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A Proposed Framework for Sustainable Development in an Industrial Low-carbon Economy

By

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Along with the rapid increase in the size of the global economy, anthropogenic carbon dioxide (CO_2) emissions have also increased over the years, intensifying the greenhouse gas effect and increasing the tension between human and natural environments. Governments have set national and industrial targets for reducing CO_2 emissions, while research is being carried out to provide theories to investigate sustainable approaches to achieving low-carbon emission to support these strategies. Pigouvian Tax Theory and the Coase Theorem provide theoretical backing for restraining CO_2 emissions through economic methods, such as taxation. The Environmental Kuznets Curve (EKC), the Theory of Coupling-Decoupling, and the IPAT Function investigate the relationship between economic growth and CO_2 emissions; however, their conclusions do not provide sufficient guidance to the industrial activities of low-carbon emission in a low-carbon economy. Most of the studies in this field are still focusing on individual factors within a low carbon economy; their conclusions represent only part of an overall system. In fact, the industrial low-carbon economy is a complex system with inter-disciplinary elements. We therefore carried out research from the perspective of systems thinking, where industrial low-carbon economy is treated as a holistic system.

Based on this principle, this research analyses the low-carbon economy with an improved philosophical and theoretical foundations, building up the research methodology, then selecting and optimising the dimensions and factors for representing this system. Seven dimensions are identified: policy and law, macro-economics, society, industrial technology, industrial economy, carrying capacity and industrial goal. These dimensions and the logic interrelationships among them comprise the dimensional structure model, qualitatively representing this system.

Further analysis applying Interpretative Structural Modelling method to the factors from each dimension identified a causal relationships model and a hierarchical structure model, presenting the logic and structure of this system. Population, industrial production technology and industrial technology for CO_2 treatment are the key factors for achieving a system to determine the goal of maintaining industrial net profit in the low-carbon economy. The population affects the system's goal through its influences on industrial GDP and industrial policy for low-carbon emission, while industrial

production technology and industrial technology for CO_2 pollution treatment influence the system's goal through their causal effects on the industrial GDP and the amount of CO_2 emissions from industrial production. From the hierarchical structure model, the logical relational model is constructed, qualitatively representing the logic within this system, with five sub-models. The models for the industrial sustainable development and the optimal approach to low-carbon emission are constructed to identify the approaches to achieve industrial sustainable development and low-carbon emission, which include maintaining net profit after the cost of reducing CO_2 emissions, and improving production technology. The theoretical model for economic growth and CO_2 emissions in an industrial low-carbon economy is constructed to illustrate the relationships between economic growth and CO_2 emissions, which is a correlation but not causal. Therefore, none of the theories of EKC, Coupling-Decoupling and IPAT Function is tenable.

The decision-making models for industrial low-carbon emission policy and industrial fiscal and monetary policy are constructed to indicate the policy-making process and their support in achieving the system's goal. Together with the first two models, they indicate that policies do not directly determine the amount of reduction of CO_2 emissions; therefore, neither Pigouvian Tax Theory nor the Coase Theorem can directly lead to reduction of CO_2 emissions.

These models are applied to and validated in the Chinese thermal electricity generation industry. They indicate that improvement in industrial production technology can lead to the achievement of both the industrial target for CO_2 emissions and this industry's sustainable development. Although the industrial target of CO_2 emissions for 2020 was calculated to be achieved early, by 2016, the 2020 national target for China will not be achieved following current practices. Moreover, there is no causal relationship between Chinese economic growth and the amount of CO_2 emissions from this industry. Therefore, there is no causal relationship between GDP and the sum of every industry's CO_2 emissions.

The development of the models provides the foundation for this study to be used to investigate analytical and managerial methods towards the reduction of carbon emissions and the achievement of sustainable development for industry in a low-carbon economy, and to identify the relationship between economic growth and CO_2 emissions. Most importantly, the research methodology constructed here can be applied as a general paradigm for future research and related policymaking regarding an industrial low-carbon economy. Therefore, this study will fulfill the knowledge gaps in the field of industrial low-carbon economy.

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Acronyms and Abbreviations

CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
DPSIR	Driving forces, Pressures, States, Impacts, Responses
EIO	Environmental Input-Output Analysis
EG	Electricity Generation
EKC	Environmental Kuznets Curve
ET	Emissions Trade
g	Gram
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GST	General System Theory
Gt	Gigatonne
IGCC	Integrated Gasification Combined Cycle
IO	Input-output
IPCC	The Intergovernmental Panel on Climate Change
ISM	Interpretative Structural Modelling
J	Joule
JI	Joint Implementation
kcal	Kilocalories
kg	Kilogram
kgce	Kilogram of Standard Coal Equivalent
kJ	Kilojoule
kt	Kiloton
KW	Kilowatt
kWh	Kilowatt Hour
m^3	Cubic Metre
LCA	Life Cycle Assessment / Analysis
MW	Megawatt
OECD	Organization for Economic Co-operation and Development

Pa	Pascal
SC	Standard Coal
SC	Supercritical
SCE	Standard Coal Equivalent
SNA	System of National Accounts
t	Ton (tonnes)
TEG	Thermal Electricity Generation
TJ	Terajoule
WCED	World Commission on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
USC	Ultra-supercritical

Chapter 1 Introduction

1.1 Research Background on Industrial Low-carbon Economy

Along with the rapid increase in the world's population and the growth of the global economy, the amount of carbon dioxide (CO_2) and other greenhouse gases (GHGs) emitted is also increasing, with the greenhouse effects intensifying over the years. The Inter-governmental Panel on Climate Change IPCC (2015) reported in their fifth assessment on climate change that "between 1750 and 2011, cumulative anthropogenic carbon dioxide emissions to the atmosphere were 2040 ± 310 Gt CO_2, which is highly related to the global warming effects. The average global temperature during the period 1986-2005 increased by around 0.55-0.65 ºC over the average temperature during 1850-1900". The IPCC (2015) is now "95 percent certain that humans are the main cause of current global warming". The climate change effects of global warming include the increasing frequency of natural disasters like heat stress, storms and extreme precipitation, inland and coastal flooding, etc.), the increasing risk of extinction of major species, and changes in oceanic acidification (Committee on the Science of Climate Change, 2001; IPCC, 2015). These effects will increase the risks of ecological and public security challenges both in urban and rural areas, and it will directly risk human beings' survival and development (IPCC, 2015; Stern, 2006).

Governments are becoming increasingly concerned about the greenhouse effects and climate change. In 1979, the first *World Climate Conference* was held in Geneva, in which global climate topics were formally identified and discussed. In 1987, the World Commission on Environment and Development (WCED, 1987) published the report *Our Common Future*, in which the effects of industrialisation started to be appraised. The IPCC was established in 1988, and since then this scientific and intergovernmental body has been methodically reporting the updated information and research contributions related to climate change, and monitoring the natural environment on earth. In 1992, the *United Nations Conference on Environment and Development* was organised by the United Nations Environment and Development Committee (UNCED) in Rio De Janeiro, Brazil. At this conference, the *Rio Declaration on Environment and Development* (also called the Earth Charter) (UNCED, 1992) and the *Agenda 21*

(United Nations, 1992) were agreed. The conference also contributed to adoption of the *Statement of Forest Principles*, the *United Nations Framework Convention on Climate Change (UNFCCC)* and the *United Nations Convention on Biological Diversity*, fundamental documents for dealing with related environmental issues. In 1997, the Kyoto Protocol, which supplemented the UNFCCC, was agreed. "This international treaty entered into force on 16 February 2005, and commits the participants to reducing and curbing the GHG emissions into an appropriate emissions level to avoid the damages caused by the severe changes in climate" (United Nations, 1998).

The low-carbon economy was proposed in the British government report *Energy White Paper: Our Energy Future-Create a Low Carbon Economy* (Department of Trade and Industry, 2003), in which it was presented as reducing the emissions of GHG. While the concept of transforming the traditional economy into a low-carbon economy was proposed by Stern (2006) in his report *The economics of climate change: Stern review on the economics of climate change*. Stern (2006) mentioned that under the consideration of cost-effectiveness, immediately reducing emissions would only cost around 1% of global GDP a year, while if actions were not taken, then the cost of the losses from damage resulting from climate change would be around 5%-20% of global GDP a year in the future. Therefore, he suggested that governments worldwide should take practicable actions to transform into the low-carbon economies as soon as possible.

In July 2007, the United States Senate introduced the *Low Carbon Economy Act of 2007* to promote action; however, it did not enact. The current enacted Act in this area is *American Business Act on Climate Pledge*, which 154 companies have joined. Moreover, *The Clean Power Plan* set a goal to reduce 32% of GHG emissions from the energy sector by 2030, and President Obama set a national target of reducing 26%-28% of GHG emissions by November 2025 (The White House, 2015). The UK, which was the first country to legislate on long-term significant carbon reducing targets, passed the *Climate Change Act 2008* in 2007; this Act set a target of 80% reduction of the UK's carbon emissions by 2050, compared to 1990 levels, to promote the transition into a low-carbon economy. This law also set a milestone, aiming to reduce GHG emissions by 26% - 32% by 2020 (Tullo, 2008). The Chinese government first announced its national target for reducing CO_2 emissions at the *Copenhagen Summit* (*United Nations Climate Change Conference*) in 2009: to reduce CO_2 emissions per unit of GDP by

40%-45% by 2020 compared with 2005 levels. Five years later, the Chinese government issued the *National Climate Change Action Programme (2014-2020)*, and on 30 June 2015, it submitted the document, *Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions*, to the Secretariat of the UNFCCC. This document commits China to reduce CO_2 emissions per unit of GDP by 60%-65% by 2030 compared with 2005 levels.

1.2 The Research Gaps in Industrial Low-carbon Economy

There are two main aspects within the field of industrial low-carbon economy. First are the Pigouvian Tax Theory and the Coase Theorem, theoretical research on curbing the amount of CO_2 emissions. Second are the Environmental Kuznets Curve (EKC), the Theory of Coupling-Decoupling, and the IPAT Function, which aim to identify the relationship between economic growth and CO_2 emissions.

Of the theories for controlling CO_2 emissions, the Pigouvian Tax and the Coase theorem both believe that the CO_2 emissions are externality. The Pigouvian tax values the treatment of reducing CO_2 emissions as one of social welfare (Pigou, 1920; Baumol, 1972). The Coase theorem views the solution to low-carbon emission as the benefit balance between the CO_2 emitting industry and the industry affected by CO_2 emissions (Coase, 1937; 1960; 1988; Medema and Zerbe, 2000). Both theories agree that environmental protection is the benefit balance between the pollution releasing industry and society (or the directly polluted sector), instead of regarding it solely as environmental. Neither believes that environmental protection should be the responsibility of the industrial entities during their economic activities. These theories analyse neither the direct effects, nor constraints, on the industrial sustainable development from the environment.

On the other hand, referring to the theories researching the relationship between economic growth and CO_2 emissions, EKC involved statistical models to construct the relationship between them. However, different economies and their different stages of development led to differences in the main factors, on which industrial economic growth relies. Therefore, the conclusions of the EKC models are various, and they provide no general rule for analysing the relationship between the industrial growth and

CO_2 emissions (Fan and Hu, 2002; Hu et al., 2004; Galeotti et al., 2006; Huang et al., 2008). The theory of Coupling-Decoupling constructs a model to represent the relationship between industrial economic growth and the consumption of natural resources or energy, in researching the relationship between economic growth and CO_2 emissions (Deng and Duan, 2004; Tapio, 2005b; Muangthai et al., 2014; Botzoris et al., 2015b). The analysis method of this theory should objectively represent the relationship between economic growth and CO_2 emissions, but it does not present the relationship under the influence of different industrial policies, different industrial technologies or different social effects. The IPAT function constructs a model to indicate the relationship among population, GDP, technological level and CO_2 emissions (Ehrlich and Ehrlich, 1972). However, not only are population, GDP and technological level macro variables, but the analysis does not refer to the process of industrial economic production, transport or consumption, in which CO_2 is produced. This theory also fails to represent the influences of policy, law, industrial technology and social factors on CO_2 emissions, and therefore, does not accurately represent the CO_2 emitted during industrial processes.

1.3 Research Question

The central question for this research is to determine how to establish a theoretical framework to investigate industrial low-carbon economy, which will identify critical factors related to low-carbon emission in industrial economies and a logical structure among these factors.

In order to answer this question, the scope and definition of industrial low-carbon economy must be ascertained, and the research methodology to be determined. The initial sub-questions asked include:

What is the scope of this research for the industrial low-carbon economy?

What is the definition of industrial low-carbon economy?

Which research methodology is most appropriate for studying industrial low-carbon economy systems?

Based on the research gaps identified in section 1.2, the initial delineation of the research scope, industrial low-carbon economy and research methodology are defined as following:

The research scope for an industrial low-carbon economy is of a complex system, where industrial development is restrained or promoted by policies, laws, macroeconomics, society, carrying capacity, industrial technology, industrial economy, development targets for the industrial low-carbon economy, and the industry's ability to afford to meet the required standards. This scope delineates the boundaries of this complex.

The industrial low-carbon economy is a system of economic and managerial process for industrial development, where the development must meet the standards for low-carbon emission, implying the restraints and promotions listed above.

The research methodology for investigating the industrial low-carbon economy is a series of quantitative and qualitative research methods under the guidance of the systems philosophy and based on the principles of systems science, applying systems techniques to construct the models to represent the principles of the industrial low-carbon economy.

These three initial definitions will be further discussed and refined based on the literature review, and the aspects of philosophic and theoretical foundation. After answering these questions, a theoretical model for understanding industrial low-carbon economy will be constructed and validated. The related sub-questions are:

> How to construct a theoretical model to research industrial low-carbon economy systems?
>
> How to validate the theoretical model and the research methodology?

1.4 Research Aim and Objectives

1.4.1 Research Aim

The aim is to develop a methodology to analyse the industrial low-carbon economy system, and then use this methodology to construct a multi-factor model for identifying critical factors related to low-carbon emission in industrial economies and a logical structure among these factors.

1.4.2 Objectives

Based on these research questions, the research objectives are to:

(1) Determine the research scope and definition of an industrial low-carbon economy.
(2) Construct a research methodology for constructing the multi-factor model for an industrial low-carbon economy system.
(3) Select and optimise the dimensions and factors for an industrial low-carbon economy system.
(4) Construct a dimensional structure model, which will identify critical dimensions for this industrial low-carbon economy system.
(5) Construct a multi-factor model, which identifies critical factors and the hierarchical structure among these factors for this industrial low-carbon economy system, simplifying the logical relational model into five sub-models.
(6) Validate the logical relational model and the simplified sub-models using industrial data, and then validate the constructed research methodology.
(7) Conclude by presenting the research findings, contributions, and limitations of this research.

1.5 Deliverables

1.5.1 Theoretical Contributions

This research clarifies the scope and definition of an industrial low-carbon economy, constructs a research methodology, and builds theoretical models. The research methodology and theoretical models fill the gaps in the field of industrial low-carbon economies. The theoretical models scientifically analyse the relationship between economic growth and CO_2 emissions. The model for an industrial sustainable development in low-carbon economy solves the problem between the industrial low-carbon economy and continuous industrial development. The model for the optimal approach to low-carbon emission for an industrial low-carbon economy presents the optimal approach for reducing industrial CO_2.

1.5.2 Practical Contributions

The research methodology constructed in this research could be applied as a general paradigm for researching the industrial low-carbon economy, supporting the government in establishing strategies for an industrial low-carbon economy. The model for the optimal approach of low-carbon emission is the analytical and managerial method in proceeding towards the reduction of carbon emissions in one industry. Finally, the model for the sustainable development in an industrial low-carbon economy is the analytical method for the industry sustainable development in this economy.

1.6 Thesis Structure

This thesis comprises seven chapters: an introduction, literature review, research methodology, the theoretical models for an industrial low-carbon economy system, the application of and the validation of the theoretical models with data from the Chinese thermal electricity generation industry, and a conclusion.

Chapter 1 introduces the research background for an industrial low-carbon economy, and the current research gaps in this field. It also determines the research questions, aim and objectives, and outlines the theoretical and practical contributions of this research.

Chapter 2 systematically reviews the literatures on low-carbon economy, both theory and the current empirical research. It identifies the research gaps among the current theories, such as Pigouvian Tax, and Coase Theory.

Chapter 3 presents the philosophic foundations and theoretical foundations of a research methodology for an industrial low-carbon economy system, and proceeding to construct a methodology for the system.

Chapter 4 applies the research methodology constructed in chapter 3 to construct several theoretical models for an industrial low-carbon economy system: first for the production function; secondly a dimensional structure model; thirdly a factors' relational model, which is used to develop a hierarchical structure model; the fifth for the logical relational model, which is then simplified leads to the construction of five further models. These models are for sustainable development in an industrial low-carbon economy, for an optimal approach to low-carbon emission, and for economic growth and CO_2 emissions, in an industrial low-carbon economy, as well as the decision-making models for industrial low-carbon emission policy and industrial fiscal and monetary policy in a low-carbon economy.

Chapter 5 describes the implementations of theoretical models constructed in chapter 4 to build models for the Chinese thermal electricity generation industry: the models for sustainable development, for the optimal approach of low-carbon emission, and for economic growth and the industrial CO_2 emissions in the industrial low-carbon economy.

Chapter 6 Data from the Chinese thermal electricity generation industry is then used to validate these three models. Based on these validations, the related theoretical models constructed in chapter 4 and 5 are validated, as is the research methodology for industrial low-carbon economy constructed in chapter 3.

Finally, chapter 7 presents the research findings and key conclusions. It also outlines the contributions to knowledge and practice, concluding with the limitations of the research and suggestions for future work.

Chapter 2 Literature Review

2.1 Introduction

Given the research questions and research aim determined in Chapter 1, this chapter will systematically review the literature related to carbon footprint, low-carbon emission, low-carbon economy, and low-carbon technology, discussing and summarising the main research aspects, currents conclusions and the research gaps in current research. Based on the literature review, this study will detail the research background of low-carbon economy to support the construction of the research methodology and theoretical model for an industrial low-carbon economy in Chapters 3 and 4.

