3\text{-}26)$$

In this case the solution is simply known as $\alpha_i = v(\{ i \})$.

From the above expression (7-3-24), the acceptance degree $\gamma(i)$ is the ratio of the individual increment of the G_i's final profit and the total increment of all the G_i's profits. The both increments are based on profits obtained from the non-cooperative case and the full-cooperative case. It is most acceptable when $\gamma(i) = 1$; and completely indifferent when $\gamma(i) = 0$.

Similarly, the explanation can also be given to the expression (7-3-25).

Now the rational redistribution rule can be determined with such a meaning the "Equal Acceptance Degree (EAD)". That is to set

$$\gamma(1) = \gamma(2) = \cdots = \gamma(n) = \gamma \, . \quad (7\text{-}3\text{-}27)$$

i.e.

$$\frac{\alpha_1 - \alpha_1^L}{\alpha_1^H - \alpha_1^L} = \frac{\alpha_2 - \alpha_2^L}{\alpha_2^H - \alpha_2^L} = \cdots = \frac{\alpha_n - \alpha_n^L}{\alpha_n^H - \alpha_n^L} = \gamma \, . \quad (7\text{-}3\text{-}28)$$

Therefore, with the above expressions, the multi-objective model (7-3-19) can be transferred to a simple single-objective one shown as follows:

$$\boldsymbol{G_0}^{\gamma}: \; Max. \;\; \gamma \quad (7\text{-}3\text{-}29a)$$

$$\text{s.t.} \begin{cases} \alpha_i - \alpha_i^L = \gamma\,(\alpha_i^H - \alpha_i^L), \; i = 1, 2, \ldots, n \\ \sum_{i=1}^{n} \alpha_i = v(N) \end{cases} \quad (7\text{-}3\text{-}29b)$$

It is obviously easy to obtain the solution of the above model. Let γ^* be the solution, then get the rational redistribution, finally:

$$\alpha_i = {\alpha_i}^L + \gamma^*({\alpha_i}^H - {\alpha_i}^L), \quad i = 1, 2, \dots, n; \qquad (7\text{-}3\text{-}30)$$

and correspondingly,

$$\Delta\alpha_i = \alpha_i - v(\{\, i \,\}) \,, \quad i = 1, 2, \dots, n\,. \qquad (7\text{-}3\text{-}31)$$

Finally, as mentioned in Section 5.2.3, after the value of each α_i is identified, the rising question is how to make it realized practically by a tax and subsidy policy used as an economic means. Here is given directly the formula for calculating the tax and subsidy for each G_i (see Section 5.2.3 for more details).

Let t_i stand for the amount of tax submitted to G_0 by G_i, i=1, 2, …, n, then

$$t_i = A_i(\, {X_i}^* \,) - \alpha_i = P_i(\, {X_i}^* \,) - \alpha_i \qquad (7\text{-}3\text{-}32)$$

where as for $A_i(\, {X_i}^* \,)$, see the expression (7-2-44).

If t_i is less than zero, it means that the G_i should receive a subsidy from G_0 with the amount of $|\, t_i \,|$.

Here, note that t_i is not a function in the model. It is only a value for adjusting the G_i's final profit obtained in the full-cooperative case.

8. An empirical application for total CO_2 emission control in China

8.1 Background of the application

The aim of this chapter is to study in details an application of the above model to the multisectoral system in China where all economic sectors should be responsible for reducing CO_2 total emission to a certain extent.

In fact, in order to reach the environmental target either for the emission intensity reduction or for the emission peak control on total CO_2 emission in China, it is essentially important to control the total emission among all industries (Hu Q., et al., 2018; Zhang C., et al., 2019). In other words, it is actually a problem of how to design and then enforce an effective policy of total emission control (Wang J., et al., 2010; Xu G. & Schwarzb P., et al., 2019).

So far, policy makers are still facing a fundamental and key question: how the total emission (quotas) can be effectively and fairly allocated among multiple sectors or areas (Liu H. & Lin B., 2017).

To answer the question, these following chapters discuss on how to develop an effective and fair solution for the CO_2 emission quotas. That is, an empirical application of the extended TEC model is quantitatively discussed in more detail for reducing the total CO_2 emission among all the economic sectors in China.

Specifically, in this chapter, by using the China's national input-output table with all 17 sectors, the extended model is firstly applied to calculate an optimal TEC policy scheme, respectively for total production, final use and the corresponding CO_2 emission by each sector, and identify the key sectors most responsible for total emission reduction.

Then furtherly, based on the results data, in the next chapters, it is also expected to discuss two more aspects of the core application. One is to quantitatively analyse impacts of improving emission intensity coefficient of the sector with the highest emission share on the allocations of the total CO_2 emission set as the TEC target by policy maker. And the other is to calculate the different policy schemes by changing the policy factor such as TEC targets to give alternative policy suggestions for comparison analysis.

8.2 The data preparation

Before beginning the simulating computation by the model, first the discussion should be about how to get the essential data needed in the model, such as data for input-output table, the CO_2 emission coefficients, and the maximum value of total emission (TEC policy target).

8.2.1 The data of input-output table

The application study is based on the data of China's input-output table in 2012. From the public website of National Bureau of Statistics of China, it is possible to get the data of intermediate use, final use, total output (total production), and the direct input coefficients for input output table in 2012 (National Bureau of Statistics of China, NBSC, 2017, 2019).

It is noted that since the statistics only keep stable structure within five years, direct input coefficients will be modified in every five years. Due to the lack of similar input-output tables for years of 2013-2017, as is often done in input-output analyses, it could be assumed that direct input coefficients and Leontief inverse coefficients for the years of 2013-2017 are identical to the baseline year of 2012. The input-output tables encompass 17 sectors shown in Table 8-2-1.

The data used in the application are obtained from the following public websites:

1. Data for Input-Output Table of Year 2012 released by National Bureau of Statistics of the People's Republic of China. See Table 8-2-1 here. (http://www.stats.gov.cn/tjsj/ndsj/2017/indexch.htm)

2. China Statistical Yearbook 2017 (http://www.zgtjnj.com/)

Table 8-2-1 Direct input coefficients a_{ij} of input-output table 2012 with 17 sectors

		Agriculture, Forestry, Animal Husbandry and Fishery	Mining	Manufacture of Foods, Beverage and Tobacco	Manufacture of Textile, Wearing Apparel and Leather Products	Other Manufacture	Production and Supply of Electric Power, Heat Power and Water	Coking, Gas and Processing of Petroleum	Chemical Industry	Manufacture of Nonmetallic Mineral Products	Manufacture and Processing of Metals and Metal Products	Manufacture of Machinery and Equipment	Construction	Transport, Storage, Post, Information Transmission, Computer Services and Software	Wholesale and Retail Trades, Hotels and Catering Services	Real Estate, Leasing and Business Services	Financial Intermediation	Other Services
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Agriculture, Forestry, Animal Husbandry and Fishery	1	0.14	0	0	0.11	0.06	0	0	0.04	0	0	0	0.01	0.01	0	0	0	0.01
Mining	2	0	0.13	0	0	0.01	0.19	0.61	0.04	0.13	0.15	0	0.01	0	0	0		0
Manufacture of Foods, Beverage and Tobacco	3	0.11	0	0.23	0.02	0.01	0	0.01	0.02	0	0	0	0	0.01	0.1	0	0	0.02
Manufacture of Textile, Wearing Apparel and Leather Products	4	0	0	0	0.45	0.04	0	0	0.01	0.01	0	0.01	0	0	0	0	0.01	0.02
Other Manufacture	5	0	0.01	0.01	0.01	0.29	0	0	0.01	0.03	0.04	0.01	0.03	0.01	0	0.1	0.03	0.02
Production and Supply of Electric Power, Heat Power and Water	6	0.01	0.06	0.01	0.01	0.02	0.32	0.02	0.04	0.06	0.04	0.01	0.01	0.01	0	0	0.01	0.01
Coking, Gas and Processing of Petroleum	7	0.02	0.03	0	0	0	0.04	0.08	0.06	0.04	0.04	0	0.01	0.11	0	0	0	0.01
Chemical Industry	8	0.08	0.04	0.02	0.08	0.1	0	0.02	0.43	0.08	0.02	0.06	0.04	0.01	0	0	0	0.09
Manufacture of Nonmetallic Mineral Products	9	0	0.01	0	0	0	0	0.01	0.01	0.2	0.01	0.01	0.19	0	0	0	0	0
Manufacture and Processing of Metals and Metal Products	10	0	0.05	0	0	0.06	0	0	0.01	0.05	0.39	0.17	0.2	0.01	0	0	0	0.01
Manufacture of Machinery and Equipment	11	0.01	0.06	0	0.01	0.02	0.07	0.01	0.01	0.04	0.03	0.4	0.05	0.11	0	0.1	0	0.06
Construction	12	0	0	0	0	0	0	0	0	0	0	0	0.03	0.01	0	0	0.01	0.01
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	0.01	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.04	0.02	0.03	0.04	0.15	0	0	0.05	0.05
Wholesale and Retail Trades, Hotels and Catering Services	14	0.02	0.02	0.05	0.06	0.03	0.01	0.01	0.03	0.03	0.01	0.04	0.02	0.03	0	0	0.05	0.05
Real Estate, Leasing and Business Services	15	0	0.02	0.01	0.01	0.01	0	0.01	0.02	0.01	0.01	0.01	0.01	0.03	0.1	0.1	0.16	0.03
Financial Intermediation	16	0.01	0.03	0.01	0.01	0.02	0.05	0.01	0.02	0.02	0.03	0.02	0.03	0.07	0	0.1	0.06	0.03
Other Services	17	0.01	0.02	0.01	0.01	0.01	0.01	0	0.01	0.01	0.01	0.02	0.04	0.02	0	0	0.03	0.06

8.2.2 The CO_2 emission (intensity) coefficients

Shown in Table 8-2-2 are the corresponding data for the CO_2 emission coefficients. But the latest data is only for years before 2007 (Guo J., et al., 2013). Due to this, it is necessary to find some reasonable method to adjust and calculate the data usable for years 2013-2017.

According to the context of emission intensity commitment made by Chinese government in 2009, during the period of years 2005-2020, the emission intensity per

GDP in China must be decreased by 40% to 45% of the value based on year 2005.

Also，according to the Climate Division of the National Development and Reform Commission， in 2017, China's carbon intensity was down 5.1% from the previous year, about 46% from 2005 (Li G., 2018). This suggests that actually at the end of 2017 China has already met the Chinese government's commitment to the world that China’s carbon intensity be declined by 40-45% in 2020 (Ju C., 2018).

So here it can be possibly assumed that the emission intensity has been reduced by 50% during the ten years of 2007-2017, which means improving the emission intensity with 5% progressive rate per year due to technological innovation (Nicoletta M., et al., 2010). With this assumption, based on data of year 2007 (Guo J., et al 2013) in Table 8-2-2, it is easier to calculate the CO_2 direct emission coefficients for years of 2013 to 2017 as the empirical data shown in Table 8-2-3.

In addition, even if for data in 2007, they are only for 15 sectors in which there is a lack on data for the two sectors of Sector No.15 (Financial Intermediation) and Sector No.16 (Real Estate, Leasing and Business Services). So it could be proper to set the emission coefficients of the two sectors as the same as that of Sector No.17 (Other Services sector). See Table 8-2-3.

Although there is a shortage on the exact data for the latest five years, it can be still possible to use the approximate data for studying an empirical application of the multisectoral model with an input-output analysis on the policy design for CO_2 emission control in China.

8.2.3 The target of total CO_2 emission control.

Setting a suitable emission control target is significant in implementing the TEC policy. Here, however, this topic will not be discussed in details, because there are a number of research reports or articles on the topic (NDRC-SIC, 2018; Jiang J., et al., 2019; Wang J., et al, 2010; 柴麒敏, et al., 2015, 2017; 程纪华, 2016; 刘长松, 2015; 彭水军, 2015; 刘宇, et al, 2013; 袁永娜, et al., 2012; 刘小敏, 2011; 吴国华, et al, 2011; 渠慎宁, et al, 2010).

In the present study, the policy simulation results reported by the following sources are employed to set the allowed maximum value for the total CO_2 emission per year as the TEC policy target.

Table 8-2-2 CO_2 emission coefficients β_i (Years 1997-2007 for 15 sectors) ($KgCO_2$/CNY)

No.	Sectors	CO_2 direct emission coefficients		
		Year 1997	Year 2002	Year 2007
1	Agriculture, Forestry, Animal Husbandry and Fishery	0.0314	0.0261	0.0284
2	Mining	0.4697	0.2756	0.1566
3	Manufacture of Foods, Beverage and Tobacco	0.0542	0.0356	0.0165
4	Manufacture of Textile, Wearing Apparel and Leather Products	0.0304	0.0201	0.0147
5	Other Manufacture	0.0627	0.0332	0.0265
6	Production and Supply of Electric Power, Heat Power and Water	2.6265	1.4135	0.8803
7	Coking, Gas and Processing of Petroleum	1.5747	0.9819	0.7012
8	Chemical Industry	0.2346	0.1394	0.0855
9	Manufacture of Nonmetallic Mineral Products	0.3032	0.3217	0.1789
10	Manufacture and Processing of Metals and Metal Products	0.4145	0.2392	0.1792
11	Manufacture of Machinery and Equipment	0.0432	0.0108	0.0059
12	Construction	0.0091	0.0076	0.0055
13	Transport, Storage, Post, Information Transmission, Computer Services and Software	0.1958	0.1288	0.1000
14	Wholesale and Retail Trades, Hotels and Catering Services	0.0213	0.0127	0.0131
15	Others	0.0257	0.0119	0.0077

Data Source: GUO J, WANG H., et al., 2013, The empirical analysis on the influence of international trade to industries' embodied carbon emissions in China [J], Journal of Beijing Institute of Technology, Vol.15 No.6, 2013/12 (6):1-9

Table 8-2-3 CO_2 emission coefficients β_i (years 2012-2017 for 17 sectors) (KgCO2/CNY)

Sectors 部门	**i**	**2007**	**2012**	**2017**
Agriculture, Forestry, Animal Husbandry and Fishery 农、林、牧、渔业部门	1	0.0284	0.0273	0.0142
Mining 采矿业部门	2	0.1566	0.0904	0.0783
Manufacture of Foods, Beverage and Tobacco 食品、饮料制造及烟草制品业部门	3	0.0165	0.0092	0.0083
Manufacture of Textile, Wearing Apparel and Leather Products 纺织、服装及皮革产品制造业部门	4	0.0147	0.0102	0.0074
Other Manufacture 其他制造业部门	5	0.0265	0.0176	0.0133
Production and Supply of Electric Power, Heat Power and Water 电力、热力及水的生产和供应业部门	6	0.8803	0.5110	0.4402
Coking, Gas and Processing of Petroleum 炼焦、燃气及石油加工业部门	7	0.7012	0.4690	0.3506
Chemical Industry 化学工业部门	8	0.0855	0.0516	0.0428
Manufacture of Nonmetallic Mineral Products 非金属矿物制品业部门	9	0.1789	0.1447	0.0895
Manufacture and Processing of Metals and Metal Products 金属产品制造业部门	10	0.1792	0.1188	0.0896
Manufacture of Machinery and Equipment 机械设备制造业部门	11	0.0059	0.0023	0.0030
Construction 建筑业部门	12	0.0055	0.0043	0.0028
Transport, Storage, Post, Information Transmission, Computer Services and Software 运输仓储邮政、信息传输、计算机服务和软件业部门	13	0.1000	0.0717	0.0500
Wholesale and Retail Trades, Hotels and Catering Services 批发零售贸易、住宿和餐饮业部门	14	0.0131	0.0107	0.0066
Real Estate, Leasing and Business Services 房地产业、租赁和商务服务业部门	15	0.0077	0.0043	0.0039
Financial Intermediation 金融业部门	16	0.0077	0.0043	0.0039
Other Services 其他服务业部门	17	0.0077	0.0043	0.0039

Data Source: GUO J, WANG H., et al., 2013, The empirical analysis on the influence of international trade to industries' embodied carbon emissions in China [J], Journal of Beijing Institute of Technology, Vol.15 No.6, 2013/12 (6):1-9

The simulation results data computed by The State Information Center of China (NDRC-SIC, 2018) indicated that:

For year 2030, there are three cases simulated as follows:

(1) Lower level: 10,490 million (metric) tons

(2) Middle level: 10,320 million tons

(3) Higher level: 10,050 million tons.

Also, based on a total emission control model in the context of commitment made in reduction of CO_2 emission intensity per GDP, the optimal CO_2 total emission target for China in 2020 has been suggested by CAEP, the Chinese Academy for Environmental Planning (Wang J., Cai B., et al., 2010), i.e.

For year 2020, there are two emission scenarios suggested below

(1) Lower level: 8,624 million tons

(2) Higher level: 9,471 million tons

Therefore, according to the above information, in this empirical application study, it might be reasonable to set the allowed maximum value for the CO_2 total emission per year at the level below.

x^{Total} = 10,000 million (metric) tons.

In the following discussion, this value will be considered as the basic TEC policy target and applied to calculate the optimal TEC policy scheme which is then also used as a base line in comparative analysis in the later chapters of this study.

Of course, as an adjustable policy factor, the TEC target might be changeable for different policy strategies. In Chapter 10, as examples, the different optimal TEC policy schemes will be furtherly investigated by simulations based on different TEC policy targets.

8.3 Results and discussion

8.3.1 Computation and results

By using the related tools in the Excel (Microsoft) for input-output analysis, it is easier to compute the results on a personal computer (PC) (中村愼一郎, 2000; 井出眞弘, 2003; 石村貞夫, 2009; 藤本壱, 2016).

In computation, the relevant conditions or initial values are firstly set as follows:

(1) The maximum amount of the allowed total emission from all sectors is x^{Total} = 10,000 million tons CO_2/year (see Section 8.2.3);

(2) The final use (final demand) scale for each sector F_i is set as shown in Table 8-3-1. Specifically,
F_i^{Min} is estimated based on the data of year 2012 (NBSC, 2017);
F_i^{Max} is calculated with a growth rate per year as same as that of GDP during years 2013-2017 based on the public data from the National Bureau of Statistics of China (NBSC, 2017). That is F_i^{Max} is set as 1.4104 times as that in 2012, i.e. $F_i^{Max} = 1.4104\, F_i^{Min}$.

(3) The gain (profit) of the policy-maker (or administrator or controller) under total emission control is considered as zero, i.e. setting α_0 = 0, which implies that there is no cost in implementing or operating the TEC policy.

(4) There is no environmental damage resulted from the total emission $x = \sum X_i^*$ for the case with TEC policy. That is to set $D(\sum X_i^*) = 0$ if the actual total emission $x = \sum X_i^*$ is equal to or less than x^{Total} that is set by the policy-maker G_0.

(5) No account is taken on the direct treatment cost for each sector. i.e., $C_i(X_i, x_i)$ = 0 and $X_i = x_i$ in the input-output analysis. (see Section 7.2 for the detailed reasons to set this)

(6) For the situation without the TEC policy, there is no existing emission charges standard (policy) used for the CO_2 emissions for each sector and for all the sectors. In order to be in accordance with the fact, here let's set $T_i(X_i) = 0$.

(7) The emission charges standard is also set to be zero for the non-cooperative model with total emission control. In fact it is hardly possible to find the necessary data to establish the adjustable emission charges function. Based on the real situation in China at present, the function $Tt_i(X_i)$ in the model is simply considered

useless. This means that G_i can pay no cost for its emission X_i, i.e., $Tt_i(X_i) = 0$.

Table 8-3-1 The initial values set for F_i in simulating computations (based on 2012)

Classification of Sectors	(i)	Final Use	Final Use
G_0	0	(10,000 CNY)	(10,000 CNY)
G_i	i	F_i^{Min}	F_i^{Max}
Agriculture, Forestry, Animal Husbandry and Fishery	1	286,678,966.55	404,328,302.85
Mining	2	12,469,606.10	17,586,971.00
Manufacture of Foods, Beverage and Tobacco	3	422,265,479.70	595,557,765.59
Manufacture of Textile, Wearing Apparel and Leather Products	4	273,723,635.18	386,056,271.21
Other Manufacture	5	156,099,475.02	220,160,678.58
Production and Supply of Electric Power, Heat Power and Water	6	36,716,264.12	51,784,143.56
Coking, Gas and Processing of Petroleum	7	53,713,866.81	75,757,342.33
Chemical Industry	8	160,758,386.49	226,731,547.00
Manufacture of Nonmetallic Mineral Products	9	31,114,067.60	43,882,878.12
Manufacture and Processing of Metals and Metal Products	10	123,540,156.23	174,239,436.90
Manufacture of Machinery and Equipment	11	1,511,103,203.10	2,131,240,393.71
Construction	12	1,296,852,813.94	1,829,064,418.70
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	310,788,618.34	438,332,243.59
Wholesale and Retail Trades, Hotels and Catering Services	14	421,234,155.51	594,103,199.30
Real Estate, Leasing and Business Services	15	364,389,891.23	513,930,784.91
Financial Intermediation	16	109,392,810.95	154,286,204.28
Other Services	17	996,901,848.88	1,406,017,460.98
(TEC policy target set: 10,000 million tons)	Sum	6,567,743,245.75	9,263,060,042.59

Table 8-3-2 shows the results computed for the existing situation, i.e., the case of individual decision-making without total emission control. Fig.8-3-1 demonstrates the results visually.

Here, X_i^0 is the amount of CO_2 emission that the *i*-th sector should be responsible for. F_i^0 and P_i^0 are the final use and the total production of sector i (namely G_i), respectively. And the $\lambda_i = F_i^0 / F_i^{Max}$ is the ratio of F_i^0 to F_i^{Max}.

It is observed that firstly in this situation without total emission control, as each sector's economic scale grows together with the GDP in China, each sector G_i could try to reach its maximum F_i^0 so as to get the maximum production profit P_i^0 by itself, and as the result, each G_i gets the maximum profit in total production independently and the sum of each sector's production profit is 27,110,901,854.95 (10000CNY), i.e., 271.11 trillion CNY (T.CNY). On the other hand, however, the total emission of CO_2 reaches 13,015,554,241.39 (metric) tons, i.e., 13,015.56 million tons, which is much more than 10,000 million tons - the maximum value of the allowed total emission from all sectors. Thus, some kind of policy strategy for reducing totally about 3,015.56 million tons CO_2 emission should be enforced by policy maker (namely G_0) as the all sectors' economic scale has been increasing with a growth rate per year along with the GDP in China.

Table 8-3-3 to Table 8-3-6 shows the results for the full-cooperative case with total emission control at the level of total emission of 10,000 million tons. In this case, all the sectors G_i are cooperative with G_0 in making the centralized decision making.

Table 8-3-3 or Fig.8-3-2 indicates the optimal allocations of the maximum total emission among all sectors in the full cooperative case, where X_i^* is the amount of CO_2 emission that the *i*-th sector should be responsible for. F_i^* and P_i^* are the final use and total production of the sector G_i, respectively. And the $\lambda_i = F_i^* / F_i^{Max}$ is the ratio of F_i^* to F_i^{Max}.

In the case, the total emission is controlled exactly at the level of 10,000 million tons to meet the target. The sum of all G_i's production profits is at the maximum value 21,786,990,931.53 (10000CNY), i.e. 217.87 trillion CNY (T.CNY) as well.

Table 8-3-4 or Fig.8-3-3 presents the results based on the part-cooperative model for the case with total emission control where only sector G_i is not cooperative but all other sectors are cooperative. From the results, it can be assumed that in the part-cooperative case, the not-cooperative G_i could expect to get its maximum profit which is more than that in full-cooperative case. The differences in the G_i's production profit between the both cases are shown in Table 8-3-5.

In Table 8-3-5, if checking the corresponding profits for other sectors in cooperation, it can be found that the social benefit, i.e., the sum of production profits of all the sectors including the not-cooperative sector G_i's profit, is changed in the part-coopertive case. Compared with the maximum value of social benefit ($SB^* = \Sigma P_i^*$) for the full-cooperative case in Table 8-3-3, the social benefit ($SB_i^{P*} = \Sigma P_i^{P*}$) for the part-cooperative case in Table 8-3-5 decreases for most of sectors $G_{i, i=1,2,\ldots,n}$, repectively. The differences in social benefit between the two cases are also shown in Table 8-3-5.

Now it is understood that the G_i's expected profit increases while the corresponding total amount of all G_i's profits (social benefit) decreases. In other words, an increment on the sector G_i's expected profit is at the cost of a decrement on the total profit of all other sectors.

Table 8-3-6 shows the results based on the redistribution model with the equal acceptance degree (EAD) for the fair allocation of the maximum social benefit among all the cooperative sectors (the policy maker G_0's profit is set to be zero), where, t_i is the value of "the environmental tax or subsidy". When the value of t_i is positive, it means an emission tax that G_i should pay to G_0. When the value t_i is negative, it is considered as an "environmental subsidy" that G_i is should receive from G_0.

The α_i is the final profit for each sector; and $\Delta\alpha_i$ is an increment in each sector G_i's profit in comparison with the expected value in the non-cooperative case, which could be considered as an "extra gain" from the cooperation with G_0.

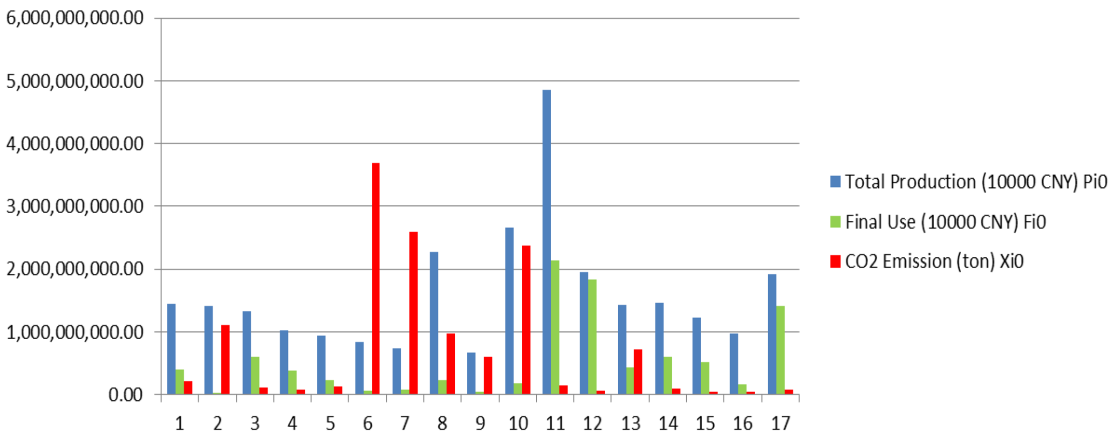


Fig.8-3-1 Results in the existing case without TEC policy

Table 8-3-2 Results based on the Individual decision-making model with I-O analysis

The case Without the total emission control policy					
Classification	G_0	Total Production	Final Use		CO_2 Emission
of Sectors	G_i	(10000 CNY)	(10000 CNY)	(%)	(ton)
G_i	i	P_i^0	F_i^0	λ_i^0	X_i^0
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,438,461,690.80	404,328,304.21	100	204,261,559.90
Mining	2	1,416,624,673.77	17,586,971.36	100	1,109,217,119.10
Manufacture of Foods, Beverage and Tobacco	3	1,322,803,903.52	595,557,765.50	100	109,131,322.24
Manufacture of Textile, Wearing Apparel and Leather Products	4	1,021,973,737.39	386,056,271.26	100	75,115,069.69
Other Manufacture	5	945,237,170.21	220,160,678.75	100	125,243,925.02
Production and Supply of Electric Power, Heat Power and Water	6	839,127,924.98	51,784,143.56	100	3,693,421,561.49
Coking, Gas and Processing of Petroleum	7	740,703,619.82	75,757,342.32	100	2,596,906,890.29
Chemical Industry	8	2,264,235,878.63	226,731,548.41	100	967,960,838.06
Manufacture of Nonmetallic Mineral Products	9	665,346,706.87	43,882,878.12	100	595,152,629.28
Manufacture and Processing of Metals and Metal Products	10	2,651,121,900.97	174,239,438.18	100	2,375,405,223.63
Manufacture of Machinery and Equipment	11	4,853,910,178.20	2,131,240,391.84	100	143,190,350.34
Construction	12	1,942,781,709.81	1,829,064,418.95	100	53,426,497.01
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,425,202,832.44	438,332,244.27	100	712,601,415.69
Wholesale and Retail Trades, Hotels and Catering Services	14	1,465,188,803.21	594,103,198.92	100	95,969,866.41
Real Estate, Leasing and Business Services	15	1,231,360,418.89	513,930,785.08	100	47,407,376.11
Financial Intermediation	16	966,514,843.73	154,286,204.21	100	37,210,821.47
Other Services	17	1,920,305,861.71	1,406,017,461.26	100	73,931,775.66
Total		27,110,901,854.95	9,263,060,046.18	100	13,015,554,241.39
		271.11	92.63		13,015.56
		ΣP_i^0 (T.CNY) ↑	ΣF_i^0 (T.CNY) ↑		$x^0 = \Sigma X_i^0$ (M.t) ↑

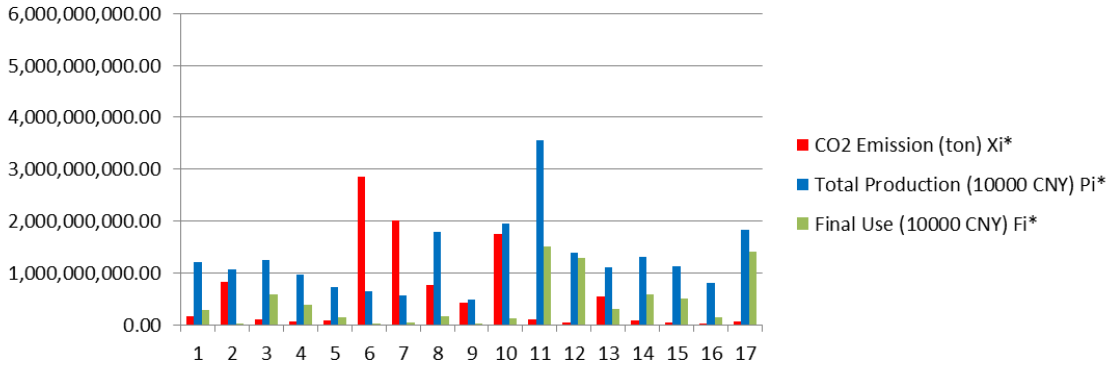


Fig.8-3-2 Results in the full-cooperative case with TEC target of 10,000 million tons

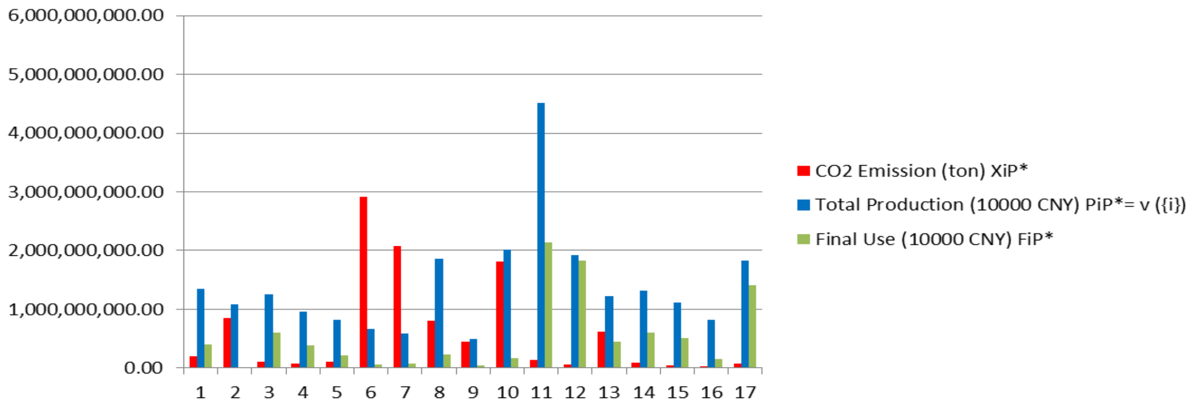


Fig.8-3-3 Results in the part-cooperative case with TEC target of 10,000 million tons

Table 8-3-3 Results based on the Full-cooperative model with I-O analysis

The case with the total emission control policy at the level of 10,000 million tons					
Classification	G_0	CO_2 Emission	Total Production	Final Use	
of Sectors	G_i	(ton)	(10000 CNY)	(10000 CNY)	(%)
G_i	i	X_i^*	P_i^*	F_i^*	λ_i^*
Agriculture, Forestry, Animal Husbandry and Fishery	1	172,794,116.59	1,216,859,975.99	293,283,528.65	72.54
Mining	2	838,779,680.27	1,071,238,416.70	12,469,606.59	70.90
Manufacture of Foods, Beverage and Tobacco	3	103,000,920.76	1,248,496,009.24	595,557,765.64	100.00
Manufacture of Textile, Wearing Apparel and Leather Products	4	70,740,790.65	962,459,736.69	386,056,271.20	100.00
Other Manufacture	5	96,538,951.50	728,595,860.37	156,099,475.02	70.90
Production and Supply of Electric Power, Heat Power and Water	6	2,845,193,490.34	646,414,515.58	36,716,263.77	70.90
Coking, Gas and Processing of Petroleum	7	2,010,113,660.12	573,335,328.04	53,713,866.75	70.90
Chemical Industry	8	765,266,627.33	1,790,097,373.87	160,758,386.12	70.90
Manufacture of Nonmetallic Mineral Products	9	429,467,798.42	480,120,512.49	31,114,067.57	70.90
Manufacture and Processing of Metals and Metal Products	10	1,742,890,216.23	1,945,189,973.47	123,540,156.60	70.90
Manufacture of Machinery and Equipment	11	105,150,949.92	3,564,438,980.35	1,511,102,861.89	70.90
Construction	12	38,143,852.09	1,387,049,166.82	1,296,852,813.94	70.90
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	551,231,406.53	1,102,462,813.07	310,788,618.50	70.90
Wholesale and Retail Trades, Hotels and Catering Services	14	86,080,577.74	1,314,207,293.75	594,103,199.30	100.00
Real Estate, Leasing and Business Services	15	43,143,238.96	1,120,603,609.33	513,930,784.90	100.00
Financial Intermediation	16	31,216,887.66	810,828,250.87	154,286,204.28	100.00
Other Services	17	70,246,834.92	1,824,593,114.88	1,406,017,460.98	100.00
Total		10,000,000,000.05	21,786,990,931.53	7,636,391,331.70	82.44
		10,000.00	217.86	76.36	
		$x^* = \Sigma X_i^*$ (M.t) ↑	$SB^* = \Sigma P_i^*$ (T.CNY) ↑	ΣF_i^* (T.CNY) ↑	

Table 8-3-4 Results based on the Part-cooperative model with I-O analysis (1)

The case with the total emission control policy at the level of 10,000 million tons					
Classification		CO_2 Emission	Total Production	Final Use	
of Sectors	G_0	(ton)	(10000 CNY)	(10000 CNY)	(%)
G_i	i	X_i^{P*}	$P_i^{P*}= v(\{i\})$	F_i^{P*}	λ_i^{P*}
Agriculture, Forestry, Animal Husbandry and Fishery	1	191,670,084.19	1,349,789,325.26	404,328,595.89	100.00
Mining	2	843,111,537.07	1,076,770,800.85	17,586,983.40	100.00
Manufacture of Foods, Beverage and Tobacco	3	103,000,910.38	1,248,495,883.36	595,557,765.87	100.00
Manufacture of Textile, Wearing Apparel and Leather Products	4	70,740,791.48	962,459,748.03	386,056,271.32	100.00
Other Manufacture	5	108,014,691.48	815,205,218.71	220,160,678.56	100.00
Production and Supply of Electric Power, Heat Power and Water	6	2,912,568,150.81	661,721,720.05	51,784,143.48	100.00
Coking, Gas and Processing of Petroleum	7	2,071,019,368.02	590,707,178.56	75,757,395.83	100.00
Chemical Industry	8	797,356,693.62	1,865,161,856.42	226,731,707.50	100.00
Manufacture of Nonmetallic Mineral Products	9	443,475,957.19	495,780,835.32	43,882,878.12	100.00
Manufacture and Processing of Metals and Metal Products	10	1,806,567,288.97	2,016,258,135.02	174,239,436.91	100.00
Manufacture of Machinery and Equipment	11	133,182,435.40	4,514,658,827.12	2,131,240,393.71	100.00
Construction	12	53,010,579.09	1,927,657,421.34	1,829,064,418.70	100.00
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	614,761,090.72	1,229,522,181.45	438,332,554.17	100.00
Wholesale and Retail Trades, Hotels and Catering Services	14	86,080,577.79	1,314,207,294.54	594,103,198.37	100.00
Real Estate, Leasing and Business Services	15	43,143,239.26	1,120,603,617.22	513,930,784.89	100.00
Financial Intermediation	16	31,216,887.86	810,828,259.25	154,286,204.40	100.00
Other Services	17	70,246,834.93	1,824,593,118.78	1,406,017,460.98	100.00
Total		10,379,167,118.05	23,824,421,421.27	9,263,060,872.09	
		10,379.16	238.24	92.63	
		$x^{P*}=\Sigma X_i^{P*}$ (M.t) ↑	ΣP_i^{P*} (T.CNY) ↑	$\Sigma F_i^{P}*$ (T.CNY) ↑	

Table 8-3-5 Results based on the Part-cooperative model with I-O analysis (2)

The case with the total emission control policy at the level of 10,000 million tons					
Classification	G_0	CO_2 Emission	Total Production		
of Sectors	G_i	(ton)	(10000 CNY)	(10000 CNY)	(10000 CNY)
G_i	i	$\Delta X_i = X_i^{P*}-X_i^*$	$\Delta P_i = P_i^{P*}-P_i^*$	$\Delta SB_i = SB_i^{P*}-SB^*$	$SB_i^{P*}=\Sigma B_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	18,875,967.60	132,930,231.71	-17,841,217.30	21,769,149,453.36
Mining	2	4,331,856.79	5,532,366.05	-19,362,295.51	21,767,628,375.15
Manufacture of Foods, Beverage and Tobacco	3	0	0	0	21,786,990,674.57
Manufacture of Textile, Wearing Apparel and Leather Products	4	0	0	0	21,786,990,674.57
Other Manufacture	5	11,475,739.98	86,609,341.84	-54,160,949.55	21,732,829,721.12
Production and Supply of Electric Power, Heat Power and Water	6	67,374,660.46	15,307,201.42	-291,273,868.26	21,495,716,802.41
Coking, Gas and Processing of Petroleum	7	60,905,707.89	17,371,863.51	-291,366,643.14	21,495,624,027.52
Chemical Industry	8	32,090,066.29	75,064,538.24	-247,643,112.88	21,539,347,557.78
Manufacture of Nonmetallic Mineral Products	9	14,008,158.77	15,660,314.21	-71,765,112.05	21,715,225,558.62
Manufacture and Processing of Metals and Metal Products	10	63,677,072.74	71,068,001.08	-309,645,607.53	21,477,345,063.13
Manufacture of Machinery and Equipment	11	28,031,485.48	950,219,279.23	-718,903,736.88	21,068,086,933.79
Construction	12	14,866,727.00	540,608,254.17	-1,309,664,299.05	20,477,326,371.61
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	63,529,684.19	127,059,358.52	-341,232,311.88	21,445,758,358.78
Wholesale and Retail Trades, Hotels and Catering Services	14	0	0	0	21,786,990,676.37
Real Estate, Leasing and Business Services	15	0	0	0	21,786,990,676.37
Financial Intermediation	16	0	0	0	21,786,990,676.37
Other Services	17	0	0	0	21,786,990,676.37
Total		379,167,118.00	2,037,430,750.61	-3,672,859,123.39	
		37.92	20.37	-36.72	
		$\Sigma \Delta X_i$ (M.t) ↑	$\Sigma \Delta P_i$ (T.CNY) ↑	$\Sigma \Delta SB_i$ (T.CNY) ↑	

Table 8-3-6 Results based on Redistribution model with Equal Acceptance Degree

The case with total emission control policy at the level of 10,000 million tons CO_2				
Classification		With TEC policy : G_i's final gain and tax or subsidy		
of Sectors	G_0	G_0: full cooperative case		
	G_i	γ^*= (0.55472608)	Final profit (gain)	Tax or subsidy
G_i	i	$\Delta\alpha_i$	α_i	t_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	-9,896,988.57	1,339,744,208.84	-122,884,232.85
Mining	2	-10,740,770.33	1,065,869,273.82	5,369,142.88
Manufacture of Foods, Beverage and Tobacco	3	0	1,248,495,883.36	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	0	962,459,748.03	0
Other Manufacture	5	-30,044,491.33	815,205,218.71	-86,609,358.34
Production and Supply of Electric Power, Heat Power and Water	6	-161,577,211.67	497,726,188.37	148,688,327.21
Coking, Gas and Processing of Petroleum	7	-161,628,676.32	426,659,411.96	146,675,916.08
Chemical Industry	8	-137,374,093.70	1,725,731,689.87	64,365,684.00
Manufacture of Nonmetallic Mineral Products	9	-39,809,979.42	455,375,021.45	24,745,491.04
Manufacture and Processing of Metals and Metal Products	10	-171,768,494.62	1,841,918,787.85	103,271,185.62
Manufacture of Machinery and Equipment	11	-398,794,653.17	4,109,895,429.49	-545,456,449.14
Construction	12	-726,504,945.12	1,190,278,904.23	196,770,262.59
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	-189,290,463.36	1,037,398,614.90	65,064,198.17
Wholesale and Retail Trades, Hotels and Catering Services	14	0	1,314,207,294.54	0
Real Estate, Leasing and Business Services	15	0	1,120,603,617.22	0
Financial Intermediation	16	0	810,828,259.25	0
Other Services	17	0	1,824,593,118.78	0
Total		-2,037,430,750.61	21,786,990,670.66	(error 260.87) → 0
(T.CNY)		-20.37	217.87	0

8.3.2 Discussion on the policy scheme

Totally, in the above scheme, because the total emission control policy is enforced by the centralized decision-making approach, the total emission reduction target is reached at the allowed maximum value, i.e., 10,000.00 million tons, and also, the sum of all G_i's profit defined as the social benefit is maximized up to the value of 21,786,990,931.53 (10000CNY), i.e., 217.86 trillion CNY, which is more than that in any part-cooperative case where only G_i is not cooperative. This means that if the G_i cooperates with G_0, the total profit (social benefit) could increase and thus it could be rationally considered that each G_i can make a contribution, to a certain extent, to the increment in social benefit by changing the decision from the not-cooperative attitude to the cooperative one. The increased social benefit makes it possible that G_0 could be expected to provide each G_i with an increment in the G_i's profit due to its cooperation.

As a conclusion, therefore, the results data in Table 8-3-3 to Table 8-3-6 could be proposed as a scheme of total emission control policy, whose details are discussed as follows:

The scheme shows in Table 8-3-3 that the production scale for each sector is respectively allowed to increase up to the 70.90% - 100% of the largest scale. For the 1st sector (Agriculture, Forestry, Animal Husbandry and Fishery) it is 72.6% and the six sectors (the 3rd: Manufacture of Foods, Beverage and Tobacco; the 4th : Manufacture of Textile, Wearing Apparel and Leather Products; the 14th: Wholesale and Retail Trades, Hotels and Catering Services; the 15th : Real Estate, Leasing and Business Services; the 16th: Financial Intermediation; and the 17th : Other Services) do not need to control their production scale even if the total emission control policy is enforced among all sectors. All other sectors have to control the scale to reduce their CO_2 emissions under the total emission control policy (see Table 8-3-3).