2.2 Carbon Footprint, Low-carbon Emission, Low-carbon Economy, and Technologies for Low-carbon Emission

The carbon footprint is the foundation that provides information about CO_2 emissions, supporting the activities of low-carbon emission plans and determining the low-carbon emission targets. The low-carbon economy is a new economic mode under the constraints of low-carbon emission targets. This economic mode is supported and achieved by referring to the technologies for low-carbon emission. This section therefore systematically reviews the related literature on these four topics.

2.2.1 Carbon Footprint

Carbon footprint, originating from the concept of an ecological footprint, is "an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area", as proposed by Wackernagel and Rees (1996). The mostly widely recognised concept for carbon footprint is "a measure of the total amount of CO_2 emissions directly and indirectly caused by an activity or accumulated over the life stages of a product", originally defined by Wiedmann and Minx (2008), and rewritten by Gao et al. (2013). The new definition of carbon footprint is "as a comprehensive GHG indicator, which the quantity of GHGs expressed in terms of CO_2

equivalent, emitted into the atmosphere by an individual, organization, process, product or event from within a specified boundary” (Pandey et al., 2011). Based on these definitions, the rapid increase in the world’s population and the growth of the global economy lead to the rise of the amount of carbon footprint, which is related to the intensified greenhouse effects over the years. IPCC (2015) reported, “between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 Gt CO_2, of which 78% of the emissions were caused by the fossil fuel combustion and the industrial production process”.

The carbon footprint is calculated by four methods: the Life Cycle Assessment / Analysis (LCA), the IPCC’s Calculation of Emissions (2006), the Environmental Input-Output (EIO) Analysis, and the Kaya Identity proposed by Kaya (1990), which are presented in Table 2-1.

Table 2-1 The Four Methods for Measuring Carbon Footprint

Methods	**Factors Involved**	**Procedures with Example**	**Application and Limitation**	**References**
Life Cycle Assessment / Analysis (LCA)	Factors related to the production of individual products.	Bottom-up method: together with process analysis as PA-LCA, understanding the environmental impacts of individual products from cradle to grave.	Applied to calculate carbon footprint for individual products. Inappropriate for large entities.	(Wiedmann and Minx, 2008)
IPCC’s Calculation of Emissions	The data of the energy and fossil fuel consumptions for one producing process; 2006 IPCC Guidelines for National Greenhouse	Based on the coefficient for converting energy/fossil fuel into GHG, to calculate the GHG emissions from the quantity of energy consumption.	Applied to scenarios with clear energy consumption data.	(Pandey and Agrawal, 2014)

	Gas Inventories.			
Environmental Input-Output (EIO) Analysis	Macro-economic production data; the statistical coefficient of input-output table from the System of National Accounts (SNA).	Top-down method: using input-output table of total production to estimate emissions.	Applied to estimate the emissions for macro-level or industrial production. Not entirely accurate.	(Wiedmann and Minx, 2008)
Kaya Identity	F: global CO_2 emissions; P: global population; G: GDP; E: global energy consumption.	IPAT Function: $F = P \times (G / P) \times (E / G) \times (F / E)$, leading to identity of CO_2.	Applied to measure the macro-level CO_2 emissions.	(Kaya, 1990; Lin et al., 2015)

Based on Table 2-1, LCA generally is a micro-level measurement for the individual product or production with the advantage of accurate measurement, while EIO analysis and Kaya identity are macro-level methods for estimating the CO_2 emissions for one industry and the entire macro-economy. IPCC focuses on the conversion from energy (fossil fuel) to CO_2; with information of energy consumption and the validated coefficient, it could be used to measure the carbon footprint for both the micro- and macro-level perspectives. Referring to these methods for measuring the carbon footprint, researchers can then monitor and estimate the total amount of CO_2 emissions, which is the foundation for reducing the emissions and determining the targets for low-carbon emission.

2.2.2 Low-carbon Emission

Low-carbon emission is the reduction of GHG, specifically CO_2 released by fossil fuel combustion and other industrial processes; IPCC (2015) reported that 78% of anthropogenic CO_2 emissions are caused by them. Because human-caused global warming leads to effects that increase the risks to ecological and public security and directly risk human beings' survival and development (IPCC, 2015; Stern, 2006), the

UNCED has organised and led the research and inter-governmental cooperation on low-carbon emission since 1987: the *United Nations Conference on Environment and Development* in 1992, the *Rio Declaration on Environment and Development* (UNCED, 1992) and *Agenda 21* (United Nations, 1992), and also the *Statement of Forest Principles*, the *UNFCCC* and the *United Nations Convention on Biological Diversity*. The *Kyoto Protocol* was adopted in 1997; it "commits the participants to reducing and curbing the GHG emissions into an appropriate emissions level, to avoid the damages caused by the severe changes in climate" (United Nations, 1998). The *Kyoto Protocol* proposed addressing this environmental problem through market mechanisms, and gave the *UNFCCC* the quantitative targets for CO_2 emissions for developed countries and countries in economic transition: reducing CO_2 emissions by 5.2% compared with the level in 1990 during the period 2008 to 2012; it came into force on 16 February 2005, and was the first legislation for curbing GHG emissions.

As party to the Protocol, countries are expected to take corresponding responsibility for their low-carbon emissions, according to their economic status and their economic and environmental technology capabilities. With these actions from all nations, it is expected to limit the human-induced growth of the average global temperature within 2ºC by 2100 compared with the level in 1861-1880, which means the "cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$ (with a range of 2550 to 3150 $GtCO_2$ depending on non-CO_2 drivers). Moreover, the cumulative CO_2 emissions from 2012 to 2100, should be less than 100 $GtCO_2$, and should be within the rage of 650- 3550Gt CO_2" (IPCC, 2015).

Therefore, the national targets for low-carbon emission are settled. For instance, in March 2007, European leaders together agreed that by 2020, the GHG emitted by European countries would be 20% below the 1990 level. The Chinese government first announced its national target for reducing CO_2 emissions at the *Copenhagen Summit* in 2009: to reduce CO_2 emissions per unit of GDP by 40% - 45% by 2020 compared with 2005 levels. Under the constraints of these national targets, the economic mode has started the transformation from the traditional economy to a greener mode: the low-carbon economy.

2.2.3 Low-carbon Economy

A low-carbon economy has low fossil-fuel energy consumption, low pollution and low CO_2 emissions, which all increased with economic development after industrialisation (Chen and Quan, 2008; Jiang, 2008; Su and Ruan, 2009). In the *United Nations Conference on Environment and Development* in 1992, the indivisible relationship between economic development and environmental protection was recognised, while the traditional economic mode with high-energy consumption, high pollution and high GHG emissions was rejected. Therefore, as proposed in the British government *Energy White Paper: Our Energy Future-Create a Low Carbon Economy* (Department of Trade and Industry, 2003), this new mode, low-carbon economy has become the means of transformation from the traditional economy to a greener future. Stern (2006) suggested that governments worldwide should take practicable actions to transform into low-carbon economies as soon as possible, because immediate action was the most cost-effective way to reduce CO_2 emissions: around 1% of global GDP a year, against actions not being taken now, when the future cost of the losses from damage resulting from climate change would be around 5% - 20% of global GDP a year (Stern, 2006).

The current procedures for low-carbon emission for large economies are as follows. The current legislation enacted in relation to the low-carbon economy in the USA is the *American Business Act on Climate Pledge*, which 154 companies have joined. *The Clean Power Plan* set a goal to reduce 32% of GHG emissions from the energy sector by 2030, and President Obama set a national target of reducing 26% - 28% of GHG emissions by November 2025 (The White House, 2015). In 2007, the European Council adopted low-carbon emission targets of reducing 20% of CO_2 emissions by 2020, and 60% - 80% by 2050 (Commissions of the European Commnuiteis, 2007; Ren, 2009; Liao and Sun, 2011). The UK, which was the first country to legislate on long-term significant carbon-reduction targets, passed the *Climate Change Act 2008* in 2007; this Act set a target of 80% reduction of the UK's carbon emissions by 2050, compared to 1990 levels, to promote the transition into a low-carbon economy. This law also set a milestone, aiming to reduce GHG emissions by 26% - 32% by 2020 (Tullo, 2008). In 2007, the German government published, *The New High-Tech Strategy Innovations for Germany*, to support the low-carbon emission activities and achieve their target (Federal Ministry of Education and Research, 2007). In Japan, the *Fukuda Blueprint* was settled to regulate the low-carbon development and related targets. In 2009, the Chinese government settled the low-carbon emission for 2020, by issuing the Chinese government issued the *National Climate Change Action Programme (2014-2020)*. On 30 June 2015, it submitted the document, *Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions*, to the Secretariat of the UNFCCC to committing it to reducing CO_2 emissions per unit of GDP by 60% - 65% by 2030 compared with 2005 levels. As largest economies have begun the transformation to low-carbon modes, their influence on economic development has spread worldwide (Ren, 2009; Liao and Sun, 2011).

2.2.4 The Technologies for Low-carbon Emission

The development of the low-carbon economy and the achievement of the low-carbon emission targets, depend on innovation in related technologies. There are three main technologies for low-carbon emission: reducing the carbon emission in sectors with high-energy consumption and high CO_2 emissions, by more efficient consumption of clean-coal and exploration into mining coal-bed methane resources; non-carbon emissions, renewable energy production; and carbon capture and storage (CCS). The first two types mainly concern the technologies of industrial production, while CCS directly captures the CO_2 from the atmosphere to reduce its concentration.

In detail, CCS is "a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere" (Working Group III, 2005a; 2005b). IPCC (2015) believes that CCS technology will largely support the reduction of CO_2 in the 2030s to 2050s. Carbon capture, utilisation and storage (CCUS), is based on CCS, but includes the process of using CO_2 for industrial production, as promoted in China; however, some of this utilisation will lead to CO_2 being released into the air, which will not achieve the purpose of low-carbon emission (Han et al., 2012; Zhong et al., 2012). For carbon storage, there are four main methods: "geological storage (in geological formations, such as oil and gas fields, un-minable coal beds and deep saline formations), ocean storage (direct release into the ocean water column or onto the deep seafloor), industrial fixation of CO_2 into inorganic carbonates, and the application of carbon dioxide in industry" (Working Group III, 2005b). However, as IPCC (Working Group III, 2005b) reports, the industrial use of liquid or gaseous CO_2 will not promote the reduction of CO_2 emissions. CCS technologies are mainly still at the research and partial pilot phases, with only parts of the technology in practical application (Working Group III, 2005b). Moreover, there are some disadvantages for CCS and CCUS, such as high-energy consumption, high cost, and the insecurity of long-term carbon storage. For examples, the traditional thermal power plant will cost around 29 to 51$ per ton to capture CO_2, the total CCS will cost 75 to 115$ per ton, which is less competitive compared with renewable energy. Furthermore, the loss in electricity production caused by CCS will increase 20% - 30%, in turn increasing the standard coal consumption per unit of electricity produced by about 100 g/kWh, and the cost per unit of electricity production by around 0.1 yuan/kWh (Cheng and Meng, 2016). Therefore, unless the government provides subsidies, or introduces carbon taxation to increase the economic incentives for related industries, CCS will remain unfeasible.

2.3 Literature Review of Low-carbon Economy

2.3.1 Theory of Pigouvian Tax

In 1912, Professor Arthur C. Pigou published *Wealth and Welfare,* the first academic book to present perspectives in the economics of welfare (Pigou, 1920). In this book, he explained economic externalities, and the divergence between marginal private interest and marginal social interest. He believed that if others could benefit from marginal private interest, then the marginal social interest would be larger than the private one, called marginal social benefits; or if they were less, then the marginal social interest would be smaller than the private one, called marginal social costs. Externality is the inconsistency between marginal private costs and marginal social costs, and between marginal private benefits and marginal social benefits. Pigou argued, "Industrialists sought their own marginal private interest. When the marginal social interest diverges from the marginal private interest, the industrialist has no incentive to internalise the cost of the marginal social cost. The social resources could not achieve Pareto optimal allocation. Governments, therefore, should make appropriate economic policies, such as taxation and subsidy, to eliminate this divergence." (Pigou, 1920). When there is marginal social benefit, then governments could subsidise the related private parties, equally imposing a levy on these private parties in the case of marginal social cost. These policies could internalise the effects of externality, and were called the “Pigouvian tax” (Baumol, 1972). Since the 1990s, this theory has been introduced to support arguments for the low-carbon economy. In 1990, Finland was the first to propose a carbon tax, effectively a Pigouvian tax, followed by Sweden, the Netherlands, Italy, the UK, Japan, Canada and many other developed countries. The carbon taxes were levied on the proportion of carbon in the fossil fuel products, such as coal and petrol, aviation fuel and natural gas, to achieve reduction of fossil fuel consumption and CO_2 emissions (Nakata and Lamont, 2001; Rubio and Escriche, 2001; Keen et al., 2002; Wei, 2011; Chen and Nie, 2016; Kuo et al., 2016; Shi, 2016; Wesseh Jr et al., 2017).

2.3.2 Coase Theorem

Coase identified and clarified the “significance of the transaction fee and the property right to the economic structure and its operation”. The Coase Theorem states that “with the standard assumptions of competitive markets (especially, that the costs of transacting are zero), an efficient and invariant outcome can be achieved through the negotiations among affected parties, as long as rights are well-defined” (Coase, 1960). An efficient and invariant outcome is the optimal allocation of resources, and negotiations are related to bargaining. Stigler (1966) supported the Coase Theorem because it “asserts that under perfect competition private and social costs will be equal”. This means that this theory may thus replace the Pigouvian tax, solving the problem of externalities (Medema and Zerbe, 2000). However, if the transaction costs are not zero, the legal position (property rights) affects the total cost-benefit and then impacts the results of bargaining (Coase, 1937; 1950; 1960; 1988). After the 1970s, researchers explored ways to apply the Coase Theorem to solve environmental problems. Frech (1979) extended the definition: “if there were no wealth effects on demand, no transaction costs and rights to pollute or control pollution, the allocative solution would be invariant and optimal, regardless of the initial assignment of rights”. Accordingly, the environmental problems are externalities, and deal with the emissions trading systems, such as the three emission reduction mechanisms proposed in the Kyoto Protocol: the Clean Development Mechanism (CDM), the Joint Implementation Mechanism (JI) and the Emissions Trading Mechanism (ET).

2.3.3 Theory of Environmental Kuznets Curve

The Kuznets Curve was proposed by Simon Smith Kuznets in 1955, representing the relationship between economic growth and per capita income. In 1990, this concept was adopted in environmental economics by Grossman and Krueger (1991) to represent the relationship between economic growth and environmental quality (amount of pollution), and proposed as the Environmental Kuznets Curve (EKC). EKC proposes that environmental quality will first become worse, in line with economic development (or the increase of per capita income); however, after a turning point, it will be better and the pollution will be reduced, in an inverted U shape relationship. In promoting the low-carbon economy, the relationship between CO_2 emissions and economic growth based on this theory, has been widely researched and examined (Fan and Hu, 2002; Hu et al., 2004).

2.3.4 Theory of Coupling-Decoupling

The theory of Coupling-Decoupling is popularly applied in research fields, such as the environment, energy and ecology, based on the Driving Forces-Pressures-States-Impacts-Responses Framework (DPSIR); this represents the relationship between economic growth and consumption of resources such as fossil fuel. Coupling represents the positive correlation between economic development and resource consumption, while decoupling is the economic process with less resource consumption but with the same or better economic growth. Decoupling means that economic growth does not rely on an increase in resources for production. In energy decoupling, the energy consumption increases slowly, or even decreases, compared with the growth of the economy, not caused by uncertain factors, but as the result of national development, such as technological improvement. Relative decoupling is defined as the continuous economic growth rate exceeding the growth rate of environmental pressure (the energy consumption rate), while absolute decoupling is when economic growth and the environmental pressure are stable or decreasing (OECD, 2001; Tapio, 2005a; Finel and Tapio, 2012; Muangthai et al., 2014; Botzoris et al., 2015a; Ma et al., 2016).

2.3.5 Theory of IPAT Function

Ehrlich and Ehrlich (1972) proposed the IPAT function, I = P × A × T, representing the human impact on the environment (I), where P is population, A is affluence and T is technology, indicating that the human impact results from the compound influence of population, affluence and technology. Some researchers have defined affluence as economic development, and quantified it with GDP or GNP, while technology is represented as the pollution produced per unit of GDP, and is also defined as energy consumption or the coefficient of energy converting CO_2 (Chertow, 2000).

Later research focuses on detailed analysis of population, economic development or affluence and energy consumption and their causal relationships. Puliafito et al. (2008) and Dalton et al. (2008) applied different models for estimating the trend of population, CO_2 emissions, energy consumption and their future relationships, identifying that not only the size of the population would affect the CO_2 emissions, but also its structure. Dalton et al. (2008) found that the "aging population would reduce 40% of CO_2 emissions in a small population scenario". Chertow (2000) claimed that the positive effects from technology, can even balance the influence of population and affluence.

2.4 Review of Empirical Research on Industrial Low-carbon Economy

2.4.1 Empirical Research on the Pigouvian Tax

Since the 1990s, most countries have determined their carbon taxation based on the Pigouvian Tax Theory, in order to curb their CO_2 emissions. Various research has been done to analyse the effects of carbon taxes. However, the influence of these carbon taxes on industry is uncertain in various countries. Nakata and Lamont (2001) found that in Japan, although "carbon and energy taxes could decrease the CO_2 emissions to the target amount", the primary concern for Japan is energy security, which means that "the policies for reducing the consumption of coal are not desirable". Moreover, they identified that "the carbon taxes would cause the shift of energy use from coal to gas", which still releases CO_2 emissions to the atmosphere (Nakata and Lamont, 2001). In China, Lu et al. (2010) found that the carbon tax would largely promote the reduction of

CO_2 emissions; supported by complementary policies, the small but negative impact of carbon taxes on the economic development could be diminished. However, Bruvoll and Larsen (2004) found that in Norway, the effect of the carbon tax contributed only 2% of the reduction in CO_2, compared with the achievement of a total 14% reduction from 1990 to 1999.