Particularly, from Table 8-3-2 and Table 8-3-3, it can be understood that there are three key sectors with the much higher emission intensity, which should take the greatest responsibility to control the CO_2 emission first. The 6th sector (Production and Supply of Electric Power, Heat Power and Water) with the highest emission intensity is supposed to cut the CO_2 emission from 3,693,421,561.49 tons (3.69 billion tons) to 2,845,193,490.34 tons (2.85 billion tons); The 7th sector (Coking, Gas and Processing of Petroleum) is required to decrease its emission from 2,596,906,890.29 tons (2.59 billion tons) to 2,010,113,660.12 tons (2.01 billion tons); And finally the 10th sector

(Manufacture and Processing of Metals and Metal Products) is also needed to reduce its emission from 2,375,405,220.33 tons (2.38 billion tons) to 1,742,890,216.23 tons (1.74 billion tons). The amounts of emission reductions by the three sectors are respectively 28.13%, 19.46% and 20.98% of the total emission reduction which should be decreased by the optimal decision making in the full cooperative case with the total emission control policy.

For other sectors' situations of emission reduction, check Table 8-3-7 below or see Fig.8-3-4 on the next page.

Table 8-3-7 Emission reduction amounts and percentages for 17 sectors

Sectors G_i	i	Emission Reduction ΔX_i (ton)	Percentage (%)
Agriculture, Forestry, Animal Husbandry and Fishery	1	31,467,443.11	1.04
Mining	2	270,437,437.85	8.97
Manufacture of Foods, Beverage and Tobacco	3	6,130,401.44	0.20
Manufacture of Textile, Wearing Apparel and Leather Products	4	4,374,279.17	0.15
Other Manufacture	5	28,704,973.47	0.95
Production and Supply of Electric Power, Heat Power and Water	6	848,228,068.95	28.13
Coking, Gas and Processing of Petroleum	7	586,793,228.18	19.46
Chemical Industry	8	202,694,209.03	6.72
Manufacture of Nonmetallic Mineral Products	9	165,684,830.74	5.49
Manufacture and Processing of Metals and Metal Products	10	632,515,004.10	20.98
Manufacture of Machinery and Equipment	11	38,039,400.48	1.26
Construction	12	15,282,644.92	0.51
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	161,370,009.27	5.35
Wholesale and Retail Trades, Hotels and Catering Services	14	9,889,289.15	0.33
Real Estate, Leasing and Business Services	15	4,264,137.12	0.14
Financial Intermediation	16	5,993,933.81	0.20
Other Services	17	3,684,940.63	0.12
Total (ton)		3,015,554,231.44	100.00
Total (million tons)		3,015.55	

Also note that in Table 8-3-6, the final value of tax t_i is less than zero for some G_i, which means the G_i will be compensated for a loss in profit in the full cooperative case. (Notice: instead of the emission charges or fines, the environmental tax or subsidy concept is used in the computation for the cooperative case. The environmental "tax or subsidy" is such a definition formally similar to, but, conceptually different from, "the emission charges" in the individual decision-making case under the TEC policy, see Section 5.2.3).

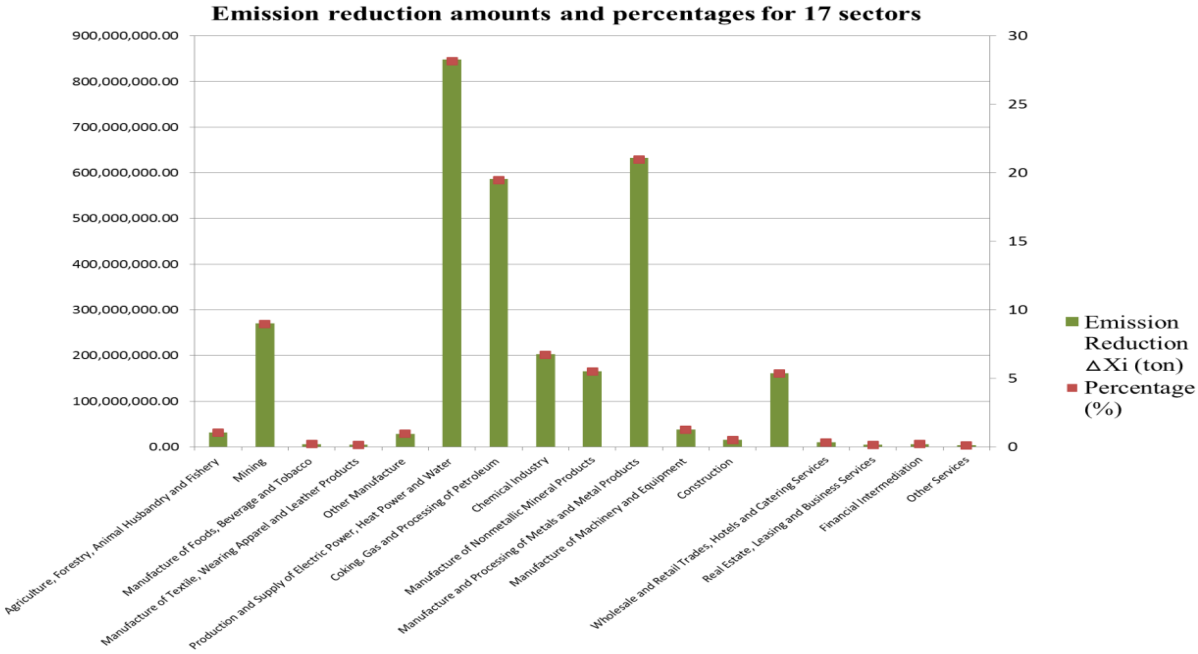


Fig.8-3-4 Emission reduction amounts and percentages for 17 sectors

As a result, most of the sectors should pay a certain amount of tax to the administrator, but inversely, a few of sectors are supposed to receive some subsidy from the administrator. From the results data in Table 8-3-6, specifically, the 1st (Agriculture, Forestry, Animal Husbandry and Fishery), the 5th (Other Manufacture) and the 11th (Manufacture of Machinery and Equipment) sectors should obtain the subsidies, 123,033,243.14 (10000CNY), 56,564,850.51 (10000CNY) and 551,424,626.06 (10000CNY), i.e. 1.23 trillion CNY, 0.56 trillion CNY and 5.51 trillion CNY, respectively.

Also, from Table 8-3-5 and Table 8-3-6, it can be seen that in the part-cooperative case taking no account of the emission cost and the environmental damage compensation, the maximum net profit P_i^{P*} expected individually by each sector gets more than or equal to the final profit α_i in the full-cooperative case, while at the meantime, the corresponding total profit (the social benefit) becomes less than the maximum amount achieved in the full-cooperative case.

On the other hand, however, from the calculated results in Table 8-3-6, it is clearly noted that regarding the final profit of each sector, all $\Delta\alpha_i \leq 0$, which means that the G_i's final profit is no more than the profit expected separately by G_i in the non-cooperative case or part-cooperative case. This is of an implication that all G_i have to pay a cost to some extent for emission X_i so as to satisfy the total emission control target because the each sector's production scale is enforced to be decreased to some extend by implementing the total emission control policy among all the sectors G_i. Therefore, strictly speaking, the scheme is not a stable one. This is discussed below.

Finally, it should be noted that the emission cost (charges) $Tt_i(X_i)$ and the environmental damage $D(\sum X_i)$ have not been taken into account in the above scheme.

8.3.3 Policy design analysis of the scheme

In the following, specifically based on the calculated results, the total emission control policy scheme would be analysed in terms of designing an environmental economic policy. For using the model in simulating an optimal design process, some concepts are introduced here to discuss how to assess or measure the total emission control policy scheme.

As mentioned in the above discussion, from the calculated results, it is seen that the G_i's final profit gained in the full-cooperative case is almost less than the maximum net profit expected by the G_i in the non- or part-cooperative case. Of course, the scheme can be still explained to be a better option for the total emission control policy with these two reasons.

Firstly, the decreased amount of the G_i's final profit (i.e., a profit loss in G_i's expectation) could be considered as a cost for the G_i to have to pay for the responsibility for emission X_i when the total emission control policy is imposed among all sectors G_i by a direct administrative regulation.

And then, the scheme makes the maximum social benefit be achieved and the profit difference between the maximum total profit (social benefit) in the full-cooperative case and the sum of all G_i's maximum profits expected in the part-cooperative case is shared (distributed) among all the cooperative G_i based on the concept "equal acceptance degree". So in such a meaning, the scheme is supposed to be an optimal, fair and rational total emission control policy.

Instead, however, standing on the G_i's side, it is reasonable for each G_i to expect a more profit received in the full-cooperative case than that obtained by taking a not-cooperative attitude. But the computed results show the opposite. So the fully cooperative coalition (the grand coalition) may break up easily and thus it is not an imputation in the cooperative game theory!

In this meaning, the policy scheme is not a "stable" one.

The basic concept on the stability of the TEC policy scheme has been discussed in detail in Section 6.5 of Part Two. Here it is effective too to use the similar concept to define the "stable" conditions for a TEC policy scheme in a multisectoral system as follows.

(i) It makes the total emission reduced or controlled under the allowed maximum value to meet the environmental emission control targets or standards; and meanwhile

(ii) It ensures that a final gain distributed to each player G_i in the cooperative case is no less than the profit which may be expected in the non-cooperative case or the part-cooperative case.

Actually the both conditions can be expressed below respectively by using the model discussed previously.

(a) $\sum_{i=1}^{n} X_i \leq x^{Total}$ and

(b) $\alpha_i \geq v\,(\{\,i\,\})$

However, the above condition (b) is not absolutely satisfied for any case. Because the condition of $\alpha_i \geq v\,(\{\,i\,\})$ is not set in the full-cooperative model, it is possible that there is not a "stable" solution for the total emission control policy. In other words, if the condition (b) is met finally, it means that it is possible for the policy scheme to provide an economic incentive for each sector and the scheme is considered to be a stable one.

Hence, for finding a "stable" scheme, it needs to simulate different policy schemes so as to

(1) make α_i be more, or

(2) make $v\,(\{\,i\,\})$ be less

For the former, in order to make it possible to increase the final profit of each sector, it is absolutely necessary to maximize the total production profit and then redistribute the maximum gain among all sectors by using the environmental tax or subsidy concept in the full cooperation.

Oppositely, as for the latter, it is possible to decrease the each sector's expected profit in the non-cooperative case or part-cooperative case by modifying the adjustable policy factors, such as, in this study, the emissions charges standard, i.e., emission charges function $Tt_i(X_i)$ as policy vector.

Now let's analyse specifically the above policy scheme more concretely.

Shown in Table 8-3-8 and Table 8-3-9 are the emissions and profits, respectively, of each sector for both cases. Fig.8-3-5 and Fig.8-3-6 demonstrate the results intuitively.

Obviously, looking at the detailed data in Table 8-3-8, the sum of each sector's emission expected in each part-cooperative case is 10,379,167,118.05 tons (10,379.16 million tons) which is 379.16 million tons more than the target amount 10,000 million tons. This means that the policy target of total emission control might not be achieved without realizing the overall cooperation.

Meanwhile, the results data in Table 8-3-9 show that the scheme is already the optimal one because it has reached the maximum total profit (maximum social benefit) over all sectors. It is also obvious, however, that although the total profit of all the sectors (social benefit) arrived at the maximum amount, i.e., 217.86 trillion CNY in the full-cooperative case, it is still less than the amount 238.23 trillion CNY, the sum of the maximum profit expected respectively by each sector in the part-cooperative case. The difference in amount is 20.37 trillion CNY, which is considered as a total profit loss in each sector's expectation and shared among all the sectors with the equal acceptance degree. Even if so, the *i*-th sector's final profit α_i distributed in the full-cooperative case is less than or equal to the profit P_i^{P*} expected in the part-cooperative case.

In one other word, the policy scheme does not meet simultaneously the both conditions defined for a stable solution in the cooperative game. Anyway, as a conclusion, the policy scheme is a socially optimal and rationally fair one but not a theoretically "stable" one.

Here in fact, it is worth reminding that the scheme has not been concerned with the environmental emission cost and the environmental damage compensation from the sector G_i. Phrased in another way, if it is realistic to impose some proper emission charges regulation or policy included in the simulating computation, there would be a possibility to calculate and simulate a "stable" policy scheme.

Regarding how to design a stable policy scheme, it will be furtherly discussed in Section 10.2 of Chapter 10.

Table 8-3-8 Stability of the policy scheme (1): comparison on **Emissions** in each case

The case with total emission control policy at the level of 10,000 million tons CO_2					
Classification of Sectors		Without TEC	With TEC policy		
	G_0	Non-	Part-	Full-cooperative case	
		Individual decision-making by G_i		Centralized decision-making by G_0	
	G_i	Maximum emission	Expected emission	Optimal emission allocation	Reduced emission
G_i	i	X_i^0 $(=X_i^{t*})$	X_i^{P*}	X_i^*	$\Delta X_i^*=X_i^{P*}-X_i^*$
Agriculture, Forestry, Animal Husbandry and Fishery	1	204,261,559.90	191,670,084.19	172,794,116.59	18875967.6
Mining	2	1,109,217,119.10	843,111,537.07	838,779,680.27	4,331,856.80
Manufacture of Foods, Beverage and Tobacco	3	109,131,322.24	103,000,910.38	103,000,920.76	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	75,115,069.69	70,740,791.48	70,740,790.65	0
Other Manufacture	5	125,243,925.02	108,014,691.48	96,538,951.50	11,475,739.98
Production and Supply of Electric Power, Heat Power and Water	6	3,693,421,561.49	2,912,568,150.81	2,845,193,490.34	67,374,660.47
Coking, Gas and Processing of Petroleum	7	2,596,906,890.29	2,071,019,368.02	2,010,113,660.12	60,905,707.90
Chemical Industry	8	967,960,838.06	797,356,693.62	765,266,627.33	32,090,066.29
Manufacture of Nonmetallic Mineral Products	9	595,152,629.28	443,475,957.19	429,467,798.42	14,008,158.77
Manufacture and Processing of Metals and Metal Products	10	2,375,405,223.63	1,806,567,288.97	1,742,890,216.23	63,677,072.74
Manufacture of Machinery and Equipment	11	143,190,350.34	133,182,435.40	105,150,949.92	28,031,485.48
Construction	12	53,426,497.01	53,010,579.09	38,143,852.09	14,866,727.00
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	712,601,415.69	614,761,090.72	551,231,406.53	63,529,684.19
Wholesale and Retail Trades, Hotels and Catering Services	14	95,969,866.41	86,080,577.79	86,080,577.74	0
Real Estate, Leasing and Business Services	15	47,407,376.11	43,143,239.26	43,143,238.96	0
Financial Intermediation	16	37,210,821.47	31,216,887.86	31,216,887.66	0
Other Services	17	73,931,775.66	70,246,834.93	70,246,834.92	0
Total		13,015,554,241.39	10,379,167,118.05	10,000,000,000.05	379,167,118.00
Total emission ΣX_i	mt	13,015.56	10,379.16	10,000.00	379.16
TEC target x^{Total}	mt		10,000.00	10,000.00	0.00

Table 8-3-9 Stability of the policy scheme (2): comparison on **Profits** in each case

The case with total emission control policy at the level of 10,000 million tons CO_2					
Classification of Sectors	G_0	Without TEC	With TEC policy: Non-	Part-	Full-cooperative case
		Individual decision-making		Centralized decision-making	
	G_i	Maximum $v(\{i\})$	Expected $v(\{i\})$	Optimal $v(N)=\Sigma P_i^*$	Final gain $\gamma(i)=\gamma^*$
G_i	i	P_i^0 $(=P_i^{t*})$	P_i^{P*}	P_i^*	α_i^*
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,367,630,542.56	1,349,789,325.26	1,216,859,975.99	1,339,744,208.84
Mining	2	1,096,133,096.36	1,076,770,800.85	1,071,238,416.70	1,065,869,273.82
Manufacture of Foods, Beverage and Tobacco	3	1,248,495,883.36	1,248,495,883.36	1,248,496,009.24	1,248,495,883.36
Manufacture of Textile, Wearing Apparel and Leather Products	4	962,459,748.03	962,459,748.03	962,459,736.69	962,459,748.03
Other Manufacture	5	815,205,218.71	815,205,218.71	728,595,860.37	815,205,218.71
Production and Supply of Electric Power, Heat Power and Water	6	952,995,588.31	661,721,720.05	646,414,515.58	497,726,188.37
Coking, Gas and Processing of Petroleum	7	882,073,821.70	590,707,178.56	573,335,328.04	426,659,411.96
Chemical Industry	8	2,112,804,969.30	1,865,161,856.42	1,790,097,373.87	1,725,731,689.87
Manufacture of Nonmetallic Mineral Products	9	567,545,947.37	495,780,835.32	480,120,512.49	455,375,021.45
Manufacture and Processing of Metals and Metal Products	10	2,325,903,742.55	2,016,258,135.02	1,945,189,973.47	1,841,918,787.85
Manufacture of Machinery and Equipment	11	5,233,562,564.00	4,514,658,827.12	3,564,438,980.35	4,109,895,429.49
Construction	12	3,237,321,720.39	1,927,657,421.34	1,387,049,166.82	1,190,278,904.23
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,570,754,493.33	1,229,522,181.45	1,102,462,813.07	1,037,398,614.90
Wholesale and Retail Trades, Hotels and Catering Services	14	1,314,207,294.54	1,314,207,294.54	1,314,207,293.75	1,314,207,294.54
Real Estate, Leasing and Business Services	15	1,120,603,617.22	1,120,603,617.22	1,120,603,609.33	1,120,603,617.22
Financial Intermediation	16	810,828,259.25	810,828,259.25	810,828,250.87	810,828,259.25
Other Services	17	1,824,593,118.78	1,824,593,118.78	1,824,593,114.88	1,824,593,118.78
Total		27,443,119,625.76	23,824,421,421.27	21,786,990,931.53	21,786,990,670.66
(T.CNY)		274.43	238.24	217.87	217.87
Total emission ΣX_i	mt	13,015.56	10,379.16	10,000.00	

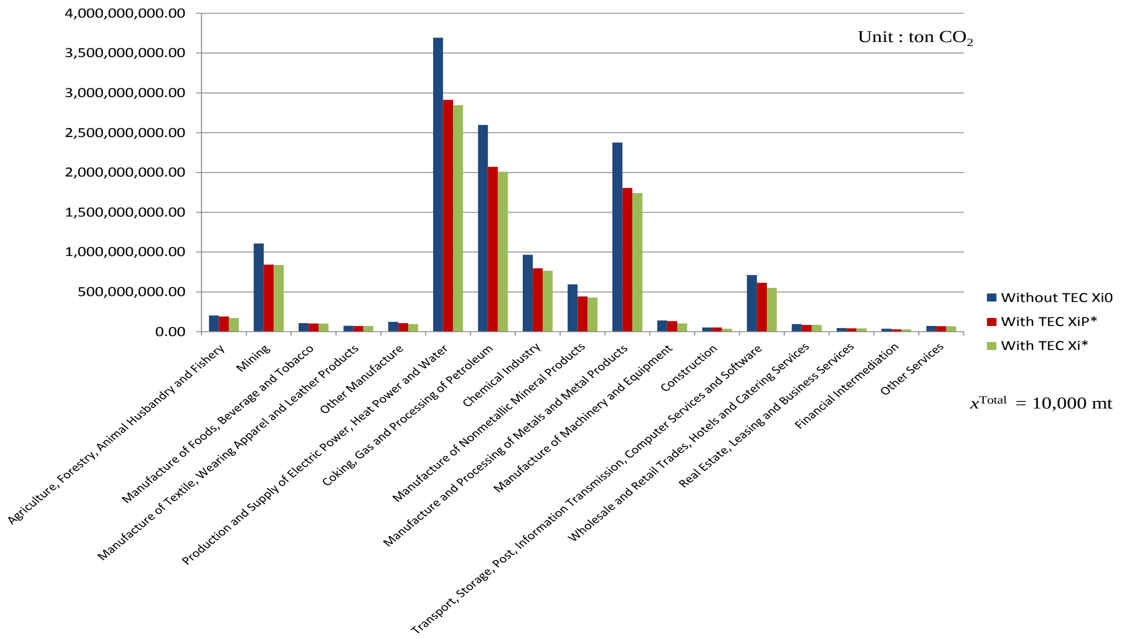


Fig.8-3-5 Stability of the policy scheme (1): comparison on **Emissions** in each case

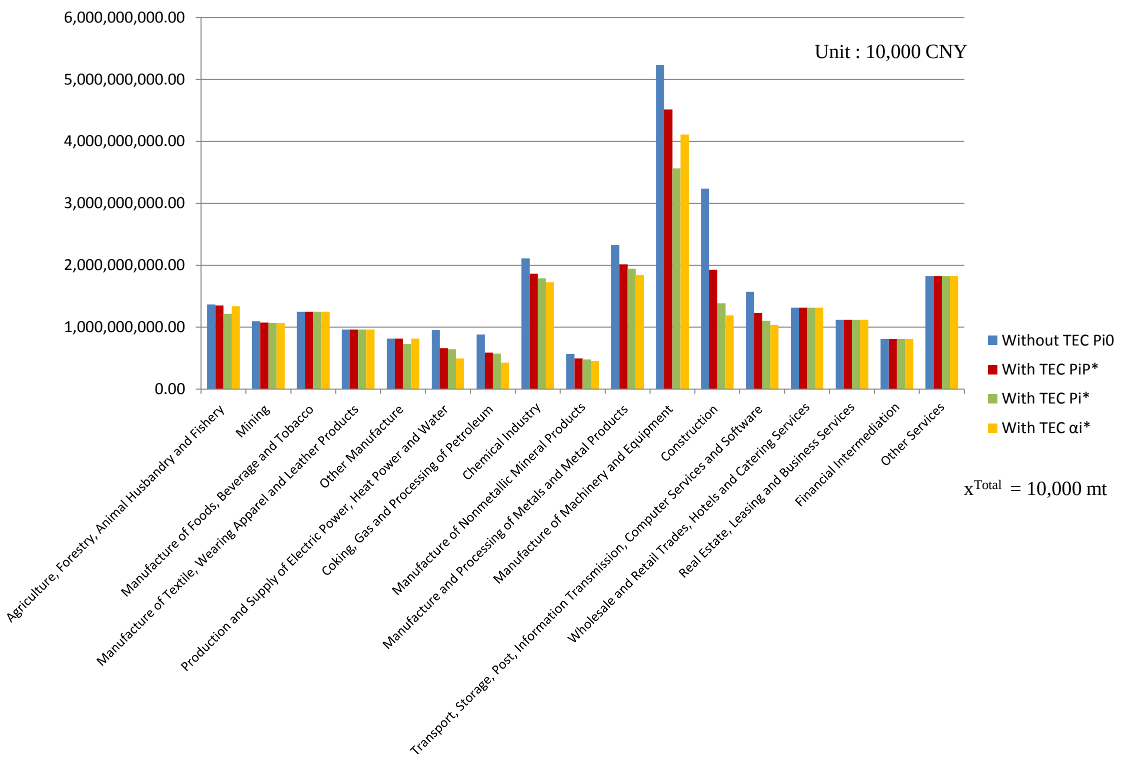


Fig.8-3-6 Stability of the policy scheme (2): comparison on **Profits** in each case

9. Impact analysis based on the TEC model

In the above, this study has focused on discussion and analysis about how to design methodologically a specific policy scheme by simulating computation based on the TEC model. This chapter shows how to investigate and predict the impacts on CO_2 emissions over sectors if some related sector's emission intensity coefficient is improved to a certain extent by technological innovations. Actually, the topic can be basically described by using the extended TEC model with the input-output analysis.

In this chapter, discussion is emphasized on how to adjust the relative emission coefficients to reflect the technological improvement due to an innovation or a technology transfer from some advanced country. Regarding the impact analysis topic, these two aspects of the application are furtherly discussed on policy analysis by using the model from a viewpoint of policy design. It can be expected to discuss them by choosing the 6^{th} sector (Production and Supply of Electric Power, Heat Power and Water) as an example in simulation because the sector is the most crucial one in reducing CO_2 total emission in China. Furthermore, the chapter also aims to verify the effects expected by the carbon market with the initial phase covering the power sector only in China.

Specifically, in Section 9.1, the data of the sector with the highest emission share are used as an example to investigate the impact of the key sector's technological innovation on all other sectors' emissions in a multisectoral system. And then in Section 9.2, furtherly based on the same sector's data, the impact analysis is also carried out by considering a technology transfer from some advanced country. In Section 9.3, finally, as the model's more important application the impact analysis is emphased on the expected effects of the power sector in the ETS market in China.

9.1 Impact analysis of the technological innovation on emissions

As time ticks away for drastically reducing global greenhouse gas (GHG) emissions, a low-carbon technological change is ever more important for meeting the future targets of emission reduction and minimizing the cost of the effort (Fischer C., et al, 2003; Fuss S., et al., 2018; Jordi T., et al., 2019).

Large scale diffusion of low carbon technologies (LCTs) is a significant element of strategies to mitigate climate change (Jin H., et al., 2008; Wang Lina, 2011; Doris F., 2012; Jin W., et al, 2016; Ranasinghe K., et al., 2019).

9.1.1 Introdution

From the results data of the CO_2 emission reduction share in Table 8-3-7, it can be seen that the 6^{th} sector (Production and Supply of Electric Power, Heat Power and Water) has the highest percentage of CO_2 emission reduction on the total emission among the 17 sectors and is supposed to be most responsible for reducing the total CO_2 emission under the TEC policy.

In fact, this exactly conforms to the actual situation in China.

According to the report released by Ju C. (2018), it is known that the industry related to Electric Power and Heat Power is the key sector with the most emissions among all economic sectors (Cai W., et al., 2007; Cui H., et al., 2018; Lin X., et al., 2019; Wang B.J., et al., 2019).

In incomplete statistics, China currently consumes more than 1.8 billion tons of coal in thermal power generation per year, accounting for 47% of total coal consumption and produces more than 4.7 billion tons of carbon dioxide per year. And in the country, there are nearly 480,000 units of coal-fired heating industrial boilers, and about 130,000 units of a variety of kilns, which generate about 750 million tons of coal consumption yearly. The total carbon emissions from the two items of thermal power generation and industrial boilers accounted for more than 87% of the total emissions (and by the way, the sulfur dioxide emissions accounted for more than 40% of the total national emissions), which have been becoming a serious source of atmospheric pollutant emissions in China, presently (Ju C., 2018; Lindner S., et al., 2013; Wang C., et al, 2005).

With such a situation in the industry related to electric power and heat power, The National Development and Reform Commission (NDRC) of China launched the national carbon market, which would be starting by 2018-2019 firstly in the electric power industry as a trial operation.

The national carbon market has been designed as to match the policy progress of formulating and implementing the target of greenhouse gas emission control in China. In 2011, the National Development and Reform Commission (NDRC) issued “The Notices on Carbon Emission Rights Trading Pilot Project”, and then launched 7 pilots of domestic carbon emission rights trading. In November 2013, the establishment of the national carbon market was included as one of the key tasks of deepening reform overall.

In December 2014, the NDRC issued “The Interim Method for Management of Carbon Emission Rights Transactions” as to establish the overall framework of the national carbon market. In September 2015, with “Joint Declaration on Climate Change of China and United States”, the China’s government proposed that China would launch a national carbon trading system in 2017. In December 2017 the NDRC issued the program establishing National Carbon Emissions Rights Trading Market (NCERTM) (for Electric Power Industry), which marks the officially trial operation of the national carbon market (Wang K., 2018).

9.1.2 Effects of the key sector in the carbon trading market

Why is the China’s carbon trading market designed to begin the trial system from the electric power industry at first?

In recent years, the attention on greenhouse gas (GHG) emissions reduction has increased dramatically, and particularly, the electric power industry as electricity generation system would be the largest single source of GHG emissions globally (Imran K., 2019). With Cap and Trade programs, the European Union and the northeastern United States have taken initiatives which are proved to be effective since they target the sources of emissions, including thermal power plants (Jurate J. & Corrado D.M., 2012; Tokyo, 2010; 栗山昭久, 2019). Power sector is one of the most important sources of carbon emissions and a critical one for reducing total carbon emissions both in the world and in China (Elke L.H., et al., 2018; Jaraite J., et al., 2012; Michael W.W., et al., 2008).

Especially in China, the power sector accounts for more than 70% of the total carbon emissions, and the thermal power generation accounts for nearly 50% of carbon emissions. Thus the power sector should be included in carbon emissions control programs (IEA, 2017; Liu et al., 2018; Wu J., et al. 2019).

From the policy design scheme issued by The National Development and Reform Commission (NDRC, 2015), it can be seen that at this stage China does not let the carbon trading market cover the whole industry, but let it begin from the electric power sector, and push it away gradually. Li G. (2018), director of the Climate Division of the NDRC, reported that China would choose the power generation or electricity industry as a breakthrough to start the national carbon trading system in the first batch, and then spread widely into all the resources industries with high energy consumption and high emissions, such as petrochemical, chemical, building materials, steel, nonferrous, paper and aviation. The main reasons are as follows.

First, the database of the power generation industry is relatively good and the products in the sector's products are single ones, mainly including the two categories of heat and electricity. Thus, the emission data measurement facilities are complete, and data management norms are easy to verify, and then the quota allocations are simple and easy to be decided.

Second, the industry's total emissions are extremely large. There are about 1700 enterprises of first batch into the market, and their total emissions are more than 3 billion tons. By the way, the annual emissions on the EU carbon market are only about 2 billion tons, which is much less than that from the top 1700 plants (enterprises) of the electric industry in China.

Third, the management system is relatively completely established and in the industry there are mainly large enterprises. This is easy to manage the whole industry's total emissions.

Fourth, from the international experience, the carbon markets over all countries usually give a priority to the industry related to electric power.

Zhang X. (2017) pointed out that to launch the national carbon market by choosing the power industry as the leading industry is a breakthrough in establishing the National Carbon Trading System (NCTS), and a number of key emission industries will be gradually included in the future. The NCTS will cover petrochemical, chemical, building materials, steel, nonferrous, paper, electricity, aviation and other key emission industries in the future. Zhang (2018) stressed that among these industrial sectors there are about 7,000 enterprises with annual energy consumption equal to or more than 10,000 tons of standard coal. It is estimated that the total emissions of these 7,000 enterprises account for more than 75% percent of the carbon emissions of all the industrial sectors. Thus, the total emission control of the 7,000 enterprises' emissions is certainly considered to be a key policy for controlling the bulk of carbon emissions in the industrial sectors meanwhile limiting the governmental management costs within an acceptable level (Zhang X. & Qi Y., 2017; Zhou R., 2018).

The Program Establishing National Carbon Emissions Rights Trading Market (NCERTM) (for Electric Power Industry) has been issued and already scheduled for implementation by The National Development and Reform Commission (NDRC) of China. In 2018, as the period for constructing the foundation of the national carbon market, the key task is to complete the national data submission system, registration system and trading system. In 2019 as the simulating operation period, the task is to focus on the quota transactions in electric power industry and to test comprehensively the effectiveness and reliability of the various elements of the market. In 2020, as a period of development and improvement, the quota spot trading is carried out among the trading entities of the electric power industry, and the transaction is aimed only at fulfilment of emission reduction obligations. The China’s State Council proposed that in 2020 the national carbon trading market should be in operation under a "perfect, open and transparent system with active trading and meanwhile strict supervision" (Wang K., 2018).

Because of the above situation, The China’s National Carbon Emissions Rights Trading Market (NCERTM) has been planned to begin with the trial operation only for the electric power industry during 2019-2020. It would be interesting and meaningful to analyse predictively what effects will be resulted from the initial operation in the electric power industry.

Of course, this study does not mean to forecast how much the sector’s emissions will be reduced by operating the national carbon trading market. This is actually unrealistic and impossible without enough various data of the enterprises or plants in the electric power sector. However, it can be assumed that the national market will be promoting the enterprises’ technological innovations to increase their energy efficiencies in producing process, and as a result of the innovations, it is expected to make an average progress or improvement in the emission intensity over the industry, which means a decrease of emission per unit of production profit in the industry on average. And then, due to the reduction of the emission intensity in the electric power industry firstly, the emissions of the other industries are supposed to be impacted by interactions with each other and finally the total emission of all the industries in the country will be controlled under a certain level. This would be exactly the idea and objective of the China’s carbon trading market.

Here therefore, this chapter is to apply the TEC model with Sector No.6 (Electric Power, Heat Power and Water) as an example in simulation to demonstrate the impacts of improving the sector’s emission intensity on the allocations of the total emission among all the other sectors. In other words, the impacts analysis in the chapter is to reflect and estimate quantitatively what effects the carbon trading market’s initial operation in the electric power industry would be making to the total emission reduction under the TEC policy in China (Zhang L., et al., 2018).

9.1.3 Results and discussion

Although there are not the exactly suitable data to indicate how the sector will be improving the related technologies to reduce the CO_2 emission intensity in the coming years, it might be reasonably assumed that the emission intensity in the sector would have been declined or improved by 20%, 40%, 60% and 80% respectively.

With the same TEC policy target of 10,000 million tons, the extended optimal TEC model is applied to simulate the schemes for those cases with the different CO_2 emission intensity in the sector.

The calculated results are briefly shown in Table 9-1-1 and visually demonstrated in Fig.9-1-1 to Fig.9-1-4.

In the table $\triangle P_i = P_i^{\beta} - P_i^{*}$, $\triangle F_i = F_i^{\beta} - F_i^{*}$, $\triangle X_i = X_i^{\beta} - X_i^{*}$, where P_i^{β}, F_i^{β} and X_i^{β} are the results simulated with the improved emission intensity β_6 of Sector No.6, and P_i^{*}, F_i^{*} and X_i^{*} are the results with the initial emission intensity of the sector (see Table 8-3-3 in Chapter 8). Table 9-1-1 represents, respectively, the changes on total production, final use and CO_2 emission allocation of each sector which resulted from changes in emission intensity coefficients of Sector No.6.

As shown in the table, for Sector No.6 (Production and Supply of Electric Power, Heat Power and Water), there is a huge CO_2 emission reduction potential, and it is basically necessary to improve the abatement technology in the sector so as to decline the CO_2 emission per unit of production.

For instance, when the emission intensity is improved by 20% in the sector, the amount of its own emission will decrease by 499 million tons, which meanwhile will have a strong influence and result in changes on the amounts of emissions of all the other sectors. As a result, even if keeping the same TEC target at the level of 10,000 million tons, the production profit and the final use in total of all the sectors will increase by 13,975 billion CNY, and 4,397 billion CNY, respectively.

As for the other three situations with the emission intensity improvement by 40%, 60% or 80%, there are the similar effects on all the sectors' emission allocations of the total emission. The more the improvement is made, the stronger the effect is.

For more details about the cases with the emission intensity improved by 10% - 90%, respectively, see Table 9-1-2 to Table 9-1-4.

Table 9-1-1 Impact of changes in emission intensity β_i of Sector No.6 (electric, heat power and water) on each sector's production profit P_i , final use F_i and emission X_i

Sector	20% reduction in emission intensity			40% reduction in emission intensity			60% reduction in emission intensity			80% reduction in emission intensity		
G_i	ΔP_i	ΔF_i	ΔX_i	ΔP_i	ΔF_i	ΔX_i	ΔP_i	ΔF_i	ΔX_i	ΔP_i	ΔF_i	ΔX_i
i	(B.CNY)		(MT)	(B.CNY)		(MT)	(B.CNY)		(MT)	(B.CNY)		(MT)
1	1,619	1,110	25	1,803	1,110	28	2,008	1,110	31	2,213	1,110	34
2	634	0	53	1,409	0	114	2,346	0	187	3,350	51	266
3	345	0	4	477	0	5	594	0	6	739	0	7
4	213	0	2	401	0	3	507	0	4	594	0	5
5	1,147	641	16	1,484	641	21	1,916	641	26	2,162	641	30
6	**391**	**0**	**-499**	**825**	**0**	**-988**	**1,294**	**0**	**-1,547**	**1,911**	**151**	**-2,175**
7	282	0	120	582	0	225	943	0	351	1,537	102	560
8	1,150	0	63	2,217	0	108	3,092	0	146	4,724	660	216
9	109	0	11	383	0	35	1,465	0	132	1,849	128	167
10	1,558	0	149	3,695	0	340	5,586	0	510	7,044	507	640
11	4,831	2,646	15	11,253	6,201	34	12,121	6,201	36	12,875	6,201	39
12	13	0	0	605	560	2	4,901	4,712	14	5,557	5,322	15
13	426	0	28	915	0	52	1,415	0	77	3,217	1,275	167
14	432	0	4	895	0	7	1,225	0	9	1,503	0	11
15	261	0	1	561	0	3	835	0	4	1,100	0	5
16	349	0	2	753	0	3	1,166	0	5	1,548	0	6
17	214	0	7	474	0	8	781	0	9	953	0	9
sum	13,975	4,397	0	28,733	8,512	0	42,195	12,664	0	52,874	16,148	0

(ΔP_i and ΔF_i : billion CNY; ΔX_i : million tons)

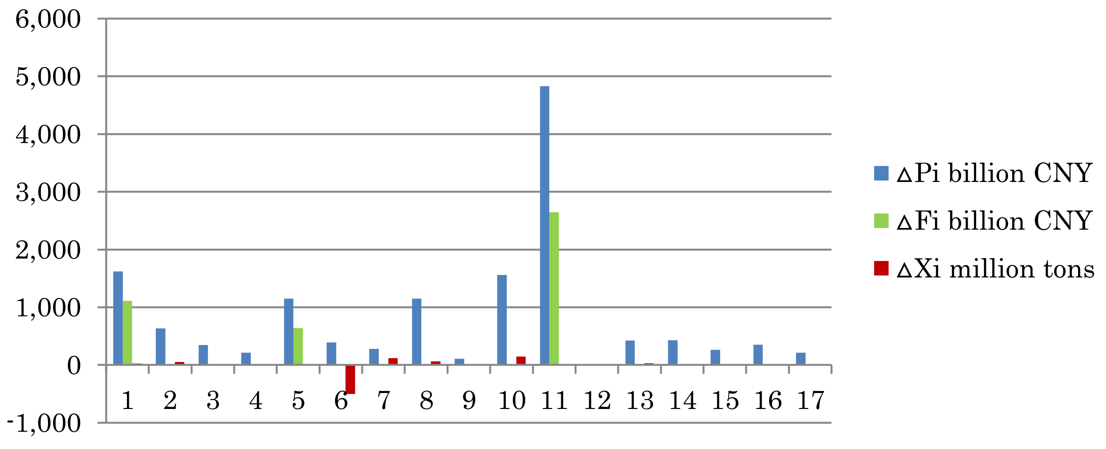


Fig.9-1-1 Impact of changes in emission intensity β_i of Sector No.6 for 20%

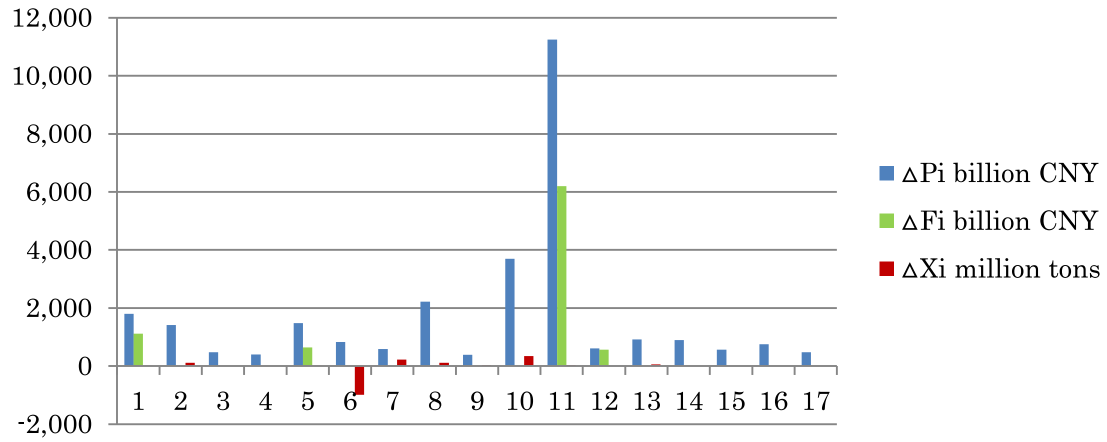


Fig.9-1-2 Impact of changes in emission intensity β_i of Sector No.6 for 40%

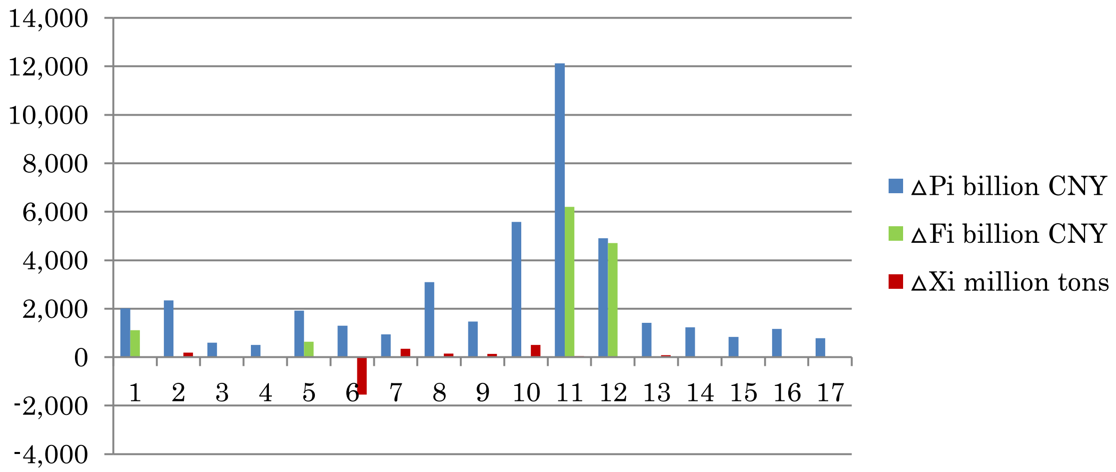


Fig.9-1-3 Impact of changes in emission intensity β_i of Sector No.6 for 60%

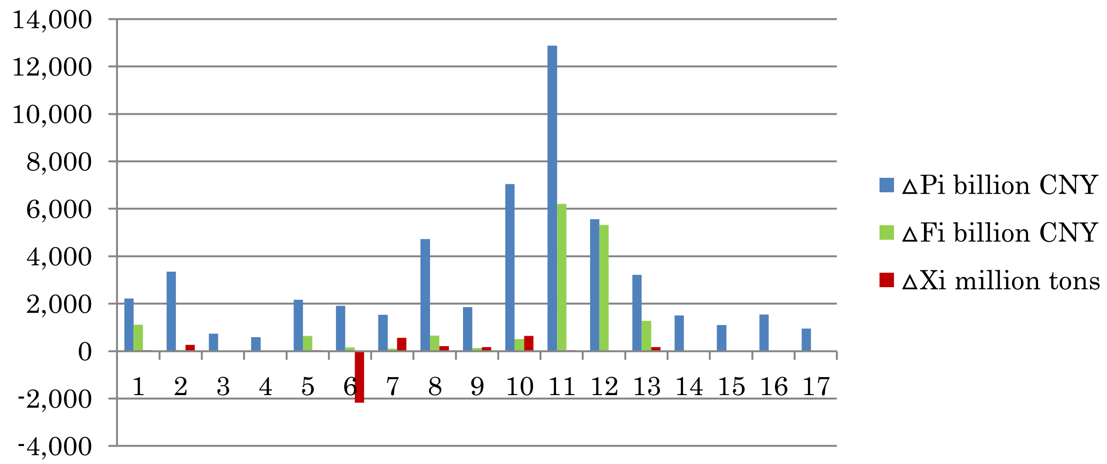


Fig.9-1-4 Impact of changes in emission intensity β_i of Sector No.6 for 80%

Table 9-1-2 Impact of changes in the emission coefficients β_i of Sector No.6 (electric, heat power and water) on each sector's Total Production P_i (billion CNY)

G_i	$\Delta P_i = P_i^{\beta} - P_i^{*}$								
	Percentage of reduction in emission intensity of sector No.6								
i	10%	20%	30%	40%	50%	60%	70%	80%	90%
1	1,535	1,619	1,663	1,803	1,902	2,008	2,160	2,213	2,216
2	285	634	817	1,409	1,863	2,346	2,771	3,350	3,454
3	282	345	377	477	534	594	696	739	743
4	120	213	262	401	452	507	565	594	595
5	997	1,147	1,226	1,484	1,693	1,916	2,050	2,162	2,166
6	191	391	495	825	1,052	1,294	1,513	1,911	1,927
7	147	282	353	582	757	943	1,227	1,537	1,674
8	639	1,150	1,417	2,217	2,641	3,092	4,514	4,724	4,741
9	40	109	145	383	907	1,465	1,655	1,849	1,852
10	544	1,558	2,088	3,695	4,611	5,586	6,021	7,044	7,059
11	1,437	4,831	6,606	11,253	11,673	12,121	12,533	12,875	12,895
12	6	13	17	605	2,686	4,901	5,546	5,557	5,557
13	199	426	545	915	1,157	1,415	2,454	3,217	3,227
14	206	432	550	895	1,055	1,225	1,396	1,503	1,510
15	120	261	335	561	694	835	993	1,100	1,108
16	161	349	447	753	953	1,166	1,380	1,548	1,557
17	96	214	276	474	623	781	887	953	957
sum	7,005	13,975	17,619	28,733	35,254	42,195	48,358	52,874	53,239

Table 9-1-3 Impact of changes in emission coefficients β_i of Sector No.6 (electric, heat power and water) on the each sector's Final Use F_i (billion CNY)

G_i	$\Delta F_i = F_i^{\beta} - F_i^{*}$								
	Percentage of reduction in emission intensity of sector No.6								
i	10%	20%	30%	40%	50%	60%	70%	80%	90%
1	1,110	1,110	1,110	1,110	1,110	1,110	1,110	1,110	1,110
2	0	0	0	0	0	0	0	51	51
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	641	641	641	641	641	641	641	641	641
6	0	0	0	0	0	0	0	151	151
7	0	0	0	0	0	0	0	102	220
8	0	0	0	0	0	0	660	660	660
9	0	0	0	0	0	0	0	128	128
10	0	0	0	0	0	0	0	507	507
11	732	2,646	3,647	6,201	6,201	6,201	6,201	6,201	6,201
12	0	0	0	560	2,571	4,712	5,322	5,322	5,322
13	0	0	0	0	0	0	727	1,275	1,275
14	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0
sum	2,483	4,397	5,398	8,512	10,524	12,664	14,662	16,148	16,267

Table 9-1-4 Impact of changes in emission coefficients β_i of Sector No.6 (electric, heat power and water) on the each sector's CO_2 Emission X_i (million tons)

G_i	$\Delta X_i = X_i^\beta - X_i^*$								
	Percentage of reduction in emission intensity of sector No.6								
i	10%	20%	30%	40%	50%	60%	70%	80%	90%
1	24	25	26	28	29	31	33	34	34
2	26	53	67	114	149	187	220	266	274
3	3	4	4	5	5	6	6	7	7
4	1	2	2	3	4	4	5	5	5
5	14	16	17	21	23	26	28	30	30
6	-276	-499	-615	-988	-1,258	-1,547	-1,859	-2,175	-2,543
7	72	120	145	225	286	351	451	560	608
8	41	63	74	108	127	146	207	216	216
9	5	11	14	35	82	132	149	167	167
10	58	149	196	340	423	510	549	640	642
11	5	15	20	34	35	36	38	39	39
12	0	0	0	2	7	14	15	15	15
13	16	28	34	52	64	77	129	167	168
14	2	4	4	7	8	9	10	11	11
15	1	1	2	3	3	4	4	5	5
16	1	2	2	3	4	5	6	6	6
17	6	7	7	8	8	9	9	9	9
sum	0	0	0	0	0	0	0	0	-309

However for the situation with the sector's emission intensity reduced by 90%, the result is a different and has a special meaning.