In summary, the research into carbon taxes focused on factors in the following fields: policy and law, macro-economy (such as GDP), industrial economy (such as industrial GDP) and the environment (the amount of CO_2 emissions). It examined studied the extent to which carbon taxes impacted the economic outcome (GDP or industrial GDP) and the CO_2 emissions. However, it did not analyse how or why CO_2 is produced and released, defining CO_2 emissions as external to the economy. Nor did it evaluate the environmental requirements for reducing CO_2. Therefore, once the negative impact of carbon taxes is set against their primary concern, the policies would not have the desired effect. Moreover, as the strength of the effects from carbon taxes on emissions is uncertain, it is hard for policymakers to predict the effects of the Pigouvian theory, increasing the difficulty in developing an appropriate low-carbon policy.

2.4.2 Empirical Research on EKC

The findings of empirical research on EKC are various. Identified in the research of Grossman and Krueger (1991), the inverted U-shape between air quality and national income was proposed as EKC; moreover, in their later research (1995), they confirmed the existence of the inverted U-shape, with a turning point of $8,000 per capita income, where the environment is improved. The EKC theory has since been applied by various researchers to analyse the relationship between economic development (represented by national income) and CO_2 emissions. The studies have looked at factors from macro-economy, social and environmental fields, and used the data from different countries, regions, even cities, to examine this inverted U-shape and to estimate the turning point for their regions (Huang et al., 2008).

Richmond and Kaufmann (2006) found the turning point (national income / CO_2 emissions) for OECD countries, but not for the non-OECD nations; thus, they suggested that there was no inverted U-shape for the latter. This conclusion was supported by

Galeotti et al. (2006) that non-OECD countries were still at the stage of increasing both their economies and CO_2 emissions. Similar results were summarised in a review paper by Huang et al. (2008), in which they concluded that the data from the USA, Canada, Japan and Germany showed the inverted U-shape relationship, while the data from Italy, Portugal and Spain indicated a positive correlation, and that for the UK and France a negative correlation between national income and CO_2 emissions.

Aslanidis and Iranzo (2009), however, proposed that there was no evidence of EKC for carbon emissions; for low-income regimes in the non-OECD countries they found a positive correlation, while for middle- to high-income nations it was negative, based on cross-sectional data from 1971 to 1997. Sanglimsuwan (2011) indicated that the inverted U-shape only lasted for a short time, when the GDP per capita reached around $26,448.76 in the basic model, and $25,735.91 in the extended model. Correlation might take the form of an N-shape, meaning that policymakers must take into consideration environmental protection when they reach that situation.

Koop (1998) explored the different results of the curve shape in developed and developing countries, and concluded that technological improvement led to the reduction of CO_2 emissions, indicated by the fact that low-income nations did not improve their technologies for reducing carbon emission as much as high-income nations did, along with their economic development, from the data from 44 nations worldwide from the 1970s to 1990s.

In conclusion, the literature shows that most researchers believed in EKC, although they could not agree on the shape of the curve, or the level of national income per capita at the turning point. As these researchers mainly relied on statistical methods, the different data sources, different factors involved and different methods of estimation led to the various results of EKC (Hu et al., 2004; Huang et al., 2008; Aslanidis and Iranzo, 2009). Therefore, the theory could not provide a general rule to represent the relationship between industrial economic growth and CO_2 emissions.

2.4.3 Empirical Research on Coupling-Decoupling Theory

Decoupling indicators for OECD countries, suggest that the phenomenon occurs widely among their members (OECD, 2001), with further economic decoupling promoted for reducing CO_2 emissions. Tapio (2005b) established the Coupling-Decoupling framework by designing indicators for measuring environmental pressure. He found that the relationship between industrial emissions of CO_2 and GDP varied, according to the country's stage of development, as some countries were still in the economic coupling period while others had already reached the turning point; this was based on data from the transport industry in 15 European countries. Similar results were also observed by Tapio (2005a); Finel and Tapio (2012); Muangthai et al. (2014); Botzoris et al. (2015a). They also suggested that in the low-carbon economy, where economic development does not rely on fossil fuel consumption, it should be possible to achieve both economic development and a reduction in CO_2 emissions at the same time.

The factors involved in these studies are GDP, energy consumption and the amount of CO_2 emissions, while factors regarding policy, law and the social field have not been considered. Therefore, the research could not present the relationships among GDP and CO_2 emissions, under the influence of different industrial policies, different industrial technologies or different social effects. Hence, this Coupling-Decoupling Theory could not support the government in formulating appropriate policies for managing the approach to sustainable development in an industrial low-carbon economy.

2.4.4 Empirical Research on IPAT Function

Based on the IPAT function theory (section 2.3.5), research focused on the relationships among macro-level factors: human impacts on the environment (CO_2 emissions), population, affluence (represented by GDP or GNP) and technology (represented by pollution produced per unit of GDP or energy consumption) (Chertow, 2000).

Chertow (2000) identified "technology as the critical factor for improving environment". Ramanathan (2006) found that CO_2 emissions are related to the CO_2 emission allowance, non-fossil fuel consumption and GDP level, in which the non-fossil fuel consumption is supported by the relative innovation of technology. In detail, "when CO_2 emissions are low, there is an expectation of a high level of non-fossil fuel consumption. If significantly higher levels of CO_2 emissions are allowed, then the non-fossil fuel consumption becomes insensitive to CO_2 emission levels. Non-fossil fuel consumption is higher when the GDP levels are higher" (Ramanathan, 2006).

Soytas and Sari (2009) applied “the Vector Auto-Regression (VAR) model to analyse the relationships among energy consumption, GDP and CO_2 emissions for Turkey, controlling for gross fixed capital formation and labour; they found that the long-term effect on CO_2 emissions was not GDP, and that Turkey did not need to forego economic development when reducing CO_2 emissions.

Stretesky and Lynch (2009) involved imports and exports as another factor to analyse the relationship with per capita CO_2 emissions, population and affluence. They found that “within country worldwide exports and the US exports are positively related to per capita CO_2 emissions. However, when both exports to the world and to the U.S. are examined simultaneously, only exports to the US were related to per capita CO_2 emissions during 1989 - 2003. The CO_2 trends in other nations are in part driven by the US demands for goods” (Stretesky and Lynch, 2009).

These empirical studies of the IPAT function identified that there are relationships between CO_2 emissions and factors in the fields of population, affluence and technology. However, along with differences in the factors selected and the data sources used, the results identified in these studies are different. Therefore, it is difficult to identify a simple and general relationship between the factors, as well as between the fields of I, P, A and T in this theory. Moreover, the IPAT function only involved macro-level factors (Chertow, 2000); it did not include the industrial-level factors, did not analyse the production process for creating economic and environmental output, and did not involve the political factors regarding low-carbon emissions. Therefore, it is impossible for both the policymaker and industry to apply this model for planning and managing the approach to sustainable development in the industrial low-carbon economy.

2.5 Chapter Summary

This chapter systematically reviewed the literature, and found that the theories about the low-carbon economy tend to focus on two areas. One is the theories focusing on curbing CO_2 emissions, such as the Pigouvian Tax Theory and the Coase Theorem; the second area aims to identify the relationship between economic growth and CO_2 emissions as in EKC, the Theory of Coupling-Decoupling, and the IPAT Function. Following the review of these theories and their respective empirical research, knowledge gaps for analysing low-carbon economy were identified.

There is no single model containing all the critical factors that relate to low-carbon emission in industrial economies.

- The Pigouvian tax and the Coase theorem mainly involve factors regarding policy and law, the amount of CO_2 emissions, macro-economy (such as GDP, energy consumption) and industrial economy (such as industrial GDP).
- The EKC mainly analysed factors related to the macro-economy (such as GDP, the coefficient of input-output table from SNA, energy consumption etc.), social field (such as GDP per capita, income per capita, educational level etc.) and the environment (the amount of CO_2 emissions).
- The Theory of Coupling-Decoupling focuses on factors, such as GDP, energy consumption and the amount of CO_2 emissions.
- The IPAT function involves macro-level factors within four fields: human impact on the environment (CO_2 emissions); affluence or macro-economy (GDP, GNP, import and export); population; and technology (pollution produced per unit of GDP, energy consumption, the coefficient of energy converting carbon emissions).

Previous research only included partial factors for the industrial low-carbon economy system. Therefore, this research aims to develop an integrated and structured framework that involves all the critical factors regarding the entire industrial low-carbon economy system.

Moreover, the previous models did not specify all the existing relationships between the critical factors, which are discussed in the following points.

- Pigouvian tax and the Coase theorem did not analyse how or why environmental pollution is produced. Both theories defined environmental pollution (CO_2 emissions) as external to the industrial economy. Pigouvian tax focuses on the balance between private and social costs, while the Coase theorem considers bargaining among the affected parties instead of the direct reduction of CO_2 emissions by the polluting party. Neither of these theories evaluated the environmental requirements for protection, and neither believed that industrial economic activities should take responsibility for environmental protection. Furthermore, they did not analyse the restraints imposed by the environment on industrial development.

- The theory of EKC was constructed to identify the relationship between economic development and CO_2 emissions. However, different economic entities and their different stages of development led to differences in the main factors, on which the models were based and on which industrial development relies. Conclusions from the EKC model vary and the theory could not provide a general rule to represent the relationship between industrial economic growth and CO_2 emissions.
- The theory of Coupling-Decoupling was constructed to represent the relationship between industrial economic growth and the consumption of natural resources or energy. Although its methods could objectively represent the relationship between economic growth and CO_2 emissions, researchers did not present the relationship under the influence of different industrial policies, different industrial technologies or different social effects.
- The IPAT function was constructed to indicate the relationships among population, GDP or affluence, technological level and CO_2 emissions. The factors selected in this model were all macro-variables that did not refer to the industrial process of production, transport or consumption, in which CO_2 is created and emitted. This theory also failed to represent the influences on CO_2 emissions by factors such as policy, law, industrial technology and society. This theory therefore cannot accurately represent the industrial low-carbon economy system.

As there is no general model containing all the critical factors involved in this industrial low-carbon economy system in these studies, the existing relationships among these factors have not yet been comprehensively presented and logically constructed.

Based on the above gaps in the literature, this study aims to develop an integrated and structured framework for analysing the industrial low-carbon economy system.

Chapter 3 The Research Methodology

3.1 Introduction

Knowledge gaps were identified in research and methods in the industrial low-carbon economy from the previous chapter. Current studies have not investigated the industrial low-carbon economy in a single system, therefore representing only part of the overall system. In fact, the industrial low-carbon economy is a complex system with the inter-disciplinary elements, and research is to be viewed from the perspective of systems thinking, where the industrial low-carbon economy is seen as one complete system. On the other hand, the systems philosophy focuses on supporting systematic research, using a systems methodology to solve this complex-system problem. This chapter therefore presents the philosophic and theoretical foundations for developing a research methodology. Systems philosophy will be the ideology for this research, while systems science will contribute principles and methods in systems engineering, which will be the techniques to construct the methodological proceeding.

3.2 The Philosophic Foundations of Research Methodology

Saunders et al. (2012) and Crotty (1998) claimed that the research philosophy is fundamental to the research approach, methodology, method and technique. Determining the philosophy enables the researcher to select the appropriate approach and methodology. The research philosophies for business and management are pragmatism, positivism, realism and interpretivism, whose differences in ontology and epistemology are presented in the research process (Saunders et al., 2012). Creswell (2013) also provides similar categories with post-positivism, constructivism, transformative views and pragmatism. Pragmatism and positivism (or post-positivism) both externally research one subject. Pragmatism focuses on "solving problems" and "the consequences of actions", and is "real-world practice oriented" (Saunders et al., 2012), without a specific perspective of objectivism or subjectivism. Positivism relies on the objectivism and reductionism to search for law-like generalisations for objective reality and causal relationships, and to verify theory with highly structured methodology (Saunders et al., 2012). Post-positivism considers "the thinking after positivism", but with a similar approach to positivism (Creswell, 2013). Realism or constructivism (also called social constructivism) is also based on objectivism, but focuses on human sensations, existence, and the relationships between the human senses and existence (Creswell, 2013). Interpretivism or the transformative approach, which are "often combined with realism" (Creswell, 2013), is based on subjectivism and focusing on subjective meaning, subject's detailed characters and social phenomena. Specifically, transformative perspectives hold that "research inquiry needs to be intertwined with politics and a political change agenda to confront social oppression at whatever levels it occurs" (Creswell, 2013). Of these four research philosophies, the pragmatism and positivism are the appropriate ones for this research, as positivism is conjectural theory and knowledge, and analysis of variables' interrelationships based on objectivism; and pragmatism is solution oriented. Realism and interpretivism are more appropriate for social or human oriented research (Gill and Johnson, 2002; Kelemen and Rumens, 2008; Hesse-Biber, 2010; Saunders et al., 2012; Creswell, 2013).

During the 1980s and 1990s, a new philosophic science, systems philosophy was established, which views the world as systems. The systems philosophy specifically supports research into systems and solves problems regarding complex systems. The systems philosophy is based on the dialectics of nature, which follows the perspectives of positivism. Nevertheless, unlike positivism, the systems philosophy supports systematic research in complex systems (Von Bertalanffy, 1968; Von Bertalanffy and Taschdjian, 1975; Hall, 1989; Wei and Zeng, 1995; Qian, 2001).

As presented in chapter 2, previous studies on industrial low-carbon economies only focus on some of the elements of this complex system; their theories therefore fail to solve the problem of increasing carbon emissions. Hence, research into industrial low-carbon economy should be done from a systems perspective. Referring to the ontology of pragmatism, the view espoused enables solving the problems (Saunders et al., 2012; Creswell, 2013), encouraging us to find a particular research philosophy to solve this systematic problem. Systems philosophy is therefore selected as the philosophic foundation for this study. The theoretical foundations for research into industrial low-carbon economy system will be guided by systems philosophy.

3.2.1 The Definition of Systems Philosophy

Systems philosophy is based on the dialectics of nature, researching objective systems, as well as combining the research contributions and theories from modern science (Qian, 1988; 2001; Wei and Zeng, 1995).

3.2.2 The Worldview of Systems Philosophy

Worldview, also known as a point of view or proposition attitude, is “a basic set of beliefs that guide action” (Guba, 1990; Creswell, 2013) and “the set of view of the world” (Wei and Zeng, 1995; Qian, 2001). The fundamental worldview from the aspect of systems philosophy is that the world is material and systematic, with the following characteristics: dialectic system, process, time and spatiality. Systems philosophers observe the world with a system view, process view, time and spatial view (Qian, 1988; 2001; Wei and Zeng, 1995; Saunders et al., 2009). “*System* is a set of objects (elements or parts), with relations between them and between their attributes (properties, or qualities). It is embedded in an *environment* containing other inter-related objects. The *system* and its *environment* together compose *universe*” (Hall, 1989).

3.2.3 The Basic Laws for Systems Philosophy

The basic laws for systems philosophy are the law of self-organisation emergence, the law of hierarchical transformation, the law of structure and function, the law of holistic optimisation, and the law of difference and synergy. Systems philosophy is a new philosophic science, containing various universal laws and research perspectives, and based on current research theory in modern science. It has features of systems connection, systems evolution and systems development, and studies on the systems thinking, process view, time and spatial view. As the systems philosophy presents a highly scientific abstraction of the evolutionary process of the *universe*, its laws and perspectives are generally applied in the natural sciences, social issues and human thinking (Qian, 1988; 2001; Wei and Zeng, 1995; Wu, 1997; Wang and Fu, 2009; Zhu, 2009; Yang, 2013; 2016).

3.2.4 The Methodology for Systems Philosophy

As the worldview of systems philosophy is of a material world, and the material world is systems, which "develop according to the laws of nature", the methodology for systems philosophy follows those perspectives to observe, research and solve problems. It consists of system synthesis and systems analysis (Qian, 1988; 2001; Wei and Zeng, 1995; Checkland, 1999).

3.2.4.1 System Synthesis

System synthesis is an integrative methodology based on the system's factors, hierarchical structure and the interaction among the system's development, copies and designs of the entire system in human thinking. The principles of system synthesis are non-summative, logical order and innovation (Qian, 1988; 2001; Wei and Zeng, 1995).

(1) The non-summative principle. A system, as a functional entirety, is composed of factors to achieve a specific function. The system therefore cannot simply summarise the physical total of the system's factors. The structure of the system determines its function.
(2) The principle of logical order. The synthesis process should follow a logical order that is the natural and factual logic order determined by the system's internal-structure.
(3) The principle of innovation. Innovation is a creating activity, from whose cognitive and practical activities human beings discover new qualities, new relationships, and new rules for objectives to build up new concepts, new ideas and new theories to represent the essence of the objectives.

3.2.4.2 Systems Analysis

Systems analysis comprises system factors analysis, system dynamic analysis and system hierarchical analysis (Qian, 1988; 2001; Wei and Zeng, 1995).

(1) System factors analysis:

This analysis is based on the system's perspectives. The research subject is analysed within the system, where the subject is physically located; the subject is also researched in the special environment in which the system is involved. The factors or sub-systems for this system, however, are studied according to their relationship with the entire system, as well as their inter-relationships with other factors or sub-systems.

(2) System dynamic analysis:

This research studies the process of change in the system, focusing on the factors' structure at different periods of system development. It also investigates changes in the internal-structure of the system, to identify and present the logical order and interrelationships of the different periods of system development.

(3) System hierarchical analysis:

This is a new analytical method, developed as a result of the rejection of traditional analysis methods and the perspectives of reductionism. It supports the cognition of the internal hierarchical structure for the material world, and identifies the special rules at each level to solve related problems not solved by traditional analytical methods.

3.3 The Theoretical Foundations for Research Methodology

As systems philosophy supports the study of complex systems, this research follows the theory, methodology and methods developed under it.

3.3.1 Systems Science

Systems science (or systems theory) is a science, in which the system is the research subject and the applying object, with general rules on the system's structure and function. Systems science was developed under systems philosophy, and includes systematics, such as general system theory, and systems technology (systems engineering) (Xue et al., 1982; Qian, 1988; 2001; Tan et al., 1999).