From the last number in the above table, it can be seen that the sum of the 17 sectors' emissions is – 309 million tons, which implies that the total emission of the TEC scheme with Sector No.6's emission intensity reduced by 90% will be 309 million tons less than the 10,000 million tons set as the target for the TEC policy. If the policy target is to control the total emission just at the level of 10,000 million tons, there is an extra room for the total CO_2 emission and thus the TEC policy scheme should not be considered as an optimal one maximizing the total profits (social benefit).

In such a meaning, when the electric power sector's emission intensity is improved by 90% due to the technological innovations, there would be two ways to adjust the TEC policy in order to realize an optimal scheme. One is to set a stricter TEC policy target to better protect the environment. The other is to set a bigger initial range for some sector's final use (final demand) and allow some sectors to grow faster on average to pursue a more total production profit.

If expressed in another way, the result implies that if the technological innovations take place to improve the energy efficiency and reduce the existing emission intensity by about 90% and more in the electric power industry, it could be completely realistic for China's economy to keep developing with a greater growth even if the CO_2 total emission control policy target is kept at the same level of 10,000 million tons.

9.2 Impact analysis of the technology transfer on emissions

9.2.1 Introduction

It is notable that from the simulated results in the above section, there would be gradually greater impacts of decreasing the electric power sector's emission intensity coefficient by 10% - 90% on all other sectors' emissions and production profits.

But here, the questions below could be asked naturally that at last, to what extent the technological innovations could reduce the emission intensity in the electric power industry, to what extent this could influence on the emissions of all the other sectors, and then to what extent it could bring the total economic profit at most.

In this section, the topic is indeed discussed in a different angle by comparing the situations between China and some technologically advanced country such as Japan.

Although there is a lack of the detailed data that can demonstrate the differences between China and Japan respectively for each sector's carbon emission control technology, it is obviously easy to understand from the data in Table 9-2-1 (Li Q., 2017), that indeed there is still a great difference on technological innovations of controlling carbon emissions even if the data here are for carbon emissions in producing the exported products.

Anyway, at least, it could be assumed that the technology transfer in the electric power industry would have taken place from Japan to China presently and the CO_2 emission intensity in the sector in China has been lessened to the same level as in Japan (Adrian L., et al., 2016; Rasmus L. et al., 2012; 段海燕, 2016). If choosing Sector No.6 (Production and Supply of Electric Power, Heat Power and Water) as an example, then, it is just needed to find the corresponding data of the electric power industry in Japan.

9.2.2 Data and results

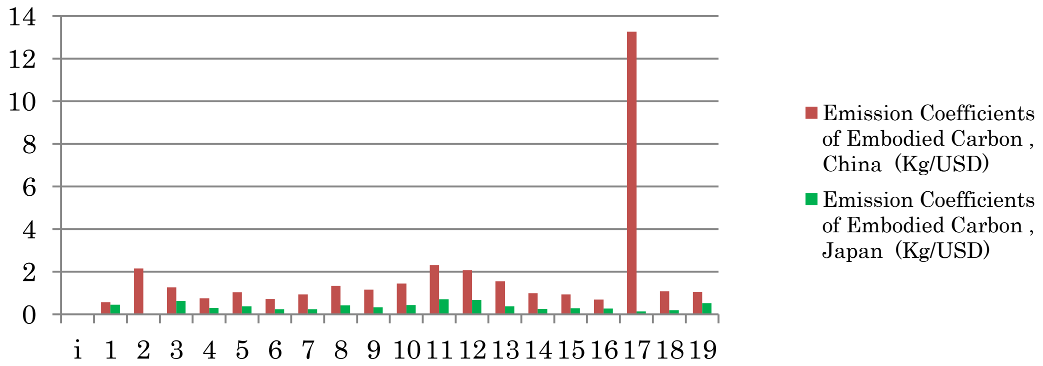
Fortunately the data are found regarding the emission (intensity) coefficients of embodied carbon in trade of China and Japan (see Table 9-2-2). Strictly speaking, it is not thought that the data are exactly correct to reflect the actual situation in Japan, but since the selected sector is relatively close to that in Japan in terms of industries' classification, the data might be used in the empirical application to explain methodologically the impacts on the emissions of all the sectors in China if improving the electric sector's emission intensity to the same level as in Japan by technology transfer (Duan H. et al., 2016).

Table 9-2-1
Embodied carbon in trade of China and Japan with countries along the belt and road (mt)

	China			Japan		
Year	Embodied carbon in export	Embodied carbon in import	Embodied carbon in net export	Embodied carbon in export	Embodied carbon in import	Embodied carbon in net export
2004	316. 32	195. 85	120. 47	77. 87	150. 90	-73. 03
2007	526. 87	230. 95	295. 92	98. 91	145. 43	-46. 52
2011	621. 95	321. 66	300. 29	95. 68	152. 71	-57. 02

注：由于保留两位小数点，隐含碳净出口可能与出口隐含碳和进口隐含碳之差存在细微误差
Data Source: Li Qingru, 2017, The Embodied Carbon in Trade of China and Japan with Countries along the Belt and Road and Their Determinants [J], (in Chinese), Journal of Contemporary Economy of Japan, 2017 (4):69-84

In Table 9-2-2 and Fig.9-2-1 are shown the comparison data on the emission coefficients of embodied carbon in trade of China and Japan that are provided by the source (Li Q., 2017). The data in Kg/CNY are calculated with the rate of 6.5 CNY/USD in the table. In the simulation, the Japanese coefficient in the sector (Electric Power, Heat Power and Water) is adopted as an approximately estimated value for the corresponding sector in China. That is, to set the 6th sector's emission coefficient β_6 = 0.0215 $KgCO_2$/CNY.



Data Source: Li Qingru, 2017, The Embodied Carbon in Trade of China and Japan with Countries along the Belt and Road and Their Determinants [J], (in Chinese), Journal of Contemporary Economy of Japan, 2017 (4):69-84

Fig.9-2-1 Emission coefficients of embodied carbon in trade of China and Japan

Table 9-2-3 and Fig.9-2-2 show the results by setting the 6th sector's emission coefficient β_i to the level of the corresponding data in Japan, based on the full-cooperative model under the same TEC policy target of 10,000 million tons.

And then Table 9-2-4 and Fig.9-2-3 show the impact by adjusting the 6th sector's emission coefficient β_i to the data in Japan

Table 9-2-2 Emission coefficients of embodied carbon in trade of China and Japan

No.	Sectors	Emission Coefficients of Embodied Carbon				
		China		Japan		China / Japan
i		(Kg/USD)	(Kg/CNY)	(Kg/USD)	(Kg/CNY)	
1	农林牧渔 Agriculture, forestry, animal and fishery	0.57	0.0877	0.46	0.0708	1.24
2	能源 Energy	2.15	0.3308	n/a	n/a	n/a
3	其他资源 Other resources	1.27	0.1954	0.63	0.0969	2.02
4	食品加工 Food processing	0.76	0.1169	0.30	0.0462	2.53
5	纺织服装 Textile and garment	1.04	0.1600	0.38	0.0585	2.74
6	皮革制品 Leather Products	0.72	0.1108	0.24	0.0369	3.00
7	木制品 Wood Products	0.94	0.1446	0.25	0.0385	3.76
8	造纸印刷 Paper printing	1.34	0.2062	0.42	0.0646	3.19
9	煤炭和石油制品 Coal and petroleum products	1.16	0.1785	0.33	0.0508	3.52
10	化学工业 Chemical industry	1.45	0.2231	0.44	0.0677	3.30
11	非金属矿业制品 Non-metallic mining products	2.32	0.3569	0.71	0.1092	3.27
12	钢铁和有色金属 Steel and non-ferrous metals	2.08	0.3200	0.68	0.1046	3.06
13	金属制品 Metal products	1.55	0.2385	0.38	0.0585	4.08
14	运输设备 Transportation equipment	1.00	0.1538	0.26	0.0400	3.85
15	机械设备 Machinery and equipment	0.93	0.1431	0.29	0.0446	3.21
16	其他制造业 Other manufacturing	0.70	0.1077	0.27	0.0415	2.59
17	水电燃气 Water Electricity Heat	13.27	2.0415	0.14	**0.0215**	94.79
18	建筑业 Construction T	1.09	0.1677	0.20	0.0308	5.45
19	交通运输业 Traffic transport industry	1.06	0.1631	0.53	0.0815	2.00
20	其他服务业 Other services	0.45	0.0692	0.12	0.0185	3.75
	全行业 All the sectors	1.12	0.1723	0.36	0.0554	3.11

Data Source: LI Qingru, 2017, The Embodied Carbon in Trade of China and Japan with Countries along the Belt and Road and Their Determinants [J], (in Chinese), Journal of Contemporary Economy of Japan, 2017 (4):69-84

Table 9-2-3 Results by adjusting the 6th sector's emission coefficient β_i =Japan Data (1)
Based on the full-cooperative model under the TEC target of 10,000 million tons

Sector No. G_i	Emission (Ton) X_i^{β}	Total Production (10000 CNY) P_i^{β}	Final Use (10000 CNY) F_i^{β}	Scale (%) λ_i^{β}
1	204,261,559.71	1,438,461,688.06	404,328,301.47	100.00
2	1,109,217,118.10	1,416,624,671.90	17,586,970.94	100.00
3	109,131,322.11	1,322,803,904.38	595,557,766.19	100.00
4	75,115,069.82	1,021,973,738.99	386,056,272.24	100.00
5	125,243,924.98	945,237,169.63	220,160,678.54	100.00
6	180,412,503.75	839,127,924.40	51,784,143.56	100.00
7	2,596,906,888.69	740,703,619.14	75,757,342.39	100.00
8	967,960,836.21	2,264,235,874.18	226,731,546.19	100.00
9	595,152,629.18	665,346,706.74	43,882,878.12	100.00
10	2,375,405,220.43	2,651,121,897.80	174,239,435.70	100.00
11	143,190,350.40	4,853,910,182.98	2,131,240,395.35	100.00
12	53,426,497.01	1,942,781,709.57	1,829,064,418.77	100.00
13	712,601,415.81	1,425,202,831.62	438,332,243.74	100.00
14	95,969,866.96	1,465,188,808.53	594,103,204.22	100.00
15	47,407,376.08	1,231,360,417.77	513,930,783.66	100.00
16	37,210,821.49	966,514,843.79	154,286,204.56	100.00
17	73,931,775.55	1,920,305,858.51	1,406,017,458.27	100.00
Total	9,502,545,176.27 95.03	27,110,901,848.00 271.11	9,263,060,043.89 92.63	100.00

Table 9-2-4 Results by adjusting the 6th sector's emission coefficient β_i =Japan Data (2)
Compared to the basic scheme under the TEC target of 10,000 million tons with the China Data

Sector No. G_i	Emission (Ton) $\Delta X_i = X_i^{\beta} - X_i^{*}$	Total Production (10000 CNY) $\Delta P_i = P_i^{\beta} - P_i^{*}$	Final Use (10000 CNY) $\Delta F_i = F_i^{\beta} - F_i^{*}$	Value Added (10000 CNY) $\Delta AV_i = AV_i^{\beta} - AV_i^{*}$
1	31,467,568.65	221,602,596.15	111,045,487.23	130,745,531.73
2	270,437,424.38	345,386,238.03	5,117,365.12	169,239,256.64
3	6,130,411.90	74,308,023.00	0	17,833,925.52
4	4,374,278.35	59,513,991.22	0	11,902,798.24
5	28,704,971.29	216,641,292.74	64,061,203.35	58,493,149.04
6	-2,664,781,001.06	192,713,405.53	15,067,879.18	50,105,485.44
7	586,793,274.20	167,368,304.11	22,043,475.11	31,799,977.78
8	202,694,232.84	474,138,556.35	65,973,160.05	90,086,325.71
9	165,684,823.61	185,226,186.26	12,768,810.91	46,306,546.57
10	632,514,860.49	705,931,763.94	50,699,279.54	127,067,717.51
11	38,039,383.75	1,289,470,635.70	620,137,192.18	244,999,420.78
12	15,282,644.92	555,732,542.71	532,211,605.06	150,047,786.53
13	161,370,005.21	322,740,010.43	127,543,626.40	129,096,004.17
14	9,889,289.13	150,981,513.43	4.92	93,608,538.32
15	4,264,136.83	110,756,800.79	0	62,023,808.44
16	5,993,933.52	155,686,584.82	0	93,411,950.89
17	3,684,940.49	95,712,740.01	0	50,727,752.21
Total	-497,454,821.49 -4.97	5,323,911,185.21 53.24	1,626,669,087.71 16.27	1,328,704,667.55 13.29

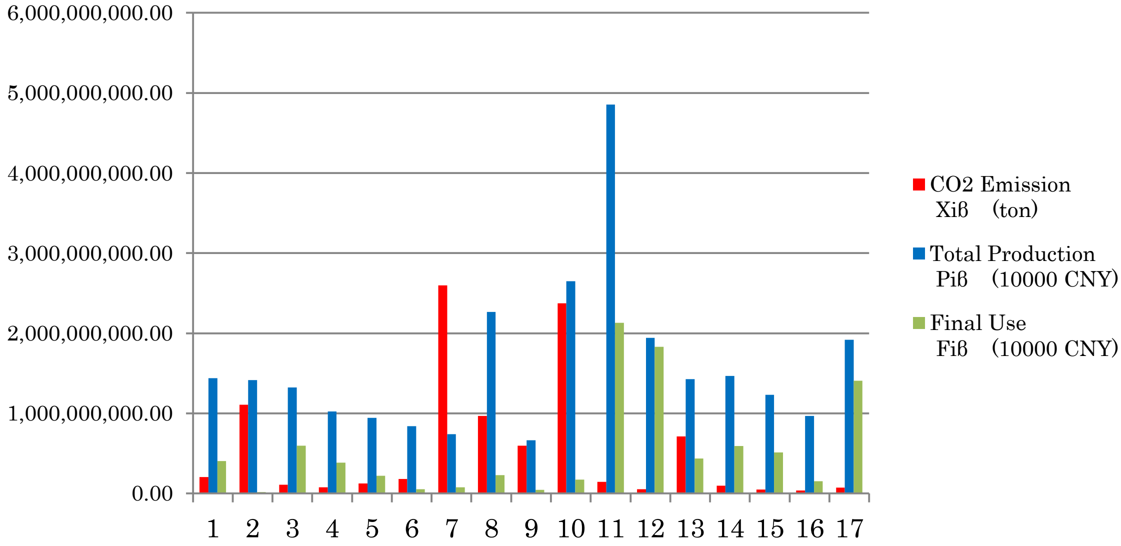


Fig. 9-2-2 Results by adjusting the 6th sector's emission coefficient β_i =Japan Data (1)

(Based on the full-cooperative model under the TEC target of 10,000 million tons)

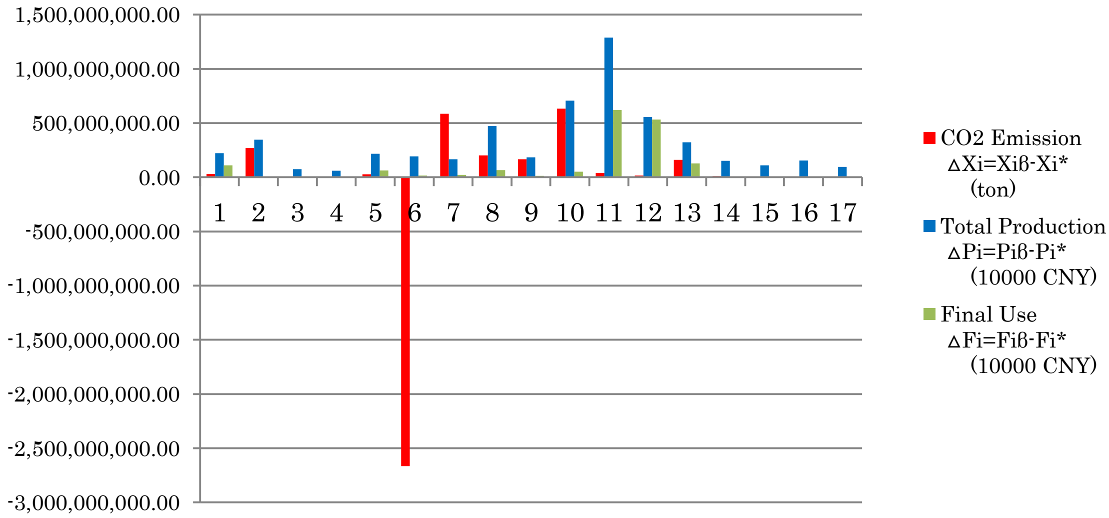


Fig. 9-2-3 Results by adjusting the 6th sector's emission coefficient β_i =Japan Data (2)

(Compared to the basic scheme under the TEC target of 10,000 million tons with the China Data)

9.2.3 Discussion

Based on the results data, it can be understood from Table 9-2-3 that each sector's total production profit P_i and final use F_i will reach their maximum value and so will the sum of P_i and the sum of F_i as those results in the case without TEC policy (see Table 8-3-2).

But in regard to the each sector's CO_2 emission X_i and the total emission of all the 17 sectors, the situation is quite different. Only the emission X_6 of Sector No.6 (Production and Supply of Electric Power, Heat Power and Water) has decreased to 180,412,503.75 tons (180.41 million tons).

Form Table 9-2-4 and Fig.9-2-3, it can be also seen that the reduced emission is about 3,513 million tons by comparing the emission amount 3,693,421,561.49 tons (3,693.42 million tons) in the case without the TEC policy, and about 2,664 million tons by comparing the emission amount of 2,845,193,490.34 tons (2,845.19 million tons) in the full-cooperative case with the TEC policy. And it makes the total emission of all the 17 sectors decreased to the level of 9,502,545,176.27 tons, i.e., roughly 9,503 million tons, which is about 497 million tons less than the target value 10,000 million tons set by the TEC policy.

In other words, the results data imply that if the CO_2 TEC policy target is kept at the same level of 10,000 million tons, China's economy will have a potential to keep growing up until the total emission also increases by about 497 million tons.

Specifically, if the electric power sector's emission intensity is improved to the same level as that in Japan, the total emission of all the 17 sectors can be controlled at the 9,503 million tons and meanwhile the sum of total production profits and the sum of the final use will increase by 5,323 billion CNY and 1,626 billion CNY, respectively.

As discussed in the previous Section 9.1, similarly these results data have a policy implication that if the electric power sector's emission intensity is improved to the same level as in Japan, by technology transfer for example, there will be resulting in an extra room for the total CO_2 emission under the same TEC policy target.

In such a meaning, this is not an optimal scheme. In order to achieve an optimal scheme, it could be expected to set a stricter TEC policy target to better protect the environment or set a greater initial range for some sector's final use (final demand) and let some sectors grow faster on average for pursuing a more total production profit.

This might be one of topics for the further study.

9.3 Impact expected by the trading market in power sector on emission reduction

9.3.1 Introduction

In China, the power sector's CO_2 emission is approximately 4.0 billion tons covering 40%-50% of the country's total emissions. In June 2020, the China Electricity Enterprise Federation (CLP) recently released the Annual Development Report of China's Power Industry 2020（中国电力企业联合会，2020). The report shows that by the end of 2019, the installed capacity of all-caliber non-fossil energy power generation in China is 844.1 million kilowatts, 8.8% more than in 2018 and it accounts for 42.0% of the total installed capacity with 1.2% over the previous year. In 2019, non-fossil energy generated 2,392.7 billion kWh with an increase of 10.6% over the year 2018 and it accounts for 32.7% of total power generation which is 1.7% more than in 2018. In 2019, for the coal power plants with 6,000 kW or above in China, the standard coal consumption is 306.4 g/kWh which is 1.2 g/kWh lower than the previous year. In addition, for energy consumption structure in China, coal, oil, natural gas and non-fossil energy account for 59.0%, 18.9%, 7.8% and 14.3% , respectively, of energy consumption in 2018. Compared with that in 2017 they are down 1.4%, up 0.1%, 0.8% and 0.5%, respectively.

As for carbon emissions, in 2019, the national CO_2 emission per unit of thermal power generation is about 838 g/kWh, a decrease of 3 g/kWh compared with the previous year, and CO_2 emission per unit of electricity generation is about 577 g/kWh, a decrease of 15g/kWh per month. Since 2005 the base year, from 2006 to 2019, the power industry has reduced CO_2 emissions by about 15.94 billion tons, 37.0% of which is owing to the reduction of coal consumption and 61.0% to the development of non-fossil energy(中电联，2020).

China is the world's second largest power producer and consumer. The coal-fired thermal power accounts for more than 70% of the country's total installed capacity and due to the energy structure, coal power will occupy a long-term dominant position. The power industry is the largest carbon emission sector in China and the CO_2 emission per unit of electricity generation is much higher than that of developed countries, so the power industry is the key to China's transition to low-carbon economy. (Shi J., 2016).

As discussed in the above sections, the sector No.6 (Production and Supply of Electric Power, Heat Power and Water) is the most important sector with strong influences on reducing total CO_2 emission among all the other sectors. The impacts of the power sector are so great that the sector should be considered as the leading industry in which technological innovation is absolutely needed to improve the CO_2 emission efficiency (intensity) at first in implementing the TEC policy scheme.

In fact, the Chinese government has already realized the issues and announced in December 2017 the national Emissions Trading System (ETS) as a significant part of its Total Emission Control (TEC) strategy. Actually, the national ETS is expected to start after 2020 and the power industry should be the first sector covered by the ETS at its initial operation.

With the background, therefore, this section is to try to discuss what ripple effects will be expected by the ETS's initial operation in the power sector even if it is difficulty to investigate exactly the real results of the trial ETS operation without the relevant data published at present.

Due to the lack of the realistic data directly reflecting changes of the sector's emission reductions owing to the ETS operation in China, this study tries to discuss the topic in terms of the emission intensity values expected in the regional ETS pilots and the national ETS, with the assumption process shown in in Fig.9-3-1.

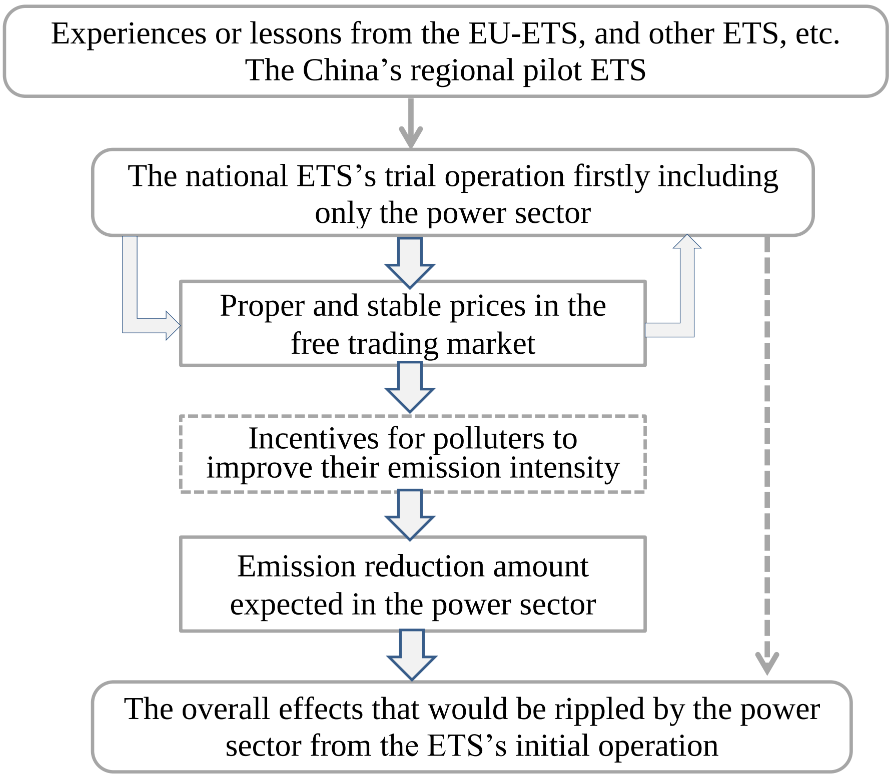


Fig.9-3-1 Estimating the ripple impact on CO_2 reduction by power sector in ETS

9.3.2 China's emission trading system in practice

The Emissions Trading System (ETS) is a market-based policy designed to reduce or control pollutant emissions, and usually operates on a cap-and-trade basis. The cap sets the emissions of all participating companies or facilities, i.e. the sum of all emission allowances. For a certain amount (generally each ton) of emissions emitted, they must waive one emission allowance at the end of the compliance period. The upper limit (cap) can be absolute or intensity-based and the ETS policy allocates allowances (quotas) under fixed rules to the companies or facilities, free of charge or auctioned, or some kind of combination between the two.

Although the cap is decided by the authorities, the allowances are tradable and the price of each allowance is determined by the market. This allows flexibility in considering if it is necessary and how to reduce emissions and thus ensures the emissions reductions to be achieved in the most cost-effective way. It also encourages the emitters (or makes an incentive for them) to invest in new technologies promoting a low-carbon economy.

In 2005, the European Union introduced the first major carbon market and thereby started the emission trading to achieve its climate goal. Since then, ETS has gradually expanded and there are now functioning systems in place in Asia, the Pacific and North America. With the launch of the China's national ETS, jurisdictions covered by an ETS account for over 50% of global GHG including systems on the national, subnational and city-level (ICAP, 2020).

(1) China's ETS Pilots projects

Before the national ETS was announced in the end of 2017, China has already established 8 regional ETS pilots since 2011, which are located in five cities (namely, Beijing, Shanghai, Tianjin, Chongqing and Shenzhen) and three provinces (namely, Guangdong, Hubei and Fujian).

Although the pilot trading markets have some features in common, they vary largely in, such as, the sectors coverage, allowances allocation, market price uncertainty and stabilization, dominated players, offsets, enforcement and compliance, etc. (Zhang Z., 2015). Detailed information on the different design features of each pilot can be accessed from the respective open websites (see Table 9-3-1).

Table 9-3-1 The industrial coverage and quota allocation of the 8 pilot ETS

ETS Pilots	Opening Date	GHG	Access Rules	Industry or sector initially covered	Quotas Allocation	Quotas Issued
Beijing	Nov 28, 2013	CO_2	The average emissions exceeded 10,000 tons	Electric power, heat power, cement, petrochemicals, other industries and services.	Historical emissions	Free
Tianjin	Dec 26, 2013	CO_2	Enterprises and civil buildings that have discharged more than 20,000 tons since 2009	Steel, chemical, electric power, heat power, petrochemical, oil and gas exploration and other key emission industries and civil construction fields.	Historical emissions and Baseline	Free and paid
Shanghai	Nov 26, 2013	CO_2	Emissions exceeded 20,000 tons (industrial) 10,000 tons (non-industrial)	1. Steel, chemicals, electric power, etc. 2. Non-industrial sectors: hotels, shops, ports, airports, aviation, etc.	Historical emissions and Baseline	Free
Chongqing	June 19, 2014	CO_2 etc.	Emissions exceeding 20,000 tons or annual energy consumption exceeding 10,000 tons of standard coal	Industrial sectors: Electricity, electrolytic aluminum, ferroalloy, calcium carbide, caustic soda, cement, steel	Historical emissions and Baseline	Free
Hubei	Apr 2, 2014	CO_2	60,000 t standard coal energy consumption enterprise	Power, steel, cement, chemical and other industries.	Historical emissions and Baseline	Free
Guangdong	Dec 19, 2013	CO_2	Emissions exceeding 20,000 tons or energy consumption exceeding 10,000 tons of standard coal	Electricity, heat power, cement, petrochemicals, other industries and services.	Historical emissions and Baseline	Free and paid
Shenzhen	Jun 1, 2013	CO_2	Enterprises that emit more than 20,000 tons, large public buildings of 0.2 million tons	1. Electric power, water, gas, manufacturing, etc. 2. Public facilities or construction, 3. Transportation	Historical emissions and Baseline	Free
Fujian	Jun 1, 2016	CO2	Energy consumption 10,000 tons/year for any year between 2013-2016.	Electricity, iron and steel, petrochemical, chemical, building materials, etc.	Historical emissions and Baseline	Free

Source: Relevant policies and documents published in each pilot as well as trading websites below (in Chinese):

Beijing Carbon Emissions Trading Center: http://www.bjets.com.cn/ (accessed on July 22, 2020).
Tianjin Carbon Emissions Trading Center: http://tianjin.tanjiaoyi.com/ (accessed on July 22, 2020).
Shanghai Carbon Emissions Trading Center: http://shanghai.tanjiaoyi.com/ (accessed on July 22, 2020).
Hubei Carbon Emissions Trading Center: http://www.hbets.cn/ (accessed on July 22, 2020).
Guangdong Carbon Emissions Trading Center: http://www.cnemission.com/ (accessed on July 22, 2020).
Shenzhen Carbon Emissions Trading Center: http://www.cerx.cn/ (accessed on July 22, 2020).
Chongqing Carbon Emissions Trading Center: https://tpf.cqggzy.com/download/ (accessed on July 22, 2020).
Fujian Carbon Emissions Trading Center: http://fujian.tanjiaoyi.com/ (accessed on July 26, 2020).

Based on data from the operation of these pilots, China's carbon market as a whole has become the world's second largest carbon trading system. As of December 2016, there were approximately 2,729 companies and units that included by the pilot carbon trading platforms, with a total allocation of approximately 1.2 billion tons of carbon quotas. As of October 31, 2017, the cumulative quota volume reached 406 million tons CO_2 equivalent, or about 10,255 millionCNY.

Indeed, the purpose of the pilot ETS was to encourage the pilot regions to test different design options and explore best practices. The experiences from the pilots have promoted the establishment and implementation of the national ETS. A gradual transition of the regional ETS pilots is foreseen by the governmental plan. In the short term, the existing ETS pilots are expected to operate in parallel to the national market for covering the non-power sectors. According to Chinese officials, the regional ETS pilots will continue operating until 2025, and afterwards they themselves will eventually be integrated into the national market once it is fully operational (ETS in China, 2019, https://ets-china.org/news/).

(2) China's national unified ETS market

In December 2017 China announced the launch of its national ETS by the Work Plan for Construction of the National Emissions Trading System (Power Sector). The objective of the national ETS is to contribute to the effective control and gradual reduction of carbon emissions in China. The national ETS is expected to become the most important policy instrument that motivates companies and facilities to reduce GHG (especially CO_2) emissions in the coming decades.

As scheduled in the plan, the national ETS will be introduced gradually in three phases. The first phase (roughly 2018-2019) would focus on the completion of the basic infrastructure. In the second phase (roughly 2019-2020), simulation trading for the power sector will be tested. And in the third phase (after 2020), the allowances' spot trading in the power sector shall be introduced, and then the coverage is expanded and trading products is diversified.

The national ETS will be expected to regulate about 1,700 companies from the power sector which emit more than 26,000 tons GHG or consume more than 10,000 tons coal equivalent per year. The system would cover more than 3 billion tons of CO_2 in its initial phase, accounting for about 30% of the whole national emissions (by the way, the EU-ETS's volume is about 2 billion tons in 2017-2018). The national ETS's scope is to be further expanded in the future and it gradually covers other sectors, including chemical industry, iron and steel, building materials, petrochemical industry, paper making, non-ferrous metals and civil aviation.

Upon the trial operation of the national unified carbon market the scale of quota trading is projected to reach 100 billion CNY totally in the short term 2017-2019. According to the calculation, China's mandatory quota for the next two years is approximately 4 billion tons of CO_2 equivalent, covering 40% -50% of the country's total carbon emissions, which is close to the EU-ETS market's coverage ratio in the EU-ETS phases I and II.

In the short term, the national carbon market spot trading volume may be 1.2 billion to 8 billion CNY based on a 1%-5% turnover rate and an initial carbon price of 30-40 CNY/ton.

In the long run, China has committed itself to keeping annual total CO_2 emissions below 10 billion tons in 2016-2020 and then peaking at about 15 billion tons per year around 2030. If China's carbon market coverage industry continues to expand and include more enterprises, according to the calculation with the same coverage target of 60% as in EU-ETS phaseⅢ, China's future distribution quota of up to 6-9 billion tons could be expected with the same turnover rate as high as 400% and finally the quota trading volume will climb to 24-36 billion tons.

In order to enhance the power of enterprises to reduce emissions, the quota issuance will be tightened gradually. In addition, a significant increase in turnover rate will inevitably promote the price of quotas. If considering the carbon price as the level of 100 CNY/ton, the spot market transaction volume will be between 2-3 trillion CNY. If taking into account of the derivatives market, the carbon market transaction scale will even exceed 100 trillion CNY (Ciin, 2018).

Additionally, according to a study on China's carbon finance market, jointly released by Green Finance Committee (GFC) and the Beijing Environment Exchange (GFC & CBEE, 2016), the trading value in the conservative scenario could reach 100 to 120 billion CNY after 2020 if the relevant carbon financial trading instruments are introduced. According to the NDRC's plan, the national unified carbon market will cover 2 to 3 billion tons of carbon emissions, and with the gradual expansion of the participants and participating industries, China's carbon trading market will be even larger (Sun Q. & Qu F., 2018)

9.3.3 The experience of carbon markets on power sector’s emission reduction

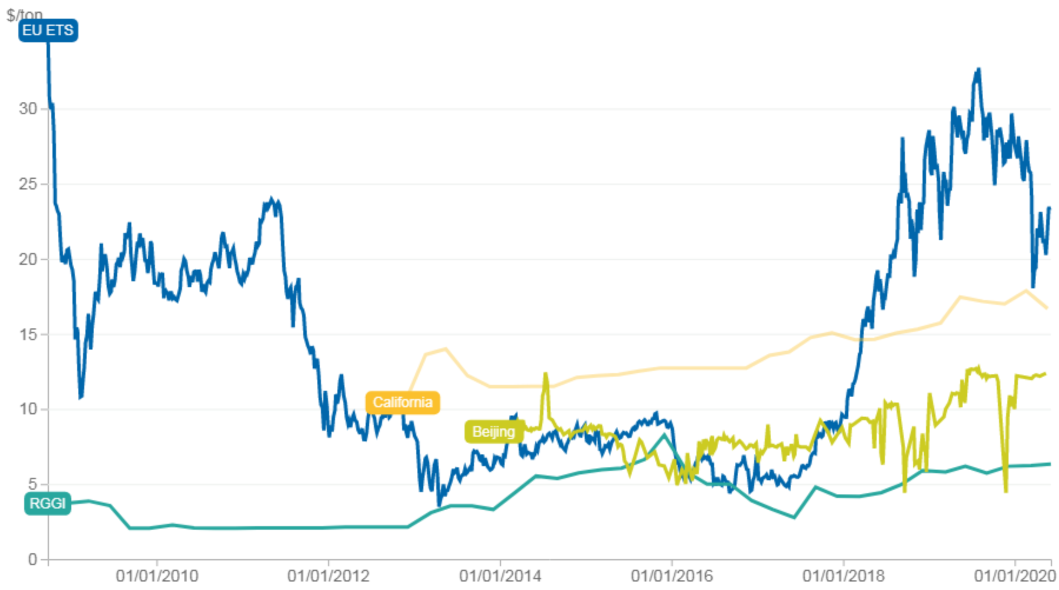
From a worldwide perspective, the power sector emits the most CO_2 and so the sector is a key one responsible for carbon emissions reduction, meanwhile one of the main players in the carbon trading market.

(1) International experience of the carbon markets

Can the national ETS really drive the power sector to reduce emissions?

At first, it is worth learning the international experience of the other carbon markets in the world to promote low-carbon development in the power industry.

Fig.9-3-4 shows the carbon trading prices in the EU-ETS, the RGGI and Beijing markets, etc.



Source: Wan Y., by using the ICAP Allowance Price Explorer, https://icapcarbonaction.com/en/ets-prices

Fig.9-3-2 The prices in EU-ETS, RGGI and Beijing markets 2010 to 2020

The United States does not have a unified carbon market at the federal level, but at the regional level, the Regional Greenhouse Gas Initiative (RGGI) and California's carbon market have matured for many years. RGGI is a carbon market in which only the power industry is involved. Prior to its launch in 2009, there were a number of coal-fired power plants in 9 northeastern states of the RGGI area. In 2009 the RGGI region generated 180 million tons of carbon emissions from electricity generation. After 10 years of the carbon market, there are few coal-fired power plants left in the region, and carbon emissions from power generation are significantly reduced to 58 million tons in 2019, falling down by about 70% compared to 10 years ago.

California's carbon market includes the power industry and other industries, but given the state's long-standing environmental and climate concerns, its power generation industry largely excludes coal-fired power generation.

The European carbon market (EU-ETS) launched in 2005, has a similar situation. The power sector is the industry with the highest share of emissions in the EU carbon market. Over the past 15 years in combination with the EU's carbon market and other related policies, the EU's electricity greenhouse gas emissions have fallen by 38.5% from 1,358 million tons in 2005 to 835 million tons in 2019. In addition, the EU's renewable energy generation has grown rapidly in the past 15 years and it accounts for 34.6% of the EU's renewable energy generation capacity in 2019, more than double the amount it generated when the EU-ETS was just in its infancy in 2005 (Zhang J., 2020).

The American and European experiences have proved that the carbon trading market has the advantage of efficient allocation of resources and the market can promote the power industry to lessen the emission intensity by making the coal-fired power generation fall greatly or switching coal to non-fossil energy generation (Zhang J., 2020).

In particular, the EU-ETS's experiences and effectiveness may be applied on the China's national ETS. Comparing the situation in the initial phase, the China's market is similar to EU-ETS's one in many aspects, such as system design, allowances allocation, trading scope and prices level, etc., even if they are two different systems (Xiong L., et al., 2016).

Overall, the carbon market can promote the low-carbon development through tighter quotas. In the long run, the carbon market promotes the structural optimization of electricity through the market mechanism based on the carbon price. In the short term, under the framework of quota allocation, it appears that carbon cost will increase the enterprises' production cost, affecting their competitiveness, but under the premise of China's high level of power development, the carbon cost may stimulate enterprises to adopt more economical and reasonable technology in reducing emissions.

(2) The experience in the China's pilot ETS markets

Can the China's regional pilots markets influence the emission intensity of the power sector? There are a few of researches and reports analysing the effects of the pilot trading markets.

Zhang K., et al. (2019) used the policy assessment method to evaluate the inhibition by ETS of carbon emission intensity. The assessment scope includes six provincial pilots and pilot industries covered by the regional ETS. Their results show that ETS has significant suppression of carbon emission intensity only in Beijing and Guangdong pilots. There is no significant impact on the carbon emission intensity of Tianjin, Shanghai, Chongqing, and Hubei pilots. Through the carbon emission intensity inhibition analysis of the industries covered by ETS from Beijing and Chongqing pilots, the results show that in Beijing pilot the sectors of the production and supply of electric power, steam and hot water, petroleum processing and coking have a significant impact on the ETS, but in Chongqing pilot, only the sector of the smelting and pressing of ferrous metals does.

Moreover, there are some papers concerning the efficiency and the trading price in the China's carbon market. Zhou J., et al. (2019) studied the efficiency of carbon trading market in China and the results indicate that although the China's carbon trading market is gradually maturing and implemented but the majority of the carbon trading markets are inefficient and only Beijing, Hubei, and Fujian markets are efficient. Also they show that the liquidity, volume, allocation allowance, and transparency in information are significant factors having impact on the market efficiency.

The trading price is the key factor in the China's trading market but the trading price would be far from the desired emission quota price at the trial stage (Yamamoto R., 2018). The ETS price and emission reduction have a significant positive correlation. ETS prices are unpredictable when the mechanism is not yet fully determined because of the high relationship between ETS price and the mechanism of ETS (Lin B. & Jia Z., 2018). The prices and the rate of free payment in the current pilot cities in China are still relatively conservative. China should reduce the total carbon rights to increase the carbon price in 2017, and gradually reducing the proportion of free quota, from 90% in 2017 to 50% or less in 2030, by which the peak year of CO_2 emission can meet in 2025 (Li W. & Jia Z.，2016). Different quota allocation schemes have impacts on electricity price, and there are some spillover effects to other industries (Zhang L., et al., 2018).