3.3.1.1 General System Theory

General System Theory (GST) "is the formulation and derivation of those principles which are valid for 'systems' in general". GST is based on systems thinking. The core research question is how to achieve the optimisation of a system based on its characteristics. The fundamental principles of GST are holism, dynamism, interaction, hierarchical order, unity and system isomorphism (Von Bertalanffy, 1968; Qian, 1988; 2001).

3.3.1.2 Systems Engineering

Systems engineering is a science and scientific technology, which organises and manages system planning, research, design, experimentation and implementation, in order to change the objective world directly. Systems engineering is a highly integrated management engineering technology, containing applied mathematics, systems theory like information theory, cybernetics, systems technology like systems simulation, and other sciences from difference disciplines, such as economics, management, and sociology (Qian, 1988; 2001; Tan et al., 1999).

3.3.1.2.1 Hall's Systems Engineering Theory

Hall's three-dimensional theory divides the systems engineering process into seven logical steps and seven project management stages. It also considers the related knowledge and professional technology to support the process. Hall (1969) developed the three-dimensional structure based on the dimensions of logic, knowledge or content and time (Hall, 1989; Qian, 1988; Tan et al., 1999; Wang and Fan, 2010).

(1) Logic Dimension

There are seven general steps in Hall's theory to guide the procedures to logically solve problems (Hall, 1989; Tan et al., 1999). However, as this research is theoretical rather than an engineering project, this section only details the first five steps necessary to support our research methodology referring to Hall (1989) and Tan et al. (1999).

Step 1: Problem definition: clarify the character of the systematic research question to determine the research scope.

Step 2: Value system design: select the goal for the system to illustrate the system logic.

Step 3: System synthesis: collect all necessary information, invent or find all the possible system structures for the process of achieving the system's goal.

Step 4: System analysis: qualitatively and quantitatively analyse to deduct those structures by the value system representing the researched system. In this step, there are two main actions.

i. Select the dimensions and factors that accurately represent the essence of the research question.

ii. Construct a model relying on the factual logic of the research subject to determine the relationships among the dimensions or factors to build up a structural model.

Step 5: Optimisation: based on the knowledge from the disciplines related to the research scope, this step optimises the selection of dimensions and factors, optimises the logical relationships among dimensions or factors, and optimises the structural model.

(2) Knowledge Dimension

The knowledge or content, dimension "refers to subject matter fields or domains of knowledge, representing what today are called professions, disciplines or technologies" (Hall, 1989). This dimension informs both general knowledge (such as natural science) and the professions (knowledge from related disciplines and related technologies), which must be applied, in order to conduct a product in the system engineering process (Hall, 1989).

(3) Time Dimension

The time dimension "scales the sequence from birth to death of the system. This dimension is segmented by major decision milestones; the intervals between are called phases, which may have gaps between them or they may overlap, but in any case they define a coarse structure in the life cycle" (Hall, 1989). The seven phases are programme planning, project planning, system development, production, distribution, development (or phase-in), operations and retirement (or phase-out), mainly regarding project management and time management for engineering projects. Therefore, the phases in this time dimension are adopted but adjusted to time management for academic research. Moreover, the retired phase, which takes place "over a period of time while some new system takes its place" (Hall, 1989).

3.3.1.2.2 Interpretative Structural Modelling (ISM)

Interpretative Structural Modelling (ISM) is a structural modelling method within systems engineering. It identifies the relationship among factors to decompose a complex system into several sub-systems, and the factors within sub-systems to establish a multi-level hierarchical structural level (Lee, 1999; Tan et al., 1999; Attri et al., 2013).

(1) Assumption

The fundamental assumption for the ISM method is that for system factor e_i, if there is a passage for factor e_i to access factor e_j, while there is also a passage for factor e_j to reach e_k, and then there will be a passage for factor e_i to achieve factor e_k. Thus, the assumption is that the relationship is transitive (Tan et al., 1999).

(2) ISM Method

Tan et al. (1999) presented the theory of the ISM method, as follows.

a) Adjacency matrix

For system S with n factors S = (e_1, e_2… e_n), the adjacency matrix based on the logical relationship between the factors, and the element a_{ij} within this matrix are determined following these rules:

- If factor e_i directly affects factor e_j, then the related element in the adjacency matrix $a_{ij} = 1$.
- If factor e_i does not directly affect factor e_j, then the related element in the adjacency matrix $a_{ij} = 0$.

With all the data of a_{ij}, there is the n × n adjacency matrix A = $\begin{pmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{pmatrix}$.

For example, for a system with four elements S_1 = (e_1, e_2, e_3, e_4), the direct relationships among elements are: there are self-reference relationships for elements e_1 and e_2; there are direct causal effects from element e_1 to element e_3, from element e_1 to element e_4, from element e_2 to element e_3, from element e_3 to element e_1, from element e_3 to element e_4, from element e_4 to element e_3. Based on these relationships, the adjacency matrix for this system S_1 is $A_{S1} = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$ (Tan et al., 1999).

b) Reachability matrix

The reachability matrix represents all the possible relationships, both direct and indirect relationships, among the elements within one system. Based on the n × n adjacency matrix $A = \begin{pmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{pmatrix}$, and the n × n identity matrix I, referring the Boolean operation for calculating the union of two matrices, the reachability matrix is calculated based on the calculation for the matrices $(I \cup A)^{2^{k-1}}$, $(I \cup A)^{2^k}$and $(I \cup A)^{2^{k+1}}$, k = 1, 2, …, ∞. As k is a constant from 1 to infinitude (∞), these three matrices are continuously and repeatedly calculated from k = 1; until for one value of k, the equation $(I \cup A)^{2^{k-1}} \neq (I \cup A)^{2^k} = (I \cup A)^{2^{k+1}}$ is satisfied, when the reachability matrix M therefore equals $(I \cup A)^{2^k}$ with k in that value (Tan et al., 1999).

For example, in order to identify the entirely possible relationships among the four elements within this system S_1, the reachability matrix for system S_1 is calculated based on the adjacency matrix (A_{s1}) for this system. Starting from k = 1, when $2^{k-1} = 2^0 = 1$, $2^k = 2^1$, and $2^{k+1} = 2^2 = 4$, with $A_{S1} = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$ and $I = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$, the unions of $(I \cup A)^1$, $(I \cup A)^2$ and $(I \cup A)^4$ are calculated based on the Boolean operation. Thus, $(I \cup A) = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$, $(I \cup A)^2 = (I \cup A) \cup (I \cup A) = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \end{pmatrix}$ and $(I \cup A)^4 = (I \cup A)^2 \cup (I \cup A)^2 = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix}$. As the $(I \cup A)^1 \neq (I \cup A)^2 \neq (I \cup A)^4$, then the calculation is continued for k = 2; thus, $2^{k-1} = 2^1 = 2$, $2^k = 2^2$, and $2^{k+1} = 2^3 = 8$, where $(I \cup A)^8 = (I \cup A)^2 \cup (I \cup A)^2 \cup (I \cup A)^2 =$

$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix} = (I \cup A)^4$. Therefore, when k = 2, $(I \cup A)^2 \neq (I \cup A)^4 = (I \cup A)^8$, the calculation stops and the reachability matrix for this system S_1 is $M_{s1} = (I \cup A)^4 = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix}$. This matrix M_{s1} presents all the direct and indirect relationships among the four elements within this system S_1, for instance, element e_2 indirectly affect element e_1 through the logic process, which element e_2 directly affect element e_3 then element e_3 directly affect element e_1.

c) Level partition for reachability matrix

Finally, for reachability matrix M, if the factor e_i could affect e_j, then e_j is in the reachability set of e_i, while alternatively if factor e_j could affect e_i, then e_j is in the antecedent set of e_i. Then, the reachability set and antecedent set for each factor e_i should be identified; calculating the intersection, which is based on this operation: Intersection for factor e_i = Reachability Set ∩ Antecedent Set. If the intersection for factor e_i equals its antecedent set, then the factor e_i is a bottom factor. If the intersection for factor e_i equals its reachability set, then the factor e_i is a top factor. Once the factor is determined as bottom or top, it will be excluded from the next round of level partition. The level determined in later rounds always settles in the middle of the previous top and bottom levels (Tan et al., 1999).

For example, based on the reachability matrix calculated in above section for system S_1, $M_{S1} = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix}$, the reachability set, antecedent set and the intersection for these for elements are presented in Table 3-1.

Table 3-1 Level Partition for the Reachability Matrix for the System S_1

Factors	**Reachability Set**	**Antecedent Set**	**Intersection**	**Level Partition**
e_1	e_1, e_3, e_4	e_1, e_2, e_3, e_4	e_1, e_3, e_4	Top Factors: Level I
e_3	e_1, e_3, e_4	e_1, e_2, e_3, e_4	e_1, e_3, e_4	Top Factors: Level I
e_4	e_1, e_3, e_4	e_1, e_2, e_3, e_4	e_1, e_3, e_4	Top Factors: Level I
e_2	e_1, e_2, e_3, e_4	e_2	e_2	Bottom Factor: Level II

As the intersections for elements e_1, e_3, e_4 equal their reachability sets, these three elements are in the top level (I); while as the intersection of element e_2 equals its antecedent set, element e_2 is in the bottom level (II). Therefore, this system is partitioned into two levels.

d) The construction of the hierarchical structure model

Based on the level partition of the reachability matrix, the factors in the adjacency matrix are represented in the order of the level partition, which constructs the hierarchical structure model for one system. The hierarchical structure model for one system could be presented in both matrix and diagram expressions. For instance, the hierarchical structure model for system S_1 in above section is shown in Table 3-2 and Figure 3-1.

Table 3-2 The Hierarchical Structure Model for System S_1 (Matrix Expression)

Level	**Factors**	**e_1**	**e_3**	**e_4**	**e_2**
I	e_1	1	1	1	0
I	e_3	1	0	1	0
I	e_4	0	1	0	0
II	e_2	0	1	0	1

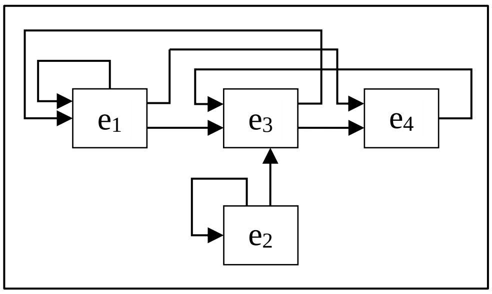

Figure 3-1 The Hierarchical Structure Model for System S_1 (Diagram Expression)

3.4 The Research Methodology for an Industrial Low-carbon Economy System

Based on the worldviews of systems philosophy that are systems thinking, process view, time and spatial view, and the basic laws of systems philosophy and the fundamental principles of systems theory, this section will first determine the scope of the research and the definition of the industrial low-carbon economy based on the initial one from section 1.3. It then refers to economic theory to formulate the production function for an industrial low-carbon economy. Then, based on Hall's systems engineering theory, the method for selecting and optimising the dimensions and factors for an industrial low-carbon economy system is determined, as is the method for building the dimensional structure model for this system. Referring to the ISM method, the methods for constructing the factor's relational model and for calculating the hierarchical structure model for the industrial low-carbon economy system are established. The method to build up the logical relational model is decided. Finally, based on graph theory, the principle of simplification for the hierarchical structural model, the principles of factors' stability and limitations, the method for simplifying the logical relational model for this system is determined.

3.4.1 The Research Scope and Definition of Industrial Low-carbon Economy

Based on the literature review in chapter 2, the current research indicated that the analysis of an industrial low-carbon economy should involve the factors in the following areas: environmental measurement (carbon footprint) (Wackernagel and Rees, 1996; Wiedmann and Minx, 2008; Pandey et al., 2011; Gao et al., 2013; IPCC, 2015), targets for low-carbon emission (United Nations, 1998), technologies for low-carbon emission (Working Group III, 2005a; 2005b; Han et al., 2012; Zhong et al., 2012; IPCC, 2015; Cheng and Meng, 2016), policy and law (Pigou, 1920; Frech, 1979; United Nations, 1998; Nakata and Lamont, 2001; Rubio and Escriche, 2001; Keen et al., 2002; Department of Trade and Industry, 2003; Ren, 2009; Su and Ruan, 2009; Wei, 2011; Chen and Nie, 2016; Kuo et al., 2016; Shi, 2016; Wesseh Jr et al., 2017), macro-economy (Kaya, 1990; Fan and Hu, 2002; Hu et al., 2004; Deacon and Norman, 2006; Galeotti et al., 2006; Yu, 2006; Huang et al., 2008; Aslanidis and Iranzo, 2009), industrial technology (Hu et al., 2004; Yu, 2006), industrial economy (regarding the production process) (Tapio, 2005b; Lu et al., 2007; Finel and Tapio, 2012; Muangthai et al., 2014; Botzoris et al., 2015b; Ma et al., 2016) and social factors (Ehrlich and Ehrlich, 1972; Chertow, 2000; Hu et al., 2004; Yu, 2006; Dalton et al., 2008; Puliafito et al., 2008; Stretesky and Lynch, 2009).

The worldview of systems philosophy, which comprises the systems view, process view, time and spatial views, suggests that the researcher should systematically analyse the world, the systems' process determining the system's goal and each system that is presented within a certain time and spatial location. Therefore, this research systematically identifies from previous research the factors that internally and externally impact the industrial production process in the industrial low-carbon economy, and integrates them into a single systemic framework. The industrial low-carbon production process determines that the system's goal should represent how the industrial economy could achieve sustainable development in the low-carbon economy. The industrial low-carbon economy is at the stage, where industries still consume fossil fuels in their production. This analysis process for determining the research scope and the definition of industrial low-carbon economy based on system philosophy is presented in Figure 3-2.

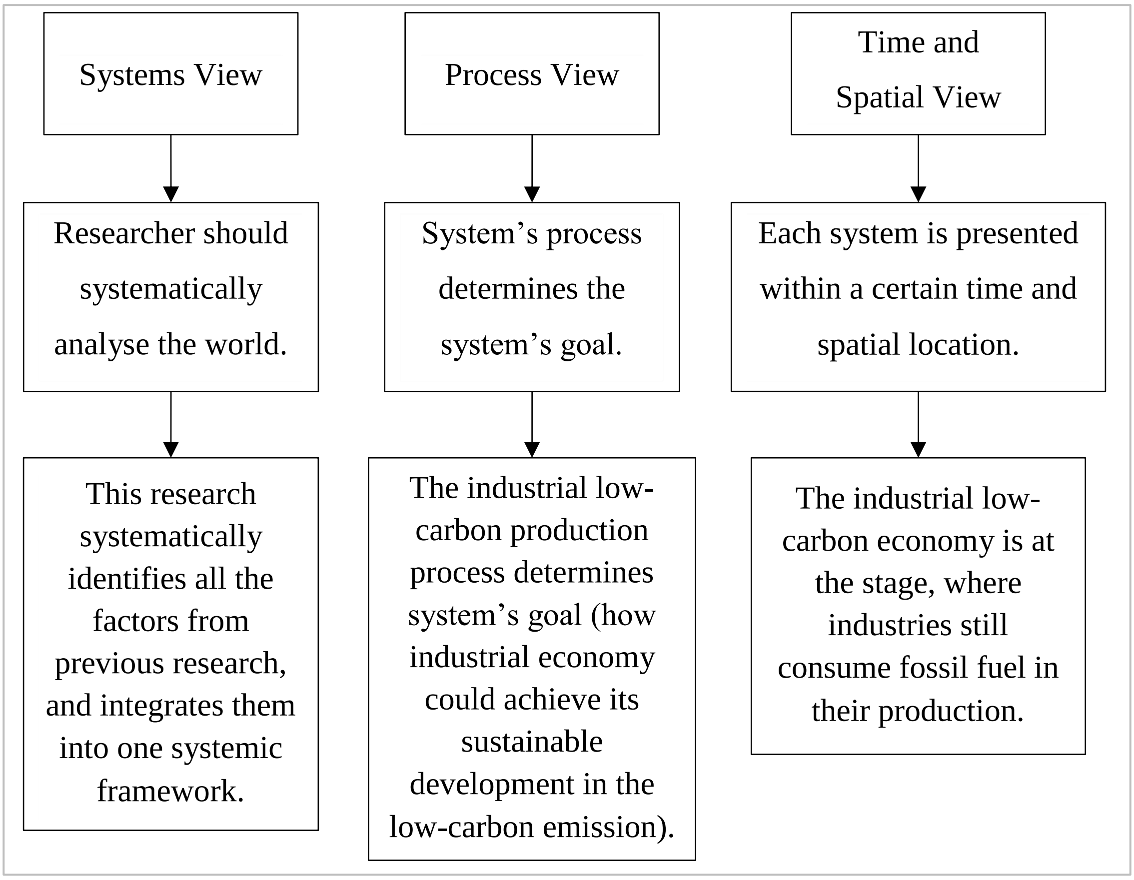

Figure 3-2 The Process to Determine the Research Scope and the Definition of Industrial Low-carbon Economy Based on System Philosophy

Therefore, referring to the analysis in Figure 3-2, following the principles in systems philosophy and theories in systems science, based on the literature review in chapter 2, this section determines the research scope and the definition of industrial low-carbon economy system from the initial definition in section 1.3.

The research scope for an industrial low-carbon economy is of a complex system process, involving industrial development under a number of restraints and promotions, including policies, laws, macroeconomics, society, carrying capacity, industrial technology, industrial economy, and the development target for the industrial low-carbon economy.

Based on the scope, the definition of the industrial low-carbon economy is a system of economic and managerial processes for industrial development within clearly defined low-carbon emission standards, and under the restraints and promotions listed above.

3.4.2 The Method for Formulating the Production Function for an Industrial Low-carbon Economy

Based on the research scope and definition of an industrial low-carbon economy, as well as referring to traditional production functions in economics, this section presents the formulation of a production function for illustrating an industrial low-carbon economy. The traditional production function in economics proposes that $Q = A \times f(L, K)$, in which Q represents the quantity of total production, A represents the technology level, L is the quantity of labour involved in the production and K is the capital employed; while f indicates that there is a relationship between production and these three factors, which these factors jointly determine the production (Cobb and Douglas, 1928; Zhang, 2007; Besanko et al., 2011). This research adds the cost of reducing CO_2 emissions to the elements in the traditional production function. The cost of reducing CO_2 emissions is the cost within the industrial low-carbon economic product process and is used to meet the targeted amount of CO_2 emissions.