Lin B. & Jia Z., (2019) analysed the influence of different ETS price level on energy consumption, CO_2 emissions, and the economy. The results show that the output of energy industries is more sensitive to ETS price than other industries. Higher ETS price, lower marginal reduction of fossil energy consumption of ETS price. Moreover, low ETS prices will undermine the capacity of the carbon market to reduce emissions.

Higher ETS price will lead to a higher reduction in CO_2 emission, but the economic costs cannot be ignored. Therefore, ETS prices in China's ETS pilot cities are too low, and would provide little emission reduction. Carbon price between $10 (65 CNY) /ton and $20 (130 CNY) /ton is the best option for China's national ETS.

Lundgren T., et al (2014) analyzed the Carbon prices and incentives for technological development and the impact of price setting climate policy measures on firm productivity. The results suggest that the carbon prices faced by the industry through EU ETS and the CO_2 tax have been too low. When designing policy to mitigate CO_2 emissions, it is vital that the policy creates a carbon price that is high enough – otherwise the pressure on technological development will not be sufficiently strong. Price-setting policy can stimulate development of low-carbon technologies but politically set carbon prices have been too low to encourage technological progress.

Schleich J., Rogge K. & Betz R., (2009) explored the incentives for energy efficiency induced by the EU Emissions Trading Scheme (EU-ETS) for installations in the energy and industry sectors. Their analysis suggests that the price and cost effects for improvements in carbon and energy efficiency in the energy and industry sectors will be stronger than in phase 1 (2005–2007), but only because the European Commission has substantially reduced the number of allowances to be allocated by the Member States. To the extent that companies from these sectors (notably power producers) pass through the extra costs for carbon, higher prices for allowances translate into stronger incentives for the demand-side energy efficiency.

Based on the above discussion, it is possible to conclude that in general, the ETS market can be expected to have an effect on improving the carbon emission intensity in the power sector but it depends considerably on the factors including trading prices in the market.

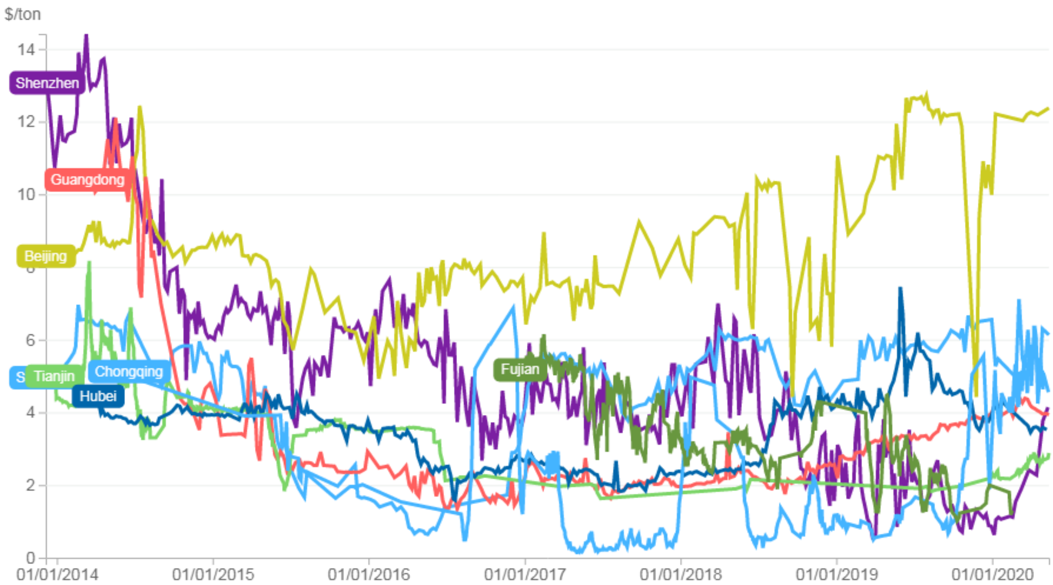
A proper and stable price could be making an incentive to improve the carbon emission intensity of the power sector.

9.3.4 Effects expected in Chinese ETS market on the power sector

After generally discussing in the above, this section tries to explore specifically impact of the China's national ETS market on the CO_2 emission of the power sector and its spillover effect on all other sectors' emissions by using the total emission control (TEC) model. The discussion is based on the trading prices or the emission intensity expected by the pilot markets.

(1) Based on prices in the regional pilots markets

The trading prices on the 8 regional pilot ETS markets during 2013 to 2018 are shown in Fig.9-3-2. The price varies widely among the regional trading markets.



Source: Wan Y., by using the ICAP Allowance Price Explorer, https://icapcarbonaction.com/en/ets-prices

Fig.9-3-3 The trading prices on the 8 regional pilot ETS markets during 2013 to 2020

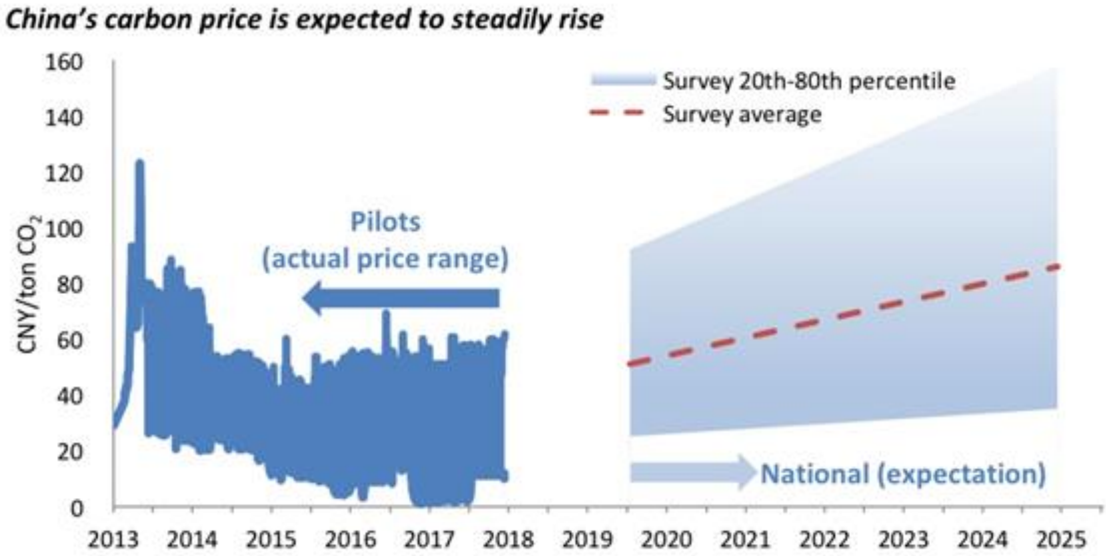
In 2014, the price difference of the carbon market pilots varied considerably and its volatility was greater. In 2015, the prices ranges gradually narrowed and prices in various markets gradually stabilized. Since 2016, the spreads and volatility have been on the rise again. The trading prices of the carbon markets in 2014-2017 were generally on a downward trend, with the carbon prices of some individual regions rising. The carbon prices of the four carbon markets of Shanghai, Guangdong, Hubei and Tianjin fluctuate around 20 CNY/ton and are more stable, while the carbon prices of the two carbon markets in Beijing and Shenzhen fluctuate around 40 CNY/ton, and the carbon prices of the Chongqing carbon market fluctuate mostly (Ciin, 2018).

The average price of the carbon trading regions in 2013-2018 was 14.4 CNY/ton, with the transaction prices in Hubei, Shenzhen and Fujian higher than the average, while the trading prices in the remaining five regions were below the average, the lowest of which was Shanghai, at 2.44 CNY/ton (FBIC, 2018). The trading prices on the main trading markets in 2018 show that with exception of Tianjin and Chongqing whose trading volumes are low, the prices of the remaining markets are basically at around 23 CNY/ton, the highest of which is the Beijing market, reaching 52.72 CNY/ton (FBIC, 2018)..

According to the 2018 China Carbon Pricing Survey (Slater H., et al, 2018), the China's carbon price is expected to steadily rise.

As shown in Fig.9-3-3, at the time of the 2018 survey, the average price expectations in the national ETS are 51 CNY/ton in 2020 and 86 CNY/ton in 2025.

However, the price levels remain highly uncertain, especially in the more distant future. The 20th and 80th percentiles for 2025 are 35 CNY/ton and 158 CNY/ton respectively. By the way, the future price expectations are lower than those at the time of the 2017 survey. See Table 9-3-2.



Source: Slater H., et al, 2018, The 2018 China Carbon Pricing Survey, July 2018, China Carbon Forum, Beijing. https://ets-china.org/wp-content/uploads/2018/07/2018-CCPS-EN-E-version.pdf

Fig. 9-3-4 Prices in the pilot markets and estimated prices for the national unified market.

Table 9-3-2 The average prices expected in the national ETS (CNY/ton)

Time →	2017	2018	2020	2025	20th percentiles for 2025	80th percentiles for 2025
2018 survey			51	86	35	158
2017 survey	38	51	74	108	50	200

Source: Slater H., et al, 2018, The 2018 China Carbon Pricing Survey, July 2018, China Carbon Forum, Beijing. https://ets-china.org/wp-content/uploads/2018/07/2018-CCPS-EN-E-version.pdf

China is now seeking to set a carbon price through its national ETS and result in an incentive to reduce the total carbon emission via the free emission trading market

(Annette W., 2020). By the way, although an “Environmental Protection Tax” was officially introduced on January 1, 2018 in China, a specific carbon tax for industry is not considered currently (Cicenia A., 2018).

Main factors influencing prices are identified as “cap setting and free allocation” and “government regulation and intervention” (Cicenia A., 2018). In the short term, the price of quotas depends on demand and supply decisions, but in the long run, carbon quota prices should be close to the level of the average cost of emission reductions.

The principle of carbon trading is to establish such a carbon market controlling total emissions, where companies with lower emission costs and larger space to reduce emissions can reduce emissions more and meanwhile can sell the remaining carbon quotas to other companies with higher reduction costs to make a profit. Thus, the price of carbon should reflect the average cost of reducing emissions in a country or region.

Although the industry has not yet made clear the cost of emission reduction in China, a variety of research data have demonstrated a range of from 20 to 100 USD/ ton, i.e., roughly from 130 to 650 CNY/ton. Therefore the current carbon price in China’s pilot markets is approximately from 20 to 30 CNY/ton which is extremely below the average cost of carbon reduction (Ciin, 2018).

In addition, according to the preliminary estimates of the National Development and Reform Commission (NDRC), in the long run, the carbon price of 300 CNY/ton is a price standard that can really play a low-carbon guiding role in making an incentive for emitters to improve the emission efficiency.

According to the above investigation, it is understood easily that any of the pilot trading markets has not formed a stable trading price.

Table 9-3-3 Beijing pilot market (BEA) during Jun 22-Jul 21, 2020

Date (mm/dd)	Price (CNY/ton)	Volume (ton)	Value (CNY)
7/21	88.64	8,590.00	761,451.00
7/20	92.58	4,005.00	370,776.00
7/17	94.00	5,175.00	486,450.00
7/15	94.00	100.00	9,400.00
7/14	84.87	18,420.00	1,563,231.00
7/13	85.13	12,740.00	1,084,508.00
7/10	93.50	100.00	9,350.00
7/09	86.92	8,989.00	781,332.20
7/08	87.29	11,186.00	976,382.20
7/07	100.00	1,548.00	154,800.00
7/06	92.94	3,095.00	287,664.00
7/02	93.79	1,421.00	133,274.40
6/30	93.00	100.00	9,300.00
6/29	88.83	5,861.00	520,630.00
6/24	90.00	15,800.00	1,422,000.00
6/22	93.70	132.00	12,368.40
Sum	1,459.19	97,262.00	8,582,917.20
Average	91.20	6,078.88	536,432.33

Source: Beijing Carbon Emissions Trading Center: http://www.bjets.com.cn/ (accessed on July 22, 2020).

Among them, it seems suitable to use the trading price in the Beijing pilot ETS market as example to quantify the impact of the ETS operation in power sector on the CO_2 emissions.

Table 9-3-3 shows the latest price data during June 23-July 22, 2020.

Using the average price 91.20 CNY/ton as the emission cost for the sector No.6 (the power sector), the respective optimal TEC scheme is computed by the TEC model established in Chapter 7.

In addition to the newest average price in Beijing pilot, 91.2 CNY/ton, the several market prices are also used as example cases in the computation, including: 51 CNY/ton (expected for 2020) and 58 CNY/ton (for 2025) as well as the prices 35 CNY/ton(20th percentiles), 158 (80th percentiles), 300CNY/ton.

The calculated results are shown in Table 9-3-3.

From the results, it is clearly seen that the set prices are possibly too low to stimulate the polluters to improve the emission reduction.

Table 9-3-4 Impact of Trading prices expected by ETS (with TEC x^{Total}=10,000 mt)

Price (CNY /ton)	Sector 6 (power sector)			Compared to the base case		
	Pi (10000 CNY)	Fi (10000 CNY)	Xi (ton)	ΔPi=Pi-Pi* (10000 CNY)	ΔFi=Fi-Fi* (10000 CNY)	ΔXi=Xi-Xi* (ton)
35	643,426,032.36	36,716,263.87	2,876,706,316.60	-2,988,486.51	0.00	31,512,811.80
51	642,029,614.69	36,716,263.96	2,891,123,557.91	-4,384,904.18	0.00	45,930,053.11
86	638,922,807.40	36,716,263.93	2,923,199,628.40	-7,491,711.47	0.00	78,006,123.60
91	638,460,020.47	36,716,264.24	2,927,977,653.88	-7,954,498.40	0.00	82,784,149.07
158	632,306,770.10	36,716,264.01	2,991,506,560.03	-14,107,748.77	0.00	146,313,055.22
300	617,998,818.82	36,716,264.13	3,134,366,409.29	-28,415,700.05	0.00	289,172,904.48
Price (CNY /ton)	Total amount affected by Sector 6 (power sector)			Compared to the base case		
	sPi (10000 CNY)	sFi (10000 CNY)	sXi (ton)	ΔsPi= sPi-sPi* (10000 CNY)	ΔsFi= sFi-sFi* (10000 CNY)	ΔsXi= sXi-sXi* (ton)
35	21,658,030,005.69	7,580,827,761.43	10,000,000,000.00	-128,960,657.10	-55,563,194.75	0.00
51	21,598,170,768.86	7,555,354,762.20	10,000,000,000.00	-188,819,893.94	-81,036,193.98	0.00
86	21,464,993,499.94	7,498,681,395.74	10,000,000,000.00	-321,997,162.86	-137,709,560.44	0.00
91	21,445,155,533.70	7,490,239,383.20	10,000,000,000.00	-341,835,129.09	-146,151,572.98	0.00
158	21,181,388,595.35	7,377,993,798.74	10,000,000,000.00	-605,602,067.44	-258,397,157.44	0.00
300	20,546,096,759.66	7,143,239,546.91	10,000,000,000.00	-1,240,893,903.13	-493,151,409.27	0.00

(2) The emission intensity improvement expected in the ETS markets

Table 9-3-5 shows the ETC reduction targets in carbon emission intensity by 2020 for each pilot ETS market. The average value of the markets' reduction targets in emission intensity is - 4.075% per year. It could be used as an example in the simulating computation by the TEC model with such an assumption that the all pilots have achieved their emission intensity reduction targets by 2020.

Table 9-3-5 Pilot ETC reduction targets in carbon emission intensity by 2020

No.	Pilots	Target percentage	Compared Year	Average per year
1	Beijing	20.5%	2015 levels (13th Five Year Plan).	4.1%
2	Tianjin	20.5%	2015 levels (13th Five-Year Plan)	4.1%
3	Shanghai	20.5%	2015 levels (the total CO_2 emissions to be limited within 250 million tons).	4.1%
4	Hubei	19.5%	2015 levels	3.9%
5	Chongqing	19.5%	2015 levels (13th Five-Year Plan)	3.9%
6	Guangdong	20.5%	2015 levels	4.1%
7	Shenzhen	45.0%	2005 levels	4.5%
8	Fujian	19.5%	2015 levels (overall GHG reduction target)	3.9%
The average value of the markets' reduction targets in emission intensity				**4.075%**

Source: International Carbon International Carbon Action Partnership (ICAP), Access ETS profiles, Overall GHG reduction target. https://icapcarbonaction.com/en/ (accessed on July 22, 2020).

The results data are shown in Table 9-3-6 to Table 9-3-8 below.

Comparing the results computed for each case in the tables, it is obvious to understand that the emission intensity improvement by just about 4% is expected to result in a greater ripple effect on the emissions allocation of both the power sector itself and all the other sectors.

Table 9-3-6 Impact of emission intensity expected by ETS (with TEC x^{Total}=10,000 mt)

Sector No.	Improved by 4.075% in power sector			Compared to the base case		
	Pi	Fi	Xi	△Pi=Pi-Pi*	△Fi=Fi-Fi*	△Xi=Xi-Xi*
	(10000 CNY)	(10000 CNY)	(ton)	(10000 CNY)	(10000 CNY)	(ton)
1	1,360,204,859.98	404,328,302.85	193,149,090.12	143,345,768.07	111,045,488.60	20,355,099.07
2	1,081,002,538.26	12,469,606.08	846,424,987.46	9,764,104.39	0.00	7,645,293.74
3	1,271,456,166.50	595,557,765.62	104,895,133.74	22,960,285.11	0.00	1,894,223.52
4	965,937,579.66	386,056,271.24	70,996,412.10	3,477,831.88	0.00	255,620.64
5	762,284,121.86	178,345,877.87	101,002,646.15	33,688,244.97	22,246,402.68	4,463,692.46
6	**653,751,880.91**	**36,716,264.11**	**2,760,544,786.75**	**7,337,362.04**	**0.00**	**- 84,648,718.06**
7	580,434,943.85	53,713,866.88	2,035,004,913.14	7,099,628.82	0.00	24,891,298.65
8	1,820,405,015.57	160,758,386.59	778,223,144.16	30,307,697.74	0.00	12,956,540.79
9	480,960,248.43	31,114,067.59	430,218,942.22	839,727.95	0.00	751,136.65
10	1,952,586,510.99	123,540,156.23	1,749,517,513.84	7,396,377.13	0.00	6,627,153.91
11	3,573,085,347.87	1,511,103,203.04	105,406,017.76	8,645,800.59	0.00	255,051.12
12	1,387,257,829.44	1,296,852,813.94	38,149,590.31	208,662.57	0.00	5,738.22
13	1,109,481,071.25	310,788,618.41	554,740,535.62	7,018,250.06	0.00	3,509,125.03
14	1,322,294,313.86	594,103,199.40	86,610,277.56	8,087,018.75	0.00	529,699.73
15	1,124,643,625.49	513,930,784.87	43,298,779.58	4,040,008.51	0.00	155,540.33
16	816,497,697.42	154,286,204.27	31,435,161.35	5,669,438.45	0.00	218,273.38
17	1,828,105,667.51	1,406,017,460.98	70,382,068.20	3,512,549.01	0.00	135,233.14
sum	22,090,389,418.83	7,769,682,849.95	10,000,000,000.06	303,398,756.04	133,291,893.77	0.00
	220.90 Trillion CNY	**77.70** Trillion CNY	**100.00** Billion ton	**3.03** Trillion CNY	**1.33** Trillion CNY	**0.00** Billion ton

Table 9-3-7 Impact of emission intensity expected by ETS (with TEC x^{Total}=10,500mt)

Sector No.	Improved by 4.075% in power sector			Compared to the base case		
	Pi	Fi	Xi	△Pi=Pi-Pi*	△Fi=Fi-Fi*	△Xi=Xi-Xi*
	(10000 CNY)	(10000 CNY)	(ton)	(10000 CNY)	(10000 CNY)	(ton)
1	1,379,278,863.21	404,328,302.58	195,857,598.58	3,348,404.23	0.00	475,473.40
2	1,136,860,236.88	12,469,604.96	890,161,565.48	13,843,939.91	0.00	10,839,804.95
3	1,283,346,656.22	595,557,765.61	105,876,099.14	2,488,938.62	0.00	205,337.44
4	984,348,529.49	386,056,271.27	72,349,616.92	3,707,184.16	0.00	272,478.04
5	844,279,914.68	220,160,678.50	111,867,088.70	5,951,980.95	0.00	788,637.48
6	**686,767,755.13**	**36,716,264.31**	**2,899,958,228.02**	**7,921,600.80**	**0.00**	**- 88,322,543.33**
7	602,409,930.29	53,713,866.28	2,112,049,215.60	5,372,352.92	0.00	18,835,469.34
8	1,908,303,543.12	160,758,388.68	815,799,764.68	20,267,944.52	0.00	8,664,546.28
9	491,428,728.70	31,114,066.44	439,582,997.82	2,745,034.73	0.00	2,455,433.57
10	2,107,322,546.27	123,540,159.05	1,888,161,001.46	40,214,272.17	0.00	36,031,987.87
11	4,068,751,394.58	1,787,678,690.12	120,028,166.14	134,666,580.40	75,940,833.79	3,972,664.12
12	1,388,381,263.19	1,296,852,813.84	38,180,484.74	275,665.20	0.00	7,580.79
13	1,146,481,194.73	310,788,618.62	573,240,597.36	9,009,172.76	0.00	4,504,586.38
14	1,358,787,897.20	594,103,199.10	89,000,607.27	8,945,399.95	0.00	585,923.70
15	1,147,632,672.89	513,930,784.99	44,183,857.91	5,614,256.60	0.00	216,148.88
16	846,868,559.12	154,286,202.34	32,604,439.53	7,438,826.70	0.00	286,394.83
17	1,846,718,718.96	1,406,017,460.93	71,098,670.68	4,677,271.84	0.00	180,074.97
sum	23,227,968,404.65	8,088,073,137.62	10,500,000,000.00	276,488,826.47	75,940,833.42	0.00
	232.28 Trillion CNY	**80.88** Trillion CNY	**105.00** Billion ton	**2.76** Trillion CNY	**0.76** Trillion CNY	**0.00** Billion ton

Table 9-3-8 Impact of emission intensity expected by ETS (with TEC x^{Total} = 9,500 mt)

Sector No.	Improved by 4.075% in power sector			Compared to the base case		
	Pi	Fi	Xi	△Pi=Pi-Pi*	△Fi=Fi-Fi*	△Xi=Xi-Xi*
	(10000 CNY)	(10000 CNY)	(ton)	(10000 CNY)	(10000 CNY)	(ton)
1	1,179,912,129.80	286,678,965.81	167,547,522.43	34,899,280.75	0.00	4,955,697.87
2	1,033,544,440.92	12,469,606.09	809,265,297.24	8,367,131.22	0.00	6,551,463.75
3	1,220,582,094.44	595,557,765.52	100,698,022.79	13,536,499.32	0.00	1,116,761.19
4	937,522,785.57	386,056,271.21	68,907,924.74	205,816,943.89	112,332,636.03	15,127,545.38
5	697,355,999.49	156,099,475.05	92,399,669.93	5,140,555.66	0.00	681,123.63
6	621,155,371.58	36,716,264.12	2,622,902,163.41	8,106,066.75	0.00	- 75,740,876.43
7	546,576,931.06	53,713,866.75	1,916,298,720.28	5,410,932.99	0.00	18,970,731.07
8	1,686,772,461.43	160,758,386.60	721,095,227.26	38,172,375.03	0.00	16,318,690.33
9	474,858,082.24	31,114,067.60	424,760,554.56	888,601.72	0.00	794,854.24
10	1,902,027,860.90	123,540,156.24	1,704,216,963.37	4,949,501.87	0.00	4,434,753.68
11	3,483,718,828.67	1,511,103,203.14	102,769,705.45	9,745,407.27	0.00	287,489.51
12	1,380,242,068.19	1,296,852,813.91	37,956,656.88	233,831.03	0.00	6,430.35
13	1,054,065,698.30	310,788,618.40	527,032,849.15	9,711,203.79	0.00	4,855,601.90
14	1,268,695,913.92	594,103,199.23	83,099,582.36	17,410,279.30	0.00	1,140,373.29
15	995,416,477.69	429,227,385.34	38,323,534.39	2,236,194.86	-4,669,484.01	86,093.50
16	769,497,857.40	154,286,204.45	29,625,667.51	6,404,916.45	0.00	246,589.28
17	1,379,219,189.86	996,901,848.89	53,099,938.81	4,329,296.38	0.00	166,677.91
sum	20,631,164,191.46	7,135,968,098.36	9,500,000,000.56	375,359,018.32	107,663,149.49	0.45
	206.31 Trillion CNY	**71.36** Trillion CNY	**95.00** Billion ton	**3.75** Trillion CNY	**1.08** Trillion CNY	**0.00** Billion ton

Table 9-3-9 Impact on emission allocations with the emission intensity improved by 4.075% in power sector expected by ETS initial operation in China.

Sector No.	Setting TEC target x^{Total} = 10,500 mt			Setting TEC target x^{Total} = 9,500 mt		
	Compared to the base case			Compared to the base case		
	△Pi=Pi-Pi*	△Fi= Fi-Fi*	△Pi=Xi-Xi*	△Pi=Pi-Pi*	△Fi=Fi-Fi*	△Xi=Xi-Xi*
	(10000 CNY)	(10000 CNY)	(ton)	(10000 CNY)	(10000 CNY)	(ton)
1	162,419,771.29	111,045,488.34	23,063,607.52	-36,946,962.11	-6,603,848.44	-5,246,468.62
2	65,621,803.01	0.00	51,381,871.76	-37,693,992.95	0.00	-29,514,396.48
3	34,850,774.84	0.00	2,875,188.92	-27,913,786.95	0.00	-2,302,887.42
4	21,888,781.71	0.00	1,608,825.46	-24,936,962.20	0.00	-1,832,866.72
5	115,684,037.79	64,061,203.31	15,328,135.01	-31,239,877.40	0.00	-4,139,283.76
6	**40,353,236.26**	**0.00**	**54,764,723.21**	**-25,259,147.29**	**0.00**	**-222,291,341.40**
7	29,074,615.26	0.00	101,935,601.11	-26,758,383.97	0.00	-93,814,894.21
8	118,206,225.29	0.00	50,533,161.31	-103,324,856.40	0.00	-44,171,376.11
9	11,308,208.22	0.00	10,115,192.25	-5,262,438.24	0.00	-4,707,251.01
10	162,132,412.41	0.00	145,270,641.52	-43,162,272.96	0.00	-38,673,396.57
11	504,311,847.29	276,575,486.96	14,877,199.50	-80,720,718.61	0.00	-2,381,261.20
12	1,332,096.33	0.00	36,632.65	-6,807,098.67	0.00	-187,195.21
13	44,018,373.54	0.00	22,009,186.77	-48,397,122.89	0.00	-24,198,561.44
14	44,580,602.09	0.00	2,920,029.44	-45,511,381.19	0.00	-2,980,995.47
15	27,029,055.92	0.00	1,040,618.65	-125,187,139.29	-84,703,399.43	-4,819,704.86
16	36,040,300.15	0.00	1,387,551.56	-41,330,401.57	0.00	-1,591,220.46
17	22,125,600.46	0.00	851,835.62	-445,373,928.64	-409,115,612.00	-17,146,896.25
sum	1,440,977,741.86	451,682,181.44	500,000,002.24	-1,155,826,471.33	-500,422,857.82	-499,999,997.20
	14.41 Trillion CNY	4.52 Trillion CNY	5.00 Billion ton	-11.56 Trillion CNY	-5.00 Trillion CNY	-5.00 Billion ton

(3) Discussion and implication for policy design

According to the National Development and Reform Commission (NDRC, 2017), the national unified carbon market is expected to cover about 1,700 companies with total emissions of more than 3 billion tons CO_2 in equivalent per year in its initial phase for power sector only. Actually, the official data are just very close to the result computed by this study.

Based on the simulating computation, the power sector would be reaching the maximum total emission 3.69 billion tons in the existing situation without any TEC policy, which accounts for one third of the all total emission of sectors in 2017 and indicates that the power sector is the largest one to emit CO_2 in China. But if keeping the national total emission under the 10 billion tons as the TEC policy target, the power sector needs to reduce 0.85 billion tons for making its emission fall from 3.69 to 2.84 billion tons. These results in this study are likely close to what published actually by the government. Specifically, the national carbon trading market is expected to cover more than 3 billion tons in the initial operation in power sector and it means that the total emission in the power sector is supposed to be that amount. This is exactly the extent that this study suggests the power sector's emission limit.

Of course, the conclusion is only for the case with the national TEC target being set at the level of 10 billion tons per year. It is now difficult to guess exactly how many (much) the "cap" (the total allowance) will be set by the national trading market at the initial operation in the power sector, it seems possible to consider reasonably the national total emission is allowed to change around 10.0 billion tons, for instance, from 9.5 billion tons to 11.0 billion tons. Based on such an assumption, the calculated results of this study also suggests that the "cap" set in the ETS market for the power sector should be about 2.70 to 3.13 billion tons.

In order to apply furtherly the TEC model on checking the actual effects expected in the China's emission trading markets, especially the impact from the national unified emission trading system, the analysis in this section is furtherly quantified by using some meaningful prices from 35 CNY/ton to 300 CNY/ton, as well as the emission intensity reduction targets set by the China's ETS markets.

The results indicate that the prices are not the key factor affecting greatly the emission reduction in the power sector but the emission intensity improvement by just about 4% is expected to result in a greater ripple effect on the emissions allocation of both the power sector itself and all the other sectors.

10. Comparison analysis based on the TEC model by changing policy factors

With the analytical framework as a policy design tool, the extended TEC model developed in this study can be also used to compare and select policy schemes by changing the corresponding policy factors (vector). In this chapter, the topic is briefly discussed with the TEC policy target or the emission charges function as an example.

10.1 Comparison analysis of schemes with different TEC targets

In the above, the policy scheme is calculated and then discussed just with the CO_2 reduction target of the total emission under 10,000 million tons. Actually there are several choices for decision making from different points of view.

The following Table 10-1-1 to Table 10-1-6, and Fig.10-1-1 to Fig.10-1-6 show the various results data for different schemes which are computed by using the extended TEC model with different values set for the TEC policy targets, respectively, i.e.,

(1) x^{Total} = 12,000 million tons;
(2) x^{Total} = 11,000 million tons;
(3) x^{Total} = 10,500 million tons;
(4) x^{Total} = 10,000 million tons;
(5) x^{Total} = 9,500 million tons, and
(6) x^{Total} = 9,000 million tons.

And finally the Table 10-1-7 and the Fig.10-1-7 show the comparison of the alternative policy schemes with different TEC policy targets

Table 10-1-1 Results based on the full-cooperative model (1) (x^{Total}=12,000 million tons

Sector	G_0	Total Production	Final Use		CO_2 Emission
	G_i	(10000 CNY)	(10000 CNY)	(%)	(Ton)
	i	P_i	F_i	F_i/F_i^{Max}	X_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,416,308,752.25	404,328,303.35	1.00	201,115,842.82
Mining	2	1,299,872,885.86	12,469,606.36	0.71	1,017,800,469.63
Manufacture of Foods, Beverage and Tobacco	3	1,307,160,754.06	595,557,765.47	1.00	107,840,762.21
Manufacture of Textile, Wearing Apparel and Leather Products	4	1,012,515,538.59	386,056,271.23	1.00	74,419,892.09
Other Manufacture	5	917,439,909.57	220,160,678.88	1.00	121,560,788.02
Production and Supply of Electric Power, Heat Power and Water	6	772,850,027.12	36,716,263.84	0.71	3,401,699,394.35
Coking, Gas and Processing of Petroleum	7	665,309,763.50	53,713,867.36	0.71	2,332,576,030.85
Chemical Industry	8	2,093,693,900.58	160,758,386.49	0.71	895,054,142.50
Manufacture of Nonmetallic Mineral Products	9	619,713,915.35	31,114,069.67	0.71	554,334,097.28
Manufacture and Processing of Metals and Metal Products	10	2,491,716,481.62	123,540,157.42	0.71	2,232,577,967.53
Manufacture of Machinery and Equipment	11	4,770,989,752.75	2,131,240,393.75	1.00	140,744,197.71
Construction	12	1,849,690,709.32	1,741,513,900.30	0.95	50,866,494.51
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,240,745,950.51	310,788,618.35	0.71	620,372,975.25
Wholesale and Retail Trades, Hotels and Catering Services	14	1,434,568,366.34	594,103,199.13	1.00	93,964,228.00
Real Estate, Leasing and Business Services	15	1,202,328,870.23	513,930,784.96	1.00	46,289,661.50
Financial Intermediation	16	924,826,484.28	154,286,204.00	1.00	35,605,819.64
Other Services	17	1,900,707,469.15	1,406,017,461.16	1.00	73,177,237.56
Sum	Sum	25,920,439,531.07	8,876,295,931.70	0.96	12,000,000,001.44
		(T.CNY)	(T.CNY)		(M.ton)
		259.20	88.76		12,000.00

Table 10-1-2 Results based on the full-cooperative model (2) (x^{Total}=11,000 million tons

Sector	G_0	Total Production	Final Use		CO_2 Emission
	G_i	(10000 CNY)	(10000 CNY)	(%)	(Ton)
	i	P_i	F_i	F_i/F_i^{Max}	X_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,389,530,148.78	404,328,302.85	1.00	197,313,281.13
Mining	2	1,179,244,071.78	12,469,606.17	0.71	923,348,108.20
Manufacture of Foods, Beverage and Tobacco	3	1,290,966,647.65	595,557,765.55	1.00	106,504,748.43
Manufacture of Textile, Wearing Apparel and Leather Products	4	995,698,235.50	386,056,271.22	1.00	73,183,820.31
Other Manufacture	5	862,502,166.08	220,160,678.58	1.00	114,281,537.01
Production and Supply of Electric Power, Heat Power and Water	6	711,020,081.76	36,716,264.12	0.71	3,129,554,889.86
Coking, Gas and Processing of Petroleum	7	618,857,626.18	53,713,866.86	0.71	2,169,714,837.38
Chemical Industry	8	1,970,354,733.73	160,758,386.49	0.71	842,326,648.67
Manufacture of Nonmetallic Mineral Products	9	499,832,772.54	31,114,067.59	0.71	447,100,415.03
Manufacture and Processing of Metals and Metal Products	10	2,230,440,300.56	123,540,156.25	0.71	1,998,474,509.30
Manufacture of Machinery and Equipment	11	4,481,039,043.39	2,020,174,887.66	0.95	132,190,651.78
Construction	12	1,389,225,224.64	1,296,852,813.94	0.71	38,203,693.68
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,174,063,170.91	310,788,618.34	0.71	587,031,585.46
Wholesale and Retail Trades, Hotels and Catering Services	14	1,386,174,628.51	594,103,199.25	1.00	90,794,438.17
Real Estate, Leasing and Business Services	15	1,164,820,963.70	513,930,784.95	1.00	44,845,607.10
Financial Intermediation	16	869,642,868.65	154,286,204.32	1.00	33,481,250.44
Other Services	17	1,861,038,392.06	1,406,017,460.98	1.00	71,649,978.09
Sum	Sum	24,074,451,076.39	8,320,569,335.14	0.90	11,000,000,000.03
		(T.CNY)	(T.CNY)		(M.ton)
		240.74	83.21		11,000.00

Table 10-1-3 Results based on the full-cooperative model (3) (x^{Total}=10,500 million tons

Sector	G_0	Total Production	Final Use		CO_2 Emission
	G_i	(10000 CNY)	(10000 CNY)	(%)	(Ton)
	i	P_i	F_i	F_i/F_i^{Max}	X_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,172,055,196.40	286,678,965.29	0.71	166,431,838.00
Mining	2	1,137,607,627.06	12,469,606.11	0.71	890,746,772.05
Manufacture of Foods, Beverage and Tobacco	3	1,227,063,774.04	595,557,765.64	1.00	101,232,761.36
Manufacture of Textile, Wearing Apparel and Leather Products	4	761,661,836.95	273,723,635.18	0.71	55,982,145.01
Other Manufacture	5	739,937,792.37	156,099,474.96	0.71	98,041,757.50
Production and Supply of Electric Power, Heat Power and Water	6	677,469,812.22	36,716,264.13	0.71	2,981,883,376.97
Coking, Gas and Processing of Petroleum	7	584,503,996.51	53,713,866.81	0.71	2,049,271,013.17
Chemical Industry	8	1,813,376,494.14	160,758,386.32	0.71	775,218,451.28
Manufacture of Nonmetallic Mineral Products	9	496,305,700.46	31,114,067.59	0.71	443,945,449.06
Manufacture and Processing of Metals and Metal Products	10	2,224,712,041.95	123,540,156.27	0.71	1,993,341,989.47
Manufacture of Machinery and Equipment	11	4,572,298,930.43	2,131,240,393.76	1.00	134,882,818.44
Construction	12	1,382,134,220.41	1,296,852,813.95	0.71	38,008,691.06
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,117,265,054.66	310,788,618.49	0.71	558,632,527.45
Wholesale and Retail Trades, Hotels and Catering Services	14	1,323,636,664.37	594,103,199.32	1.00	86,698,201.51
Real Estate, Leasing and Business Services	15	1,028,985,476.12	424,922,847.91	0.83	39,615,940.73
Financial Intermediation	16	822,655,163.13	154,286,204.34	1.00	31,672,223.77
Other Services	17	1,412,832,290.19	996,901,848.94	0.71	54,394,043.16
Sum	Sum	22,494,502,071.42	7,639,468,115.01	0.82	10,500,000,000.02
		(T.CNY)	(T.CNY)		(M.ton)
		224.94	76.39		10,500.00

Table 10-1-4 Results based on the full-cooperative model (4) (x^{Total}=10,000 million tons

Classification	G_0	CO_2 Emission	Total Production	Final Use	
of Sectors	G_i	(ton)	(10000 CNY)	(10000 CNY)	(%)
G_i	i	X_i^*	P_i^*	F_i^*	F_i/F_i^{Max}
Agriculture, Forestry, Animal Husbandry and Fishery	1	172,794,116.59	1,216,859,975.99	293,283,528.65	72.54
Mining	2	838,779,680.27	1,071,238,416.70	12,469,606.59	70.90
Manufacture of Foods, Beverage and Tobacco	3	103,000,920.76	1,248,496,009.24	595,557,765.64	100.00
Manufacture of Textile, Wearing Apparel and Leather Products	4	70,740,790.65	962,459,736.69	386,056,271.20	100.00
Other Manufacture	5	96,538,951.50	728,595,860.37	156,099,475.02	70.90
Production and Supply of Electric Power, Heat Power and Water	6	2,845,193,490.34	646,414,515.58	36,716,263.77	70.90
Coking, Gas and Processing of Petroleum	7	2,010,113,660.12	573,335,328.04	53,713,866.75	70.90
Chemical Industry	8	765,266,627.33	1,790,097,373.87	160,758,386.12	70.90
Manufacture of Nonmetallic Mineral Products	9	429,467,798.42	480,120,512.49	31,114,067.57	70.90
Manufacture and Processing of Metals and Metal Products	10	1,742,890,216.23	1,945,189,973.47	123,540,156.60	70.90
Manufacture of Machinery and Equipment	11	105,150,949.92	3,564,438,980.35	1,511,102,861.89	70.90
Construction	12	38,143,852.09	1,387,049,166.82	1,296,852,813.94	70.90
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	551,231,406.53	1,102,462,813.07	310,788,618.50	70.90
Wholesale and Retail Trades, Hotels and Catering Services	14	86,080,577.74	1,314,207,293.75	594,103,199.30	100.00
Real Estate, Leasing and Business Services	15	43,143,238.96	1,120,603,609.33	513,930,784.90	100.00
Financial Intermediation	16	31,216,887.66	810,828,250.87	154,286,204.28	100.00
Other Services	17	70,246,834.92	1,824,593,114.88	1,406,017,460.98	100.00
Total		10,000,000,000.05	21,786,990,931.53	7,636,391,331.70	82.44
		10,000.00	217.86	76.36	
		$x^*=\Sigma X_i^*$ (M.t) ↑	SB*=ΣP_i^* (T.CNY) ↑	ΣF_i^* (T.CNY) ↑	

Table 10-1-5 Results based on the full-cooperative model (5) (x^{Total}=9,500 million tons

Sector	G_0	Total Production	Final Use		CO_2 Emission
	Gi	(10000 CNY)	(10000 CNY)	(%)	(Ton)
	i	P_i	F_i	F_i/F_i^{Max}	X_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,145,029,126.14	286,678,965.87	0.71	162,594,135.91
Mining	2	1,025,210,858.18	12,469,606.12	0.71	802,740,101.96
Manufacture of Foods, Beverage and Tobacco	3	1,207,062,184.10	595,557,765.64	1.00	99,582,630.19
Manufacture of Textile, Wearing Apparel and Leather Products	4	731,722,996.30	273,723,635.18	0.71	53,781,640.23
Other Manufacture	5	692,263,154.70	156,099,475.17	0.71	91,724,868.00
Production and Supply of Electric Power, Heat Power and Water	6	613,063,789.62	36,716,264.13	0.71	2,698,400,270.01
Coking, Gas and Processing of Petroleum	7	541,194,831.46	53,713,866.86	0.71	1,897,429,079.10
Chemical Industry	8	1,648,639,729.13	160,758,386.27	0.71	704,793,484.20
Manufacture of Nonmetallic Mineral Products	9	473,973,802.45	31,114,067.60	0.71	423,969,566.29
Manufacture and Processing of Metals and Metal Products	10	1,897,119,387.92	123,540,156.35	0.71	1,699,818,971.58
Manufacture of Machinery and Equipment	11	3,474,047,513.15	1,511,103,203.09	0.71	102,484,401.64
Construction	12	1,380,015,006.14	1,296,852,813.93	0.71	37,950,412.67
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,044,390,140.18	310,788,618.42	0.71	522,195,070.09
Wholesale and Retail Trades, Hotels and Catering Services	14	1,251,323,376.65	594,103,199.55	1.00	81,961,681.17
Real Estate, Leasing and Business Services	15	993,723,528.69	434,382,382.02	0.85	38,258,355.85
Financial Intermediation	16	763,156,980.86	154,286,204.32	1.00	29,381,543.76
Other Services	17	1,374,903,552.78	996,901,848.95	0.71	52,933,786.78
Sum	Sum	20,256,839,958.47	7,028,790,459.46	0.76	9,499,999,999.43
		(T.CNY)	(T.CNY)		(M.ton)
		202.57	70.29		9,500.00

Table 10-1-6 Results based on the full-cooperative model (6) (x^{Total}=9,000 million tons

Sector	G_0	Total Production	Final Use		CO_2 Emission
	G_i	(10000 CNY)	(10000 CNY)	(%)	(Ton)
	i	P_i^*	F_i^*	F_i/F_i^{Max}	X_i^*
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,019,905,584.38	286,678,966.74	0.71	144,826,592.98
Mining	2	1,004,422,612.61	12,469,606.00	0.71	786,462,905.67
Manufacture of Foods, Beverage and Tobacco	3	937,901,285.30	422,265,479.99	0.71	77,376,856.04
Manufacture of Textile, Wearing Apparel and Leather Products	4	724,605,152.18	273,723,635.19	0.71	53,258,478.69
Other Manufacture	5	670,196,974.31	156,099,475.03	0.71	88,801,099.10
Production and Supply of Electric Power, Heat Power and Water	6	594,962,849.94	36,716,264.06	0.71	2,618,728,984.00
Coking, Gas and Processing of Petroleum	7	525,177,539.50	53,713,866.79	0.71	1,841,272,453.49
Chemical Industry	8	1,605,400,331.34	160,758,386.49	0.71	686,308,641.65
Manufacture of Nonmetallic Mineral Products	9	471,747,597.47	31,114,067.61	0.71	421,978,225.93
Manufacture and Processing of Metals and Metal Products	10	1,879,712,288.90	123,540,156.19	0.71	1,684,222,210.86
Manufacture of Machinery and Equipment	11	3,441,544,734.70	1,511,103,203.16	0.71	101,525,569.67
Construction	12	1,377,481,238.39	1,296,852,813.94	0.71	37,880,734.06
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,010,504,723.37	310,788,618.50	0.71	505,252,361.69
Wholesale and Retail Trades, Hotels and Catering Services	14	1,038,855,407.32	421,233,778.72	0.71	68,045,029.18
Real Estate, Leasing and Business Services	15	873,065,512.41	364,389,890.66	0.71	33,613,022.23
Financial Intermediation	16	685,283,211.90	109,392,656.66	0.71	26,383,403.66
Other Services	17	1,361,545,282.90	996,901,848.79	0.71	52,419,493.39
Sum	Sum	19,222,312,326.93	6,567,742,714.51	0.71	9,228,356,062.27
		(T.CNY)	(T.CNY)		(M.ton)
		192.22	65.67		9,228.36
				x^{Total}	9,000.00

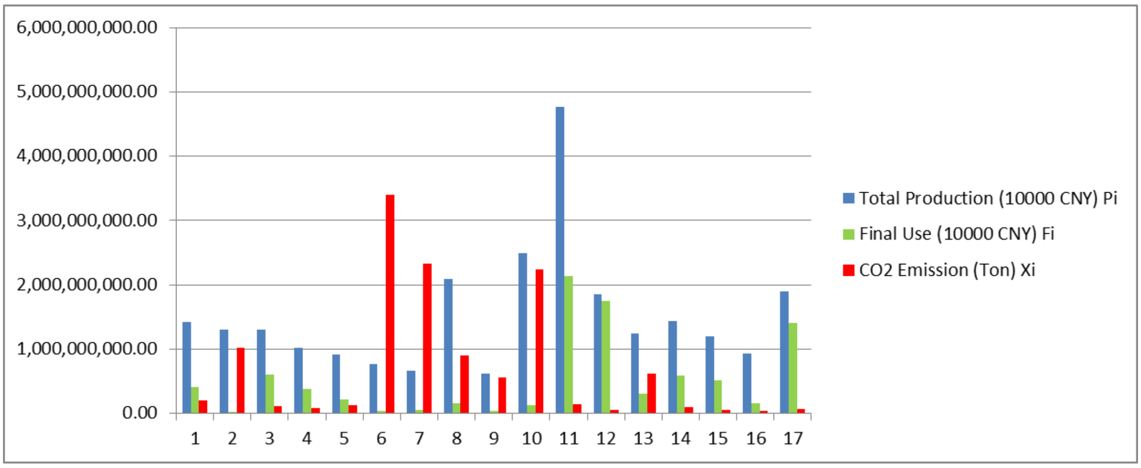


Fig.10-1-1 The case with TEC policy target at the level of 12,000 million tons

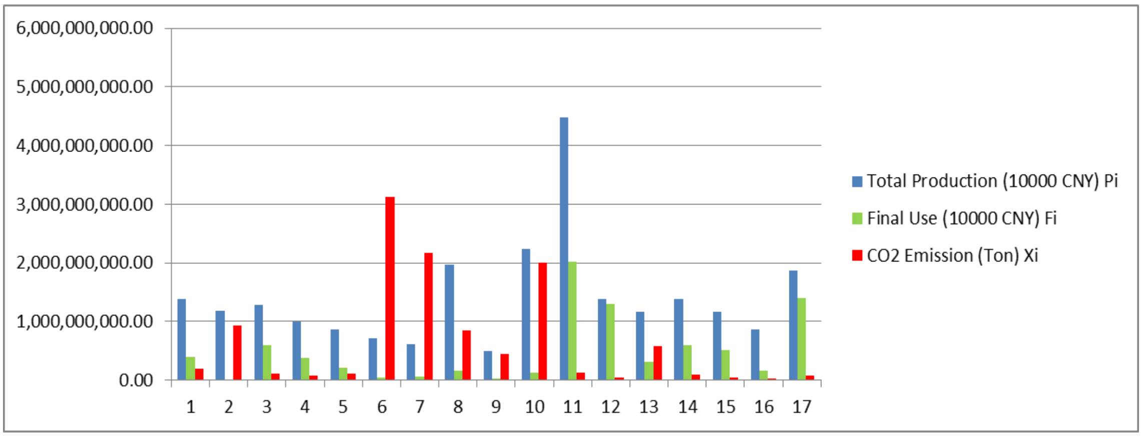


Fig.10-1-2 The case with TEC policy target at the level of 11,000 million tons

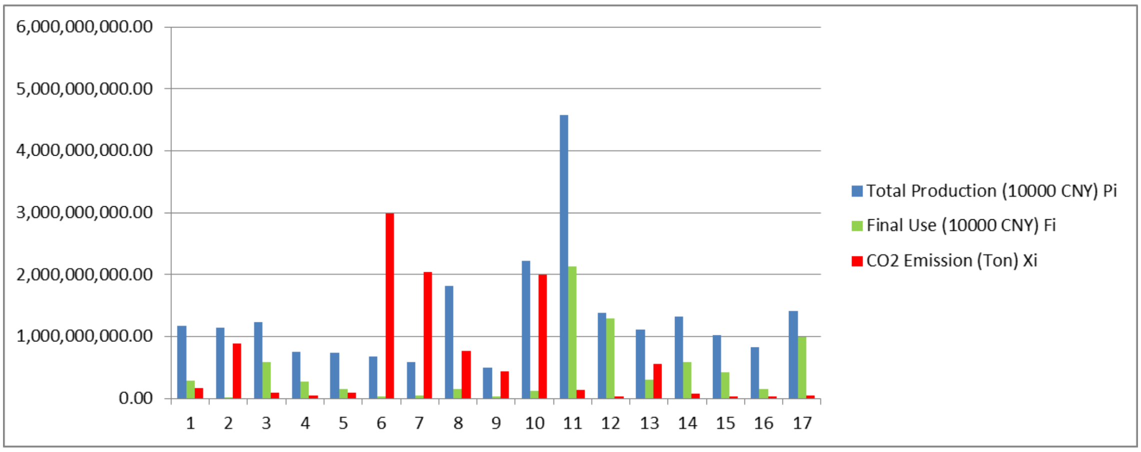


Fig.10-1-3 The case with TEC policy target at the level of 10,500 million tons

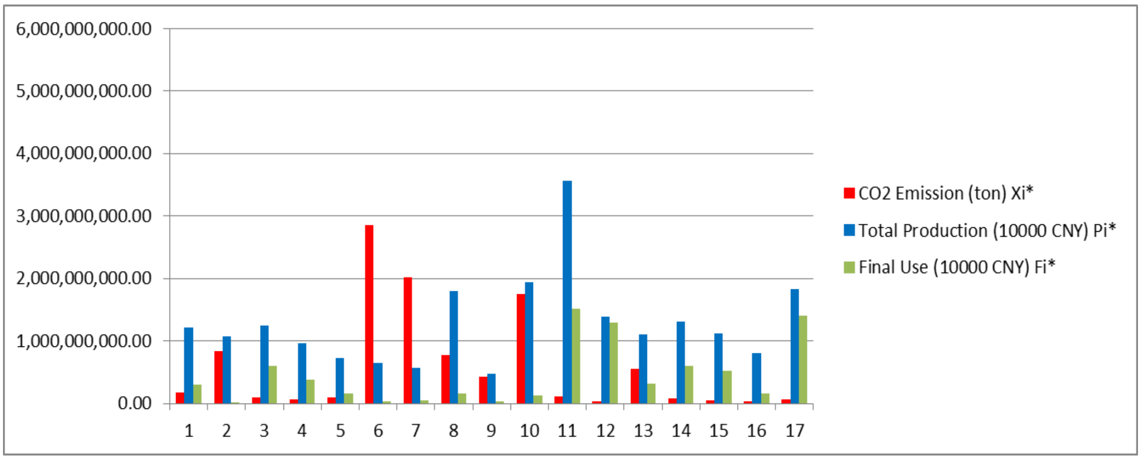


Fig.10-1-4 The case with TEC policy target at the level of 10,000 million tons

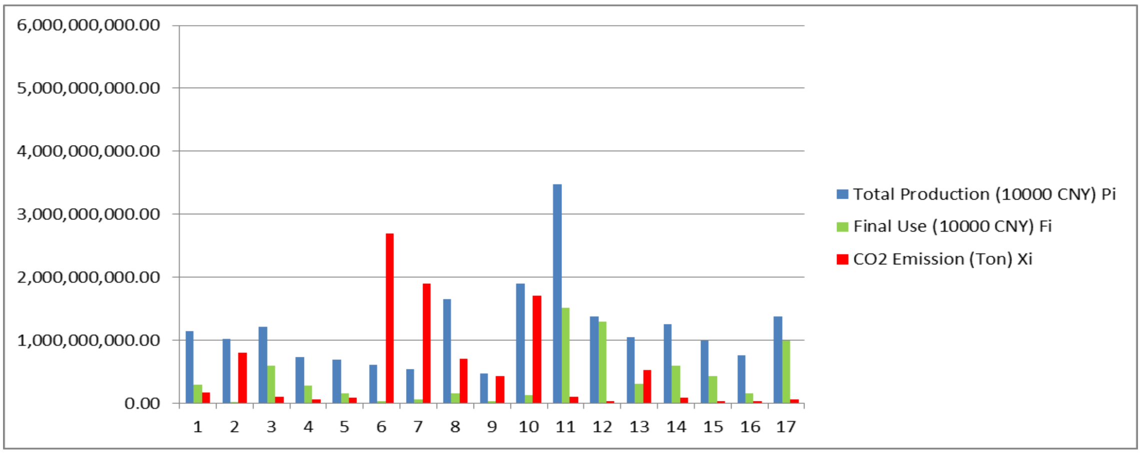


Fig.10-1-5 The case with TEC policy target at the level of 9,500 million tons

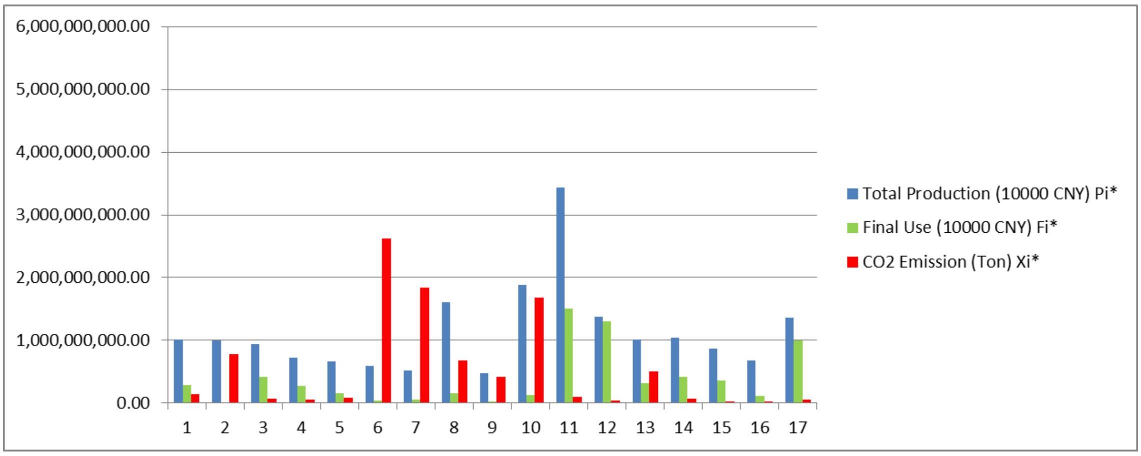


Fig.10-1-6 The case with TEC policy target at the level of 9,000 million tons

Table 10-1-7 The comparison of schemes with different TEC policy targets

Policy Scheme No.	Target Setting (million tons) x^{Total}	Total Production (10000 CNY) ΣP_i^*	Final Use (10000 CNY) ΣF_i^*	CO_2 Emission (Ton) ΣX_i^*	(%) λ^*
0	without TEC	27,110,901,854.95	9,263,060,046.18	13,015,554,241.39	100
1	12,000	25,920,439,531.07	8,876,295,931.70	12,000,000,001.44	96
2	11,000	24,074,451,076.39	8,320,569,335.14	11,000,000,000.03	90
3	10,500	22,494,502,071.42	7,639,468,115.01	10,500,000,000.02	83
4	10,000	21,786,990,931.53	7,636,391,331.70	10,000,000,000.05	82
5	9,500	20,256,839,958.47	7,028,790,459.46	9,499,999,999.43	76
6	9,000	19,222,312,326.93	6,567,742,714.51	9,228,356,062.27	71

Comparision of the schemes with different TEC targets (based on 10,000 million tons)

Policy Scheme No.	Target Setting (million tons) x^{Total}	Total Production (10000 CNY) ΣP_i^*	Difference (10000 CNY) $\triangle \Sigma P_i^*$	Final Use (10000 CNY) ΣF_i^*	Difference (10000 CNY) $\triangle \Sigma F_i^*$	CO_2 Emission (Ton) ΣX_i^*	Difference (10000 CNY) $\triangle \Sigma X_i^*$	(%) λ^*
0	without TEC	27,110,901,855	5,323,910,923	9,263,060,046	1,626,668,714	13,015,554,241	3,015,554,241	100
1	12,000	25,920,439,531	4,133,448,600	8,876,295,932	1,239,904,600	12,000,000,001	2,000,000,001	96
2	11,000	24,074,451,076	2,287,460,145	8,320,569,335	684,178,003	11,000,000,000	1,000,000,000	90
3	10,500	22,494,502,071	707,511,140	7,639,468,115	3,076,783	10,500,000,000	500,000,000	83
4	10,000	21,786,990,932	0	7,636,391,332	0	10,000,000,000	0	82
5	9,500	20,256,839,958	-1,530,150,973	7,028,790,459	-607,600,872	9,499,999,999	-500,000,001	76
6	9000	19222312327	-1034527632	6567742715	-461047745	9228356062	-271643937	71

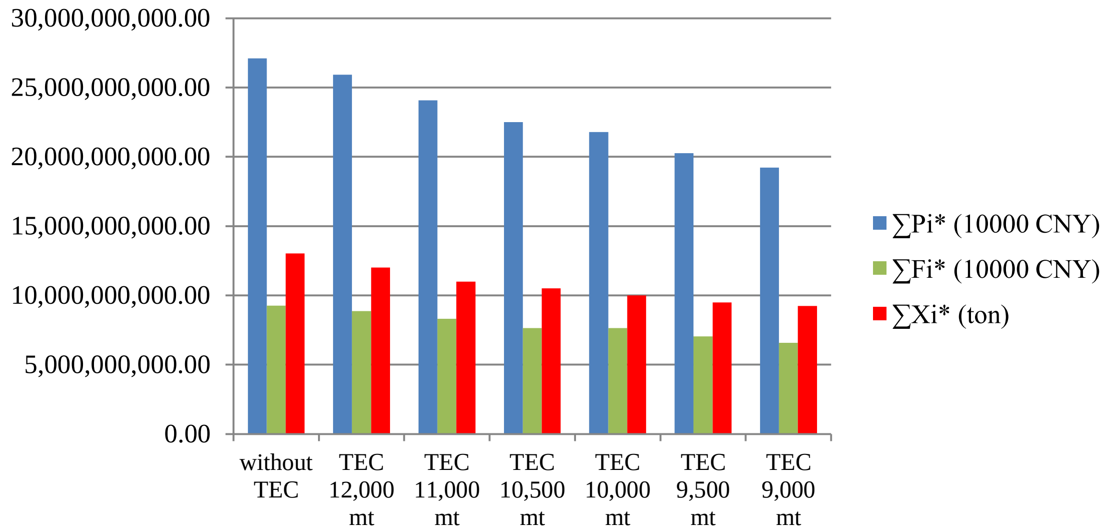


Fig.10-1-7 The comparison of schemes with different TEC policy targets

10.2 Comparison analysis by adjusting the emission charges

As mentioned in Section 8.3.3, for designing a stable policy scheme, it needs to adjust and find a suitable environmental emission charges function $Tt_i(X_i)$ to make a decrease both in the G_i's expected profit and in the CO_2 emission in the not-cooperative case (Dong H., et al., 2017).

In the previous simulations for the above optimal TEC policy scheme, the emission charges function has been set as $Tt_i(X_i) = 0$.

Now in this section, however, in order to better describe how to develop a stable and optimal TEC policy scheme by adjusting effectively some policy factors (vector), as an example for simple computation, the emission charges standard function $Tt_i(X_i)$ is defined here as

$$Tt_i(X_i) = \xi_i X_i \tag{10-2-1}$$

where X_i is the CO_2 emission (ton) that resulted from G_i's production and so G_i is responsible for, and

ξ_i is the price coefficient (10000CNY/ton) for the *i*-th sector.

Then, the model in formula (7-2-25) is modified to

$$\begin{aligned} Bt_i(X_i) &= P_i(X_i) - Tt_i(X_i) \\ &= (1/\beta_i)\, X_i - \xi_i X_i = (1/\beta_i - \xi_i)\, X_i \end{aligned}$$

i.e.,

$$Bt_i(X_i) = (1/\beta_i - \xi_i)\, X_i \tag{10-2-2}$$

Similarly, each G_i can make decision optimally as follows:

$\boldsymbol{G_i}$: $i = 1, 2, \dots, n$

$$Max.\ Bt_i\,(X_i) = (1/\beta_i - \xi_i)X_i \tag{10-2-3a}$$

s.t.

$$\begin{cases} (\underline{\boldsymbol{I}} - \underline{\boldsymbol{A}})\underline{\boldsymbol{\beta}}^{-1}\underline{\boldsymbol{X}} \le \underline{\boldsymbol{F}}^{Max} \\ \underline{\boldsymbol{X}} \ge \underline{\boldsymbol{X}}^{Min} \\ \sum_{i=1}^{n} X_i \le x^{Total} \end{cases} \tag{10-2-3b}$$

Now, in a lack of the relevant data for the environmental emission charges standard or environmental taxes on CO_2 in China, ξ_i could be set here as follows, only for giving examples.

Example 1

In regard to the price of CO_2 emission, there are three situations suggested in the trading market of China, based on the latest information provided by Economic Forecasting Department of State Information Center (Cai S., et al., 2017; Tang B.J, et al., 2019). See Table 10-2-1 below.

Table 10-2-1 CO_2 emission prices coefficients ξ_i (CNY/tonCO_2)

	Situation 1	Situation 2	Situation 3
2017-2022	30	50	100
2022-2029	50	100	100
2030-	100	100	100

Data Sources: Cai S., et al. (2017) Economic Forecasting Department of State Information Center, Beijing, China

Besides, Zhang X. (2017) reported that it is important to have a more reasonable level of carbon prices in China now. The level of carbon prices in the future is related to the future's control trajectory of China's total carbon emissions. For example, there are three possible tracks in China. The top trajectory is basically one with the emission peak in 2030, which China has promised at the Paris climate conference. The second is the trajectory with the emission peak before 2030, which is basically assumed to be in 2025. And the third possible trajectory is that with the emission peak now. For the first, the second and the third options respectively with peak in 2030, 2025 and now, the annual carbon intensity should be declined by 4%, 5% and 6%, respectively. The carbon prices for different trajectories are not the same level. The more the trajectory is on backward, the higher the price becomes. For instance, as for the case with early peak in 2025, the annual carbon intensity must be reduced by 5% and the carbon prices will be reaching more than $100 USD by 2050. But by 2020, presently, the three tracks' carbon price level is similar, roughly 7 dollars to 9 dollars. Zhang (2017) also reported that a more reasonable level of carbon prices in China should be about 10 dollars (Zhang X., 2017).

Based on the above, it is suitable to choose the 100 CNY/ton as the emission charges standard (regulation) for all the sectors. Thus, the emission charges function or cost function can be defined as

$$Bt_i\,(X_i) = \xi_i\,X_i\ ,\quad \text{where}\quad \xi_i = 100 \text{ CNY/ton} = 0.01 \text{ (10000 CNY/ton)}$$

In Table 10-2-2 are shown the results based on the model with an adjusted environmental emission charges function

$$Bt_i(X_i) = 0.01 * X_i \quad \text{(10000 CNY/ton).} \qquad (10\text{-}2\text{-}4)$$

And in Table 10-2-3 are shown the differences in comparison between the No.1 scheme with ξ_i= 100 CNY/ton in Example 1, and the No.0 scheme with ξ_i= 0 in the previous section.

From the results data, it can be understood that:

(a) The emission charges policy on all the sectors with 100 CNY/ton can make the potential total emission be decreased from 10,379,167,118.05 tons to 10,144,404,503.91 tons, which means the potentially reduced amount is about 234,762,614.61 tons, i.e., 234.76 million tons.

(b) The sum of the expected profit for each sector is declined from 23,824,421,421.27 (10000CNY) to 23,720,629,750.08 (10000CNY), which indicates that the difference is about 103,791,671.19 (10000CNY), i.e. 1,037.91 billionCNY.

(c) The final profit of each sector is changed because of the redistribution based on the expected profit in the part-cooperative case, but the total amount of all the profits is not changed because the maximum social benefit keeps the same as in the basic scheme No.0. (Actually for all situations the objective function in the optimization is the same in the model.)

(d) The expected increment $\triangle\alpha_i$ in each sector's final profit is increased while the expected profit is decreased due to enforcing the emission charges regulation.

(e) The amount of the emission tax or subsidy in the scheme is also changed among all sectors. Note that even if for the six sectors whose amounts of the taxes are all zero in the basic scheme considering no emission charges, they should pay their taxes for their emissions after adjusting the emission charges function. In other words, amending the emission charges regulation would make such a quite different scheme that it brings an influence on which sector (who) is the greater beneficiary or which sector (who) is the benefactor in the policy scheme.

Totally in conclusion, the alternative scheme of Example 1 (Scheme No.1) is a relatively better policy in such a stable meaning because adjusting the emission charges function could make the expected profit value be less and then result in an extra increment in the each sector's final profit, compared relatively to the previous profit expected in the part-cooperative case.

However from the Table 10-2-2, it is understandable that the final profit of each sector is still less than that expected in the non- or part-cooperative case. This explains that the policy scheme with the emission charges system of 100 CNY/tonCO_2 is not so proper enough to play an adjustable role in making the TEC policy scheme be a stable one yet.

<u>Example 2</u>

In order to demonstrate how to calculate a stable scheme by the model, try to set some greater value for ξ_i as the adjustable policy factors such as, just for example.

$$\xi_i = (P_i^{P*} - P_i^{*}) / X_i^{*} \qquad (10\text{-}2\text{-}5)$$

The simulating results are shown in Table 10-2-4 even if the setting is hardly considered to have a really practical meaning.

Table 10-2-2 Results simulated with adjusted Emission Charges function ξ_i= 100 CNY/ton

The case with total emission control policy at the level of 10,000 million tons					
Classification of Sectors		With TEC policy		With TEC policy	
	G_0	Part (or Non)-cooperative case		Full-cooperative case	
	G_i	Expected profit $v(\{i\})$	Profit increment	Final profit	Tax or subsidy
G_i	i	Bt_i	$\Delta\alpha_i$	α_i	t_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,347,872,624.42	-9,533,393.80	1,338,339,230.61	-121,480,137.07
Mining	2	1,068,339,685.48	-10,346,176.77	1,057,993,508.71	13,244,926.10
Manufacture of Foods, Beverage and Tobacco	3	1,247,465,874.26	0.00	1,247,465,874.26	1,030,007.49
Manufacture of Textile, Wearing Apparel and Leather Products	4	961,752,340.11	0.00	961,752,340.11	707,407.85
Other Manufacture	5	814,125,071.80	0.00	814,125,071.80	-85,529,194.93
Production and Supply of Electric Power, Heat Power and Water	6	632,596,038.54	-155,641,201.17	476,954,837.38	169,459,681.25
Coking, Gas and Processing of Petroleum	7	569,996,984.88	-155,690,775.12	414,306,209.76	159,029,105.29
Chemical Industry	8	1,857,188,289.48	-132,327,255.38	1,724,861,034.10	65,236,284.08
Manufacture of Nonmetallic Mineral Products	9	491,346,075.75	-38,347,443.62	452,998,632.13	27,121,888.98
Manufacture and Processing of Metals and Metal Products	10	1,998,192,462.13	-165,458,077.59	1,832,734,384.54	112,455,749.40
Manufacture of Machinery and Equipment	11	4,513,327,002.77	-384,143,767.52	4,129,183,235.24	-564,743,687.35
Construction	12	1,927,127,315.55	-699,814,665.34	1,227,312,650.21	159,736,516.96
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,223,374,570.54	-182,336,325.66	1,041,038,244.88	61,424,578.05
Wholesale and Retail Trades, Hotels and Catering Services	14	1,313,346,488.76	0.00	1,313,346,488.76	860,807.01
Real Estate, Leasing and Business Services	15	1,120,172,184.83	0.00	1,120,172,184.83	431,432.28
Financial Intermediation	16	810,516,090.37	0.00	810,516,090.37	312,168.86
Other Services	17	1,823,890,650.43	0.00	1,823,890,650.43	702,468.30
Total		23,720,629,750.08	-1,933,639,081.97	21,786,990,668.11	0
(T.CNY)		238.24		217.87	
$\sum X_i^* \rightarrow$	M.t	10,000.00			

Table 10-2-3 Comparison between schemes No.1 (ξ_i= 100CNY/ton) and No.0 (ξ_i= 0)

The case with total emission control policy at the level of 10,000 million tons					
Classification of Sectors		With TEC policy		With TEC policy	
	G_0	Part (or Non)-cooperative case		Full-cooperative case	
	G_i	Expected profit	Profit increment	Final profit	Tax or subsidy
G_i	i	Δ (1-0)Bt_i	Δ(1-0)$\Delta\alpha_i$	Δ (1-0)α_i	Δ (1-0)t_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	-1,916,700.84	363,594.77	-1,404,978.23	1,553,106.07
Mining	2	-8,431,115.37	394,593.56	-7,875,765.11	8,036,521.82
Manufacture of Foods, Beverage and Tobacco	3	-1,030,009.10	0.00	-1,030,009.10	1,030,007.49
Manufacture of Textile, Wearing Apparel and Leather Products	4	-707,407.91	0.00	-707,407.92	707,407.85
Other Manufacture	5	-1,080,146.91	30,044,491.33	-1,080,146.91	-28,964,344.42
Production and Supply of Electric Power, Heat Power and Water	6	-29,125,681.51	5,936,010.50	-20,771,350.99	23,189,671.00
Coking, Gas and Processing of Petroleum	7	-20,710,193.68	5,937,901.20	-12,353,202.20	14,772,292.48
Chemical Industry	8	-7,973,566.94	5,046,838.32	-870,655.77	2,926,728.62
Manufacture of Nonmetallic Mineral Products	9	-4,434,759.57	1,462,535.80	-2,376,389.32	2,972,223.77
Manufacture and Processing of Metals and Metal Products	10	-18,065,672.89	6,310,417.03	-9,184,403.31	11,755,255.86
Manufacture of Machinery and Equipment	11	-1,331,824.35	14,650,885.65	19,287,805.75	-13,319,061.29
Construction	12	-530,105.79	26,690,279.78	37,033,745.98	-26,160,173.99
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	-6,147,610.91	6,954,137.70	3,639,629.98	-806,526.79
Wholesale and Retail Trades, Hotels and Catering Services	14	-860,805.78	0.00	-860,805.78	860,807.01
Real Estate, Leasing and Business Services	15	-431,432.39	0.00	-431,432.39	431,432.28
Financial Intermediation	16	-312,168.88	0.00	-312,168.88	312,168.86
Other Services	17	-702,468.35	0.00	-702,468.35	702,468.30
Total		-103,791,671.19	103,791,685.64	0.00	0.00
(T.CNY)		-103.79			
$\sum X_i^* \rightarrow$	M.t	10,000.00			

Table 10-2-4 Results simulated with the adjusted Emission Charges function $Tt_i(X_i) = \xi_i X_i$

The case with total emission control policy at the level of 10,000 million tons						
Classification of Sectors	G_0	Emission charges		Total production	Final profit	
	G_i	(10000CNY/Ton	(10000CNY)	(10000CNY)	(10000CNY)	
G_i	i	ξ_i	Tt_i	Bt_i	$\Delta\alpha_i$	$\alpha_i = P_i$
Agriculture, Forestry, Animal Husbandry and Fishery	1	0.6935	132,930,231.71	1,216,859,093.55	0	1,216,859,975.99
Mining	2	0.0066	5,532,366.05	1,071,238,434.80	0	1,071,238,416.70
Manufacture of Foods, Beverage and Tobacco	3	0.0000	0.00	1,248,495,883.36	0	1,248,496,009.24
Manufacture of Textile, Wearing Apparel and Leather Products	4	0.0000	0.00	962,459,748.03	0	962,459,736.69
Other Manufacture	5	0.8018	86,609,341.84	728,595,876.87	0	728,595,860.37
Production and Supply of Electric Power, Heat Power and Water	6	0.0053	15,307,201.42	646,414,518.63	0	646,414,515.58
Coking, Gas and Processing of Petroleum	7	0.0084	17,371,863.51	573,335,315.05	0	573,335,328.04
Chemical Industry	8	0.0941	75,064,538.24	1,790,097,318.18	0	1,790,097,373.87
Manufacture of Nonmetallic Mineral Products	9	0.0353	15,660,314.21	480,120,521.11	0	480,120,512.49
Manufacture and Processing of Metals and Metal Products	10	0.0393	71,068,001.08	1,945,190,133.94	0	1,945,189,973.47
Manufacture of Machinery and Equipment	11	7.1347	950,219,279.23	3,564,439,547.89	0	3,564,438,980.35
Construction	12	10.1981	540,608,254.17	1,387,049,167.17	0	1,387,049,166.82
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	0.2067	127,059,358.52	1,102,462,822.93	0	1,102,462,813.07
Wholesale and Retail Trades, Hotels and Catering Services	14	0.0000	0.00	1,314,207,294.54	0	1,314,207,293.75
Real Estate, Leasing and Business Services	15	0.0000	0.00	1,120,603,617.22	0	1,120,603,609.33
Financial Intermediation	16	0.0000	0.00	810,828,259.25	0	810,828,250.87
Other Services	17	0.0000	0.00	1,824,593,118.78	0	1,824,593,114.88
Total			2,037,430,749.97	21,786,990,671.29	0	21,786,990,931.53
(T.CNY)			20.37	217.87		217.87
$\Sigma X_i^* \rightarrow$	M.t	10,000.00				

10.3 Simulating process for policy design in a multisectoral system

In the previous sections, the established TEC model has been used to calculate and then compare the alternative policy schemes by changing the TEC policy target or the emission charges standard (function) as the adjustable policy factors (vector), for example.

But actually, it can be expected to design any better policy scheme by repeating the computation based on the extended TEC model. This simulating process for the TEC policy design in a multisectoral system is shown in Fig.10-3-1 below, as a summary of Part Three.

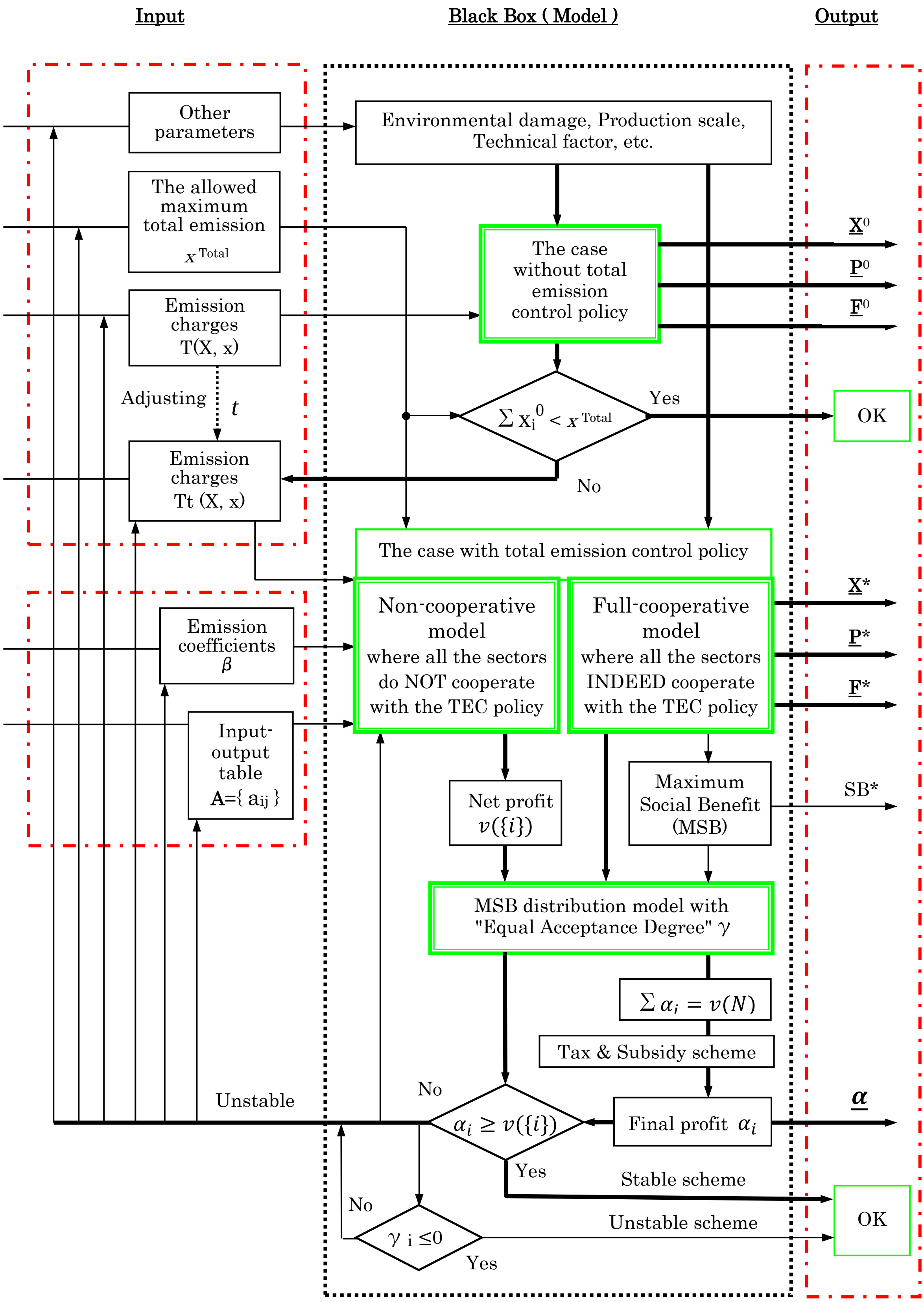


Fig.10-3-1 Simulating process for TEC policy with I-O analysis for a multisectoral system

Part Four: Conclusion

11. Concluding remarks

In managing an environmental-economic system, it is essentially significant to design and then enforce an effective total emission control (TEC) policy, which should be considered to be a comprehensive solution for solving the conflict between environment and economy (Liang Z., et al., 2016; Steger U., et al., 2005). The total emission control of some kind of pollutant discharged into a given region is one of the most important problems in making a good use of the regional natural absorption capability as one kind of usable rare resource meanwhile protecting environment quality in the region (Nakano S. & Washizu A., 2017).

In this study, a model (a set of models) is first established methodologically as an analytical framework for a regional system to design and analyse, quantitatively, an optimal TEC policy scheme with an economic incentive for achieving the fully cooperative optimization, and its brief application is then discussed as a case study on water quality planning to abate wastewater discharges in a given river area.

And then, furtherly with a realistic application background on reducing all industries' environmental emission, the previous TEC model is newly extended with an input-output analysis to be applicable for a multisectoral system. As a first try, based on the modified optimal TEC model, an empirical application is also explored in details as the core application for reducing CO_2 total emission among all sectors in China.

11.1 The model for the TEC policy design

In this study, with the cooperative game theoretical approach, multi-objective optimization and simulation, an optimal TEC model is established to compute and simulate the policy-making process for an incentive-based policy scheme pursuing a maximum social profit as well as achieving the TEC goal at the meantime.

11.1.1 The basic model for a regional system

As an objective of optimization, the model is established to maximize the “social benefit”, which is defined as a comprehensive index considering both economic profits and the regional environmental damage.

By using the ideas and techniques of systems analysis (systems engineering), the model is developed with a simple decision structure in process of allocating the total emission in the region, which is interpreted in the theoretical framework of a cooperative game in characteristic function form. The process of executing a total emission control policy is described as a cooperative game in which one player can be defined as a regional environmental administrator or a policy maker who aims at maximizing the social benefit based on not only the polluters’ economic profits but also the regional environmental damage; and the other players can be considered as all the polluters who are supposed to be independent decision-makers respectively interested in only their own economic profits as much as possible. It is clear that only if all the polluters select the decision to cooperate with the policy, could the maximum total benefit be produced from the all polluters’ cooperation. But which option each polluter will choose depends on how much it can obtain more profit from the cooperation than that from the not-cooperative case. Essentially, this is an allocation problem of the maximum benefit in a cooperative game.

With the solution concepts from cooperative game with characteristic function, the model is used mainly on developing such a mechanism so as to solve the two allocation problems. The first one is how to allocate optimally the maximum total emission among all the polluters in the region as to maximize the "social benefit", which is solved by non-linear programming techniques. And the other is, then, how to divide rationally the maximum benefit attained among all the cooperative polluters to make the optimal cooperation stable, which is transferred to a multi-objective decision-making problem and solved by introducing the "equal acceptance degree" for each cooperative polluter.

In the model, the target of total emission control is realized by direct regulation in the full-cooperative decision-making, while the optimal allocation of regional total emission and the fair redistribution of the corresponding maximum social benefit are realized through an economic means such as the emission charges or environmental taxes (subsidies) policy.

11.1.2 The extended model with input-output analysis for a multisectoral system

Furtherly, the analytical framework considering an input-output structure is established with the background of another application in an environmental-economic system with multiple industries. By modifying the above model, the new allocation model is also developed with an input-output approach for a multisectoral system.

Using the direct input coefficients of input-output table and all the sectors' emission coefficients, the extended model is established to decide an optimal set of emission allocations to maximize the overall profit (here defined as the social benefit) among all sectors under the TEC policy. Based on an input-output analysis, the model allows a policy-maker to allocate the total emissions (quotas) to each sector as an optimal TEC policy scheme while the economy is growing up.

Also the model can be used to analyse the impacts of changes in one sector's emission (intensity) coefficient on all the sectors' emissions and identify the key sectors most responsible for reducing total environmental emission. Moreover, by adjusting some policy factors, it can be easily applied for computing, comparing and selecting different policy schemes.

As a point to be emphasized, the extended model mainly proposes a methodology as an analytical framework which could be an innovation on how to design quantitatively suitable TEC policy schemes for a multisectoral environmental-economic system by aiming at a socially optimal balance between economic development and environmental protection.

11.2 Policy implications and suggestions in applications

For applying the model, this study has explored two practical issues. One is a brief case study on planning water quality (COD) in a river region. And the other is an empirical application discussed in detail for reducing the total CO_2 emission in China as the core application in this study.

11.2.1 The regional system with TEC policy on water quality planning

The brief application has been discussed as a case study on water quality planning with the TEC policy in a river region. A key area called Songjiang district is specifically selected as one example on the upper reaches of Huangpu River in Shanghai, China. Because the main water pollution in the district is due to COD wastewater, the discussion focused on calculating and analysing, quantitatively, a feasible alternative scheme of the TEC policy for the pollutant COD.

According to the data possibly collected, 39 plants or factories are picked up finally to be studied. It means that in the model, there are 39 polluters, i.e. n=39. So, the allocation optimization model is a non-linear programming with 78 variables and 118 constraints.

At first, after calculating the optimal value of the natural absorption capacity by a dynamic model of river water quality, as well as deciding the shapes of the basic functions respectively, the TEC model is formulated in details to compute the quantities of the optimal emissions, and the environmental taxes or subsidies for each plant. Then, the results are discussed and the stability of the alternative policy schemes is analysed from a viewpoint of the environmental-economic policy design.

It is quite obvious that the expected simulating results have been obtained, from which some discussions and suggestions on the policy scheme could be represented as follows (see Chapter 6 for details):

Firstly, as for an analysis on the present situation without the TEC policy, it is clearly observed that the free functioning of the economic market mechanism will result in an increasing regional emission totally up to 3,635.69 kg/day, the level of an amount exceeding 2,260.00 kg/day, the maximum value allowed by the national environmental standards for the river region (see Table 6-4-1). It is therefore proved that there is a need to set a stronger emission charges regulation (standard) and implement the TEC policy to abate the total emission in the region.

Secondly, a scheme for the TEC policy is designed by simulating calculation. If it is based on the existing emission charges standard which is reflected in the emission charges function, i.e. setting $Tt_i(X_i) = T_i(X_i)$, there is not a stable optimal scheme of the TEC policy. If, however, the emission charges are increased by 100% from the existing standard, i.e. setting $Tt_i(X_i) = 2T_i(X_i)$, there will be an incentive for each plant to take a positive attitude to form the full-cooperation in which a stable optimal solution for the policy scheme can be reached as shown in Table 6-4-2 to Table 6-4-4.

Thirdly, the simulated optimal scheme represents, specifically, that when the full-cooperation takes place, the regional total emission can be controlled at the level of 2,600 kg/day of the allowed maximum value to meet the regional environmental target; and meanwhile the maximum social benefit is 378511.25 CNY/day which is more than 377646.87 CNY/day of the total amount of all plants' profits gained by individual decision-making in the non-cooperative case, and this assures all the plants of no less profit in the full-cooperative case than that in the non-cooperative case; and in redistributing the maximum social benefit, most plants should pay environmental taxes while a few plants should receive subsidies (see Table 6-4-4).

Lastly, note that the policy scheme can be optimized only for the adjusted emission charges standard. Although this implies that the model does not necessarily include a "stable optimal solution" for setting the emission charges standard itself, the problem of how to identify it in a comprehensively appropriate way can be solved by using the model to repeat the simulating computation according to the criterion from the stable scheme concept.

11.2.2 The multisectoral system with TEC policy for reducing CO_2 emissions

As the core application of the extended model, this study has focused on discussing quantitatively about policy design for reducing all industries' total CO_2 emission in China. By using the national data of Input-Output Table in 2012, the expected results are obtained by simulating in detail the CO_2 emissions in 17 sectors and meanwhile calculating approximately the respective optimal solutions for total production (output), final use (demand) and the relevant emission taxes among all the sectors. Based on the results, the main conclusions and implications are proposed as follows.

(1) At first, the optimal TEC policy scheme is computed and analysed with a CO_2 total emission control target being set at the level of 10,000 million tons per year, and a growing rate of each sector's production being set as same as the GDP growth in China.

From the scheme, it is easily understood that in the existing situation of the individual decision-making without total emission control, each sector could reach its maximum production profit independently and the sum of each sector's total production profit is 271.10 trillion CNY. Instead, however, the CO_2 total emission could increase up to 13,015.56 million tons, which is much more than the policy target set as 10,000.00 million tons, the maximum value of the allowed total emission from all sectors. Thus, some kind of policy strategy for reducing totally about 3,015.56 million tons CO_2 emission should be enforced as the each sector's economic scale has been increasing with a growth rate per year along with the GDP of China.

(2) Then, the results data also indicates that there exists an optimal allocation of the

maximum total emission among all sectors in the full cooperative case. In the case, absolutely, the total emission is controlled exactly at the level of 10,000 million tons to meet the reduction target set by policy maker, and meanwhile the total production profit is attained at the maximum value 217.87 trillion CNY as well.

Totally in the scheme, because the TEC policy is executed by the centralized decision-making approach, the total emission reduction target is reached and also, the sum of all sectors' total profit defined as the social benefit is maximized up to the value of 217.86 trillion CNY, which is more than the expected total profit in the part-cooperative case for any not–cooperative sector. Hence the increased total profit (social benefit) makes it possible that each sector can expect an incentive due to its cooperation.