3.4.3 The Method for Selecting the System's Dimensions and Factors for an Industrial Low-carbon Economy System

The dimensions in this research represent the "subject matter fields" or the "objects that are the parts or components of a system, and unlimited in variety" (Hall, 1989). Each independent field constitutes one individual dimension. Based on the research scope and the definition of the industrial low-carbon economy, the dimensions are selected by applying the value system design and systems analysis method in the logic dimension of Hall's systems engineering theory. Then, these selected dimensions are optimised and determined based on domain knowledge from politics, law, economics, society, ecology, and other related subjects, as suggested by the knowledge dimension of Hall's theory.

Factors in this research are the variables or attributes that could represent the properties or qualities of the dimensions in this system (Hall, 1989). These factors are also selected based on the research scope and the definition of this system, and then optimised and determined by the encompassing theories and knowledge from related disciplines, applying the logical and knowledge dimensions of Hall's theory.

3.4.4 The Method for Constructing the Dimensional Structure Model for an Industrial Low-carbon Economy System

In order to construct the dimensional structure model, first is to describe the logical relationship among the dimensions of this industrial low-carbon economy system, relying on the system synthesis method for the logic dimension in Hall's systems engineering theory. This thesis then optimises the logic relationships among these dimensions, referring to the knowledge dimension. Finally, the logic relationships among the dimensions are presented by the mathematical expression to construct the dimensional structure model for this industrial low-carbon economy system. This mathematical expression refers to the theory of systems engineering, in which any system can be represented as $S = f(E_i, R_j)$, where E_i means the element or factor in one system, and R_j means the relationships among factors within the system, while f represents that the system is composed of elements and the relationships among factors (Tan et al., 1999).

3.4.5 The Method for Constructing the Factors' Relational Model for an Industrial Low-carbon Economy System

To construct the factors' relational model, first presents the dimensions from the dimensional structure model by relevant factors. Then, referring to the ISM method, the presentation of the logical causal relationships among the factors in a logic matrix is worked out, which is the adjacency matrix, also is the factors' relational model for this system.

3.4.6 The Method for Constructing the Hierarchical Structure Model for an Industrial Low-carbon Economy System

The method for constructing the hierarchical structure model mainly refers to the ISM method, in which the reachability matrix is first calculated from the adjacency matrix (the factors' relational model), based on the Boolean operation. Then, relying on the level partition of the reachability matrix, the adjacency matrix is represented based on the order from these partitioned levels, to construct the hierarchical structure model for this system. This model can be presented as both a matrix and a diagram (Tan et al., 1999; Sushil, 2012).

3.4.7 The Method for Constructing the Logical Relational Model for Industrial Low-carbon Economy System

By representing the factors' causal relationships in the hierarchically structural model through the expression of causal logic diagram, the logical relational model for this industrial low-carbon economy system is constructed.

3.4.8 The Method for Simplifying the Logical Relational Model for an Industrial Low-carbon Economy System

The simplification of the logical relational model refers to graph theory, the principle of simplification for the hierarchical structural model, the principle of factors' stability, and the principle of factors' limitations. There are four steps within the simplifying process.

(1) The simplification of the factors' self-reference and their cross-layer logical relationships

In the logical relational model, the factors' self-reference relationships construct a loop, while the cross-layer logical relationship appears as the parallel edge. Referring to the graph theory, the deduction of the loop (also called self-loop) and parallel edge will not influence the reachability of the factors (Tan et al., 1999; Diestel, 2010). Therefore, this research deducts these factors' self-reference relationships and cross-layer logical relationships to simplify the logical relational model.

(2) The simplification of the factors regarding practical limitations

During the implementation of the system model, consideration of the practical limitations of factors is necessary. Sometimes, because of the limitations of the factor itself, or because the factor is seriously restrained by technological, social or other issues, some factors will not be possible in the practical process. However, based on the research scope and systems' definition, these defective factors are required for constructing a model that can represent the entire system. Therefore, these limited factors are simplified from a practical approach. Thus, the logical relational model as a part of the implementation process will deduct these factors for simplification.

(3) The simplification based on causal relationships among the factors

Referring to construction of the hierarchical structural model, especially seen in the diagram for this model, the factors on the bottom level are the causative factors, while the factors on top level are the resulting factors. The top represents the information and the influences from the factors on bottom level as the results. Therefore, in the logical relational model, the factors closed to the top are selected as logical starting points for analysis, to the final system goal. Of course, these nearest factors should also be data accessible, or their data should be able to be calculated. On the other hand, this research validates the accuracy of the accessed data for these nearest factors, through the implementation of the logical approaches from the bottom factors to these nearest factors and the related calculation based on the approaches.

(4) The simplification of factors based on stability

In a certain period, the macro factors, such as politics and laws rarely change. Therefore, in a certain macro-environment, the logical relational model can deduct these relatively stable factors, focusing on the dynamic or adjustable ones, and analyse the logic related to the sub-systems composed of these factors.

3.4.9 The Method for Validation

Validity "is concerned with the integrity of the conclusions that are generated from a piece of research"(Bryman and Bell, 2011). The Department of Information Techonology and Media (2002) and Kvale (1989) define validity as the epitomised question: "are we measuring what we think we are measuring?", while Kvale he also presented "a broader concept validity, which pertains to the extent that a method investigates what it is intended to investigate". Kvale (1989) further defines validation as the "investigation, continually checking, questioning and theoretically interpreting the findings". Moreover, Bryman and Bell (2011) stated that the main types of validity are measurement validity, internal validity, external validity and ecological validity.

- Measurement validity "applies primarily to quantitative research and to search for measures of social scientific concepts", in other words, "it is to do with the question of whether or not a measure that is devised of a concept, really does reflect the concept that it is supposed to be denoting" (Bryman and Bell, 2011).
- Internal validity focuses on the issue of causality, and is concerned with the question of whether a conclusion represents the causal relationship between two or more variables (Bryman and Bell, 2011; Saunders et al., 2012).
- External validity is concerned with the question of "whether the results of a study can be generalised beyond the specific research context" (Bryman and Bell, 2011); validation methods, such as Delphi method, interview and questionnaire, are all work appropriate examining the external validity for the research (Bryman and Bell, 2011; Saunders et al., 2012).
- Ecological validity is concerned with the question of "whether or not social scientific findings are applicable to people's everyday, natural social setting", in which the three validation methods mentioned in examining external validity are applied (Bryman and Bell, 2011).

However, the systems engineering theory suggests that the framework or model must be examined in a real-world scenario to assess its validity (Hall, 1989; Tan et al., 1999). Therefore, this research will apply the framework to the Chinese thermal electricity generation industry, using industrial data to validate the framework. As the logical relational model is simplified and segmented into sub-models, this research will first validate the quantified sub-models, then validate the logical relational model and the hierarchical structure model, and finally, validate the research methodology constructed for building up these models. Therefore, this integrated framework for sustainable development in an industrial low-carbon economy is comprehensively validated.

3.5 Chapter Summary

The systems philosophy is developed based on positivism and applied to solve systematic problems, suggested from the perspective of pragmatism. The research focuses on the industrial low-carbon economy, which is a complex system. Therefore, systems philosophy and systems science has been chosen as the most appropriate philosophic and theoretical foundation for the investigation of this complex system. The systematic approach and systems methodology were then selected as the research approach and methodology. Referring to all these systems theories, the research methodology and methods for studying this industrial low-carbon economy system are developed. In chapter four, the dimensions and factors selected and theoretical models constructed for this system will be presented in detail.

Chapter 4 Theoretical Models for an Industrial Low-carbon Economy System

4.1 Introduction

In the previous three chapters, we presented the research background, research questions, literature review, research methodology and methods for building up the theoretical models for industrial low-carbon economic system. This chapter presents the theoretical models developed under this research methodology.

4.2 Production Function for an Industrial Low-carbon Economy

Relying on the research method described in section 3.4.2, a new production function is defined for the industrial process in a low-carbon economy: $Q_{LC} = A \times f(L, K, C)$, where Q_{LC} represents the quantity of total production, A represents the technology level, L is the quantity of labour involved in the production, K is the capital employed, and C is the cost of reducing CO_2 emissions; while f indicates that there is relationship between production and these four factors, which jointly determine production in the low-carbon economy.

4.3 Selection and Analysis of the Dimensions and Factors for an Industrial Low-carbon Economy System

Following the research method described in section 3.4.3, this section presents the research scope and definition for the low-carbon economy system's dimensions and factors. The initial dimensions are policy and law, macro-economy, society, industrial technology, industrial economy, nature environment, and industrial development goal. Theories and knowledges from politics, laws, economics, sociology and ecology are also applied to optimise and finally determine the dimensions and factors for our industrial low-carbon economy system, detailed in the following sub-sections.

4.3.1 Political and Legal Dimension and Factors

Based on the research scope and definitions of the low-carbon economy system, as well as the research methodology presented in chapter 3, one of the analytical dimensions selected as determined above is the perspective from policy and law.

4.3.1.1 Selection and Analysis of the Policy and Law Dimension

Policy is the detailed plans, which government organisations, political parties and other social groups have standardised with authority to regulate the goals, principles for action, tasks required to complete, methods for implementation, general procedures and detailed measures for a certain period, to achieve their interests and visions (Liu, 1992; Mackerras et al., 1998; Collin, 2004).

Law is the rules and social norms which are recognised by the public and legislated by the national authorised legislature, and implemented by the national coercive power (mainly the judiciary), to regulate the rights and obligations of the litigants, and which generally constraints the entire society as special conduct codes (Mackerras et al., 1998; Collin, 2004).

The politic, economic, social, technological and environmental protection actions of any organisation come under the protection and restraint of policy and law. Policy and law dimension is therefore relevant to the present study, and determined.

4.3.1.2 Selection and Analysis of the Political and Legal Factors

Based on the definitions above and in section 3.4.1, policy and law are relevant to industrial low-carbon economy systems in improving the educational level and cultural standards, the fiscal and monetary policy for maintaining the economic development in general and the industrial economy, the industrial policy for structural adjustment, and the industrial policy for reducing carbon emission. Therefore, these five factors are selected to represent the dimension of policy and law.

4.3.1.2.1 Policy and Law in Improving the Educational Level and Cultural Standards

The policies and laws for education cover compulsory, higher, and vocational education and other educational aspects, regarding improving the educational level of the entire nation. For culture, the government issues policies and laws with regard to culture aspects at certain times and in certain social situations (Mackerras et al., 1998; Zhang, 2011; Ao, 2013; Shi, 2016).

4.3.1.2.2 Fiscal and Monetary Policy for Macro-economy

Fiscal policy is the economic principles determined by government, based on national aims for political, economic and social development over a certain period, to guide the fiscal work. Fiscal policy relies on the adjustment of government expenses and taxation policies to regulate and influence the total demand, then affect the employment and national income. It is one component of entire economic policies (Zhang, 2007; Baumol and Blinder, 2010; Rodrik and Rosenzweig, 2010; Mankiw, 2013b).

Monetary policy is decided by the central bank to achieve a certain target; various tools are applied to control the money supply to adjust the market interest, and maintain the price stability and general trust in the currency. The central bank influences private investment through the adjustment of market interest. Through the effects on private investment, the central bank influences the total demand, and finally affects the operation of the national macro-economy. The main tools of monetary policy are open market operations, the discount rate and the reserve requirements (Zhang, 2007; Baumol and Blinder, 2010; Rodrik and Rosenzweig, 2010; Mankiw, 2013b).

4.3.1.2.3 Industrial Policy for Structural Adjustment

Referring to the definition and theories of industrial policy from Okuno-Fujiwara (1991); Khan (2003); Robinson (2009); Zu (2015); Bain (1954), the industrial policy for structural adjustment maintains the industry’s stable economic development. Based on this policy’s function, there are three main types of industrial policy for structural adjustment: industrial structure policy, industrial organisation policy and industrial composition policy. These policies normally work together with the corresponding fiscal and monetary policies for industrial economy to achieve its purpose (Zu, 2015).

Industrial structure policy indicates trends and procedures for change in industrial structure, relying on the interrelationships within economic development. It also refers to the principles of change to industrial structures to promote industrial development and finally support national economic development. It regulates the supply structure, eventually resolves conflicts between demand and supply structures (Okuno-Fujiwara, 1991; Zu, 2015).

Industrial organisation policy determines the industrial organisational form, promoting high return, high efficiency of natural resources and rationalised configuration to ensure the stable increase of the supply structure, and solve conflicts between supply and demand. Implementation of this policy could achieve the rationalisation of industrial organisations and promote a fair market competitive environment. This policy is essential for supporting the industrial structure policy (Khan, 2003; Zu, 2015).

Industrial composition policy is for configuring industrial spatial patterns. It mainly addresses utilising the agglomeration effect caused by the relative concentration of production, to narrow the gaps in the level of economic development among different regions, which is led by regional differences in the density of economic activities and in their industrial structure (Bain, 1954; Zu, 2015).

4.3.1.2.4 Fiscal and Monetary Policy for Industrial Economy

The fiscal policy for industrial economy is government policy to guide fiscal principles, determined by the political, economic and social goals of a nation at a particular time, and which influences and regulates the total industrial demand through changes to fiscal expense and tax policy (McKenzie, 1993).

The monetary policy for industrial economy is similarly formulated by government to achieve certain targets, through applying various tools to adjust the money supply to regulate the market interest rate; through changes in the interest rate to influence private investment; and finally influencing industries' total demand (McKenzie, 1993).

4.3.1.2.5 Industrial Policy for Low-carbon Emission

In order to protect the natural environment and maintain a good living environment for human beings, government formulate a series of policies and laws regarding low-carbon emission. These policies contain regulations for industrial standards for reducing and releasing CO_2 (Stern, 2006; IPCC, 2015). IPCC (2015) suggested that there is some evidence for agreement that industrial policy for low-carbon emission is more widespread than nation-wide policy.

4.3.2 Dimension and Factors for Macro-economy

Referring to the research scope and definition for industrial low-carbon economy, the dimensions representing macro-economic effects are identified.

4.3.2.1 Selection and Analysis of Macroeconomic Dimension

Macro-economy is the entire national economy and its economic activities and operations. The main aim of macroeconomics is high quality and a high-speed increase of production, a low unemployment rate and steady price level. Its main concerns include total demand and total supply; gross domestic product (GDP) and GDP growth rate; industrial structure in macro-economy; inflation; employment and unemployment rate; money supply; and import and export scale and movement. (Zhang, 2007; Hall and Lieberman, 2009; Rodrik and Rosenzweig, 2010; Mankiw, 2013b). For these reasons, the macro-economy is selected as one of the dimensions.

4.3.2.2 Selection and Analysis of Factors in the Macro-economy Dimension

In the macroeconomic dimension for an industrial low-carbon economy system, the important related factors are GDP and GDP growth rate, as detailed below.

4.3.2.2.1 GDP

Gross Domestic Product (GDP) is "the market value of all final goods and services produced within a country (within its national boundaries) in a given period" (Mankiw, 2013b). GDP is the core measurement for national economic accounting, and important in evaluating the national or regional economic statement. Based on differences in calculating prices, nominal GDP is "the production of goods and services (GDP) valued at current prices, while real GDP is the production of goods and services valued at constant prices of base year"(Zhang, 2007; Mankiw, 2013b). The real GDP could provide the economy's overall production of goods and services changes over time, as it avoids the influence of the prices, and only provides the information of the total production of goods and services. It also be used by economists and policy makers to measure and compare the total quantity of production within one country over time (Zhang, 2007; Mankiw, 2013b).

The real GDP does not normally equal nominal GDP, except that the data for the base year for calculating real GDP equals nominal GDP of that year. The relationship between real GDP and nominal GDP is Real GDP = Nominal GDP / the GDP deflator, where the GDP deflator sets the base year as 1; thus, the Nominal GDP = Real GDP × the GDP deflator.

4.3.2.2.2 GDP Growth Rate

The GDP growth rate indicates the change in the level of GDP compared with the previous year. National Bureau of Statistics of China (2015) provided the data of the indices of GDP for both preceding year and year 1978 as base year, which indicate the "trend and degree of changes in GDP for a certain period of time calculated at constant prices".

As simple version for calculating GDP growth rate = (GDP_t - GDP_{t-1}) / GDP_{t-1}, where t represents year t, the relationship between Nominal GDP growth rate and Real GDP growth rate is: Nominal GDP growth rate = (1+Real GDP growth rate) × (1 + the GDP deflator) - 1; and Real GDP growth rate = (1+ Nominal GDP growth rate) / (1+ the GDP deflator) - 1.

However, as an economic variable, the movement of GDP cannot only be expressed by the comparison between adjacent two years, but can also be investigated by analysing an average and compound growth rate of a series of GDPs over time (Anson et al., 2010). This method is therefore the compound annual growth rate (CAGR), which is proposed in the evaluation of investment management with assumption that the growth is stable and continuous, then is applied in various area. The equation for calculating nominal GDP CAGR over years is:

$\text{CAGR For Nominal GDP} = \sqrt[N]{\text{Nominal GDP}_t/\text{Nominal GDP}_0}$ -1, where t is year t, t = 0, 1, 2… N, and where t = 0 means the base year.

The calculation for real GDP CAGR is:

$\text{CAGR for Real GDP} = \sqrt[N]{\text{Real GDP}_t/\text{Real GDP}_0} - 1$, where t is year t, t = 0, 1, 2… N, and where t = 0 means the base year.

4.3.3 Dimension and Factors for Social Aspects

Referring to the research scope and definition of industrial low carbon economy system, the dimension representing social aspects is considered.

4.3.3.1 Selection and Analysis of the Dimension of Society

Society is "human collectivity, in which people are related and connected with each other, and conveying a sense of ways of doing things in common, with characteristic patterns of behaviour, and organisation" (Jenkins, 2002). By this definition, the essence of society is people and their organisation. The population determines the scale and status of a society, while the orgainsation determines its character and productive relationships (Mackerras et al., 1998; Zhang, 2011; Ao, 2013). Society is therefore a dimension for investigating the industrial low-carbon economy system.

4.3.3.2 Selection and Analysis of Factors in the Social Dimension

In the social dimension, the factors related to the industrial low-carbon economy system are population, national income per capita, disposable income per capita and the educational level and cultural standards.

4.3.3.2.1 Population

Population is the total number of residents, categorised into different sub-groups based on location (urban or rural), age, gender, occupation etc. The population is the foundation and entity for economic production. However, in different societies', there are different levels of economic development, and different demographic trends. Therefore, the human sensations, understanding and reflections about population are different, which results in various theories in demography (Mackerras et al., 1998; Zhang, 2007; Mankiw, 2013b; National Bureau of Statistics of China, 2015).

4.3.3.2.2 National Income per Capita

National income per capita indicates the average income earned per person in a certain period (generally for a year) in one country; it is calculated by dividing the national income by the size of the population and enables the comparison of gross national income and population (Zhang, 2007).

4.3.3.2.3 Disposable Income per Capita

Disposable income per capita is the amount available for final expenditure and savings for each resident. It includes income both in cash and in kind. The source of disposable income falls into four categories: income from wages and salaries, net business income, net income from property and net income from transfer (National Bureau of Statistics of China, 2015). The disposable income per capita is an essential factor in determining the consumption expenses, and in evaluating national living standards. In China, disposable income per capita is measured for the family unit, and called the Disposable Income of Households.

4.3.3.2.4 Residents' Educational Level and Cultural Standards

Education is the teaching and spreading of culture, is "the process of imparting knowledge or skills to another, or the acquisition of knowledge, skills, values, beliefs and habits" (Merriam Webster Thesaurus). Efficiency, efficacy and performance are integrated in the expression of the educational level for a country. Culture is the summation of the material and spiritual wealth created and inherited by human beings. The cultural standards is evaluated by the amount of material and spiritual wealth that have been inherited (Dictionary Editting Office in Institute of Languages in Chinese Academy of Social Sciences, 2011; Zhang, 2011; Ao, 2013; Shi, 2016).

4.3.4 Dimension and Factors for Industrial Technology

Referring to the research scope and definition for industrial low-carbon economy, industrial technology represents the technological level of the industrial low-carbon economy system as one of the dimension.

4.3.4.1 Selection and Analysis of the Dimension for Industrial Technology

Industrial technology is the accumulated knowledge, experience, techniques and tools of a certain industry, developed by humans in their long-term activities with reference to scientific principles. Technology supports the industrial production, allowing people to satisfy their personal requirements and aspirations (Zhang, 2007). Therefore, industrial technology is selected one dimension in this study.

4.3.4.2 Selection and Analysis of Factors in the Industrial Technology Dimension

The factors related to the industrial low-carbon economy system are industrial production technology and the industrial technology for CO_2 pollution treatment.

4.3.4.2.1 The Industrial Production Technology

Industrial production technology is "understanding of the best ways to produce goods and services" (Mankiw, 2013a; 2013b), which includes the techniques, equipment and system for production processes.

In relation to the technological level, the consumption of natural resources, and the use of natural resources under different technologies, are especially important and concerned in this study.

4.3.4.2.2 The Industrial Technology for CO_2 Pollution Treatment

Industrial technology for CO_2 pollution treatment comprises the technologies, equipment and digital systems used for treating CO_2 pollution in one industrial production, while the industrial technologies combine the technologies for low-carbon emissions introduced in section 2.2.4, like the technology of carbon capture and storage (IPCC, 2015), with the industrial production scenario.

4.3.5 Dimension and Factors for Industrial Economy

Referring to the research scope and definition of this industrial low-carbon economy system, the characteristics of the industrial economy are critical in this study of a low-carbon economy system.

4.3.5.1 Selection and Analysis of the Dimension for Industrial Economy

Industry is the enterprises or organisations that produce similar or related kinds of goods or services in the economy. Industrial economy is representing the dimension regarding the industrial production process, which is one the essential dimension for this industrial low-carbon economic study. The main characteristics for a given industry include economic scale, market position, the size of the market and market growth rate, barriers to enter or exit this industry, the requirement for natural resources, average payback period for investment, the number and scale of companies in this industry, technological innovation cycle, and total profit (Clarke, 1985; Porter, 1998; Zu, 2015). The following sub-sections analyse and select the factors to express industrial economy and production.

4.3.5.2 The Selection and Explanation of the Factors in Industrial Economy Dimension

The factors related to an industrial low-carbon economy system are industrial GDP, the natural resources required, capital employed, and quantity of labour involved, industrial cost of reducing CO_2 emissions, amount of CO_2 emissions from industrial production, total profit for industry from a low-carbon economy, and income tax payable by industry in the low-carbon economy.

4.3.5.2.1 Industrial GDP

Industrial GDP is the total final products and services produced by an industry in its economic activities over a certain period. It is the measurement of the value of the industrial economy. It cannot only represent the performance of the overall industrial economy, but also present the capacity and wealth of a given industry. The calculation of the industrial GDP is similar to that for national GDP, but just in the scope of the industry (Zu, 2015).

4.3.5.2.2 Natural Resources Required in Industrial Production

Natural resources required are “the inputs into the industrial production of goods and services that are provided by nature, such as land, rivers, and mineral deposits” (Mankiw, 2013b; Zhang, 2007). In this analysis, the total amount of the resources and the amount of resources per unit of production are both used to express the use of natural resources in the production process.

4.3.5.2.3 Capital Employed in Industrial Production

This is the capital input involved in industrial production, and is the capital investment necessary for the operation of the industrial production (Cobb and Douglas, 1928; Zhang, 2007; Besanko et al., 2011).

4.3.5.2.4 Quantity of Labour Involved in Industrial Production

This is the number of people employed in an industry. This factor represents the input of labour to industrial production (Cobb and Douglas, 1928; Zhang, 2007; Besanko et al., 2011).

4.3.5.2.5 Industrial Cost of Reducing CO_2 Emissions

The industrial cost of reducing CO_2 emissions means the additional cost to industry in its production in a low-carbon economy (Horner, 2013; Chen, 2011). Generally, there are two methods for calculating this cost. The first is based on the industrial target for reducing CO_2 emissions and the price of carbon trading, where the target is the amount of CO_2 required to be reduced during the production process. The equation is Industrial Cost of Reducing CO_2 Emissions = the Reduction Target of CO_2 emissions × the Price in Carbon Trading. Second, this cost can also be calculated based on the practical cost of improving the industrial production technology, calculated according to the price differential between the old equipment and the improved equipment. The equation is

Industrial Cost of Reducing CO_2 Emissions = (the Unit Price for the Updated Equipment - the Unit Price for the Equipment before the Technological Improvement) × the Amount of the Equipment to be updated or introduced.

4.3.5.2.6 Amount of CO_2 Emissions from Industrial Production

This is the amount of CO_2 emitted during the industrial production process (IPCC, 2006).

4.3.5.2.7 Total Profit for Industry

"Total profit refers to the operation results in a certain accounting period, and it is the balance of various incomes minus various spending in the course of operation, reflecting the total profits and losses of enterprises in an industry in the reference period" (National Bureau of Statistics of China, 2015). This calculation is also based on the principle of accounting in China, which is total profit for industry = operating profits + non-operating income – non-operating expense (Chen, 2011). In this study, the total profit for industry represents total profit in a traditional economy not considering the cost for reducing CO_2 emissions, while the total profit for industry in a low-carbon economy is including the cost of low-carbon emission. Referring to the production function in low-carbon economy in section 4.2, the industrial cost of reducing CO_2 emissions is the element in industrial production function. Therefore, it will be calculated as one cost in the production process to be deducted from operating profits. The total profit for industry in a low-carbon economy is then calculated as Total Profit for Industry in the Low-carbon Economy = Total Profit for Industry (in Traditional Economy) ± Industrial Cost of Reducing CO_2 Emissions.

4.3.5.2.8 Income Tax Payable by Industry

The income tax payable is the tax that one industry is required to pay, based on an industry's income from production and operation, as determined under the national taxation laws. The calculation of income tax payable by industry is Income Tax Payable by Industry = Taxable Income of Industry × Income Tax Rate ± the Income Tax Adjustments (Chen, 2011).

4.3.6 Dimension and Factors for Natural Environment

Referring to the research scope and definition for industrial low-carbon economy, environment is one of main measures in defining a low-carbon economy, and therefore an essential dimension for this system.

4.3.6.1 Selection and Analysis of the Natural Environment Dimension

The environmental dimension represents the natural damage resulting from human activities and affecting the environmental capacity for carrying out human activities, measured as the carrying capacity, so named as bearing capacity. From the aspect of reducing pollution, it is defined as the maximum capacity of the environment to carry a pollutant, without affecting human survival or damaging the ecological system (Arrow et al., 1995; Shmelev, 2012). Pollution affordability thresholds for atmosphere, water, earth and natural species have been adopted. Once the amount of pollution exceeds the maximum carrying capacity, the ecological balance and the ecological functions will be destroyed. Therefore, carrying capacity is used here as the environmental dimension.

4.3.6.2 Selection and Analysis of Factors in the Carrying Capacity Dimension

CO_2 is the pollutant considered in this study, so the factor selected here for this carrying capacity dimension is the industrial target for CO_2 emissions. This target is the standard amount or allowance of CO_2 that the industry can emit during production. It is regulated by the government, based on the related policy and law for low-carbon emission (Stern, 2006; IPCC, 2015).

4.3.7 Dimension and Factor for Industry’s Development Goal

Developing a goal for industrial low-carbon economy, concerns the dimension of both the industrial development and environmental restraint, referring to the scope and definition for this system.

4.3.7.1 Selection and Analysis of the Dimension for Developing a Goal for an Industrial Low-carbon Economy

The development goal for industry in a low-carbon economy should both focus on the industrial economy and reflect the environment's limitations. Referring to the production function formulated in section 4.2, this study places the cost of low-carbon emission in the industrial economy process. Therefore, the development goal is the economic capacity of an industry in achieving its low-carbon emission target, and the dimension reflects both the economic perspective and environmental requirements.

4.3.7.2 Selection and Analysis of Factors in the Development Goal Dimension

Traditionally, the industrial economic system ignored the issue of low-carbon emission; the economic status of an industry was measured by industrial net profit, an accounting issue. Industrial GDP indicates the economic scale; however, it does not represent information about the cost of industrial production, which is one of the core elements for management and strategy making (Chen, 2011; Horner and Mott, 2013). As explained in section 4.2, the industrial low-carbon economy process includes an additional element to the traditional economic process, the cost of reducing CO_2 emissions. Therefore, this study selects net profit for industry in a low-carbon economy, as the factor for this dimension. Accountants calculate the industrial net profit in low-carbon economy from the total profit for industry and the income tax payable for a low-carbon industry (Chen, 2011; Horner and Mott, 2013). Here, the low-carbon emission cost is deducted from the traditional total profit for industry and transferred to the total profit for industry in the low-carbon economy. This deduction represents the industry's economic process for affording the cost of low-carbon emission. Industrial net profit in a low-carbon economy is this total profit for industry deducting the income tax payable by industry in the low-carbon economy: Industrial Net Profit in Low-carbon Economy = Total Profit for Industry in the Low-carbon Economy - Income Tax Payable by Industry in the Low-carbon Economy.

This industrial net profit in the low-carbon economy represents the industry's capacity for sustainable low-carbon development from both economic and environmental perspectives. If the net profit is above zero, the industry could afford the environmental cost, and it is sustainable in the low-carbon economy. However, if the net profit is below zero, the industry could not afford the cost for reducing low-carbon emission, and it would not be sustainable in the low-carbon economy. Therefore, the industrial net profit is a factor in the development goal dimension.

4.3.8 Selected Dimensions and Factors for the Industrial Low-carbon Economy System

Based on the initial selection and related analysis, the dimensions representing the industrial low-carbon economy system and the factors expressing these dimensions have been selected.

4.3.8.1 Selected Dimensions

The selected dimensions are confirmed as policy and law (P), macro-economy (E), society (S), industrial technology (T_i), industrial economy in the low-carbon economy (E_i), carrying capacity (N_e), and development goal for industrial low-carbon economy (G_{ce}).

4.3.8.2 Selected Factors

The factors for explaining the selected dimensions were selected based on the definition and scope of each dimension, and on the research scope defined in section 3.4.1.

For the policy and law dimension, the selected factors are policy and law in improving the educational level and cultural standards, fiscal and monetary policy for macro-economy, industrial policy for structural adjustment, fiscal and monetary policy for industrial economy, and industrial policy for low-carbon emission.

For the macro-economy dimension, the selected factors are GDP and GDP growth rate.

In the social dimension, the selected factors are population, national income per capita, disposable income per capita, and educational level and cultural standards.

For the industrial technology dimension, the selected factors are industrial production technology and industrial technology for CO_2 pollution treatment.

In the industrial economy dimension, the selected factors are industrial GDP, natural resources required in industrial production, capital employed in industrial production, quantity of labour involved in industrial production, industrial cost of reducing CO_2 emissions, amount of CO_2 emissions from industrial production, total profit for industry in a low-carbon economy, and income tax payable by industry in a low-carbon economy.

For the carrying capacity dimension, the selected factor is the industrial target for CO_2 emissions.

In the development goal for industrial low-carbon economy dimension, the selected factor is industrial net profit in the low-carbon economy.

4.3.8.3 Summary of the Direct Causal Relationships among Selected Factors for the Industrial Low-carbon Economy System

Based on the dimensions and factors selected above, as well as referring to the knowledge related to each factor in sections 4.3.1 to 4.3.7, Table 4-1 presents the directly causal relationships between factors. This table also allocates a symbol to each dimension and factor. Referring to the worldview of systems philosophy, in which the world can be understood from process and time views, this suggests consideration of the trend of factors when time varies. Therefore, the direct causal relationship of factor's self-reference is considered for each factor in this research (Qian, 1988; Hall, 1989; Wei and Zeng, 1995; Checkland, 1999; Tan et al., 1999; Qian, 2001; Yang, 2013).

Table 4-1 Summary of the Direct Causal Relationships among Selected Factors

Factor No.	**Dimensions**	**Factors**	**Direct Causal Relationships among Factors**	**References**
1	Policy and Law Dimension (P)	Policy and law in improving the educational level and cultural standards	Directly affect the educational level and cultural standards (Factor 11).	(Mackerras et al., 1998; Zhang, 2011; Ao, 2013; Shi, 2016)
2		Fiscal and monetary policy for macro-economy	Directly influence the growth rate of GDP (Factor 7).	(Zhang, 2007; Baumol and Blinder, 2010; Rodrik and Rosenzweig, 2010;

				Mankiw, 2013b)
3		Industrial policy for structural adjustment	Directly support the fiscal and monetary policy for industrial economy (Factor 4).	(Okuno-Fujiwara, 1991; Khan, 2003; Robinson, 2009; Zu, 2015; Bain, 1954)
4		Fiscal and monetary policy for industrial economy	Directly determine the income tax payable by industry in the low-carbon economy (Factor 21).	(McKenzie, 1993; Zu, 2015)
5		Industrial policy for low-carbon emission	Directly determine the industrial target for CO_2 emissions (Factor 22) through directly affecting the industrial policy for structural adjustment (Factor 3) to directly impact the amount of CO_2 emissions from industrial production (Factor 19).	(National Development and Reform Commission, 2004; State Council, 2006; Stern, 2006; 2014a; IPCC, 2015; National Development and Reform Commission, 2016; Shi, 2016)
6	Macro-economy Dimension (E)	GDP	Directly affect the fiscal and monetary policy for macro-economy (Factor 2), national income per capita (Factor 9) and industrial GDP (Factor 14).	(Zhang, 2007; Hall and Lieberman, 2009; Mankiw, 2013b; Mankiw, 2013a; Zu, 2015)
7		GDP growth rate	Directly affect the fiscal and monetary policy for macro-economy (Factor 2) and GDP (Factor 6).	(Zhao, 1999; Collin, 2004; Zhu, 2009; Baggini and Sumper, 2012; Zhang, 2013)
8	Society Dimension (S)	Population	Directly impact national income per capita (Factor 9), disposable income per capita (Factor 10) and quantity of labour involved in industrial production (Factor 17).	(Mackerras et al., 1998; Zhang, 2007; Mankiw, 2013b; National Bureau of Statistics of China, 2015)
9		National income per capita	Directly affect policy and law in improving the educational level and cultural standards	(Zhang, 2007)

			(Factor 1) and disposable income per capita (Factor 10).	
10		Disposable income per capita	Directly impact GDP (Factor 6) and the educational level and cultural standards (Factor 11).	(Zhang, 2007)
11		Educational level and cultural standards	Directly affect the policy and law in improving the educational level and cultural standards (Factor 1) and industrial policy for low-carbon emission (Factor 5).	(Dictionary Editing Office in Institute of Languages in Chinese Academy of Social Sciences, 2011; Zhang, 2011; Ao, 2013; Shi, 2016)
12	Industrial Technology Dimension (T_i)	Industrial production technology	Directly determine the industrial GDP (Factor 14), natural resources required in industrial production (Factor 15) and capital employed in industrial production (Factor 16).	(Mankiw, 2013a; 2013b)
13		Industrial technology for CO_2 pollution treatment	Directly determine the industrial GDP (Factor 14), capital employed in industrial production (Factor 16) and amount of CO_2 emissions from industrial production (Factor 19).	(Working Group III, 2005a; Working Group III, 2005b; Han et al., 2012; Zhong et al., 2012; IPCC, 2015; Zhang, 2007)
14	Industrial Economy Dimension in the low-carbon economy (E_i)	Industrial GDP	Directly affect GDP (Factor 6) and total profit for industry in the low-carbon economy (Factor 20).	(Zu, 2015)
15		Natural resources required in industrial production	Directly affect industrial policy for structural adjustment (Factor 3), industrial GDP (Factor 14) and amount of CO_2 emissions from	(Mankiw, 2013b; Zhang, 2007)

			industrial production (Factor 19).	
16		Capital employed in industrial production	Directly impact industrial GDP (Factor 14).	(Cobb and Douglas, 1928; Zhang, 2007; Besanko et al., 2011)
17		Quantity of labour involved in industrial production	Directly impact industrial GDP (Factor 14).	(Cobb and Douglas, 1928; Zhang, 2007; Besanko et al., 2011)
18		Industrial cost of reducing CO_2 emissions	Directly affect the total profit for industry in the low-carbon economy (Factor 20) and industrial target for CO_2 emissions (Factor 22).	(Chen, 2011)
19		Amount of CO_2 emissions from industrial production	Directly determine the industrial policy for low-carbon emission (Factor 5) and industrial target for CO_2 emissions (Factor 22).	(IPCC, 2006)
20		Total profit for industry in the low-carbon economy	Directly impact the income tax payable by industry in the low-carbon economy (Factor 21) and industrial net profit in the low-carbon economy (Factor 23).	(Chen, 2011; National Bureau of Statistics of the Peoples' Republic of China, 2011)
21		Income tax payable by industry in the low-carbon economy	Directly affect the fiscal and monetary policy for industrial economy (Factor 4) and industrial net profit in the low-carbon economy (Factor 23).	(Chen, 2011; National Bureau of Statistics of the Peoples' Republic of China, 2011)
22	Carrying Capacity Dimension (N_e)	Industrial target for CO_2 emissions	Directly affect the industrial cost of reducing CO_2 emissions (Factor 18).	(Stern, 2006; IPCC, 2015)
23	Development Goal for Industrial	Industrial net profit in the low-carbon	Factor's self-reference in time-varying (Factor 23).	(Chen, 2011; National Bureau of Statistics of the

	Low-carbon Economy Dimension (G_{ce})	economy		Peoples' Republic of China, 2011)

4.4 Dimensional Structure Model for the Industrial Low-carbon Economy System

Referring to the research scope and the research method in section 3.4.4, this section represents the logic relationships among the dimensions through systematic expressions, as S_S = f (P, E, S, T_i, E_i, N_e, G_{ce}, R_j), where S_S is the industrial low-carbon economy system; P is the policy and law dimension; E is macro-economy dimension; S is society dimension; T_i is the industrial technology dimension; E_i is the industrial economy dimension; N_e is the carrying capacity dimension; G_{ce} is the industrial goal dimension for this industrial low-carbon economic development; R_j is the logic relationships among the dimensions, P, E, S, T_i, E_i, N_e, G_{ce}, and j is a natural number 1, 2, .. n.