The scheme also shows that the production scale for each sector is respectively allowed to increase up to the 70.9% - 100% of the largest scale. The sector of Agriculture, Forestry, Animal Husbandry and Fishery is 72.6% and the six sectors (the 3rd: Manufacture of Foods, Beverage and Tobacco; the 4th : Manufacture of Textile, Wearing Apparel and Leather Products; the 14th: Wholesale and Retail Trades, Hotels and Catering Services; the 15th : Real Estate, Leasing and Business Services; the 16th: Financial Intermediation; and the 17th : Other Services) do not need to control their production scale even if the TEC policy is implemented among all sectors. All the other sectors have to control the scale to reduce their CO_2 emissions under the TEC policy.

Especially, there are three key sectors with the much higher emission intensity, which should first bear the greatest responsibility for controlling the CO_2 emissions. The 6th sector (Production and Supply of Electric Power, Heat Power and Water) with the highest emission intensity is required to reduce its CO_2 emission from 3.69 billion tons to 2.85 billion tons; The 7th sector (Coking, Gas and Processing of Petroleum) is needed to cut its emission from 2.59 billion tons to 2.01 billion tons; And finally the 10th sector (Manufacture and Processing of Metals and Metal Products) is supposed to reduce its emission from 2.38 billion tons to 1.74 billion tons. The amounts of emission reductions by the three sectors are respectively 28.13%, 19.46% and 20.98% of the decreased total emission reduction by the optimal decision making in the full cooperative case under the TEC policy.

Then, the value of tax or subsidy for each sector is finally calculated according to the optimal allocation data. As a result, most of the sectors should pay a certain amount of tax to the administrator, but inversely, a few of sectors are supposed to receive a subsidy from the administrator. Specifically, the 1st (Agriculture, Forestry, Animal Husbandry and Fishery), the 5th (Other Manufacture) and the 11th (Manufacture of Machinery and Equipment) sectors should obtain the subsidies, respectively, 1.23

trillion CNY, 0.56 trillion CNY and 5.51 trillion CNY.

On the other hand, however, the calculated results also indicate obviously that the final profit gained in the full-cooperative case is almost less than that expected individually by each sector in the part-cooperative case. This means that some sectors have to pay a cost to some extent for their emissions when the TEC policy is imposed among all sectors. In the meaning, it is not a stable scheme. Indeed, in the part-cooperative case taking no account of the emission cost and the environmental damage compensation, the profit expected by each sector gets more than or equal to that in the full-cooperative case while the corresponding total profit of all sectors becomes less than the maximum amount achieved in the full-cooperative case. In the full-cooperative case the total profit arrives at the maximum amount, i.e., 217.86 trillion CNY, but it is still less than the amount 238.23 trillion CNY, the sum of the individual maximum profit expected respectively by each sector in the part-cooperative case. The difference in amount is 20.37 trillion CNY, which is considered as a total profit loss in each sector's expectation and redistributed (shared) among all the sectors in a rationally impartial way based on the equal acceptance degree. In this sense, even if the scheme is considered unstable but it is still optimal and fair one.

(3) Furthermore, in the core application, the extended model is also used to analyse the impacts of improving the emission intensity of some sector on all other sectors' emissions. Given the highest share in total CO_2 emission reduction among the 17 sectors, Sector No.6 (Production and Supply of Electric Power, Heat Power and Water) is chosen as an example. The corresponding TEC schemes are calculated when the emission intensity of the sector is declined or improved by 20%, 40%, 60% or 80%. The result data show that when the emission intensity is improved by 20% in the sector, for instance, the amount of its emission will decrease by 499 million tons and then will have a strong influence and result in changes on the amounts of emissions of all the other sectors. As a result, even if keeping the same TEC target of 10,000 million tons, the production profit and the final use in total of all the sectors will increase by 13,975 billion CNY, and 4,397 billion CNY, respectively. Regarding the other three situations with the emission intensity improvement by 40%, 60% or 80%, there are the similar effects on all the sectors' emission allocations of the total emission. The more the improvement is made, the stronger the effect is.

Furtherly, based on an assumption of technology transfer from Japan to China, the impact analysis by the TEC model is applied for the effects of the technology transfer on CO_2 emissions. Roughly the simulated results show that if the electric power sector's emission intensity is improved to the same level as that in Japan, the total emission of the 17 sectors can be controlled at the 9,503 million tons and meanwhile the sum of total production profits and the sum of the final use will increase by 5,323 billion CNY and 1,626 billion CNY, respectively.

The impact analysis results suggest that the sector No.6 (Production and Supply of Electric Power, Heat Power and Water) is the most significant one with strong influences on reducing total CO_2 emission among all the sectors. Finally it is recommended that with technical effects, this sector should be considered as the leading industry in which technological innovation is absolutely needed to decrease the CO_2 emission per unit of production at first while implementing the TEC policy scheme.

Also, finally in order to apply furtherly the TEC model on checking the actual effects expected in the China's emission trading markets, especially the impact from the national unified emission trading system in China, this study tries to make a use of some meaningful prices from 35 CNY/ton to 300 CNY/ton, as well as the emission intensity reduction targets which are set by the China's ETS markets. The results indicate that the prices are not the key factor affecting greatly the emission reduction in the power sector in the initial operation but the emission intensity improvement by just about 4% is expected to result in a greater ripple effect on the emissions allocations of both the power sector itself and all the other sectors. Therefore, it is desirable to implement the total emission control of about 10 billion tons/year with the operation of the emissions trading market. Furthermore, in the case of further control, rather than a realistic increase in carbon tax prices, it is more efficient to reduce CO_2 emissions by improving the emission efficiency due to technological advances and affect the emissions in all industries, which will make the CO_2 total emission allocations much more efficient.

(4) In Addition, by changing the related policy factors such as the TEC policy target, different alternative policy schemes (strategies) are also computed for comparison analysis in decision making. Lastly, the model is also applied to give the simulating process on how to develop a stable and optimal TEC policy scheme.

11.3 Further researches

In this study, the problem of the TEC policy has been studied only at regional level or for a national multisectoral system, but still the established methodology (model) can be widely introduced as an analytical framework of an optimal TEC policy also at a national or international level, or for a regional or an international multisectoral system, or a multiregional system (as shown in Fig.11-3-1 on next page for example) to stimulate a cooperative strategy for preparing, developing and analysing an environmental-economic policy based on total emission control.

Although this study is concerned with the COD discharges in a regional system or the CO_2 emissions in a multisectoral system as an example in application, the optimal TEC model can be actually suitable also for the other kinds of pollutants. The difference is merely on how to establish the related basic functions.

In this study, it is because of the specific application background that only the function of emission charges or environmental tax (subsidy) policy is selected as an adjustable policy factor (vector) and the discussion has concentrated on how to set the proper and rational level of the emission charges as an economic instrument. However, the model can be also used effectively to design and analyse an environmental-economic policy in terms of other parameters such as the allowed maximum total emission (the TEC policy target), the treatment efficiency, etc. For example, for analysing the impact of technology improvement, the treatment percentage or the emission intensity can be assumed as an input variable in the simulating computation.

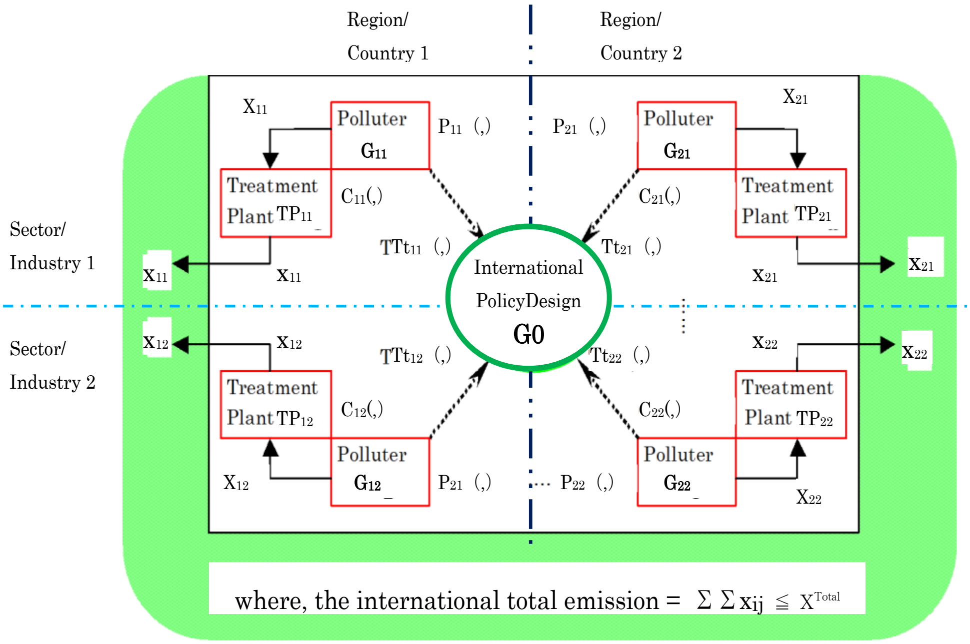


Fig. 11-3-1 A multisectoral and/or multiregional system at international level

Concerning the topic about the implementation of the TEC policy, it is in fact of the problem of how to make a policy scheme realized practically by an economic instrument or with an incentive. It is really interesting and meaningful to develop a set of policies between administrative regulations and emission permits trading markets. Specifically in practicing the TEC policy, it should be more efficient and more effective if introducing it in combination with other environmental-economic policy instruments such as the emission trading system (ETS) covering all the economic sectors to pursue a comprehensive impact on TEC policy (Jesper J., et al., 2000).

At last, to achieve decarbonized economy in the future, in addition to an efficiency-approach where energy and resource efficient products are promoted, there is surely a great need to design and implement a new sufficiency-policy by indicating an appropriate structure of consumption and production and by changing consumer's lifestyle (PECoP-Asia, 2018).

From this viewpoint, this study could be certainly improved further, but firstly here it is just expected to motivate a debate or a hint on the quantitative methodology for environmental-economic policy design, particularly, for the TEC policy schemes.

Nomenclature

G_0	game player G_0 : controller (policy-maker, administrator, agency, etc.)
G_i	game player G_i : polluter i (plant, region, country, industry or sector, etc.)
X_i	amount of pollutant generated by polluter i before waste treatment
x_i	amount of pollutant discharged from polluter i after waste treatment
$P_i (X_i)$	production profit of polluter i before waste treatment
$C_i (X_i, x_i)$	cost of waste treatment for i-th polluter's treatment plant which reduces waste from X_i to x_i
$T_i (X_i, x_i)$	emission charges (fines) paid by polluter i when the amount of pollutant discharge is x_i, where total emission control (TEC) policy is not adopted
$Tt_i (X_i, x_i)$	emission charges (fines) paid by polluter i when the amount of pollutant discharge is x_i, where the TEC policy is adopted and polluter i does not cooperate with the TEC policy
$t_i (X_i, x_i)$	emission taxes (subsidies) paid by polluter i when the amount of pollutant discharge is x_i, where the TEC policy is adopted and polluter i cooperates with the TEC policy
$A_i (X_i, x_i)$	initial profit of polluter i after waste treatment
$B_i (X_i, x_i)$	final profit (net profit) of polluter i as function of X_i where the cost of waste treatment and the emission cost (emission charges) are taken into account
$B_i (X_i)$	profit of polluter (sector) i for a multisectoral system where no waste treatment cost is considered, i.e., $X_i = x_i$
SB	social benefit when all polluters cooperate with TEC policy
SB_i	social benefit when all polluters cooperate with TEC policy except polluter i
x^{Total}	total emission control target value set by the TEC policy
x^T	total emission discharged into a given region (city, country, industry, etc.)
$D(x^T)$	environmental damage due to the total emission x^T to a given region in

	monetary terms that could be defined as a social cost
n	number of polluters
N	set of n polluters
Ñ	set of all players including n polluters (G_i) and controller (G_0)
S	set of polluters who cooperate with TEC policy
Q	set of polluters who do not cooperate with TEC policy
v (S)	characteristic function value for coalition S
v (N-{i})	characteristic function value for all polluters except polluter i
α_0	final profit or gain (benefit) of controller G_0
α_i	final profit or gain (benefit) of polluter i
γ (i)	acceptance degree of individual polluter i
t_i	tax or subsidy for polluter i who cooperates with TEC policy
P_i	total production (output) of sector i
F_i	final use (demand) of sector i
a_{ij}	direct input coefficients, i.e., requirement on sector i per unit output of sector j
β_i	environmental emission (intensity) coefficient of sector i, (i.e., the amount of the environmental emission generated from per unit output of sector i)
η_i	waste treatment efficiency (for COD waste water)
λ_i	emission reduction percentage or share (for CO_2 emission reduction)
ξ_i	CO_2 emission prices coefficients for sector i
I	identity matrix
L	input-output multipliers or Leontief inverse matrix

References

Acquaye A, Feng K, Oppon E, Salhi S, et al., 2017, Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints [J], J. Environ Manage., 2017(187), pp.571-585.

Ahmad N., Du L., 2017, Effects of energy production and CO_2 emissions on economic growth in Iran: ARDL approach [J], Energy, 123 (2017), pp.521-537

Ali Y, Ciaschini M, et al., 2017, An analysis of CO_2 emissions in Italy through the Macro Multiplier (MM) approach [J], Journal of Cleaner Production 149 (2017), pp.238-250

Amheka A., Higano Y., Mizunoya T., Yabar H., 2014, Comprehensive Evaluation of the Feasibility to Develop a Renewable Energy Technology System and Waste Treatment Plant in Kupang City, Indonesia Based on a Kupang Input Output Table [J], Procedia Environmental Sciences, 20 (2014), pp.79-88

Ang B.W, 2004, Decomposition analysis for policymaking in energy: which is the preferred method? [J], Energy Policy 32, 1131-1139. https://doi.org/10.1016/S0301- 4215(03)00076-4

Ang B.W., H. Wang, 2015, Index decomposition analysis with multidimensional and multilevel energy data [J], Energy Economics, Vol.51, Sept.2015, pp.67-76

Ang Y., Lin X., Zhang Y., Jiang X., Peng L., 2019, Analysis of driving factors and allocation of carbon emission allowance in China[J], Science of the Total Environment 673 (2019), pp.74-82

Annette W., 2020, China Seeking to Set Carbon Price through its Emissions Trading System (ETS) [OL], China News Brief and Action Alert, March 10, 2020, https://www.climatescorecard.org/2020/03/

Aqeel A. B., Zahedi G., 2011, Sustainable energy systems: Role of optimization modeling techniques in power generation and supply-A review [J], Renewable and Sustainable Energy Reviews 15 (2011), pp.3480-3500

Arif F., Dissou Y., 2016, Regional burden sharing of GHG mitigation policies in a decentralized federation [J], Economic Modelling, Volume 52, Part B, January 2016, pp.390-399

Banks P.A., 1988, Water and Environmental Management in the Third World [J], IWEN, 1988, (3), pp.102-112

Banos R., Manzano-Agugliaro F., Montoya F.G., Gil C., Alcayde A., Gomez J., 2011, Optimization methods applied to renewable and sustainable energy: A review [J], Renewable and Sustainable Energy Reviews, Vol.15 (4), May 2011, pp1753-1766

Baumol W.J., 1971, The Use of Standards and Prices for Protection of Environment [J], Swedish J. of Economics, Vol.73, March 1971, pp.42-54

Benjamin F. Hobbs, 1995, Optimization methods for electric utility resource planning [J], European Journal of Operational Research 83 (1995), pp.1-20

Bilec M.M., Robert J. R., Matthews H. S., 2010, Life-Cycle Assessment Modeling of Construction Processes for Buildings [J], Journal of Infrastructure Systems, September 2010 Volume 16, Issue 3. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000022

Black G., Holley D., Solan D., Bergloff M., 2014, Fiscal and economic impacts of state incentives for wind energy development in the Western United States [J], Renewable and Sustainable Energy Reviews, 34(2014) 136-144

Bloemhof-Ruwaarda J.M., Paulvan Beekb, Leen Hordijka, Luk N.Van Wassenhovec, 1995, Interactions between operational research and environmental management [J], European Journal of Operational

Research 85 (1995), pp.229-243

Bothe M., 1993, The Subsidiarity Principle, Fair Principles for Sustainable Development: Essays on Environmental Policy and Developing Countries [M], pp123-137

Bower B.T., Ehler C.N. and Kneese A.V.,1977, Incentives for managing the environment [J], Environ. Sci. Technol., 1977, 11, pp.250-254

Boyd R., K.Krutilla, et al, 1995, Energy Taxation as a Policy Instrument to Reduce CO_2 Emissions: A Net Benefit Analysis, Journal. of Environmental Economics and Management 29(1995), pp.1-24

Braat L.C., W.F.J. van Lierop (1987), Environment, Policy and Modeling [J], Economic Ecological Modeling [M], Elsevier Science Publishers B.V. (North-Holland), 1987, Chapter 1, pp7-19

Brick K., Visser M., 2015, What is fair? An experimental guide to climate negotiations [J], European Economic Review, Vol.74, February 2015, pp.79-95

Bringezu S., Bleischwitz R., 2009, Visions of a sustainable resource use. In: Sustainable Resource Management - Global Trends, Visions and Policies [M], Greenleaf Publishing, Sheffield, London, U.K., Chapter 4-5, pp.61-81. https://doi.org/10.4324/9781351279284

Bye B., 2008, Macroeconomic modelling for energy and environmental analyses: Integrated economy-energy-environment models as efficient tools [M], Research Department, Statistics Norway, Documents 14(2008)

Cai W., Wang C., Wang K., et al., 2007, Scenario analysis on CO_2 emissions reduction potential in China's electricity sector [J], Energy policy, 2007,12 (12), pp.6445-6456

Cames M., Weidlich A., 2006, Emissions trading and innovation in the German electricity industry - impact of possible design options for an emissions trading scheme on innovation strategies in the German electricity industry [M], in: Antes R., Hansjargens B., Letmathe P. (eds) Emissions Trading and Business., Physica-Verlag HD 2006.

Carlin A., 1992, United States Experience with Economic Incentives to Control Environmental Pollution [M], EPA-230-R92-001, July 1992, Washington DC, USA

Cavalcanti M., Szklo A., Machado G., Arouca M., 2012, Taxation of automobile fuels in Brazil: Does ethanol need tax incentives to be competitive and if so, to what extent can they be justified by the balance of GHG emissions? [J], Renewable Energy 37 (2012), pp. 9-18

Chai Q., Xu H., 2014, Modeling an emissions peak in China around 2030: Synergies or trade-offs between economy, energy and climate security [J], Advances in Climate Change Research, 2014, 5(4), pp.169-180

Chai Q.M., Zhang X.L., 2010, Technologies and Policies for the transition to a sustainable energy system In China [J], Energy, 35(2010), pp.3995-4002

Chang K. and Chang H., 2016, Cutting CO_2 intensity targets of interprovincial emissions trading in China [J], Applied Energy, 163(2016), pp 211-221

Chang Z., Wu H., Pan K., Zhu H., Chen, J., 2017. Clean production pathways for regional power-generation system under emission constraints: a case study of Shanghai [J], Journal of Cleaner Production, Vol.143, Feb.2017, pp.989-1000

Charles D.K., 2000, Environmental Economics [M], Oxford University Press, pp.135-177

Chen F., Chen H., Guo D., Han S., Long R., 2018, How to achieve a cooperative mechanism of MSW source separation among individuals: An analysis based on evolutionary game theory [J], Journal of Cleaner Production 195 (2018), pp.521-531

Chen S., Chen B., 2016, Tracking inter-regional carbon flows: a hybrid network model [J], Environ. Sci. Technol. 50, 4731-4741, https://doi.org/10.1021/acs.est.5b06299.

Chen Z, Chen G, et al., 2010, Embodied carbon dioxide emissions of the world economy: A system input-output simulation for 2004 [J], Procedia Environmental Sciences, 2 (2010), pp.1827-1840

Chen Z.M., Chen G.Q., Chen B., 2010, Embodied Carbon Dioxide Emissions of the World Economy: A

Systems Input-Output Simulation for 2004 [J], Procedia Environmental Sciences, 2(2010), pp.1827-1840

Chong C. H., Wei Xin Tan, Zhao Jia Ting, Pei Liu, Linwei Ma, Zheng Li, Weidou Ni, 2019, The driving factors of energy-related CO_2 emission growth in Malaysia: The LMDI decomposition method based on energy allocation analysis [J], Renewable and Sustainable Energy Reviews 115-2019-109356

Christian E., 2007, The Making of the EU Emissions Trading Scheme: Status, Prospects and Implications for Business [J], European Management Journal, Vol.25 (6), Dec.2007, pp.453-463

Christoph B., Andreas L., Thomas F. R., 2014, Optimal emission pricing in the presence of international spillovers: Decomposing leakage and terms-of-trade motives [J], Journal of Public Economics, Volume 110, February 2014, pp.101-111

Christoph B., Knut E.R., 2009, Strategic partitioning of emission allowances under the EU Emission Trading Scheme [J], Resource and Energy Economics, Vol.31(3), 2009, pp.182-197

Christoph W. F., Haldi P.A., Sarlos G., 2003, Dynamic formulation of a top-down and bottom-up merging energy policy model [J], Energy Policy, Vol.31 (10, Aug.2003, pp1017-1031. https://doi.org/10.1016/S0301-4215(02)00170-2

Cicenia A., 2018, China’s Environmental Protection Tax [OL], China Briefing, January 18, 2018. https://www.china-briefing.com/news/china-environmental-protection-tax/

Ciin, 2018, 2018 China's carbon market development status analysis and future development prospects forecast [OL], China Industrial Information Network (CIIN), Jan. 15, 2018 (in Chinese). http://www.chyxx.com/industry/201801/603771.html (last access on July 23, 2020).

Clement A.Tisdell, 1991, Economics of Environmental Conservation: economics for environmental and ecological management [M], Elsevier Amsterdam, 1999

Creti A., Sanin M.E., 2017, Does environmental regulation create merger incentives? [J], Energy Policy, 105, pp.618-630

Crippa M., Oreggioni G., Guizzardi D., Muntean M., Schaaf E., Lo Vullo E., Solazzo E., Monforti-Ferrario F., Olivier J.G.J., Vignati E., 2019, Fossil CO_2 and GHG emissions of all world countries - 2019 Report [OL], EUR 29849 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-11100-9, doi:10.2760/687800, JRC117610 (Access on Dec.18, 2019).

Cui H., Zhao T., Wu R., 2018, CO_2 emissions from China's power industry: Policy implications from both macro and micro perspectives [J], Journal of Cleaner Production 200 (2018), pp.746-755

Cui L.B., Fan Y., Zhu L., Bi Q.H., 2014, How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? [J], Appl. Energy, 136, pp.1043-1052

Daniel R.S., Andrew F.A. Hoadley, Kaveh Rajab Khalilpour, 2019, A multi-objective extended input-output model for a regional economy[J], Sustainable Production and Consumption 20, pp.15-28

Dannenberg A., Tim Mennel, Ulf Moslener, 2008, What does Europe pay for clean energy?-Review of macroeconomic simulation studies [J], Energy Policy, Vol.36(4), April 2008, pp.1318-1330

Davey B., 2012, Cap & Share in Pictures by Laurence Matthews, in: Sharing for Survival - Restoring the Climate, the Commons and Society [M], FEASTA, Ireland, 2012.04, Chapter 3

David J. White, Klaus Hubacek, Kuishuang Feng, Laixiang Sun, Bo Meng, 2017, The Water Energy Food Nexus in East Asia: A tele-connected value chain analysis using inter-regional input output analysis [J], Applied Energy (2017), 2018, 210 (15): 550-567

DeCara S., Jayet P.A., 2011, Marginal abatement costs of greenhouse gas emissions from European agriculture: cost-effectiveness, and the EU non-ETS burden-sharing agreement [J], Ecol. Econ. 70 (9), pp1680-1690

Dieter H., Cameron Hepburn, Richard Mash, 2003, Credible Carbon Policy [J], Oxford Review of Economic Policy, Vol.19, Issue 3, Sept.2003, pp438-450, https://doi.org/10.1093/oxrep/19.3.438

Dommen E., 1993, Fair Principles for Sustainable Development: Essays on Environmental Policy and

Developing Countries (New Horizons in Environmental Economics) [M], Edward Elgar Publishing, Nov.1, 1993, pp1-6

Donald H., Zhihua Zhang, John C. Moore, Qi Qiao, Qi Li, 2015, Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling [J], Journal of Cleaner Production, 103 (2015), pp1-12

Dong F., Ruyin Long, Bolin Yu, Ying Wang, Jingyun Li, Yue Wang, CNYju Dai, Qingliang Yang, Hong Chen, 2018, How can China allocate CO_2 reduction targets at the provincial level considering both equity and efficiency? Evidence from its Copenhagen Accord pledge [J], Resources, Conservation & Recycling 130 (2018), pp. 31-43

Dong H., Hancheng Dai, Yong Genga, Tsuyoshi Fujita, Zhe Liu, Yang Xie, Rui Wu, Minoru Fujii, Toshihiko Masui, Liang Tang, 2017, Exploring impact of carbon tax on China's CO_2 reductions and provincial disparities [J], Renewable and Sustainable Energy Reviews 77 (2017), pp.596-603

Doris F., 2012, Challenges of low carbon technology diffusion: insights from shifts in China's photovoltaic industry development [J], Innovation & Development, 2012()

Dresner S, Dunne L, Clinch P, Beuermann C., 2006, Social and political responses to ecological tax reform in Europe: an introduction to the special issue [J], Energy Policy, 2006, vol.34, pp 895-904

Duan H., Wang H., Wang X., 2016, Study on the Influence Factors and Driving Effect on Carbon Emission in Leading Industries of Japan [J], Contemporary Economy of Japan, 2016, 208 (4), pp.70-82

Ekko C., 1993, Macroeconomic Analysis of Environmental Policy [M], Elsevier Amsterdam

Ekko I., Jan van der Straaten, Herman R. J. Vollebergh, 2001, Key issues in environmental economics, in: Economic Growth and Valuation of the Environment: A Debate [M], Edward Elgar Publishing, USA, 2001, pp90-134

Elijah I.O., 2013, A review of the Nigerian biofuel policy and incentives (2007) [J], Renewable and Sustainable Energy Reviews 22(2013), pp246-256

Elizabeth S., John Proops and Philip Gay, 1994, Carbon Taxes, Consumer Demand and Carbon Dioxide Emissions: A Simulation Analysis for the UK [J], Fiscal Studies, 1994, 15(2), pp 19?43

Elke D. Groh, Andreas Ziegler, 2018, On self-interested preferences for burden sharing rules: An econometric analysis for the costs of energy policy measures [J], Energy Economics, Volume 74, August 2018, Pages 417- 426

Elke L.H, Maxwell Brown, Stuart Cohen, Sharon Showalter, et al., 2018, U.S. energy sector impacts of technology innovation, fuel price, and electric sector CO_2 policy: Results from the EMF 32 model intercomparison study [J], Energy Economics, 73 (2018):352-370

Erhun K., 1992, Economics of Natural Resources and the Environment [M], Chapman & Hall, 1992

European Union, 2000, Directive 2000/60/EC of the European parliament and of council of 23 October 2000 establishing a framework for community action in the field of water policy [Z], Brussels, Belgium, the Council of the European Union, 2000

Evelyn H. and Abby W., 2004, EPA's environmental technology verification program: raising confidence in innovation [J], EM, 2004, (5):34 -41

Eyckmans J., Tulkens H., 2003, Simulating coalitionally stable burden sharing agreements for the climate change problem [J], Resource and Energy Economics, Vol.25(4), pp299-327

Fan J., Pan X., Li J., 2017, Production-based and consumption-based CO_2 transfers among major economies: a flow chart analysis [J], EnergyProcedia, 105(2017): 3499-3506

Fang G., Liu M., Tian L., Fu M., Zhang Y., 2018, Optimization analysis of carbon emission rights allocation based on energy justiced: The case of China [J], Journal of Cleaner Production, 202 (2018), pp.748-758

Fang J., Wang S., Yue C., et al., 2009, Scenario analysis on the global carbon emissions reduction goal proposed in the declaration of the 2009 G8 Summit [J], Science in China Series D: Earth Sciences, 2009, 52(11):1694-1702, doi:10.1007/s11430-009-0197-6

Fang K., Zhang Q., Long Y., Yoshida Y., et al., 2019, How can China achieve its Intended Nationally Determined Contributions by 2030? A multi-criteria allocation of China's carbon emission allowance [J], Applied Energy 241 (2019) 380-389

Faure M., Joyeeta Gupta, Andries Nentjes, 2003, Climate Change and the Kyoto Protocol [M], Edward Elgar Publishing, Cheltenham, UK and Northhampton MA, USA. 2003, pp248-275 & pp279-291

FBIC, 2018, China's Low Carbon Economic Outlook and Investment Strategic Planning Analysis Report [R], Forward Economist, Forward Business Information Co., Ltd, 2018, Shenzhen, China. https://bg.qianzhan.com/report/detail/20bfc49c40524e78.html

Feasta (The Foundation for the Economics of Sustainability), 2008, Cap & Share: A fair way to cut greenhouse emissions [EB/OL], May 2008, website (last access on 2019.04.20): http://www.capandshare.org/download_files/C&S_Feasta_booklet.pdf

Fei R., Lin B., 2017, The integrated efficiency of inputs-outputs and energy-CO_2 emissions performance of China's agricultural sector [J], Renewable and Sustainable Energy Reviews, 75(2017), pp.668-676

Feng C., Chu F., Ding J., Bi G., Liang L., 2015, Carbon emissions abatement (CEA) allocation and compensation schemes based on DEA [J], Omega, Volume 53, June 2015, pp.78-89

Feng Z., Tang W., Niu W., Wu Q., 2018, Bi-level allocation of carbon emission permits based on clustering analysis and weighted voting: A case study in China [J], Applied Energy 228 (2018), pp.1122-1135

Fernando S.P., Weslem Rodrigues Faria, Vinicius de Almeida Vale, 2015, The increase in Brazilian household income and its impact on CO_2 emissions: Evidence for 2003 and 2009 from input-output tables [J], Energy Economics, 52(2015), pp.228-239

Fischer C., Parry I.W.H., Pizer W.A., 2003, Instrument choice for environmental protection when technological innovation is endogenous [J], Environ. Econ. Manage, 45 (3), 2003, pp.523-545

Flues F., van Dender K., 2017, Permit allocation rules and investment incentives in emissions trading systems. In: OECD Taxation Working Papers, vol.33, OECD Publishing, Paris, 2017

Fontini, F., Pavan, G., 2014, The European Union Emission Trading System and technological change: the case of the Italian pulp and paper industry, Energy Policy, 68, pp.603-607

Fosten J., 2019, CO_2 emissions and economic activity: A short-to-medium run perspective [J], Energy Economics, 83 (2019), pp.415-429

Frank J. Diets, F.van der Ploeg, J. van der Straaten, 1991, Environmental Policy and the Economy: An Introduction [M], Environmental Policy and the Economy, Elsevier Science Publishers B.V., North-Holland, 1991, pp.1-16

Fredrik C., Kataria M., Lampi E., Lofgren A., Sterner T., 2011, Is fairness blind?---The effect of framing on preferences for effort-sharing rules [J], Ecological Economics, Volume 70, Issue 8, 15 June 2011, pp.1529-1535

Fridolin K., Simone Gingrich, Nina Eisenmenger, Karl-Heinz Erb, Helmut Haberl, Marina Fischer-Kowalski, 2009, Analysis Growth in global materials use, GDP and population during the 20th century [J], Ecological Economics, Volume 68, Issue 10, 15 August 2009, Pages 2696-2705

Friedman J.W., 1985, Game theory with applications to economics [M], Oxford: Cambridge University Press, 1985

Fudenberg D., Tirole J., 1991, Game Theory [M], Massachusetts Institute of Technology, USA, 1991

Fujimori S, Kainuma M, Masui T, Hasegawa T, Dai H, 2014a, The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation [J], Energy Policy, 2014, vol.75, pp.379-391.

Fujimori S, Masui T, Matsuoka Y, 2014b, Development of a global computable general equilibrium model coupled with detailed energy end-use technology [J], Appl Energy 128 (2014), pp.296-306.

Fuss S., Flachsland C., Koch N., Kornek U., Knopf B., Edenhofer O., 2018, A framework for assessing the performance of cap-and-trade systems: insights from the European Emissions Trading System [J], Rev. Environ. Econ. Policy 12 (2), 2018, pp.220-241

Gacitua L., Gallegos P., Henriquez-Auba R., Lorca A., Negrete-Pincetica M., Olivaresa D., Valenzuela A., Wenzel G., 2018, A comprehensive review on expansion planning: Models and tools for energy policy analysis [J], Renewable and Sustainable Energy Reviews 98 (2018), pp.346-360

Gagelmann F., 2008, 2017 The Influence of the Allocation Method on Market Liquidity, Volatility and Firms' Investment Decisions [M], Emissions Trading, Springer New York, pp.69-88.

Gambhir A., Schulz N., Napp T., Tong D., Munuera L., Faist M., Riahi K.. 2013, A hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050[J], Energy Policy, 2013(59), pp.614-632

Gao J., Hou H., Zhai Y., Woodward A., Vardoulakis S., Kovats S., Wilkinson P., Li L., Song X., Xu L., Meng B., Liu X., Wang J., Zhao J., Liu Q., 2018, Greenhouse gas emissions reduction in different economic sectors: Mitigation measures, health co-benefits, knowledge gaps, and policy implications [J], Environmental Pollution 240 (2018), pp.683-698

Gately D., 1974, Sharing the gains from regional cooperation: a game theoretic application to planning investment in electric power [J], International Economic Review 1974; 15(1), pp.195-208

GCBR (The Global Carbon Budget Report), 2017, Future Earth 2017-18 Annual Report, https://futureearth.org/wp-content/uploads/2018/10/annual_report_2017-18_final.pdf

Ge C., Chen J., Wang J., Long F., 2009, China's Total Emission Control Policy: A Critical Review [J], Chinese Journal of Population Resources and Environment, Vol.7, 2009 (2), pp.50-58

Germain M., Toint P.L., Tulkens H., 1997, Financial transfers to ensure international optimality in stock pollutant abatement, in: Duchin F., Faucheux S., Gaudy J., Nicola I. (Eds.), Sustainability and Firms: Technological Change and Changing Regulatory Environment, Edward Elgar, Celtenham, UK, 1997

GFC and CBEE, 2016, A Study on China's Carbon Finance Market [M], the Green Finance Committee (GFC) and the China Beijing Environment Exchange (CBEE), published in 2016, Beijing.

Giancarlo A., Edson de O.P., et al., 2017, An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience [J], Renewable and Sustainable Energy Reviews, 70 (2017) , pp.1090-1098

Gibbons R., 1992, Game Theory for Applied Economists [M], Princeton University Press, 1992

Glen P. Peters, 2008, From production-based to consumption-based national emission inventories [J], Ecological Economics, Vol.65, Issue 1, 15 March 2008, pp.13-23

Glen P. Peters, Andrew R., Lennox J., 2011, Constructing An Environmentally Extended Multi-Regional Input-output Table Using the GTAP Database [J], Economic Systems Research, Volume 23, 2011 - Issue 2 (Online: https://doi.org/10.1080/09535314.2011.563234)

Goto N., 1996, Macro-economic and Sectoral Impacts of Carbon Taxation: A Case for the Japanese Economy [J], Global Warming, Carbon Limitation and Economic Development, CGER-Report, pp.5-22

Grtibler A., Nakicenovic N., 1994, International burden sharing in greenhouse gas reduction [M], International Institute for Applied Systems Analysis, Vol.19, Laxenburg, Austria, 1994

Grubb M., Azar C., Persson U.M., 2005, Allowance allocation in the European emissions trading system: a commentary, Clim. Policy, vol. 5 (1), pp.127-136

Guan D., Liu Z., Geng Y., Lindner S., Hubacek K., 2012, The gigatonne gap in China's carbon dioxide inventories [J], Nature Climate Change, (2012), vol.2, pp.672-675

Guo J., Wang H., et al., 2013, The empirical analysis on the influence of international trade to industries' embodied carbon emissions in China [J], (in Chinese), Journal of Beijing Institute of Technology, Vol.15 No.6, Dec.2013, pp1-9

Guo X.Y., Lu C.C., Lee J.H., Chiu Y.H., 2017, Applying the dynamic DEA model to evaluate the energy efficiency of OECD countries and China [J], Energy, 134(2017), pp.392-399

Gupta S., Bhandari P.M., 1999, An effective allocation criterion for CO_2 emissions [J], Energy Policy 27 (12), pp.727-736

Hamilton C., 2001, Principles of Justice (Chapter1), Running from the Storm: The Development of Climate Change Policy in Australia [M], Clive Hamilton 2001, UNSW Press, Chapter 1, pp9-11

Hanaka T., Kagawa S., Ono H., Kanemoto K., 2017, Finding environmentally critical transmission sectors, transactions, and paths in global supply chain networks [J], Energy Economics, 2017(68), pp.44-52

Harland W.W., Armonk Jr., 1999, Global Environmental Macroeconomics [M], N.Y.: M.E. Sharpe, 1999, pp.167-179

Harris M., Raviv A., 1979, Optimal incentive contracts with imperfect information [J], Journal of Economic Theory, Vol.20 (2), April 1979, pp.231-259

Harry G., David G., 2016, Distributive fairness in paying for clean energy infrastructure [J], Ecological Economics, Volume 126, June 2016, pp.87-97

Harvey H., Orvis R., Rissman J., 2018, Designing Climate Solutions: A Policy Guide for Low-Carbon Energy [M], Island Press, Nov. 2018, pp.376

Hasegawa R., Kagawa S., Tsukui M., 2015, Carbon Footprint Analysis through Constructing a Multi-Region Input-Output Table: A Case Study of Japan [J], Journal of Economic Structures, 4:5(2015), pp.1-20

Hawkins J., Ma C., Schilizzi S., Zhang F., 2015, Promises and pitfalls in environmentally extended input-output analysis for China: A survey of the literature [J], Energy Economics, 48 (2015), pp.81-88

He Y., Wang L., Wang J., 2012, Cap-and-trade vs. carbon taxes: a quantitative comparison from a generation expansion planning perspective [J], Comput. Ind. Eng. 63 (3), pp.708-716

Hepburn C., 2006, Regulation by prices, quantities, or both: a review of instrument choice [J], Oxf. Rev. Econ. Policy, 22 (2), 2006, pp.226-247

Hitaj C., 2013, Wind power development in theUnited States [J], J. Environ. Econ. Manag, 2013, 65(2), pp.394-410

Hkon S., Vegard T., Christian H., Tobias D., 2019, Fairness conceptions and self-determined mitigation ambition under the Paris Agreement: Is there a relationship? [J], Environmental Science & Policy, Vol.101, Nov. 2019, pp.245-254. CICERO-Center for International Climate Research, Oslo, Norway

Hoekstra R., 2010, A complete database of peer-reviewed articles on environmentally extended input-output analysis [J], In: Towards 18th International Input output Conference of the International Input-output Association. IIOA), pp.20-25

Hong Z., Chu C., Zhang L.Linda, Yu Y., 2017, Optimizing an emission trading scheme for local governments: A Stackelberg game model and hybrid algorithm [J], International Journal of Production Economics 193 (2017), pp.172-182

Hu Q., Li X., Lin A., Qi W., Li X., Yang X., 2018, Total emission control policy in China [J], Environmental Development, vol.25, Mar.2018, pp.126-129

Ian A.M., Hanley N., Kornienko T., 2009, Using contests to allocate pollution rights [J], Energy Policy, Volume 37, Issue 7, July 2009, pp.2798-2806

ICAP, 2020, ETS Detailed Information, International Carbon Action Partnership (ICAP), https://ets-china.org/ets-in-china/, last update by 23 June 2020

Ichiishi T., 1993, Descriptive cooperative game theory [M], The Cooperative Nature of the Firm, Cambridge University Press, pp23-57

IEA, 2011, CO_2 Emissions from Fuel Combustion: Highlights (2011 edition), Paris, France: International Energy Agency (IEA), 2011, p.9, archived from the original on 17 March 2017.

Ikeda S., 1987, Economic-Ecological Models in Regional Total Systems [J], Economic-Ecological

Modeling [M] by L.c. Braatj W.F.J. & van Lierop (Editors), Elsevier Science Publishers B.V. (North-Holland) , 1987, Chapter 12, pp185-202

Imma Curiel, 1997, Cooperative Games Arising from Combinatorial Optimization Problems [M], Kluwer Academic Publishers, 1997

Imran Khan, 2019, Greenhouse gas emission accounting approaches in electricity generation systems: A review [J], Atmospheric Environment 200 (2019), pp.131-141

IPCC, 2001, Climate Change 2001: Working Group I: The Scientific Basis: figure 6-6, [OL], Archived from the original on 14 June 2006

IPCC, 2013, Intergovernmental Panel on Climate Change 2013 Summary for Policymakers [OL], Global Greenhouse Gas Emissions Data, http://templatelab.com/climatechange-WGI-AR5-SPM-brochure/EPA

Isabela Butnar, Maria Llop, 2011, Structural decomposition analysis and input-output subsystems: Changes in CO_2 emissions of Spanish service sectors (2000-2005) [J], Ecological Economics, 70(2011), pp.2012-2019

James A. Lennox, Renger van Nieuwkoop, 2010, Output-based allocations and revenue recycling: Implications for the New Zealand Emissions Trading Scheme [J], Energy Policy, Volume 38, Issue 12, December 2010, pp.7861-7872

James D. E., Jansen H. M. A., Opschoor J. B., 1978, Economic Approaches to Environmental Problems [M], Elsevier Scientific Publishing Company, 1978

James K. Boyce, 2018, Carbon Pricing: Effectiveness and Equity, Ecological Economics, Vol.150, Aug.2018, pp.52-61

Jang Y.K, Kim J.W., 1986, Total emission control strategies for the management of air pollution in Ulsan [J], Atmospheric Environment, Volume 20, Issue 10, 1986, p.2078

Janire P.G., Gonzalo G.G, Laureano J. E., Jeffrey J. S., Ignacio E.G., 2016, Macro-economic multi-objective input-output model for minimizing CO_2 emissions:Application to the US economy [J], Process Systems Engineering, 2016 American Institute of Chemical Engineers AIChE J, 62, 3639-3656. June 2016, https://doi.org/10.1002/aic.15376

Jaraite J., Corrado D.M., 2012, Efficiency, productivity and environmental policy: A case study of power generation in the EU [J], Energy Economics, Vol.34, Issue 5, Sept. 2012, pp1557-1568

Jaruwan C., 2018, Decomposition analysis of CO_2 emission in ASEAN: an extended IPAT Model [J], Energy Procedia 153 (2018), pp.186-190

Jaume F.G, David F.V, 2017, The influence of energy efficiency on other natural resources use: An input-output perspective [J], Journal of Cleaner Production, 162 (2017), pp.336-345

Jensen J. and Rasmussen T.N., 2000, Allocation of CO_2 emissions permits: A general equilibrium analysis of policy instruments [J], Journal of Environmental Economics and Management 40(2000), pp.111-136

Ji J., Zhang Z., Yang L., 2017, Comparisons of initial carbon allowance allocation rules in an O2O retail supply chain with the cap-and-trade regulation [J], International Journal of Production Economics, Vol.187, May 2017, pp.68-84

Jiang J., Ye B., Liu J., 2019, Peak of CO_2 emissions in various sectors and provinces of China: Recent progress and avenues for further research [J], Renewable and Sustainable Energy Reviews 112 (2019) pp.813-833

Jiang J., Xie D., Ye B., Shen B., Chen Z., 2016, Research on China's cap-and-trade carbon emission trading scheme: Overview and outlook [J], Applied Energy, Vol.178, 2016, pp.902-917

Jiang J., Ye B., Ma X., 2014, The instruction of Shenzhen's carbon emission trading scheme [J], Energy Policy, 75 (2014), pp.17-21

Jin H., et al., 2008, Fundamental study of CO_2 control technologies and policies in China [J], Science in China Series E: Technological Sciences, 2008, 51(7), pp.857-870

Jin W., Zhang Z., 2016, On the mechanism of international technology diffusion for energy technological progress [J], Resource and Energy Economics, 46 (2016), pp.39-61

John H. Dales, 1968, 2002, Pollution, Property & Prices: An Essay in Policy-Making and Economics [M], Toronto: University of Toronto Press, 1968, pp. vii, 111; (New Horizons in Environmental Economics series), 2002, Books, Edward Elgar Publishing, number 2553.