4.5 The Factors' Relational Model for the Industrial Low-carbon Economy System

Referring to the research method in section 3.4.5 in chapter 3, this section represents the dimensions of this industrial low-carbon economy system with related factors. The definitions and analyses of each factor are presented in the previous section 4.3, which indicated the direct logical causal relationships among these factors. For example, referring to literature from the Ministry of Education (1998); Cai (2009); Zhang (2011); Ao (2013); Shi (2016), Factor 1 (Policy and law in improving the educational level and cultural standards) guided and supported improvement of the national educational level and the maintenance of cultural standards (Factor 11). Therefore, Factor 1 directly affects Factor 11, so a_{111} = 1 in the adjacency matrix (Table 4-2). On the other hand, Factor 1 does not directly influence the macro-economy and the changes of GDP (Factor 6), therefore there is no direct causal relationship from Factor 1 to Factor 6, which a_{16} = 0. Similarly, referring to the summary of the directly causal relationships among factors in section 4.3.8.3 (Table 4-1), the factors and their inter-relationships are presented in a logic matrix, the adjacency matrix in Table 4-2, which is also known as the factors' relational model.

Table 4-2 The Adjacency Matrix (or The Factors' Relational Model) for the Industrial Low-carbon Economy System

Factors	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
5	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
6	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
7	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0
14	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
15	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0
19	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

4.6 The Hierarchical Structure Model for the Industrial Low-carbon Economy System

4.6.1 The Reachability Matrix

Referring to the research method in section 3.4.6, this section applies Boolean operations to calculate the reachability matrix (Table 4-3), based on the adjacency matrix in Table 4-2. The Excel steps for this calculation are as follows and are detailed in Appendix A.

First, input the Adjacency Matrix (A) and Identity Matrix (I) into Excel sheet.

Then, start from k = 1, to calculate the matrixes $(I \cup A)^{2^{k-1}}, (I \cup A)^{2^k}\ and\ (I \cup A)^{2^{k+1}}$ through the logically matrix multiplication, referring to section 3.3.1.2.2 b), which applies the Excel function MMULT and IF, and following these steps:

Step 1: apply the function MMULT (Matrix 1, Matrix 2) to work out a new matrix s1.

Step 2: if any element in the matrix s1 is larger than 1, then exchange for 1, while keeping the elements equal to 0 or 1 the same, through Excel function, IF (s1 >1, 1, s1). If all the elements equal either 0 or 1, then skip Step 2.

Step 3: compare these matrices $(I \cup A)^{2^{k-1}}, (I \cup A)^{2^k}\ and\ (I \cup A)^{2^{k+1}}$ to find out whether the rule $(I \cup A)^{2^{k-1}} \neq (I \cup A)^{2^k} = (I \cup A)^{2^{k+1}}$ is satisfied, through IF (Matrix 1 = Matrix 2, 1, 0). If the rule is not met, then repeat the steps with k = 2, 3, … ∞, until the rule is satisfied, when the calculation is stopped.

Table 4-3 The Reachability Matrix for the Industrial Low-carbon Economy System

Factors	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**7**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
15	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1
17	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

4.6.2 Level Partition for the Reachability Matrix

Based on the research method in section 3.4.6, and the level partition standards in the ISM method in section 3.3.1.2.2 (2), the reachability matrix (Table 4-3) is partitioned into various levels (Table 4-4). The detailed process is shown in Appendix B: first, the antecedent sets and the reachability sets for each factor are identified; then, the intersection of these two set for each factor is recognised (Intersection = Reachability Set ∩ Antecedent Set); finally, the matrix is partitioned following the standards (if Intersection = Antecedent Set, then the factor e_i is a bottom factor; if Intersection = Reachability Set, then the factor e_i is a top factor). For example, the reachability set for Factor 23 is Factor 23, and its antecedent set includes all 23 factors; thus, the intersection for Factor 23 is its reachability set (Factor 23); therefore, Factor 23 is a top factor and in level I.

Table 4-4 Level Partition for the Reachability Matrix

Factors No.	Reachability Set	Antecedent Set	Intersection	Level
23	23	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23	23	I
4	4, 21, 23	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22	4, 21	II
21	4, 21, 23	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22	4, 21	II
3	3, 4, 21, 23	1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 3, 5, 19	3	III
20	4, 20, 21, 23	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22	20	III
18	4, 18, 20, 21, 22, 23	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 22	18, 22	IV
22	4, 18, 20, 21, 22, 23	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 22	18, 22	IV
5	3, 4, 5, 18, 19, 20, 21, 22, 23	1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 5, 19	5, 19	V

19	3, 4, 5, 18, 19, 20, 21, 22, 23	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19	5, 19	V
1	1, 3, 4, 5, 11, 18, 19, 20, 21, 22, 23	1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	1, 11	VI
11	1, 3, 4, 5, 11, 18, 19, 20, 21, 22, 23	1, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	1, 11	VI
2	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
6	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
7	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
9	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
10	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
14	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23	2, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17	2, 6, 7, 9, 10, 14	VII
15	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 15	12, 15	15	VIII
16	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 16	12, 13, 16	16	VIII
17	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 17	8, 17	17	VIII
8	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 8, 17	8	8	IX
12	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 12, 15, 16	12	12	IX
13	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 14, 18, 19, 20, 21, 22, 23, 13, 16	13	13	IX

4.6.3 The Hierarchical Structure Model

Based on Table 4-4, the hierarchical structure model for this industrial low-carbon economy system was constructed. It presents in both the matrix expression (Table 4-5) and the diagram expression (Figure 4-1).

Table 4-5 The Hierarchical Structure Model for the Industrial Low-carbon Economy System (Matrix Expression)

Level	Factors	23	4	21	3	20	18	22	5	19	1	11	2	6	7	9	10	14	15	16	17	8	12	13
I	**23**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II	**4**	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
II	**21**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
III	**3**	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
III	**20**	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IV	**18**	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IV	**22**	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	**5**	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	**19**	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VI	**1**	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
VI	**11**	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
VII	**2**	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
VII	**6**	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0
VII	**7**	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
VII	**9**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0
VII	**10**	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0
VII	**14**	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
VIII	**15**	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
VIII	**16**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
VIII	**17**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
IX	**8**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0
IX	**12**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0
IX	**13**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1

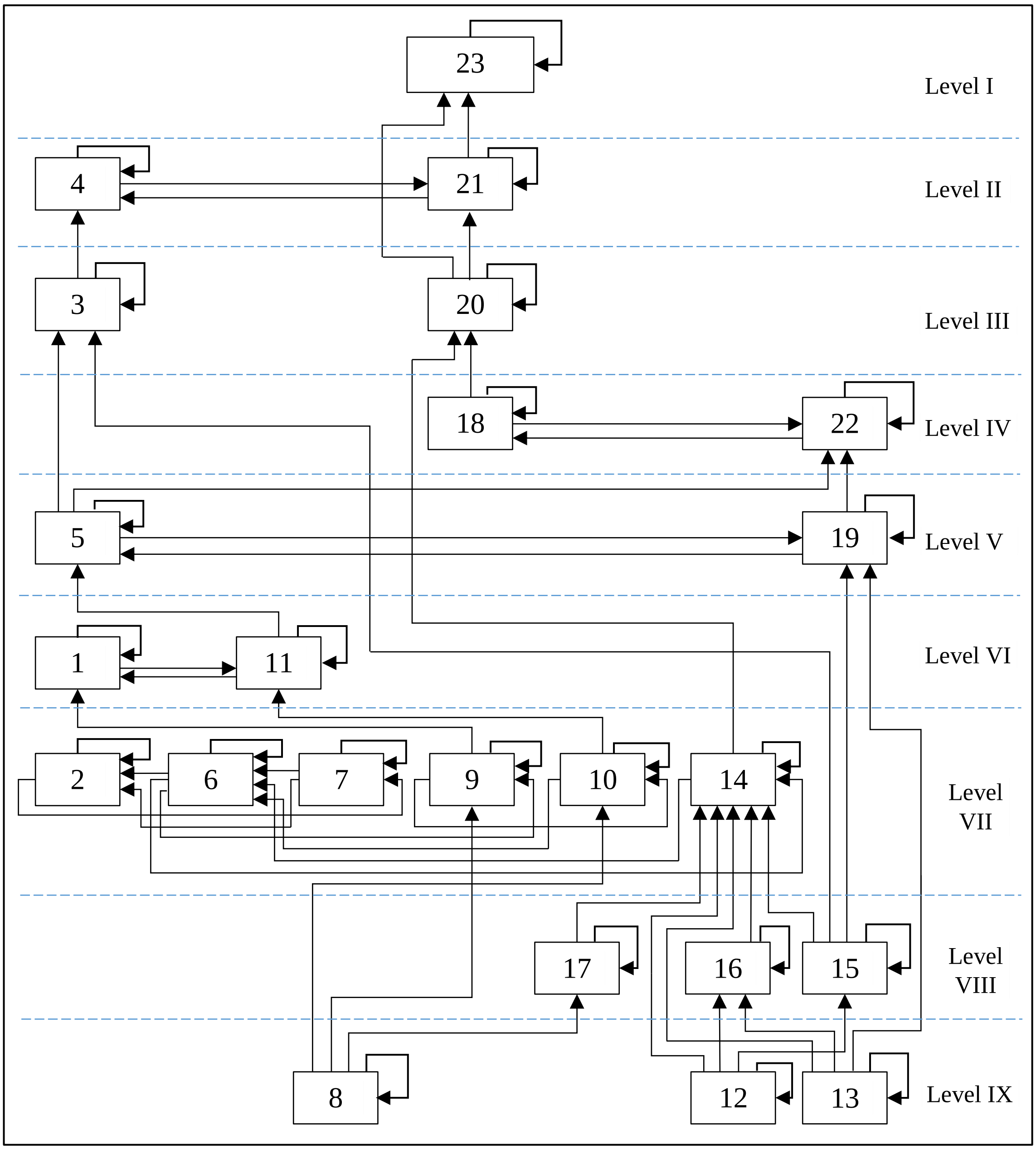

Figure 4-1 The Hierarchical Structure Model for the Industrial Low-carbon Economy System (Diagram Expression)

There are nine levels in the hierarchical structure model. The bottom-level factors, which are the basis for this model, are population (Factor 8), industrial production technology (Factor 12), and industrial technology for CO_2 pollution treatment (Factor 13). The top-level factor is the system goal, which is industrial net profit in the low-carbon economy (Factor 23). The arrows within the diagram (Figure 4-1) represent the causal relationships among the factors. Arrow from e_i to e_j means that there is a direct causal effect from factor e_i to factor e_j.

4.7 The Logical Relational Model for the Industrial Low-carbon Economy System

Referring to the research method in section 3.4.7, this study represents the logic relationships among the factors in the hierarchical structure model (Figure 4-1) with a logic diagram, the logical relational model for this industrial low-carbon economy system (Figure 4-2).

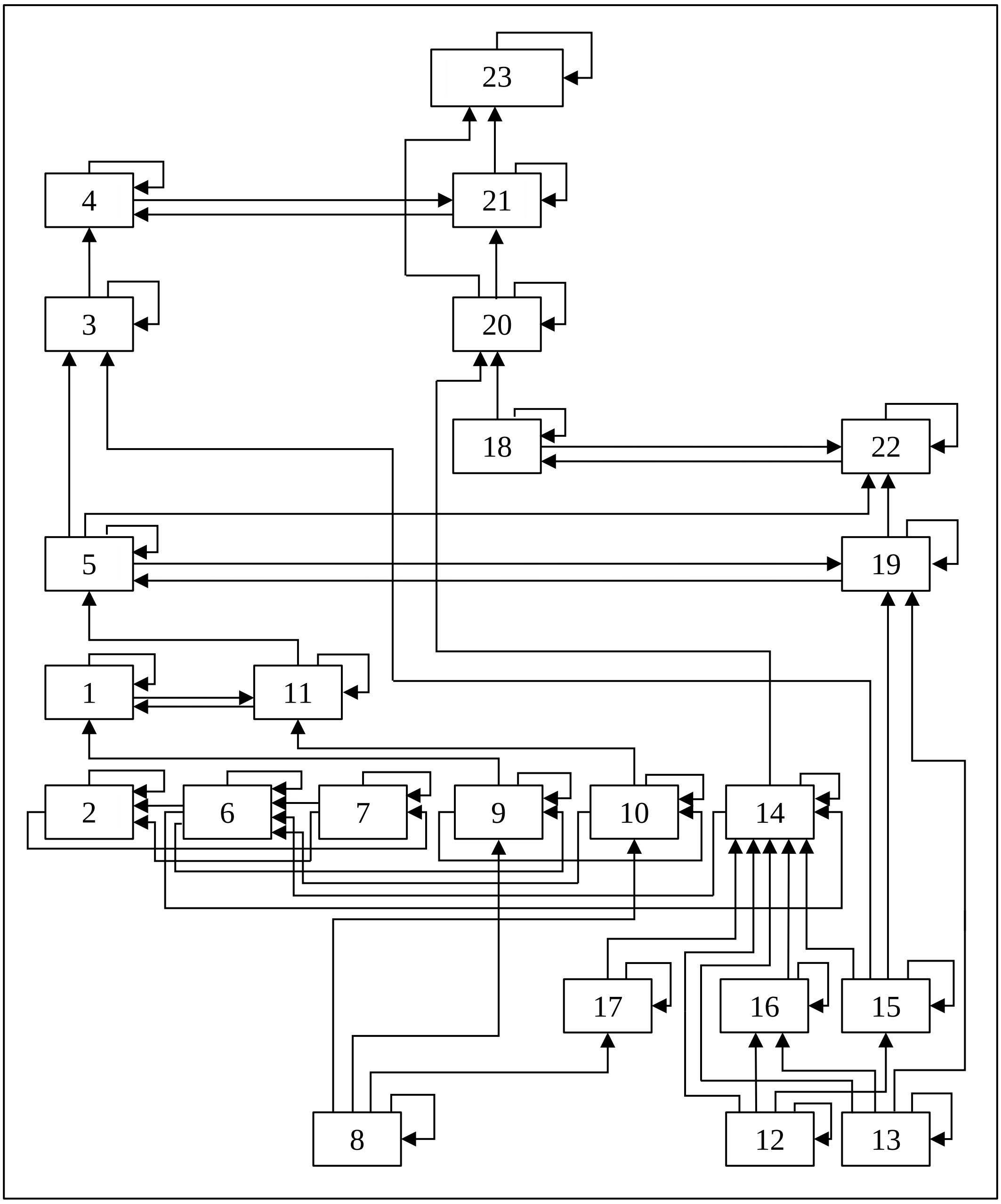

Figure 4-2 The Logical Relational Model for Industrial Low-carbon Economy System

In this model, the factors at the bottom of the figure are the root of this system, while the factor at the top is the system goal. In order to achieve the system goal of industrial net profit in the low-carbon economy (23), the root causes are population (8), industrial production technology (12), and industrial technology for CO_2 pollution treatment (13). The arrows represent direct causal relationships between two factors.

4.8 Simplification of the Logical Relational Model for Industrial Low-carbon Economy System

Referring to the research method in section 3.4.8, this section simplifies the logical relational model for an industrial low-carbon economy system in order to construct theoretical models to analyse the system. These simplified models allow us to focus on the main factors and main causal relationships within the system.

4.8.1 Simplification of Factors' Self-reference and their Cross-layer Logical Relationships

Referring to the research method in section 3.4.8 (1), the loop and parallel edge can be deleted to derive a simple graph. The loop for each factor is first deleted. The factors' cross-layer logical relationships, parallel to the other edge, are then removed. These deleted edges are the direct relationships from population (Factor 8) to national income per capita (Factor 9), from population (Factor 8) to disposable income per capita (Factor 10), from industrial production technology (Factor 12) to industrial GDP (Factor 14), from industrial technology for CO_2 pollution treatment (Factor 13) to industrial GDP (Factor 14), from natural resources required in industrial production (Factor 15) to industrial policy for structural adjustment (Factor 3), and from total profit for industry in the low-carbon economy (Factor 20) to industrial net profit in the low-carbon economy (Factor 23). The simplified model is shown in Figure 4-3. The logical structure of the system is more readily identified.