Jones A. J., 1980, Game Theory: Mathematical Models of Conflict [M], W. & J. Mackay Ltd.

Jordi T., Stefano F. V., Francesco N., 2019, The impact of the EU Emissions Trading System on low-carbon technological change: The empirical evidence [J], Ecological Economics, vol.164 (2019) 106347

Joseph E. Stiglitz, 1975, Incentives, Risk, and Information: Notes Towards a Theory of Hierarchy [J], The Bell Journal of Economics, Vol.6, No.2 (1975), pp.552-579

Joy M., Richard W. (Editor), 2010, The Sustainability Practitioner's Guide to Input-Output Analysis [M], Common Ground Publishing, June 15, 2010

Ju C., 2018, China is expected to be the world's largest carbon trading market [OL], China Daily, 2018-05-21, source on: China Carbon Emissions Trading Network (CCETN) (in Chinese): http://www.tanpaifang.com/tanjiaoyi/2018/0521/62005.html (last access on 2019.11.27)

Ju L., Chen B., 2010, An Input-output Model to Analyze Sector Linkages and CO_2 Emissions [C], International Society for Environmental Information Sciences, 2010, Annual Conference (ISEIS), Procedia Environmental Sciences, 2(2010):1841-1845

Kagawa S., Gomi T., 2005, Exploring the Relationship Between Kyoto Protocol and Efficient Resource Uses Using the International Input-Output Programming Model: An Application to the Japanese and Chinese Economies, (in Japanese), Innovation & I-O Technique: Business Journal of PAPAIOS, 13 (June 2005), pp.16-31

Kagawa S., R. Hasegawa, M.Tsukui, 2015, Carbon footprint analysis through constructing a multiregion input-output table: A case study of Japan [J], Journal of Economic Structures, 4:5 (2015), pp.1-20

Katayama T., Nabetani T., 1981, IFAC Control Science and Technology [C], The 8th Triennial World Congress, Kyoto, Japan, Vol.7 (1981), pp.3539-3545

Kaya I., Colak M., Terzi F., 2019, A comprehensive review of fuzzy multi criteria decision making methodologies for energy policy making [J], Energy Strategy Reviews 24 (2019), pp.207-228

Kjell Y.T., Dan R. J., 1985, Subrules of the equality and contribution principles: their perceived fairness in distribution and retribution [J], Social Psychology Quarterly, Vol. 48, No.3 (Sep.1985), pp.249-261

Kjell Y.T., Uriel G. F., 1983, Choice of a distribution principle: crosscultural evidence on the effects of resources [J], Acta. Sociol.,26 (2), pp.161-173, https://doi.org/10.1177/000169938302600204

Kong Y., Zhao T., Yuan R., Chen C., 2019, Allocation of carbon emission quotas in Chinese provinces based on equality and efficiency principles [J], Journal of Cleaner Production, 211 (2019), pp.222-232

Konidari P., Mavrakis D., 2007, A multi-criteria evaluation method for climate change mitigation policy instruments [J], Energy Policy, Vol. 35, Issue 12, Dec.2007, pp.6235-6257

Kumara A., Bikash S., Arvind R. S., Yan Deng, Xiangning He, Praveen Kumar, R.C. Bansal, 2017, A review of multicriteria decision making (MCDM) towards sustainable renewable energy development [J], Renewable and Sustainable Energy Reviews 69 (2017), pp.596-609

Laesa E., Mayeresb I., Rendersa N., Valkeringa P., Verbekec S., 2018, How do policies help to increase the uptake of carbon reduction measures in the EU residential sector? Evidence from recent studies [J], Renewable and Sustainable Energy Reviews 94 (2018), pp.234-250

Lamnatou C., Chemisana D., 2017, Concentrating solar systems: Life Cycle Assessment (LCA) and environmental issues [J], Renewable and Sustainable Energy Reviews, 78 (2017), pp.916-932

Leimbach M., Bauer N., Baumstark L., Edenhofer O., 2010, Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R [J], Environmental Modeling & Assessment, June 2010, Vol.15(3), pp.155-173

Lema A., Lema R., 2016, Low-carbon innovation and technology transfer in latecomer countries: Insights from solar PV in the clean development mechanism [J], Technological Forecasting & Social Change, 2016

Lenzen M., Pade L.L., Munksgaard J., 2004, CO_2 Multipliers in Multi-region Input-Output Models [J], Economic Systems Research, 16(4)2004, pp.391-412

Lenzen M., Wood R., Wiedmann T., 2010, Uncertainty analysis for multi-region input-output models: A case study of the UK's carbon footprint [J], Economic Systems Research, 2010, 22 (1), pp.43-63

Leontief W, 1970, Environmental repercussions and the economic structure: an input-output approach [J], Rev. Econ. Stat. 52 (1970), pp.262-271

Li G., 2018, Why does the China's carbon trading market begin from the electric power industry at first? How to build China's carbon market? Five questions to be clear [OL], by Zhou R., (in Chinese), source: 2018.10.08 on China Carbon Emissions Trading Network (CCETN) website: http://www.tanpaifang.com/tanguwen/2018/1008/62359_3.html

Li H., Scott K., Kangjuan L., Damien G., 2019, A systematic review of empirical methods for modelling sectoral carbon emissions in China [J], Journal of Cleaner Production, 215 (2019) pp.1382-1401

Li J., Chai Q., 2016, China's Climate Policy and Carbon Market Outlook in Post-Paris-Agreement Era [J], China International Studies, 57, 114 (2016)

Li L., Ye F., Li Y., Tan K.H., 2019, A bi-objective programming model for carbon emission quota allocation: Evidence from the Pearl River Delta region, Journal of Cleaner Production, vol.205 (2019), pp.163-178

Li L., Li Y., Ye F., Zhang L., 2018, Carbon dioxide emissions quotas allocation in the Pearl River Delta region: Evidence from the maximum deviation method [J], Journal of Cleaner Production, vol.177 (2018), pp.207-217

Li N., Zhang X., Shi M., Zhou S., 2017, The prospects of China's long-term economic development and CO_2 emissions under fossil fuel supply constraints [J], Resources, Conservation and Recycling, 121(2017), pp.11-22

Li Q., 2017, The Embodied Carbon in Trade of China and Japan with Countries along the Belt and Road and Their Determinants [J], (in Chinese), Journal of Contemporary Economy of Japan, 2017 (4), pp.69-84

Li W., Jia Z., 2017, Carbon tax, emission trading, or the mixed policy: which is the most effective strategy for climate change mitigation in China? [J], Mitigation and Adaptation Strategies for Global Change, Aug.2017, Vol.22 (6), pp.973-992

Li W.J., et al, 1982, Systems Programming of Water Pollution Control [M] (in Chinese), Tsinghua University Press, Beijing, 1982

Liang Q.M., Liu M., Liu L.C., 2014, The dynamic features of final demand carbon footprint in China from 1997-2010: an input-output analysis [J], Energy Procedia, 61:1075-1079

Liang Q.M., Fan Y., Wei Y.M., 2007, Multi-regional input-output model for regional energy requirements and CO_2 emissions in China [J], Energy Policy, 35(2007):1685-1700

Liang Z., Tian Z., Sun L., et al., 2016, Heat wave, electricity rationing, and trade-offs between environmental gains and economic losses: The example of Shanghai [J], Applied Energy, 184(2016):951-959

Liao C., Wang S., Fang J., Zheng H., Liu J., Zhang Y., 2019, Driving forces of provincial-level CO_2 emissions in China's power sector based on LMDI method [J], Energy Procedia 158 (2019) pp.3859-3864

Liao Z., Zhu X., Shi J., 2015, Case study on initial allocation of Shanghai carbon emission trading based on Shapley value [J], Journal of Cleaner Production 103 (2015) 338-344

Lin B., Jia Z., 2018， What are the main factors affecting carbon price in Emission Trading Scheme? A case study in China, Science of The Total Environment, Volume 654, 1 March 2019, Pages 525-534

Lin B., Jia Z., 2019, Energy, economic and environmental impact of government fines in China's carbon trading scheme [J], Science of the Total Environment 667 (2019) 658-670

Lin B., Jia Z., 2019, Impacts of carbon price level in carbon emission trading market, Applied Energy, Volume 239, 1 April 2019, Pages 157-170, https://doi.org/10.1016/j.apenergy.2019.01.194

Lin B., Xie X., et al., 2015, CO_2 emissions of China's food industry: an input-output approach [J], Journal of Cleaner Production 112 (2016): 1410-1421

Lin X., Zhang Y., Zou C., Peng L., 2019, CO_2 emission characteristics and reduction responsibility of industrial subsectors in China [J], Science of the Total Environment S0048-9697(19)34377-3

Lindner S., Liu Z., Guan D., Geng Y., Li X., 2013, CO_2 emissions from China's power sector at the provincial level: Consumption versus production perspectives [J], Renewable and Sustainable Energy Reviews 19 (2013) 164-172

Liu G., Wu M., Jia F., Yue Q., Wang H., 2018, Entropy-weighted comprehensive evaluation of petroleum flow in China during 1980-2015 [J], Journal of Cleaner Production, Vol.195, Sept.2018, pp593-604

Liu H., and Lin B., 2017, Cost-based modelling of optimal emission quota allocation [J], Journal of Cleaner Production, 149 (2017), pp.472-484

Liu L., Liang Q., 2017, Changes to pollutants and carbon emission multipliers in China 2007-2012: An input-output structural decomposition analysis [J], Journal of Environmental Management, vol.203 (2017), pp.76-86

Liu L., Zong H., Zhao E., Chen C., Wang J., 2014, Can China realize its carbon emission reduction goal in 2020:From the perspective of thermal power development [J], Applied Energy, Vol.124, July 2014, pp199-212

Liu Q., Long Y., Wang C., Wang Z., Wang Q., Guan D., 2019, Drivers of provincial SO_2 emissions in China: Based on multi-regional input-output analysis [J], Journal of Cleaner Production 238 (2019) 117893

Liu W., Xiao W., Huang J., Duan K.., 2011, The Total Amount Control Research Progress and Problem Analysis of Water Pollution [J], (in Chinese), China Rural Water and Hydropower, Vol.8 (2011), pp.9-12

Liu X.L, 2012, China CO_2 control strategy under the low-carbon economy [J], Procedia Engineering, 37(2012): 281-286

Liu Z., Geng Y., Dong H., Jeffrey W., Micic T., et al., 2018, Efficient distribution of carbon emissions reduction targets at the city level: A case of Yangtze River Delta region [J], Journal of Cleaner Production 172 (2018) 1711-1721

Liu Z., Zhang X., Lieu J., 2010, Design of the incentive mechanism in electricity auction market based on the signaling game theory [J], Energy, 2010, 35(4): 1813-1819.

Li W., Jia Z，2016，The impact of emission trading scheme and the ratio of free quota: A dynamic recursive CGE model in China, Applied Energy, Volume 174, 15 July 2016, Pages 1-14, https://doi.org/10.1016/j.apenergy.2016.04.086

Llop M., 2017, Changes in energy output in a regional economy: A structural decomposition analysis [J], Energy, 128(2017):145-151

Lo Prete C., Hobbs B.F., 2016, A cooperative game theoretic analysis of incentives for microgrids in regulated electricity markets [J], Applied Energy, Vol.169, May 2016, pp.524-541

Lu B., Wang K., Xu Z., 2013, China's regional energy efficiency: Results based on three-stage DEA model [J], International Journal of Global Energy Issues, 2013, 36(2/3/4): 262-276

Lundgren T., Marklunda PO., Samakovlis E., Zhou W., 2014, Carbon prices and incentives for technological development [J], Journal of Environmental Management, Volume 150, 1 March 2015, Pages 393-403, https://doi.org/10.1016/j.jenvman.2014.12.015

Mahdiloo M., Ngwenyama O., Scheepers R., Tamaddoni A., 2018, Managing emissions allowances of electricity producers to maximize CO_2 abatement: DEA models for analyzing emissions and allocating emissions allowances [J], International Journal of Production Economics 205 (2018) 244-255

Manuel B., Marcel W., Jens F. P., Nelson C.M., Antonio B. M., 2019, A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications [J], Renewable and Sustainable Energy Reviews 107 (2019) 516-534

Mardani A., Streimikiene D., Cavallaro F., Loganathan N., Khoshnoudi M., 2017, Carbon dioxide (CO_2) emissions and economic growth:A systematic review of two decades of research from 1995 to 2017 [J], Science of the Total Environment 649 (2019) 31-49

Mardania A., Edmundas K. Z., et al., 2017, A review of multi-criteria decision-making applications to solve energy management problems: Two decades from 1995 to 2015 [J], Renewable and Sustainable Energy Reviews 71 (2017) 216-256

Markus A., Lars Z., 2005, Options for Emission Allowance Allocation Under the EU Emissions Trading Directive [J], Mitigation and Adaptation Strategies for Global Change, October 2005, Volume 10, Issue 4, pp.597-645

Marland G., Boden T.A., Andres R.J., 2007, Global, Regional, and National CO_2 Emissions, In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, United States Department of Energy, Oak Ridge, Tenn., U.S.A.

Matthews L., 2010, Cap & Share: Simple is Beautiful [M], In: Douthwaite, Richard and Fallon, Gillian, eds. Fleeing Vesuvius. Dublin: Feasta, (2010) 244-256. (www.fleeingvesuvius.org)

Mattoo A., Subramanian A., 2012, Equity in Climate Change: An Analytical Review [J], World Development, Volume 40, Issue 6, June 2012, Pages 1083-1097

Maurizio C., 1988, Input-Output Analysis: Current Developments (International Studies in Economic Modelling) [M], Springer Netherlands, 1988/1/1

Megan C. E., 2018, Effective incentives for reforestation: lessons from Australia's carbon farming policies [J], Current Opinion in Environmental Sustainability 2018, 32:38-45

Meng F., Su B., Thomson E., Zhou D., Zhou P., 2016, Measuring China's regional energy and carbon emission efficiency with DEA models: a survey, Appl. Energy, 183(2016), pp.1-21.

Meyer A., 2000, Convergence: The Global Solution to Climate Change [M], Green Books, 2000.

Michael H., Andreas L., 2013, The EU Decarbonisation Roadmap 2050: What way to walk? [J], Energy Policy, Vol.55, April 2013, pp190-207

Michael H., Sebastian V., Andreas L., 2014, Designing an emissions trading scheme for China: An up-to-date climate policy assessment [J], Energy Policy, Vol.75, Dec.2014, pp57-72

Michael W.W., David G.V., 2008, A Realistic Policy on International Carbon Offsets, Program on Energy and Sustainable Development (PESD) Working Paper #74, Freeman Spogli Institute for International Studies, Encina Hall East, Room E415, Stanford University, April 18, 2008.

Michel D.E., Hoehne N., Moltmann S., 2008, The Triptych approach revisited: A staged sectoral approach for climate mitigation [J], Energy Policy, 2008, 36(3):1107-1124

Miketa A., Schrattenholzer L., 2006, Equity implications of two burden-sharing rules for stabilizing greenhouse-gas concentrations [J], Energy Policy, Vol.34 (7), pp877-891

Miller E. R, Blair D.P., 2009, Input-output analysis: Foundations and extensions [M], Cambridge University Press, New York, 2009(2nd ed.), Chapter 2.

MOEJP, 2019, History of Water Pollution Control, Conservation of the Water Environment - Chapter 1, Ministry of the Environment of Japan, http://www.env.go.jp/en/water/wq/wemj/history.html

Mori S., 1996, MARIA-Multi-regional Approach for Resources and Industry Allocation Model and Its First Simulations [M], Global Warming, Carbon Limitation and Economic Development, CGER-Report, pp.85-108

Morley D.A, 1979, Mathematical Modelling in Water and Wastewater Treatment [M], Applied Science

Publishers, London, 1979

Nagashima F., Kagawa S., Suh S., Nansai K., Moran D., 2017, Identifying critical supply chain paths and key sectors for mitigating primary carbonaceous PM2.5 mortality in Asia, Economic Systems Research, 29:1 (2017): 105-123

Nagashima S., Uchiyama Y., Okajima K.., 2017, Hybrid input-output table method for socioeconomic and environmental assessment of a wind power generation system [J], Applied Energy, vol.185 (2017):1067-1075

Nagasse Y., Emilson C.D.S., 2000, Optimal Control of Acid Rain in a Federation with Decentralized Leadership and Information [J], Journal of Environmental Economics and Management, 40(2000):164-180

Nakano S., Washizu A., 2017, A panoramic analysis of hydrogen utilization systems: using an input-output table for next generation energy systems [J], Procedia CIRP, 61 (2017):779-784

Nansai K., et al, 2009, Improving the Completeness of Product Carbon Footprints Using a Global Input-Output Model:The Case of Japan, Economic Systems Research, 21 (2009):267-290

Nansai K., Kondo Y., et al, 2012, Estimates of embodied global energy and air-emission intensities of Japanese products for building a Japanese input-output life cycle assessment database with a global system boundary [J], Environmental Science & Technology, 2012, 46(16), pp.9146-9154

Nathan R., Asbjorn T., Jan S.F., 2006, Climate agreements based on responsibility for global warming: Periodic updating, policy choices, and regional costs [J], Global Environmental Change, Volume 16, Issue 2, May 2006, Pages 182-194

NBSC (National Bureau of Statistics of China), 2017, China Statistical Yearbook [M], China Statistics Press 2017, Beijing, China

NBSC (National Bureau of Statistics of China), 2019, National Accounts, Input-Output Table Data for Year 2012 [OL], (http://data.stats.gov.cn/english/easyquery.htm?cn=C01)

NDRC (National Development and Reform Commission), 2015, Enhance Actions on Climate Change: China's Intended Nationally Determined Contributions [R], NDRC, Chinese Gov., 2015

NDRC-SIC, 2018, Path analysis of China's achievement of the 2030 peak carbon emission target, Report of The Department of Economic Forecasting [R/OL], The State Information Center, NDRC, China (Feb. 13, 2018)

Nemhauser G.L., et al, 1989, Optimization, Hanndbooks in Operations Research and Management Science [M], Elsevier Science Publishers, 1989

Nicoletta M., Timothy J.F., Peter J.G.P., 2010, Chinese low-carbon innovation: Developing technological capabilities in the solar photovoltaic manufacturing industry [J], Journal of Knowledge-based Innovation in China, Vol.2 Issue 3, 253-268

Niklas H., Michel D.E., Martin W., 2006, Common but differentiated convergence (CDC): a new conceptual approach to long-term climate policy [J], Climate Policy, 6:2, 181-199

Ning C., 2015, Changing industrial structure to reduce carbon dioxide emissions: a Chinese application [J], Journal of Cleaner Production, Vol.103, Sept. 2015, pp.40-48

Nordhaus W.D., Yang Z., 1996, A regional dynamic general-equilibrium model of alternative climate-change strategies [J], Am. Econ. Rev. , 1996, Vol.86 (4), pp.741-765.

Odu G.O., Charles-Owaba O.E., 2013, Review of multi-criteria optimization methods-theory and applications [J], IOSRJEN No.3, pp.1-14

Okereke C., Dooley K., 2010, Principles of justice in proposals and policy approaches to avoided deforestation: Towards a post-Kyoto climate agreement [J], Global Environmental Change, Volume 20, Issue 1, February 2010, Pages 82-95

Oliveira T., Varum C., Botelho A., 2019, Econometric modeling of CO_2 emissions abatement: Comparing alternative approaches [J], Renewable and Sustainable Energy Reviews, vol.105 (2019), pp.310-322

Olivier J., Peters J., 2018, Trends in Global CO_2 and Total Greenhouse Gas Emissions: 2018 Report [R], PBL Netherlands Environmental Assessment Agency.

Orlob G. T., 1983, Mathematical Modelling of Water Quality Systems [M], Lakes and Reservoirs, John Wiley & Sons, 1983

Oscar D., Manfred L., Maria A. C., 2017, Environmental and Economic Impacts of Decarbonization: Input-Output Studies on the Consequences of the 2015 Paris Agreements [M], Routledge, 2017.7.31

Owen G., 1995, Game Theory (3rd ed.), San Diego: Academic Press, ISBN 978-0-12-531151-9, p.213

Pan Y., Yang W., Ma N., Chen Z., Zhou M., Xiong Y., 2019, Game analysis of carbon emission verification: A case study from Shenzhen's cap-and-trade system in China [J], Energy Policy, 130 (2019), pp.418-428

Pang R.Z, Deng Z.Q, Chiu Y.H, 2015, Pareto improvement through a reallocation of carbon emission quotas [J], Renewable and Sustainable Energy Reviews 50 (2015) 419-430

Paul R.K., Helpman E., 1985, Market Structure and Foreign Trade: Increasing Returns, Imperfect Competition, and the International Economy [M], The MIT Press, 1985.05.01

PECoP-Asia, 2018, Policy Report for Reconfiguring Consumption and Production in Asia and the Pacific: 12 Opportunities for Accelerated Achievement of SDGs [OL], PECoP-Asia Research Project, in Jan. 2018, website: http://www.susdesign.t.u-tokyo.ac.jp/s-16/

Peter B., 2008, Climate Solutions: What Works, What Doesn't, and Why [M], Chelsea Green.

Peter G. M., Swales J. K., Turner K., 2008, The CO_2 'trade balance' between Scotland and the rest of the UK: Performing a multi-region environmental input-output analysis with limited data [J], Ecological economics, 66(2008): 662-673

Peter T. J., Jin H.J, 2017, A comparative analysis of renewable energy simulation tools: Performance simulation model vs. system optimization [J], Renewable and Sustainable Energy Reviews vol.80 (2017), pp390-398

Peters G. P., Weber C., Guan D., Hubacek K., 2007, China's growing CO_2 emissions: a race between increasing consumption and efficiency gains [J], Environmental Science and Technology, 41 (2007), pp.5939-5944. https://doi.org/10.1021/es070108f.

Phylipsen G.J.M., Bode J.W., Blok K., Merkus H., Metz B., 1998, A Triptych sectoral approach to burden differentiation; GHG emissions in the European bubble [J], Energy Policy, Volume 26, Issue 12, October 1998, Pages 929-943

Pigou A., 1918, The economics of welfare [M], London: McMillan, 1918.

Portney P.R., Stavins R.N., 2000, Public policies for environmental protection [M], Washington, D.C.: RFF Press, Forthcoming 2000, 2nd editon, Chapter 3, pp31-62.

Qi T., Weng Y., He J., 2016, An analysis of the driving factors of energy-related CO_2 emission reduction in China from 2005 to 2013 [J], Energy Economics, 60(2016):15-22

Ranasinghe K., Guan K., Gardi A., Sabatini R., (2019), Review of advanced low-emission technologies for sustainable aviation [J], Energy 188 (2019) 115945

Rasmus L., Adrian L., 2012, Technology Transfer? The Rise of China and India in Green Technology Sectors [J], Innovation and Development, 2012, 2:1, 23-44

Reutter B., Lant P., Reynolds C., Lane J., 2017, Food waste consequences: Environmentally extended input-output as a framework for analysis [J], Journal of Cleaner Production, 153(2017):506-514

Reynolds J., Muhammad W.A., Yacine R., 2018,Holistic modelling techniques for the operational optimisation of multi-vector energy systems [J], Energy & Buildings 169 (2018) 397-416

Richard M.H., 1985, The Potential for Private Cost-Increasing Technological Innovation under a Tax-Based, Economic Incentive Pollution Control Policy [J], Land Economics, 1985, 61(1):58-64

Rinaldi S., Soncini S.R., Wbimton A.B., 1979, Stable taxation schemes in regional environmental management [J], J. Environ.Econ.Manag., 1979, Vol.6, pp29-50

Ringius L., Torvanger A., Holtsmark B., 1998, Can multi-criteria rules fairly distribute climate burdens? OECD results from three burden sharing rules [J], Energy Policy, Vol.26 (10), 1998, pp.777-793

Ringius L., Torvanger A., Underdal A., 2002, Burden sharing and fairness principles in international climate policy [J], Int. Environ. Agreem. 2002, vol. 2 (1), pp.1-22

Robert C.S., Heitzig J., 2014, Carbon leakage: Grandfathering as an incentive device to avert firm relocation [J], Journal of Environmental Economics and Management, Vol.67 (2), Mar.2014, pp209-223

Robert G.C., 2002, Information, incentives, and the design of agricultural policies [M], Chapter 34, Handbook of Agricultural Economics, Volume 2, Part B, 2002, Pages 1751-1825

Robert L.C., Norman L.L., 1985, Auto -Qual Modeling Systems [M], Translated by Wu G.H., SESRI, Shanghai, 1985

Robert W.H., Gordon L.H., 1989, Where Did All the Markets Go? An Analysis of EPA's Emissions Trading Program [J], Yale Journal on Regulation, vol.6, 1989, pp.109-153

Robert W.H., 1989, A Primer on Environmental Policy Design [M], Harwood Academic Publishers

Rose A., Stevens B., 1993, The efficiency and equity of marketable permits for CO_2 emissions, Resource and Energy Economics, Volume 15, Issue 1, March 1993, pp.117-146

Rose A., Stevens B., Edmonds J., et al., 1998, International Equity and Differentiation in Global Warming Policy, Environmental and Resource Economics, 12 (1998), pp.25-51

Ross R. McKitrick, 2011, Economic Analysis of Environmental Policy [M], University of Toronto Press (2011), pp31-34; pp169-191

Santosa S. A., Leandro Gilioa, Vinecius Halmenschlagerb, Tiago Barbosa Diniza, Alexandre Nunes Almeida, 2018, Flexible-fuel automobiles and CO_2 emissions in Brazil: Parametric and semiparametric analysis using panel data [J], Habitat International 71 (2018) 147-155

Sarjiya, Budi R.F.S., Hadi S.P., 2019, Game theory for multi-objective and multi-period framework generation expansion planning in deregulated markets [J], Energy 174 (2019), pp.323-330

Schleich J., Rogge K. & Betz R., 2009, Incentives for energy efficiency in the EU Emissions Trading Scheme, Energy Efficiency 2, 37–67 (2009). https://doi.org/10.1007/s12053-008-9029-3

Schmeidler, D., 1969, The nucleolus of a characteristic function game [J], SIAM J. Appl. Math. vol.17, 1969, pp.1163-1170

SESRI (Shanghai Environmental Science Research Institute), 1986a, Investigation Data in Shongjiang Industrial District (1-21) [W] (in Chinese), Research Reports, Shanghai Environmental Science Research Institute, Shanghai

SESRI (Shanghai Environmental Science Research Institute), 1986b, Economic Analysis on Emissions Standards of Industrial Wastewater at Upper Reaches of Huangpu River in Shanghai [W] (in Chinese), Research Reports, Shanghai Environmental Science Research Institute, Shanghai

Shanghai Gov., 1985, Regulations for the protection of water resources in the upper reaches of Huangpu River [J], Shanghai Water Affairs 2 (1985), 6-8 (in Chinese)

ShanY., Guan D., Zheng H., Ou J., Li Y., Meng J., Mi Z., 2017, Data Descriptor: China CO_2 Emission Accounts 1997-2015, pp. 1-14.

Shapley L.S., 1971, Cores of convex game [J], Int. J. Game Theory, 1971, vol.1, pp.11-26

Shen L., Ya Wu, Yingli Lou, Deheng Zeng, Chenyang Shuai, Xiangnan Song, 2018, What drives the carbon emission in the Chinese cities? A case of pilot low carbon city of Beijing [J], Journal of Cleaner Production 174 (2018) 343-354

Shi J., 2016, The impact of carbon market establishment on power companies and response measures for power enterprises [OL] (in Chinese), Polaris Power Network News Center, 2016/11/22 8:32:14, http://news.bjx.com.cn/html/20161122/790700.shtml.

Shimoda M., Fujikawa K., 2012, Input output analysis model and supply constraint by the great east

Japan earthquake [J], (in Japanese), Input-Output Analysis, Innovation & I-O Technique: Business Journal of PAPAIOS, 20 (June 2012) 133-146

Slater H., De Boer D., Shu W., Qian G., 2018, The 2018 China Carbon Pricing Survey, July 2018, Carbon Forum, Beijing, China, https://ets-china.org/wp-content/uploads/2018/07/2018-CCPS-EN-E-version.pdf

Sohn I., 1986, Readings in Input-Output Analysis: Theory and Applications [M], Oxford University Press, NewYork, 1986

Solangi K.H., Islum M.R., Saidur R, Rahim N.A., Fayaz H., 2011, A review on global energy policy [J], Renew Sustain Energy Rev 2011;15:2149-63

Song G., 2005, A more appropriate total load control policy for China's market-oriented economy [J] (in Chinese), Environmental Economy, vol.21, pp41-44

Soumya B., Dennis W., 2012, Ecnomic incentives can enhance policy efforts to improve the water quality in Asia [J], International J. of Water resource development, vol.28, issue 2 (June 2012), pp.217-232

Stanislav E.S., Stefan U.S., 2018, Green fscal reform in Sweden: Econometric assessment of the carbon and energy taxation scheme [J], Renewable and Sustainable Energy Reviews 90 (2018) 969-981

Steger U., Achterberg W., Blok K., Bode H., et al., 2005, The Reality of Sustainability: Conflicts of Aims in the Choice of Instruments [M], In: Wutscher F.(eds) Sustainable Development and Innovation in the Energy Sector. Springer, Berlin, Heidelberg, 129-153, Chapter 6

Stenqvist C., Ahman M., 2016, Free allocation in the 3rd EU ETS period: assessing two manufacturing sectors [J], Climate Policy, Vol.16 (2), 2016

Steven C. Hackett, 1998, Environmental and Natural Resources Economics: Theory, Policy, and the Sustainable Society [M], M.E.Sharpe Inc, 1998, pp165-185

Su B., Ang B.W., 2012, Structural decomposition analysis applied to energy and emissions: Some methodological developments [J], Energy Economics, Vol.34 (1), Jan.2012, pp177-188

Su B., Ang B.W., 2014, Input-output analysis of CO_2 emissions embodied in trade: A multi-region model for China [J], Applied Energy, Vol.114, Feb.2014, pp377-384

Su B., Thomson E., 2016, China's carbon emissions embodied in (normal and processing) exports and their driving forces, 2006-2012 [J], Energy Economics, Vol.59, Sept.2016, pp414-422

Sun L., Wang Q., Zhang J., 2017, Analysis Inter-industrial Carbon Emission Transfers in China: Economic Effect and Optimization Strategy [J], Ecological Economics, Vol.132, Feb.2017, pp55-62

Sun Q., Qu F., 2020, The establishment of the national carbon emissions trading market is an opportunity and challenge for the development of China's carbon finance [OL] (in Chinese), 2018/1/23 18:02 https://www.sohu.com/a/218455221_806432

Supasa T., Hsiau S.S., Linb S.M., et al., 2017, Sustainable energy and CO_2 reduction policy in Thailand: An input-output approach from production- and consumption-based perspectives [J], Energy for Sustainable Development, 41(2017):36-48

Surugiu C, Surugiu M.R, Zelia B, Dinca A.I., 2012, An Input-Output Approach of CO_2 Emissions in Tourism Sector in Post-Communist Romania [J], Procedia Economics and Finance, 3 (2012): 987-992

Tamura H., Suzuki H., 1981, Total Emission Control for Managing Regional Water Quality: A Game Theoretic Decision [J], IFAC Control Science and Technology (8th Triennial World Congress) Kyoto, Japan 1981, pp1409-1414

Tamura H., Ishida T., 1985, Environmental-economic models for total emission control of regional environmental pollution: input-output approach [J], Ecological Modelling, Vol.30(3-4), Dec.1985, pp163-173

Tamura H., R.Teraoka, 2011, Assessing hybrid policy of carbon tax and emissions trading under uncertainty for preserving global environment [C], IFAC Proceedings Volumes (IFAC-Papers Online), Volume 44, Issue 1 PART 1, 2011, pp12916-12921

Tang B.J., Wang X.Y., Wei Y.M., 2019, Quantities versus prices for best social welfare in carbon reduction: A literature review [J], Applied Energy 233-234 (2019) 554-564

Tang D., Ma T., Li Z., Tang J., Brandon J. B., 2016, Trend Prediction and Decomposed Driving Factors of Carbon Emissions in Jiangsu Province during 2015-2020 [J], Sustainability 2016, 8, 1018. doi:10.3390/su8101018

Tao X., Wang P., Zhu B., 2016, Provincial green economic efficiency of China: a non-separable input-output SBM approach [J], Appl. Energy, 171 (1):58-66

Tarancon M.A., Rio P.D., 2012, Assesseing energy-related CO_2 emissions with sensitivity analysis and input-output techniques [J], Energy, 37 (2012): 161-170

Thiesen J., Torben S. C., Thomas G. K., et al., 2008, Rebound effects of price differences [J], The International Journal of Life Cycle Assessment, March 2008, 13:104

ThijsTen Raa, 2017, Handbook of Input-Output Analysis [M], Edward Elgar Pub, 2017

Tietenberg T.H., 1990, Economic Instruments for Environmental Regulation [J], Oxford Review of Economic Policy, 1990, vol. 6, issue 1, pp.17-33

Tokyo, 2010, Tokyo Cap-and-Trade Program: Japan's first mandatory emissions trading scheme [EB/OL], pp3-4, March 2010, Bureau of the Environment, Tokyo Metropolitan Government, http://www.kankyo.metro.tokyo.jp/en/climate/cap_and_trade/

Tolis I.A., Athanasios A. R., Ilias P.T., 2010, Optimisation of electricity energy markets and assessment of CO_2 trading on their structure: A stochastic analysis of the Greek Power Sector [J], Renewable and Sustainable Energy Reviews 14 (2010) 2529-2546

Tsuchiya T., 1980, Total Emission Control System of Water Quality [J], EISEI KAGAKU, vol.26 (2), pp.55-62 (1980), (in Japanese)

Underdal A., Yuan T., et al., 2015, Distributive fairness: A mutual recognition approach [J], Environmental Science & Policy, Volume 51, August 2015, Pages 35-44

UNFCCC, 2016, Report of the Conference of the Parties on its Twenty-first Session, held in Paris (Nov.30-Dec.13, 2015) [R/OL] (2016-01-29)

USEPA, 1986, Emissions Trading Policy Statement, Final Policy Statement and Accompanying Technical Issues Document, US EPA, 51 Federal Register 43814, December 4 , 1986

USEPA, 1999, Protocol for developing nutrient TMDLs [Z], Total Maximum Daily Load Program (U.S.), US EPA, Washington DC, 1999

Vaillancourt K., Waaub J.P., 2004, Equity in international greenhouse gases abatement scenarios: a multicriteria approach [J], European Journal of Operational Research, Vol.153 (2), pp489-505

Valerie C., Helene R.V., Benedicte R., 2015, Perceptions on equity and responsibility in coastal zone policies [J], Ecological Economics, Vol.119, Nov.2015, pp.284-291

Varian R. H., 1992, Microeconomic Analysis [M], Third Edition, W.W.Norton and Company, Inc. (1992)

Verbruggen H., 1991, Political Economy Aspects of Envinomental Policy Instruments [M], Envinomental Policy and the Economy, Elsevier Science Publishers B.V., North-Holland, 1991, pp141-150

Von Neumann J., Morgenstem, 1953, Theory of games and economic behavior [M], (3rd ed), Wiley, New York, 1953

Wan Y., Yang D., Zhao Y., Yanagita T., 2019, An optimal TEC model with input-output analysis and its application for reducing CO_2 emission in China [J], 2019 IOP Conf. Ser.: Earth Environ. Sci., 307, 012012, https://iopscience.iop.org/article/10.1088/1755-1315/ 307/1/012012/pdf

Wang B.J., Zhao J.L., Wei Y.X., 2019, Carbon emission quota allocating on coal and electric power enterprises under carbon trading pilot in China: Mathematical formulation and solution technique [J], Journal of Cleaner Production, Vol.239, Dec.2019, 118104.

Wang C., Chen J., and Zou J., 2005, Decomposition of energy-related CO_2 emission in China: 1957-2000. Energy 30, 73-83. https://doi.org/10.1016/j.energy.2004.04.002.

Wang H., Dai H., Dong L., Xie Y., Geng Y., Yue Q., Ma F., Wang J., Du T., 2018, Co-benefit of carbon mitigation on resource use in China [J], Journal of Cleaner Production 174 (2018) 1096-1113

Wang J., Cai B., et al., 2010, Study on carbon dioxide total emission control in the context of emission intensity commitment [J], China Environmental Science, 2010, 30(11): 1568-1572

Wang K., 2018, The development course and prospect of national carbon emissions trading market [J], (in Chinese), China Environment, p2-3/pp4 source: 2018-10-11 China Carbon Emissions Trading Network (CCETN):http://www.tanpaifang.com/tanjiaoyi/2018/1011/62369.html (last access 2019.11.27)

Wang K., Guo J., Wei Y.M., Yi W.J, Zou L.L, 2011, How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development [J], Energy Policy, 2011, 39(5):2407-2415

Wang K., Zhang X., Wei Y.M., Yu S., 2013, Regional allocation of CO_2 emissions allowance over provinces in China by 2020 [J], Energy Policy, Vol.54, Mar.2013, pp.214-229

Wang Lina, 2011, Carbon emission trading and technology innovation for low-carbon emission [C], International Conference on Electrical & Control Engineering, 2011

Wang Q., Zhao L., Guo L., Jiang R., Zeng L., Xie Y., Bo X., 2019, A generalized Nash equilibrium game model for removing regional air pollutant [J], Journal of Cleaner Production, 227 (2019): 522-531

Wang W. W., Zhang M., Zhou M., 2011, Using LMDI method to analyse transport sector CO_2 emissions in China, Energy, 36, 5909-5915

Wang X., Cai Y., Xu Y., Zhao H., Chen J., 2014, Optimal strategies for carbon reduction at dual levels in China based on a hybrid nonlinear grey-prediction and quota-allocation model [J], Journal of Cleaner Production 83 (2014) 185-193

Wang Y., Jia W., Bi Y., 2017, Provincial decomposition of China's 2030 carbon dioxide emission peak target from the perspective of efficiency: Research on the zero sum gains DEA model [J], Acta Scientiae Circumstantiae, 11(2017):4339-4408. (in Chinese)

Wang Y., Zhao H., Li L., Liu Z., Liang S., 2013, Carbon dioxide emission drivers for a typical metropolis using input-output structural decomposition analysis [J], Energy Policy, 58(2013), pp.312-318

Wang Z., Cui C., Peng S., 2018, Critical sectors and paths for climate change mitigation within supply chain networks [J], Journal of Environmental Management, 2018, 226 (15):30-36

Wei W., Liang Y., Liu F., Mei S., Tian F., 2014, Taxing Strategies for Carbon Emissions: A Bilevel Optimization Approach [J], Energies, 2014, vol.7, pp2228-2245.

Wei Y.W., Wang L., Liao H., Wang K., Murty T., Yan J., 2014, Responsibility accounting in carbon allocation: a global perspective [J], Applied Energy, 2014, Vol.130, pp122-133

Wiedmann T., 2009, A review of recent multi-region input-output models used for consumption-based emission and resource accounting [J], Ecological Economics,Volume 69, Issue 2, 15 December 2009, Pages 211-222

William F. Lucas, 1981, Game Theory and its Applications - Proceedings of Symposium in Applied Mathematics [M], American Mathematical Society (AMS), 1981, Vol. 24, pp.19-36

William J. Baumol, Wallace E. Oates, 1975, The Theory of Environmental Policy [M], 1st edition, Prentice-Hall Inc.1975; 2nd edition, Cambridge University Press 1988.

William J. Baumol, Wallace E. Oates, 1979, Economics, environmental policy and the quality of life [M], Englewood Clifls, NJ: Prentice-Hall, 1979

Wilting H.C., 2012, Sensitivity and uncertainty analysis in MRIO modelling: some empirical results with regard to Dutch carbon footprint [J], Economic System Res. 24 (2012):141-171

World Bank, 2015, Total Greenhouse Gas Emissions (kt of CO_2 Equivalent) [OL], http://data.worldbank.org.cn/indicator/EN.ATM.GHGT.KT.CE (Access on Dec.18, 2019)

Wu J., Guo Q., Yuan J., Lin J., Xiao L., Yang D., 2019, An integrated approach for allocating carbon emission quotas in China's emissions trading system [J], Resources, Conservation & Recycling, vol.143 (2019), pp.291-298

Wu P.I., Chen C.T., Cheng P.C., Liou J.L., 2014, Climate game analyses for CO_2 emission trading among various world organizations [J], Economic Modelling 36 (2014) 441-446

Xiong L., Shen B., Qi S.,, Price L.,Ye B., 2016, The allowance mechanism of China's carbon trading pilots: A comparative analysis with schemes in EU and California [J], Applied Energy, Volume 185, Part 2, 1 January 2017, Pages 1849-1859.

Xu G., Schwarzb P., Yang H., 2019, Determining China's CO_2 emissions peak with a dynamic nonlinear artificial neural network approach and scenario analysis [J], Energy Policy 128 (2019) 752-762

Xu J., Fleiter T., Eichhammer W, Fan Y, 2012, Energy consumption and CO_2 emissions in China's cement industry: a perspective from LMDI decomposition analysis [J], Energy Policy, 50(2012) :821-832

Xu X., Pan S., Ballot E., 2012, Allocation of Transportation Cost & CO_2 Emission in Pooled Supply Chains Using Cooperative Game Theory [C], Proceedings of the 14th IFAC Symposium on Information Control Problems in Manufacturing, Bucharest, Romania, May 23-25, 2012

Xu X.Y., Ang B.W., 2013, Index decomposition analysis applied to CO_2 emission studies. Ecological Economics 93, Sep. 2013, 313-329. https://doi.org/10.1016/j.ecolecon.2013.06.007

Yamamoto R., 2018, China will also learn ... Difficulties in the emissions trading market far from the desired emission quota price at the trial stage [OL] (in Japanese), Monthly Business Eneco, February 2018; Institute of International Environmental Economics, http://ieei.or.jp/2018/02/yamamoto-blog180219/

Yan J., Zhao T., Kang J., 2016, Sensitivity analysis of technology and supply change for CO_2 emission intensity of energy-intensive industries based on input-output model [J], Applied Energy, 171(2016):456-467

Yan J., Zhao T., Lin T., Li Y., 2017, Investigating multi-regional cross-industrial linkage based on sustainability assessment and sensitivity analysis: A case of construction industry in China [J], Journal of Cleaner Production, Vol.142, Part 4, 20 Jan.2017, pp2911-2924

Yan J., Liu Z., Li X., Shi X., Hua J., 2012, Study on the Effects of Emissions Control on Electricity[J], Energy Procedia 16 (2012) 14 - 20

Yang J., Zhang T., Sheng P., Joshua D.Shackman, 2016, Carbon dioxide emissions and interregional economic convergence in China [J], Economic Modelling, 52:672-680

Yang Z., et al., 1985, Studies on Huangpu River Water Quality Modeling and Planning [W], Research Report, Shanghai Environmental Science Research Institute (SESRI), 1985, Shanghai.

Ye F., Fang X., Li L., Li Y., Chang C.T., 2019, Allocation of carbon dioxide emission quotas based on the energy-economy-environment perspective: Evidence from Guangdong Province [J], Science of the Total Environment, 669 (2019), pp 657-667

Yi W., Zou L., Guo J., Wang K., Wei Y., 2011, How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development [J], Energy Policy, 2011, Vol.39 (5), pp.2407-2415

Yoshioka K, Oohira S, et al., 2013, Environmental Input-Output Analyses [M] (in Japanese), NIPPYO Press, Japan (2013), pp18-22

Yuan R., Zhao T., 2016, A combined input-output and sensitivity analysis of CO_2 emissions in the high energy-consuming industries: A case study of China [J], Atmospheric Pollution Research, vol.7 (2016), pp.315-325

Yuan Y.N., Shi M.J, Li N., Zhou S.L., 2012, Intensity Allocation Criteria of Carbon Emission Permits and China Regional Development-Based on a 30-Province-Autonomous Region Computable Equilibrium Model Analysis [J], Advances in Climate Change Research, 2012, 8(1): 60-67

Zeng M., Xue S., Ma M., Li L., Cheng M., Wang Y., 2013, Historical review of demand side management in China: Management content, operation mode, results assessment and relative incentives [J], Renewable and Sustainable Energy Reviews 25(2013) 470-482

Zetterberg L, Wrake M, Sterner T, Fischer C, Burtraw D., 2012, Short-run allocation of emissions allowances and long-term goals for climate policy, Ambio, 2012, 41 Suppl. 1:23-32, doi:10.1007/s13280-011-0238-1

Zhang C., Su B., Zhou K., Yang S., 2019, Decomposition analysis of China's CO_2 emissions (2000-2016) and scenario analysis of its carbon intensity targets in 2020 and 2030 [J], Science of the Total Environment 668 (2019) 432-442

Zhang H., Zhidong Xu, Dequn Zhou, Jie Cao, 2017, Waste cooking oil-to-energy under incomplete information: Identifying policy options through an evolutionary game [J], Applied Energy 185 (2017) 547-555

Zhang J., Ling Li, Lean Yu, Ling Tang, 2016, Comprehensive evaluation of energy intensity change for 1997-2012 based on input-output analysis: Evidence from Beijing [J], Procedia Computer Science, 91(2016):1057-1063

Zhang J., 2020, Can the carbon market really drive the power sector to reduce carbon emissions? [OL], the Beijing office, the American Environmental Protection Association, 2020/07/10. http://www.tanpaifang.com/kongpaiqiye/2020/071072350.html

Zhang K., Xu D., Li S., Zhou N., Xiong J., 2019, Has China's Pilot Emissions Trading Scheme Influenced the Carbon Intensity of Output? [J], Int J Environ Res Public Health, 2019 May 25;16(10):1854. https://doi.org/10.3390/ijerph16101854

Zhang L., Li Y., Jia Z., 2018, Impact of carbon allowance allocation on power industry in China's carbon trading market: Computable general equilibrium based analysis [J], Applied Energy 229 (2018) 814-827

Zhang M., Li H., 2018, New evolutionary game model of the regional governance of haze pollution in China [J], Applied Mathematical Modelling 63 (2018) 577-590

Zhang S., Zhao T., 2019, Identifying major influencing factors of CO_2 emissions in China: Regional disparities analysis based on STIRPAT model from 1996 to 2015[J], Atmospheric Environment 207 (2019) 136-147

Zhang W, Peng S, et al., 2016, CO_2 emissions in global supply chains of services based on a multiregional input-output model [J], Energy Policy 86 (2015): 93-103

Zhang W., Peng S., Sun C., 2015, CO_2 emissions in the global supply chains of services: An analysis based on a multi-regional input-output model [J], Energy Policy, 86(2015):93-103

Zhang X., 2017, The total quantity setting and quota in the design of national carbon trading market [OL], (in Chinese), Institute of Energy and Environmental Economics, Tsinghua University, CCETN: http://www.tanpaifang.com/tanzhibiao/201701/0458148.html

Zhang X., Bai X., 2016, Incentive policies from 2006 to 2016 and new energy vehicle adoption in 2010–2020 in China [J], Renewable and Sustainable Energy Reviews 70:24-43, Nov. 2016.

Zhang X., Qi Ye, 2017, Annual Review of Low-Carbon Development in China (2017) [M], (in Chinese), Social Science Literature Press, 2017, Beijing

Zhang Y., Wang A., Da Y., 2014, Regional allocation of carbon emission quotas in China: Evidence from the Shapley value method [J], Energy Policy, Vol.74, Nov.2014, pp454-464

Zhang Y.J., Bian X.J., Tan W., Song J., 2017, The indirect energy consumption and CO_2 emission caused by household consumption in China: an analysis based on the input-output method [J], Journal of Cleaner Production, 163(2017):69-83

Zhang Y.J., Hao J.F., Song J., 2016, The CO_2 emission efficiency, reduction potential and spatial clustering in China's industry: Evidence from the regional level [J], Applied Energy, Vol.174, July 2016, pp213-223

Zhang Z., Folmer U.Henk, 1998, Economic modelling approaches to cost estimates for the control of carbon dioxide emissions [J], Energy Economics, 20(1998):101-120

Zhang Z., Zhao Y., Su B., Zhang Y., Wang S., Liu Y., Li H., 2017, Embodied carbon in China's foreign trade: An online SCI-E and SSCI based literature review [J], Renewable and Sustainable Energy

Reviews, Vol.68, Part 1, Feb.2017, pp492-510

Zhao R., Min N., Geng Y., He Y., 2017, Allocation of carbon emissions among industries/sectors: An emissions intensity reduction constrained approach [J], Journal of Cleaner Production, Vol.142, Part 4, Jan.2017, pp3083-3094

Zhao S., Shi Y., Xu J., 2018, Carbon emissions quota allocation based equilibrium strategy toward carbon reduction and economic benefits in China's building materials industry [J], Journal of Cleaner Production, 189 (2018): 307-325 (Bi-level allocation of carbon emission)

Zheng Y., Luo D., 2013, Industrial structure and oil consumption growth path of China: Empirical evidence [J], Energy, Vol.57, Aug.2013, pp336-343

Zhou J., Huo X., Jin B. et al., 2019, The efficiency of carbon trading market in China: evidence from variance ratio tests. Environ Sci Pollut Res 26, 14362–14372 (2019). https://doi.org/10.1007/s11356-019-04778-y

Zhou J., Wang J., et al., 2019, A review of development and reform of emission permit system in China [J], Journal of Environmental Management, 247 (2019), pp.561-569

Zhou L., Zhang X., Qi T., He J., Luo X., 2014, Regional disaggregation of China's national carbon intensity reduction target by reduction pathway analysis [J], Energy for Sustainable Development, 23 (2014), pp.25-31

Zhou M., Zhou M., Pan Y., Chen Z., Zeng J., 2016, Multi-agent-based Simualtion for Policy Valuation of Carbon Emissions [C], Theory, Methodology, Tools and Applications for Modeling and Simulation of Complex Systems [M], Part 3, pp. 265-272, the proceedings of AsiaSim /SCS AutumnSim, Beijing, China, October 8-11, 2016.

Zhou P., Wang M., 2016, Carbon dioxide emissions allocation: A review [J], Ecological Economics, Volume 125, May 2016, pp.47-59

Zhou P., Ang B.W., Han J.Y., 2010, Total factor carbon emission performance: A Malmquist index analysis Energy Economics, 32, pp.194-201

Zhou P., Zhang L., Zhou D.Q., Xia W.J., 2013. Modeling economic performance of interprovincial CO_2 emission reduction quota trading in China [J], Applied Energy, Vol.112, Dec.2013, pp1518-1528

Zhou R., 2018, How to build China's carbon market? Five questions to be clear [OL], (in Chinese), source: 2018.10.08 on China Carbon Emissions Trading Network (CCETN) website: http://www.tanpaifang.com/tanguwen/2018/1008/62359_2.html

Zhou S., Tong Q., Yu S., Wang Y., Chai Q., Zhang X., 2012, Role of non-fossil energy in meeting China's energy and climate target for 2020 [J], Energy Policy, Vol.51, Dec.2012, pp14-19

Zhou Y, Wang L, McCalley JD, 2011, Designing effective and efficient incentive policies for renewable energy in generation expansion planning [J], Applied Energy, 2011, 88:2201-2209

Zhou Z., Liu C., Zeng X., Jiang Y., Liu W., 2018, Carbon emission performance evaluation and allocation in Chinese cities [J], Journal of Cleaner Production 172, Jan. 2018, pp1254-1272.

Zhu B., Jiang M., He K., Chevallier J., Xie R., 2018, Allocating CO_2 allowances to emitters in China: A multi-objective approach [J], Energy Policy 121 (2018) 441-451

Zhu Q., Peng X., and Wu K, 2012, Calculation and decomposition of indirect carbon emissions from residential consumption in China based on the input-output model [J], Energy Policy, Vol.48, 2012, pp.618-626

Zuhdi U., Prasetyo A.D., Putranto N.R.A., 2014, Analyzing the chaanges of total output of Japanese livestock sector: An input-output approach [J], Procedia-Social and Behavioral Sciences, 109(2014):649-653

Zhang Z., 2015, Carbon Emissions Trading in China: The Evolution from Pilots to a Nationwide Scheme, CCEP Working Paper 1503, April 2015. School of Economics, Fudan University.

(in Japanese)

マケケル・テーラー著, 松原望訳, 1995,『協力の可能性:協力・国家・アナーキー』, 木鐸社刊, pp.205-217

井出眞弘, 2003,『Excel による産業連関分析入門』, 産能大学出版部, 2003 年

塩田尚樹, 2001,『環境汚染の最適制御』, 勁草書房 pp.5-11

鬼塚雄丞, 岩田一政, 柳田辰雄, 2000,『経済学入門』, 東京大学出版会, pp.199-214

吉岡完治, 大平純彦, 早見均, 鷲津明由, 松橋隆, 2003, 『環境の産業連関分析』, 日本評論社, pp59-64, pp83-109

栗山 昭久, 2019, 日本の電力部門の脱炭素化に向けた公正な移行は可能か？International Forum for Sustainable Asia and the Pacific, 31 July 2019 Japan

呉錫畢等, 1999,『環境政策の経済分析』, 日本経済評論社, pp75-98

今井晴雄等, 2002,「戦略的協力ゲームと事前交渉」[M],『ゲーム理論の新展開』 勁草書房 pp.241-263

寺西俊一, 石弘光, 2002,「環境規制の政策手段」[M],『環境保全と公共政策』, 岩波書店, pp35-62, pp151-174

松原望, 2001,『意思決定の基礎』, 朝倉書店, pp139-161

植田和弘等, 1997,『環境政策の経済学・理論と現実』, 日本評論社, pp51-114

石村貞夫, 劉晨, 2009,『多変量解析による環境統計学』共立出版

淡路剛久等, 2001, 『環境政策研究のフロンティア』東洋経済新聞社 pp131

中村愼一郎, 2000, 『Excel で学ぶ産業連関分析』, エコノミスト社

中澤幸壽, 1999, 排出許可証取引の対数線形モデル[J], 経済学論集（西南学院大学）, Vol.33 No.4, pp.55-71

長谷川弘訳, 1993,『環境の経済評価テクニック--アジアにおけるケーススタディ』, 築地書館, pp199-214

田村坦之, 保手浜勝, 富山伸司, 鳩野逸生, 1999, 二酸化炭素排出抑制を目的とした炭素税とエネルギー税のシステム分析[J], システム制御情報学会論文誌, Vol.12, No.3, 184-190.

藤本壱, 2016,『Excel でできるらくらく統計解析』, 自由国民社（改訂版）

奈良宏一等, 2000, 『システム学の数理手法』, コロナ社

日本環境省, 2018, 日本地球温暖化対策税・炭素税の水準比較[EB/OL], 環境省「カーボンプライシングの活用に関する小委員会」（第 4 回）資料 2（2018 年 11 月）, website: https://www.env.go.jp/council/06earth/post_71.html

日本自然エネルギー財団, 2019, 脱炭素社会をめざす 5 つの戦略,『脱炭素社会へのエネルギー戦略－2050 年 CO_2 排出ゼロの日本へ－』[EB/OL], 2019.04.04, website: https://www.renewable-ei.org/activities/reports/20190404.php

矢部博等, 2001, 『非線形計画法』, 朝倉書店

柳川範之, 1998, 『戦略的貿易政策：ゲーム理論の政策への応用』, 有斐閣 , 1998

(in Chinese)

［英］格里菲斯, 2008, 欧盟水框架指令手册[M], 北京:中国水利水电出版社, 2008.

王毅, 2015, 后巴黎时代通过碳总量控制实现低碳转型[OL], 中科院科技政策与管理科学研究所,

p1/1. website: http://epaper.rmzxb.com.cn/detail.aspx?id=373460

王金南,蔡博峰,严刚,曹东,周颖,2011,中国 CO_2 排放总量控制区域分解方案研究[J],中国环境科学,2011,31(4):681-685

王建平, 2003, 基于 GIS 技术的大气污染物总量控制研究[D], 南京师范大学, 2003 年

王卫平, 2007, 九龙江流域水环境容量变化模拟及污染物总量控制措施研究[D], 厦门大学

夏明, 张红霞, 2013, 投入产出分析: 理论、方法与数据[M], 中国人民大学出版社, 北京, pp19-23

渠慎宁, 郭朝先, 2010, 基于 STIRPAT 模型的中国碳排放峰值预测研究[J], 中国人口·资源与环境, 2010 年第 20 卷, 第 12 期, pp10-15

熊小平, 康艳兵, 冯升波, 赵 盟, 2015, 碳排放总量控制目标区域分解方法研究[J], 中国能源, 37(11) pp15-19

高子亭, 天一, 赵文晋, 马端超, 高磊, 张宇楠, 李鱼, 2012, 基于公平与效率的地表水污染物总量分配优化模型[J], 安徽农业科学, 2012 年 14 期

柴麒敏, 徐华清, 2015, 基于 IAMC 模型的中国碳排放峰值目标实现路径研究[J], 中国人口·资源与环境, 2015(06)

柴麒敏, 傅莎, 郑晓奇等, 2017, 中国重点部门和行业碳排放总量控制目标及政策研究[J], 中国人口·资源与环境, 27(12) , pp1-7

徐树媛, 2006, 晋城市水资源保护规划与污染物总量控制研究田[D], 太原理工大学, 2006

肖伟华, 201 9, 基于基尼系数的湖泊流域分区水污染物总量分配[J], 环境科学学报, 29 (8) , pp1765-1771

肖伟华, 刘文琨, 裴源生, 黄介生, 段凯, 2011, 水环境污染物总量控制方法及模式体系研究[C], 中国环境科学学会学术年会,2011.08.17

宋国君,2000,论中国污染物排放总量控制和浓度控制[J], 环境保护,2000,(6):11-13

段海燕, 王寒凝, 王宪恩, 2016, 日本主导产业碳排放影响因素及驱动效应的分解研究[J], 现代日本经济, 2016, 208(4), pp70-82

段茂盛, 庞韬, 2014, 全国统一碳排放权交易体系中的配额分配方式研究[J], 武汉大学学报(哲学社会科学版), 2014, (5)

程声通, 2003, 河流环境容量与允许排放量[J], 水资源保护, 2003(02), 北京

程纪华, 2016, 中国省域碳排放总量控制目标分解研究[J], 中国人口·资源与环境 6(1) pp23-30

包存宽, 张敏, 尚金城, 2000, 流域水污染物排放总量控制研究[J], 地理科学 2000 (2):61-64

孟伟, 2008, 流域水污染物总量控制技术与规范[M], 北京:中国环境科学出版社, 2008

彭水军,张文城,卫瑞,2016, 碳排放的国家责任核算方案[J], 经济研究,2016(3), pp137-150

彭水军,张文城,孙传旺,2015,中国生产侧和消费侧碳排放量测算及影响因素研究[J],经济研究,2015(1), pp168-182

范英英, 2012, 基于碳排放总量控制的低碳经济发展优化模型研究[D], 华北电力大学 2012

袁永娜, 石敏俊, 李娜, 周晟吕, 2012, 碳排放许可的强度分配标准与中国区域经济协调发展:基于 30 个省区 CGE 模型的分析[J], 气候变化研究进展, 2012, 71(8):64-67

冯金鹏,吴洪寿,赵帆, 2014, 水环境污染总量控制回顾、现状及发展探讨 [J], 南水北调与水利科技, 2004 年 01 期

刘宇, 蔡松锋, 张其仔, 2013, 2025 年、2030 年和 2040 年中国二氧化碳排放达峰的经济影响:

基于动态 GTAP-E 模型[J], 经济与金融管理, Vol.25 No.02 (2013)

刘子刚, 尚金城, 姜建祥, 1997, 区域环境总量控制模型研究[J], 东北师大学报(自然科学版), 1997 年 02 期

刘小敏, 2011, 中国 2020 年碳排放强度目标的情景分析-- 基于重点部门的研究[D], 社会科学院研究生院数量经济与技术经济, 北京(2011), pp37-48

刘娜, 谢绍东, 2007, 中国不同经济区域大气污染总量分配方法的选择研究[J], 北京大学学报(自然科学版), 2007.06

刘长松, 2015, 我国碳排放总量控制与碳交易的若干问题[J], 中国发展观察战略,(国家发改委国家应对气候变化战略研究和国际合作中心), 2015, (09):50-53 & 81

吴国华, 刘清清, 吴琳, 2011, 碳减排潜力差异分析及目标设定[J], 中国人口•资源与环境, 2011, 21(12)

张玉清, 2001, 河流功能区水污染物容量总量控制的原理和方法[M], 中国环境科学出版社,北京

张天柱, 1990, 区域水污染物排放总量控制的系统理论模式[J], 环境科学动态, 1990

马中, (美)杜丹德(Daniel Dudek), 1999, 总量控制与排污交易[M], 中国环境科学出版社, 北京,1999,pp179. ISBN: 9787801359308

中国电力企业联合会, 2020,《中国电力行业年度发展报告 2020》, 北京 2020.06

Note:

- [J]: paper published in a journal
- [C]: paper published on a conference
- [W]: paper published as a workshop paper
- [M]: book published
- [D]: PhD dissertation
- [R]: report published
- [OL]: article published on website
- [EB]: electronic bulletins

专著[M]，论文集[C]，报纸文章[N]，期刊文章[J]，学位论文[D]，报告[R]，workshop[W]，标准[S]，专利[P]，数据库[DB]，计算机程序[CP]，电子公告[EB]，磁带[MT]，磁盘[DK]，光盘[CD]，联机网络[OL]

Acknowledgements

First of all, I would like to express my sincere gratitude to Professor Dr Tatsuo Yanagita. It is under his kindly guidance and constant support that I have substantially carried out this study. During my studying for Master degree and Doctor degree in The University of Tokyo, as my supervisor he had taught me the principles of the international economics, and always gave me enough time to discuss with him, stimulated me to have a challenge in a new field and encouraged me to overcome the difficulties both in studies and from other aspects.

Also, meanwhile I would like to give my deep thanks to Associate Professor Dr Maiko Sakamoto in the department of International Studies of the graduate school of Frontier Science, The University of Tokyo, for her constructive comments and valuable advices on this study. Particularly without her supportive suggestions and helps, I would not have been able to improve this study greatly and submit the dissertation on time finally.

Then, great thanks should go to Professor Dr Riki Honda, Professor Dr Masahide Horita, in the department of International Studies, who gave me the critical and positive comments which really promote me to complete and enhance this study in content.

Recalling my studying for my master degree in the department of International Studies, I'd like to thank again Professor Kunishima, Professor Yamaji, Professor Sato and Professor Ishi who gave us very interesting lectures and useful comments on my master degree thesis.

And also thanks are given to Professor Xiangming Xu, Professor Xuan Gao, Professor Jianzhong Wu in Shanghai Jiao Tong University (SJTU), and Senior Engineer Zhiming Yang in Shanghai Environmental Science Research Institute, who had instructed me and provided useful data and references for my master degree project.

Meanwhile thanks are to Yifei Zhao, my former colleague in Shanghai Jiao Tong University and my lab mate Dongming Yang for their helps in finding some related references. And thanks also are to Zhang Qian and Ju Wen for their helps in typing or drawing some figures.

Additionally, I'd like to express my thanks to some other classmates, friends, colleagues and bosses, who have given me kind helps and let me feel warm friendships during my studying and working in Japan, such as Mr.Suetsugu, Mr.Yoshioka, Mr.Ushigome, Mr.Okazaki, Mr.Tamada, Mr.Kitagawa, Mr.Nakakawa, Mr.Miyao, Mr.Imanishi, Mr.Koibuchi, Mr.Jibiki, Mr.Tsuchido, Ms.Okamoto, Ms.Hattori, and Mr.Kawaguchi, and also I have to thank Ms U. Brenda's help improving my English.

Finally, in particular, I am also greatly indebted to my family for their supporting me any time, especially to my daughter who has never disturbed my staying alone in writing the dissertation and has forgiven me for not companying her to buy beautiful clothes during these years.

Appendixes

A: List of the plants for application in Chapter 6

The plants (factories) listed below are selected as examples for the application case study in Chapter 6 and all the relevant original data used here for application in Chapter 6 come from the research reports “Investigation Data in Shongjiang Industrial District (1-21)” and “Economic Analysis on Emissions Standards of Industrial Wastewater at Upper Reaches of Huangpu River in Shanghai” provided by Shanghai Environmental Science Research Institute (SESRI,1986), except for those data with another data sources note otherwise.

Table A.6-1-1 List of Plants

i	K(i)	Name (in Chinese Pingying)
1	1	Shanghai XiaoHuang QiCai Chang
2	2	Shanghai Si Lian FengRen JiJia Chang
3	3	Shanghai YiBiao JiChuang Chang
4	4	ShinQiao ShiPing Chang
5	5	Shanghai LaGuang Zi Chang
6	6	ShongJiang LianHe Huagong Chang
7	7	Sesan Piaoran Chang
8	8	Junting nenza Chang
9	9	Shanghai Hongqi Yaomian Chang
10	10	Jiuting Nenlaxin Gang Chang
11	11	Shanghai Di’er Yielian Chang
12	12	Shingpang Huagong Chang
13	13	Zhuanqiao MaoFangZhi Chang
14	14	Junting Lasi Chang
15	15	Shanghaishi Changjiang Huagong Chang
16	16	Shongjiang Gongyibin Chang
17	17	Silian Zhengxin Pengqi Chang
18	18	Silian Zhaoyang Pengqi Chang
19	19	Junting Xiangyang Chang
20	20	Silian Lengzha Chang
21	21	Shongjiang DianzYuanjian Chang
22	22	Shongjiang Youzhi Huagong Chang
23	23	Shanghai XiaoHuang Yaoji Chang
24	24	Shongjiang Liangzhuao Chang
25	25	Shilian Shuini Ziping Chang
26	27	SheshanTaojingLengZha Chang
27	29	Shongjiang Huaqian Chang
28	30	Wuxintang Huagong Chang
29	31	Dongjing Nongji Chang
30	32	Shongjiang Ranfang Chang
31	33	Sinqiao Huagong Chang
32	35	Shanghai Shuoliao Shisi Chang
33	36	Huayang Qiaogong Nongwa Chang
34	37	Shanghai Shongjiang Zhijiang Chang
35	38	ShongjiangXian Liugang Diansi Chang
36	39	Shongjiang Tahui Jinxing Huagong Chang
37	40	ShongjiangXian Kungang Fensi Chang
38	41	ShongjiangXian Zhangzhe Huagong Chang
39	42	ShongJiang Shiping Chang

B: Other tables of the results data in Chapters 8-10

Table B-8-3-10 Results based on Part-cooperative model with setting x^{Total} =10,000 mt (2)

Classification of Sectors	G_0	Total Production (10000 CNY)	Final Use (10000 CNY)	(%)	CO_2 Emission (Ton)
G_i	G_i				
G_i	i	$SumP_i^{P*} = v(N)$	$SumF_i^{P*}$	$sF_i/sMax$	$SumX_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	21,769,149,453.36	7,640,303,697.76	82.48	9,999,999,999.71
Mining	2	21,767,628,375.15	7,627,255,671.14	82.48	9,999,999,999.71
Manufacture of Foods, Beverage and Tobacco	3	21,786,990,674.57	7,636,390,961.39	82.44	9,999,999,999.71
Manufacture of Textile, Wearing Apparel and Leather Products	4	21,786,990,674.57	7,636,390,961.39	82.44	9,999,999,999.71
Other Manufacture	5	21,732,829,721.12	7,591,568,452.07	81.96	9,999,999,999.85
Production and Supply of Electric Power, Heat Power and Water	6	21,495,716,802.41	7,507,634,249.61	81.05	9,999,999,999.85
Coking, Gas and Processing of Petroleum	7	21,495,624,027.52	7,504,908,475.78	81.02	9,999,999,999.85
Chemical Industry	8	21,539,347,557.78	7,500,219,887.64	80.97	9,999,999,999.85
Manufacture of Nonmetallic Mineral Products	9	21,715,225,558.62	7,600,364,310.34	82.05	9,999,999,999.85
Manufacture and Processing of Metals and Metal Products	10	21,477,345,063.13	7,479,677,323.81	80.75	9,999,999,999.85
Manufacture of Machinery and Equipment	11	21,068,086,933.79	7,060,785,178.70	76.23	9,999,999,999.85
Construction	12	20,477,326,371.61	6,970,741,242.00	75.25	9,999,999,999.85
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	21,445,758,358.78	7,474,205,837.51	80.69	9,999,999,999.85
Wholesale and Retail Trades, Hotels and Catering Services	14	21,786,990,676.37	7,636,390,962.08	82.44	9,999,999,999.85
Real Estate, Leasing and Business Services	15	21,786,990,676.37	7,636,390,962.08	82.44	9,999,999,999.85
Financial Intermediation	16	21,786,990,676.37	7,636,390,962.08	82.44	9,999,999,999.85
Other Services	17	21,786,990,676.37	7,636,390,962.08	82.44	9,999,999,999.85
Total					

Table B-8-3-11 Results based on Full-/ Part-cooperative model with setting x^{Total}=10,000 mt (3)

Classification of Sectors	G_0	Total Production P_i (Comparison between Full- & Part-cooperative cases)		
	G_i	(10000 CNY)	(10000 CNY)	(10000 CNY)
G_i	i	P_i^* in Full case	P_i^{P*} in Part case	$\Delta P_i=P_i^*-P_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,216,859,093.55	1,349,789,325.26	-132,930,231.71
Mining	2	1,071,238,434.80	1,076,770,800.85	-5,532,366.05
Manufacture of Foods, Beverage and Tobacco	3	1,248,495,881.75	1,248,495,883.36	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	962,459,747.96	962,459,748.03	0
Other Manufacture	5	728,595,876.87	815,205,218.71	-86,609,341.84
Production and Supply of Electric Power, Heat Power and Water	6	646,414,518.63	661,721,720.05	-15,307,201.42
Coking, Gas and Processing of Petroleum	7	573,335,315.05	590,707,178.56	-17,371,863.51
Chemical Industry	8	1,790,097,318.18	1,865,161,856.42	-75,064,538.24
Manufacture of Nonmetallic Mineral Products	9	480,120,521.11	495,780,835.32	-15,660,314.21
Manufacture and Processing of Metals and Metal Products	10	1,945,190,133.94	2,016,258,135.02	-71,068,001.08
Manufacture of Machinery and Equipment	11	3,564,439,547.89	4,514,658,827.12	-950,219,279.23
Construction	12	1,387,049,167.17	1,927,657,421.34	-540,608,254.17
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,102,462,822.93	1,229,522,181.45	-127,059,358.52
Wholesale and Retail Trades, Hotels and Catering Services	14	1,314,207,295.77	1,314,207,294.54	0
Real Estate, Leasing and Business Services	15	1,120,603,617.11	1,120,603,617.22	0
Financial Intermediation	16	810,828,259.23	810,828,259.25	0
Other Services	17	1,824,593,118.73	1,824,593,118.78	0
Total		21,786,990,670.66	23,824,421,421.27	-2,037,430,750.61

Table B-8-3-12 Results based on Full-/Part-cooperative model with x^{Total}=10,000 mt (4)

Classification of Sectors Sector	G_0	Social Benefit SB_i (Total Production $SumP_i$) (Comparison between Full- & Part-cooperative cases)		
	G_i	(10000 CNY)	(10000 CNY)	(10000 CNY)
G_i	i	$SB_i^* = SumP_i^*$ in Full case	$SB_i^{P*} = SumP_i^{P*}$ in Part case	$\Delta SB_i = SB_i^* - SB_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	21,786,990,670.66	21,769,149,453.36	17,841,217.30
Mining	2	21,786,990,670.66	21,767,628,375.15	19,362,295.51
Manufacture of Foods, Beverage and Tobacco	3	21,786,990,670.66	21,786,990,674.57	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	21,786,990,670.66	21,786,990,674.57	0
Other Manufacture	5	21,786,990,670.66	21,786,990,674.57	0
Production and Supply of Electric Power, Heat Power and Water	6	21,786,990,670.66	21,495,716,802.41	291,273,868.26
Coking, Gas and Processing of Petroleum	7	21,786,990,670.66	21,495,624,027.52	291,366,643.14
Chemical Industry	8	21,786,990,670.66	21,539,347,557.78	247,643,112.88
Manufacture of Nonmetallic Mineral Products	9	21,786,990,670.66	21,715,225,558.62	71,765,112.05
Manufacture and Processing of Metals and Metal Products	10	21,786,990,670.66	21,477,345,063.13	309,645,607.53
Manufacture of Machinery and Equipment	11	21,786,990,670.66	21,068,086,933.79	718,903,736.88
Construction	12	21,786,990,670.66	20,477,326,371.61	1,309,664,299.05
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	21,786,990,670.66	21,445,758,358.78	341,232,311.88
Wholesale and Retail Trades, Hotels and Catering Services	14	21,786,990,670.66	21,786,990,676.37	0
Real Estate, Leasing and Business Services	15	21,786,990,670.66	21,786,990,676.37	0
Financial Intermediation	16	21,786,990,670.66	21,786,990,676.37	0
Other Services	17	21,786,990,670.66	21,786,990,676.37	0
Total	sum	370,378,841,401.22	366,760,143,231.34	3,618,698,204.45

Table B-8-3-13 Results based on Full-/Part-cooperative model with x^{Total} =10,000 mt (4)

Classification of Sectors	G_0	Final Use F_i (Comparison between Full- & Part-cooperative cases)		
	G_i	(10000 CNY)	(10000 CNY)	(10000 CNY)
G_i	i	F_i^* in Full case	F_i^{P*} in Part case	ΔF_i = Full - Part
Agriculture, Forestry, Animal Husbandry and Fishery	1	293,282,815.44	404,328,595.89	-111,045,780.45
Mining	2	12,469,606.56	17,586,983.40	-5,117,376.84
Manufacture of Foods, Beverage and Tobacco	3	595,557,764.98	595,557,765.87	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	386,056,271.29	386,056,271.32	0
Other Manufacture	5	156,099,475.07	220,160,678.56	-64,061,203.49
Production and Supply of Electric Power, Heat Power and Water	6	36,716,264.04	51,784,143.48	-15,067,879.44
Coking, Gas and Processing of Petroleum	7	53,713,867.00	75,757,395.83	-22,043,528.83
Chemical Industry	8	160,758,386.01	226,731,707.50	-65,973,321.48
Manufacture of Nonmetallic Mineral Products	9	31,114,067.63	43,882,878.12	-12,768,810.49
Manufacture and Processing of Metals and Metal Products	10	123,540,155.95	174,239,436.91	-50,699,280.96
Manufacture of Machinery and Equipment	11	1,511,103,203.21	2,131,240,393.71	-620,137,190.51
Construction	12	1,296,852,813.97	1,829,064,418.70	-532,211,604.72
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	310,788,618.64	438,332,554.17	-127,543,935.53
Wholesale and Retail Trades, Hotels and Catering Services	14	594,103,199.72	594,103,198.37	0
Real Estate, Leasing and Business Services	15	513,930,784.67	513,930,784.89	0
Financial Intermediation	16	154,286,204.42	154,286,204.40	0
Other Services	17	1,406,017,460.98	1,406,017,460.98	0
Total		7,636,390,959.58	9,263,060,872.10	-1,626,669,913.66

Table B-8-3-14 Results based on Full-/Part-cooperative model with x^{Total} =10,000 mt (5)

Classification of Sectors	G_0	Total Final Use ($SumF_i$) (Comparison between Full- & Part-cooperative cases)		
	G_i	(10000 CNY)	(10000 CNY)	(10000 CNY)
G_i	i	$SF_i^* = Sum\ F_i^*$ in Full case	$SF_i^{P*} = Sum\ F_i^{P*}$ in Part case	$\triangle SF_i = SF_i^* - SF_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	7,636,390,959.59	7,640,303,697.76	-3,912,738.17
Mining	2	7,636,390,959.59	7,627,255,671.14	9,135,288.46
Manufacture of Foods, Beverage and Tobacco	3	7,636,390,959.59	7,636,390,961.39	-1.80
Manufacture of Textile, Wearing Apparel and Leather Products	4	7,636,390,959.59	7,636,390,961.39	-1.80
Other Manufacture	5	7,636,390,959.59	7,636,390,961.39	-1.80
Production and Supply of Electric Power, Heat Power and Water	6	7,636,390,959.59	7,507,634,249.61	128,756,709.98
Coking, Gas and Processing of Petroleum	7	7,636,390,959.59	7,504,908,475.78	131,482,483.81
Chemical Industry	8	7,636,390,959.59	7,500,219,887.64	136,171,071.95
Manufacture of Nonmetallic Mineral Products	9	7,636,390,959.59	7,600,364,310.34	36,026,649.25
Manufacture and Processing of Metals and Metal Products	10	7,636,390,959.59	7,479,677,323.81	156,713,635.79
Manufacture of Machinery and Equipment	11	7,636,390,959.59	7,060,785,178.70	575,605,780.89
Construction	12	7,636,390,959.59	6,970,741,242.00	665,649,717.59
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	7,636,390,959.59	7,474,205,837.51	162,185,122.08
Wholesale and Retail Trades, Hotels and Catering Services	14	7,636,390,959.59	7,636,390,962.08	-2.49
Real Estate, Leasing and Business Services	15	7,636,390,959.59	7,636,390,962.08	-2.49
Financial Intermediation	16	7,636,390,959.59	7,636,390,962.08	-2.49
Other Services	17	7,636,390,959.59	7,640,303,697.76	-3,912,738.17
Total				

Table B-8-3-15 Results based on Full-/Part-cooperative model with x^{Total} =10,000 mt (6)

Classification of Sectors	G_0	Difference for P_i , SB_i and final profit α_i (Comparison between Full- & Part-cooperative cases)		
	G_i	(10000 CNY)	(10000 CNY)	γ^*= 0.55472608
G_i	i	$\Delta P_i=P_i^*-P_i^{P*}$	$\Delta SB_i = SB_i^* - SB_i^{P*}$	$\Delta\alpha_i$
Agriculture, Forestry, Animal Husbandry and Fishery	1	-132,930,231.71	17,841,217.30	-9,896,988.57
Mining	2	-5,532,366.05	19,362,295.51	-10,740,770.33
Manufacture of Foods, Beverage and Tobacco	3	0	0	0
Manufacture of Textile, Wearing Apparel and Leather Products	4	0	0	0
Other Manufacture	5	-86,609,341.84	54,160,949.55	-30,044,491.33
Production and Supply of Electric Power, Heat Power and Water	6	-15,307,201.42	291,273,868.26	-161,577,211.67
Coking, Gas and Processing of Petroleum	7	-17,371,863.51	291,366,643.14	-161,628,676.32
Chemical Industry	8	-75,064,538.24	247,643,112.88	-137,374,093.70
Manufacture of Nonmetallic Mineral Products	9	-15,660,314.21	71,765,112.05	-39,809,979.42
Manufacture and Processing of Metals and Metal Products	10	-71,068,001.08	309,645,607.53	-171,768,494.62
Manufacture of Machinery and Equipment	11	-950,219,279.23	718,903,736.88	-398,794,653.17
Construction	12	-540,608,254.17	1,309,664,299.05	-726,504,945.12
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	-127,059,358.52	341,232,311.88	-189,290,463.36
Wholesale and Retail Trades, Hotels and Catering Services	14	0	0	0
Real Estate, Leasing and Business Services	15	0	0	0
Financial Intermediation	16	0	0	0
Other Services	17	0	0	0
Total		-2,037,430,750.61	3,672,859,123.39	-2,037,430,750.61

Table B-8-3-16 Results based on Redistribution model of MSB with x^{Total} =10,000 mt (1)

Classification of Sectors	G_0	Redistribution of the maximum SB($\underline{\mathbf{X}}^*$) with Equal Acceptance Degree (10000 CNY)		
	G_i	$\Delta\alpha_i^{Tinc}$ ($\Delta SB_i \geq 0$)	$\alpha_i^L = P_i^{P*}$	$\alpha_i^H = P_i^{P*} + \Delta\alpha_i^{Tinc}$
G_i	i	$\Delta\alpha_i^{Tdec}$ ($\Delta SB_i \leq 0$)	$\alpha_i^L = P_i^{P*} - \Delta\alpha_i^{Tdec}$	$\alpha_i^H = P_i^{P*}$
Agriculture, Forestry, Animal Husbandry and Fishery	1	17,841,217.30	1,349,789,325.26	1,367,630,542.56
Mining	2	19,362,295.51	1,076,770,800.85	1,096,133,096.36
Manufacture of Foods, Beverage and Tobacco	3	0.00	1,248,495,883.36	1,248,495,883.36
Manufacture of Textile, Wearing Apparel and Leather Products	4	0.00	962,459,748.03	962,459,748.03
Other Manufacture	5	0.00	815,205,218.71	815,205,218.71
Production and Supply of Electric Power, Heat Power and Water	6	291,273,868.26	661,721,720.05	952,995,588.31
Coking, Gas and Processing of Petroleum	7	291,366,643.14	590,707,178.56	882,073,821.70
Chemical Industry	8	247,643,112.88	1,865,161,856.42	2,112,804,969.30
Manufacture of Nonmetallic Mineral Products	9	71,765,112.05	495,780,835.32	567,545,947.37
Manufacture and Processing of Metals and Metal Products	10	309,645,607.53	2,016,258,135.02	2,325,903,742.55
Manufacture of Machinery and Equipment	11	718,903,736.88	4,514,658,827.12	5,233,562,564.00
Construction	12	1,309,664,299.05	1,927,657,421.34	3,237,321,720.39
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	341,232,311.88	1,229,522,181.45	1,570,754,493.33
Wholesale and Retail Trades, Hotels and Catering Services	14	0.00	1,314,207,294.54	1,314,207,294.54
Real Estate, Leasing and Business Services	15	0.00	1,120,603,617.22	1,120,603,617.22
Financial Intermediation	16	0.00	810,828,259.25	810,828,259.25
Other Services	17	0.00	1,824,593,118.78	1,824,593,118.78
Total		3,618,698,204.48	23,824,421,421.28	27,443,119,625.76
		SB($\underline{\mathbf{X}}$*)=∑P_i*→	21,786,990,670.66	

Table B-8-3-17 Results based on Redistribution model of MSB with x^{Total} =10,000 mt (2)

Classification of Sectors		With TEC policy : G_i's final profit and tax or subsidy		
	G_0	G_0: in Full-cooperative case		
G_i	i	P_i^*	α_i	t_i
Agriculture, Forestry, Animal Husbandry and Fishery	1	1,216,859,093.55	1,339,744,208.84	-122,885,115.29
Mining	2	1,071,238,434.80	1,065,869,273.82	5,369,160.98
Manufacture of Foods, Beverage and Tobacco	3	1,248,495,881.75	1,248,495,883.36	-1.61
Manufacture of Textile, Wearing Apparel and Leather Products	4	962,459,747.96	962,459,748.03	-0.07
Other Manufacture	5	728,595,876.87	815,205,218.71	-86,609,341.84
Production and Supply of Electric Power, Heat Power and Water	6	646,414,518.63	497,726,188.37	148,688,330.26
Coking, Gas and Processing of Petroleum	7	573,335,315.05	426,659,411.96	146,675,903.09
Chemical Industry	8	1,790,097,318.18	1,725,731,689.87	64,365,628.31
Manufacture of Nonmetallic Mineral Products	9	480,120,521.11	455,375,021.45	24,745,499.66
Manufacture and Processing of Metals and Metal Products	10	1,945,190,133.94	1,841,918,787.85	103,271,346.09
Manufacture of Machinery and Equipment	11	3,564,439,547.89	4,109,895,429.49	-545,455,881.60
Construction	12	1,387,049,167.17	1,190,278,904.23	196,770,262.94
Transport, Storage, Post, Information Transmission, Computer Services and Software	13	1,102,462,822.93	1,037,398,614.90	65,064,208.03
Wholesale and Retail Trades, Hotels and Catering Services	14	1,314,207,295.77	1,314,207,294.54	1.23
Real Estate, Leasing and Business Services	15	1,120,603,617.11	1,120,603,617.22	-0.11
Financial Intermediation	16	810,828,259.23	810,828,259.25	-0.02
Other Services	17	1,824,593,118.73	1,824,593,118.78	-0.05
Total		21,786,990,670.66	21,786,990,670.66	0.00

C: Abbreviations

3PVs	third-party verifiers
AM	asset-oriented model
APEC	Asia-Pacific Economic Cooperation
BPM	bi-objective programming model
BRIO	bi-regional input-output models
C&T	cap and trade
CAEP	Chinese Academy for Environmental Planning
CBE	consumption-based emissions
CEA	carbon emissions abatement
CET	carbon emissions trading
CGE	computable general equilibrium
CHAs	China CO_2 allowances
CNY	Chinese currency (RMB yuan)
CM	cost-oriented model
CO_2	carbon dioxide (CO_2)
COD	chemical oxygen demand (COD)
CSCE	China's sectoral carbon emissions
CWS	CLIMNEG world simulation
DEA	data envelopment analysis
DSM	demand side management
EAD	equal acceptance degree”
EE-IOA	environmentally-extended input-output analysis
EKC	environmental Kuznets curve
EPA	Environmental Protection Agency
ERCA	Environmental Restoration and Conservation Agency in Japan
ETS	emissions trading system
EU	European Union
EU ETS	the EU emissions trading system
FCAM	fixed cost allocation model
FRVs	fuzzy random variables
GCBR	global carbon budget report
GCs	generating companies
GDP	gross domestic product
GEP	generation expansion planning
GHG	greenhouse gases
HNGP-QAM	hybrid nonlinear grey-prediction and quota allocation model
IDA	index decomposition analysis
IER	independent emission reduction
IOA	input-output analysis
IOR-ARC	Indian Ocean Rim Association for Regional Cooperation
IPCC	Intergovernmental Panel on Climate Change

LCA	life cycle assessment
LCTs	low carbon technologies
LMDI	logarithmic mean divisia index
MCDA	multi-criteria decision analysis
MCOD	multi-criteria optimization model
MDM	maximum deviation method
MOEJP	Ministry of Environment of Japan
MOM	multi-objective model
MPV	modifiable policy vector
MRIO	multiregional input-output models
MRIO-LCA	MRIO and their integration with life-cycle assessment models
MSB	maximum social benefit
MSW	mechanism of municipal solid waste
MTE	maximum total emission
NAP	national allocation plan
NBSC	National Bureau of Statistics of China
NCERTM	national carbon emissions rights trading market
NCTS	national carbon trading system
NDRC	National Development and Reform Commission
NEI	national emission inventories
NEV	new energy vehicle
PBE	production-based emissions
PDM	policy dependency mapping
PoP	power-of-pull approach
PRD	pearl river delta (in China)
PTC	production tax credit
RE	renewable energy
RES	renewable energy sources
SB	social benefit
SDA	structural decomposition analysis
SEPA	State Environmental Protection Administration
SEPB	State Environmental Protection Bureau
SESRI	Shanghai Environmental Science Research Institute
SOM	single-objective model
SPA	structural path analysis
SRIO	single-region input-output models
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology
TEC	total emission control
TMDL	total maximum daily loads
UNFCCC	United National Framework Convention of Climate Change
USAN	Union of South American Nations

D: List of figures

E: List of tables

(End)