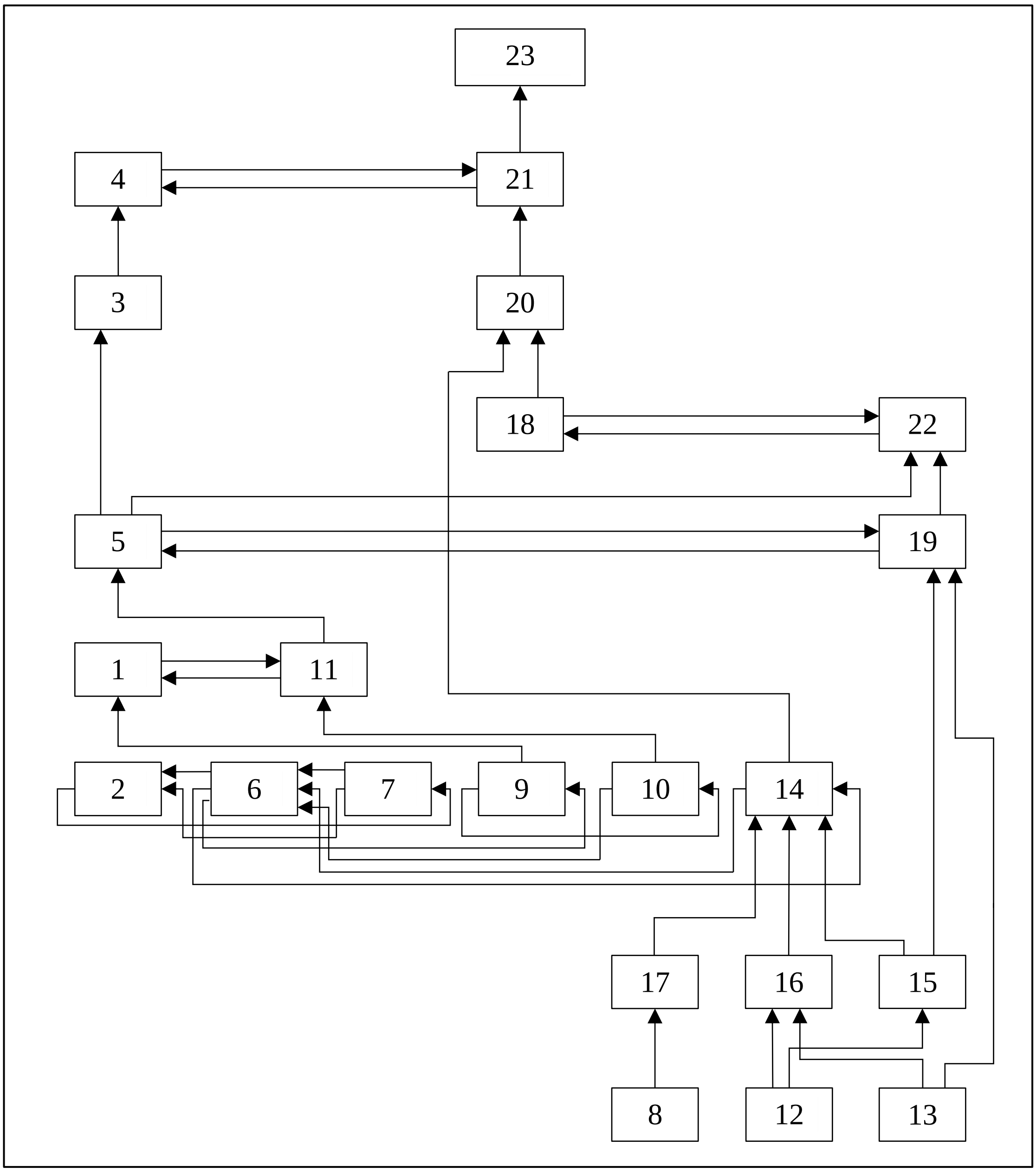

Figure 4-3 The Simplified Logical Relational Model of Simplifying Factors' Self-reference and their Cross-layer Logical Relationships

4.8.2 Simplification of Factors' Practical Limitations

Referring to the research method in section 3.4.8 (2), the logical relational model is repeatedly simplified based on the revised model in section 4.8.1. Some of the factors theoretically required for constructing the relational model, have practical limitations, and are therefore removed to provide effective guidance for implementation. The defective factor in this model is the industrial technology for CO_2 pollution treatment

(Factor 13), theoretically crucial but currently at experimental stage, and not yet widely applied in commercial processes.

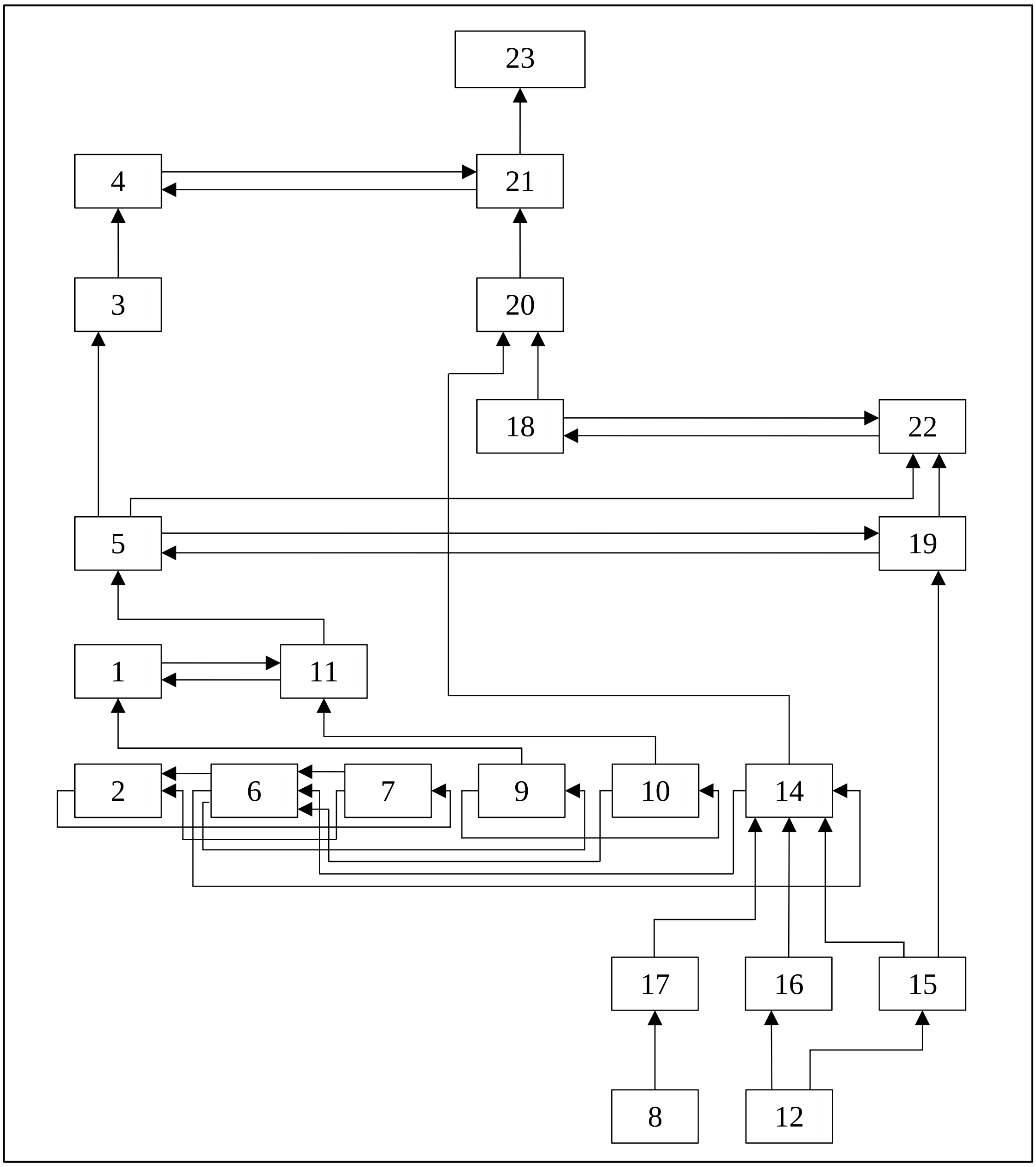

Figure 4-4 The Logical Relational Model Simplified by Removal of Impractical Factors

4.8.3 Simplification Based on Causal Relationships among the Factors and Factors' Stability

Referring to the research method in section 3.4.8 (3) and 3.4.8 (4), and considering the logic within the system, the logical relational model in Figure 4-4 is further simplified and segmented into two parts (Figure 4-6): the red part indicating the decision-making process for industrial policy for low-carbon emission (Factor 5); the blue part representing the main process in achieving the system’s goal: industrial net profit in the low-carbon economy (Factor 23), which could be further simplified. In the red part, the factors, industrial policy for low-carbon emission (Factor 5), industrial GDP (Factor 14) and amount of CO_2 emissions from industrial production (Factor 19), are determined by factors in lower levels, and work as the top-level factors in the red part. Because the information and impact from the factors in levels below these three factors is represented by them, based on the causal relationships among factors, these three factors affect the blue part as its root causes. Therefore, the logical relational model (Figure 4-4) could be segmented into two parts, which are the decision making model for industrial low-carbon policy (Figure 4-8) and the simplified logical relational model of simplification based on the causal relationships among the factors (Figure 4-7).

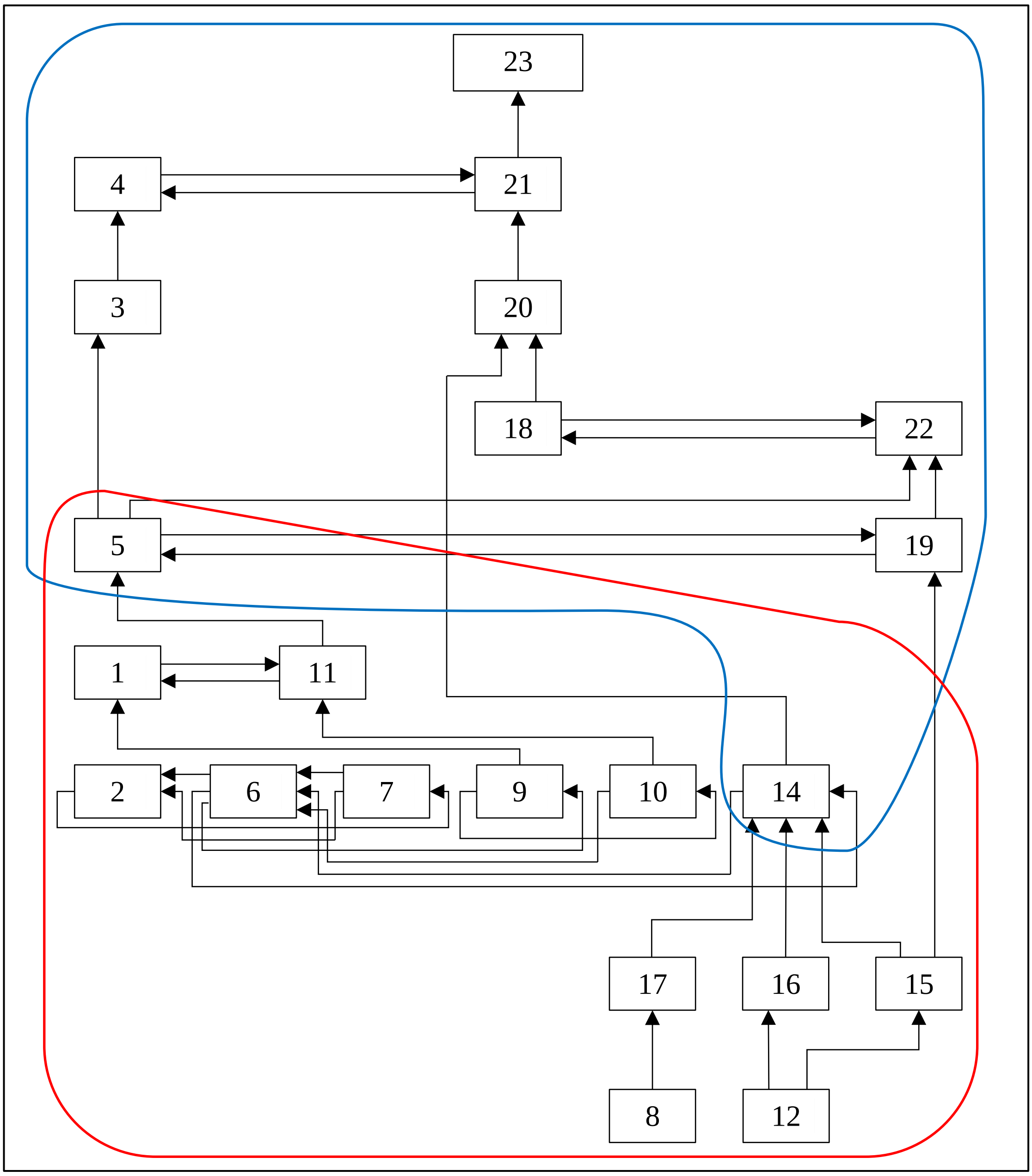

Figure 4-5 The First Simplification Process of the Logical Relational Model Basing on the Causal Relationships among the Factors

Moreover, based on the hierarchical logic shown in Figure 4-6, the green part circles the process and factors for producing and controlling the amount of CO_2 emissions from industrial production (Factor 19), in which Factor 19 is determined by Factor 15, Factor 12 and its interaction with Factor 5, while Factor 15 is determined by Factor 12. Therefore, this green part is recognised as the model for identifying the optimal approach to low-carbon emission for the industrial low-carbon economy, shown in Figure 4-11.

Furthermore, the yellow part in Figure 4-6, represents the industrial production process, in which Factors 12, 15, 16 and 17 are the input resources for the production, while Factors 6 and 14 are the economic output, and Factor 19 is the environmental output for this industrial production. Therefore, a model for recognising the relationships between economic growth and CO_2 emissions is constructed, shown in Figure 4-12.

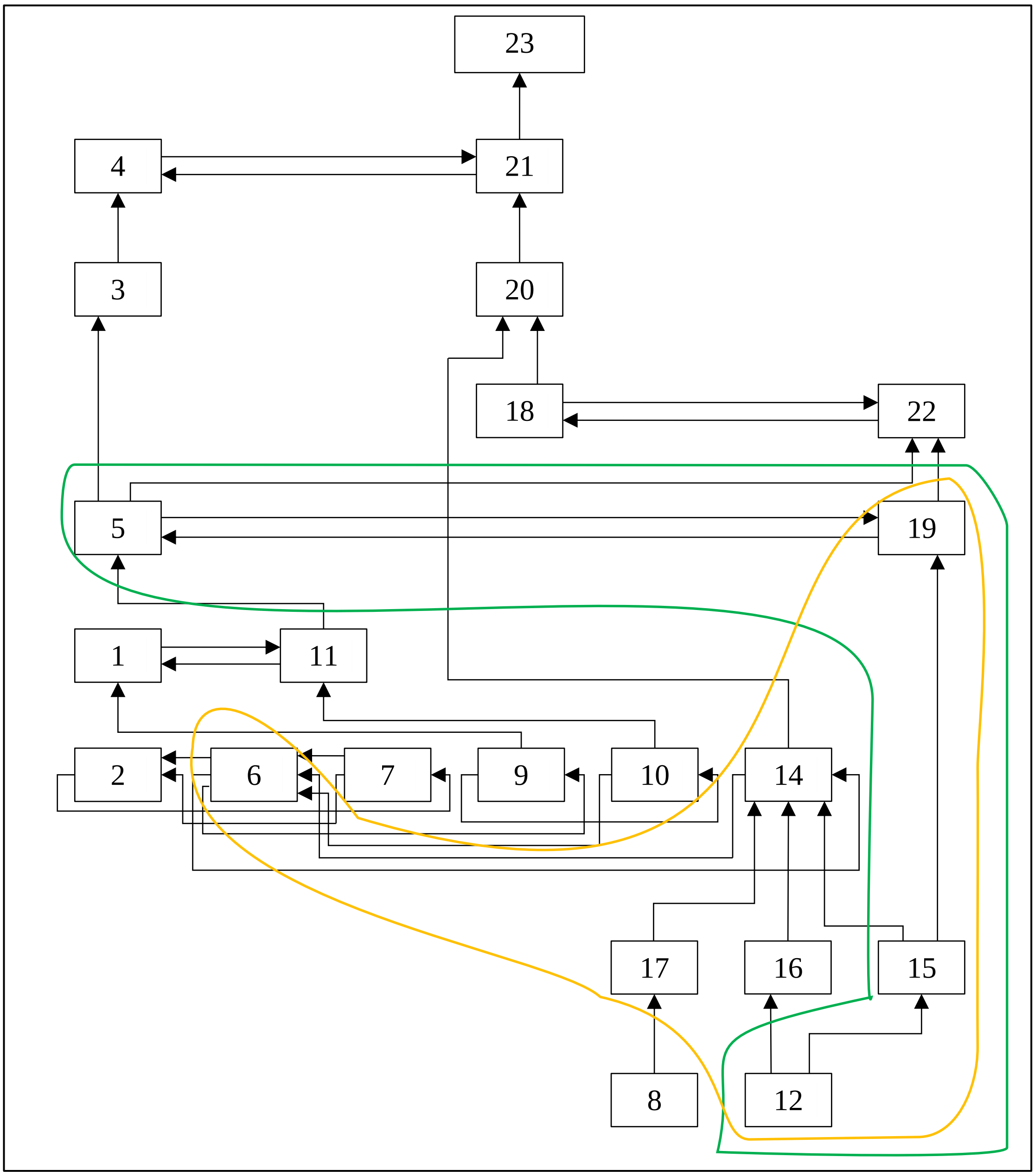

Figure 4-6 The Second Simplification Process of the Logical Relational Model Based on the Causal Relationships among the Factors

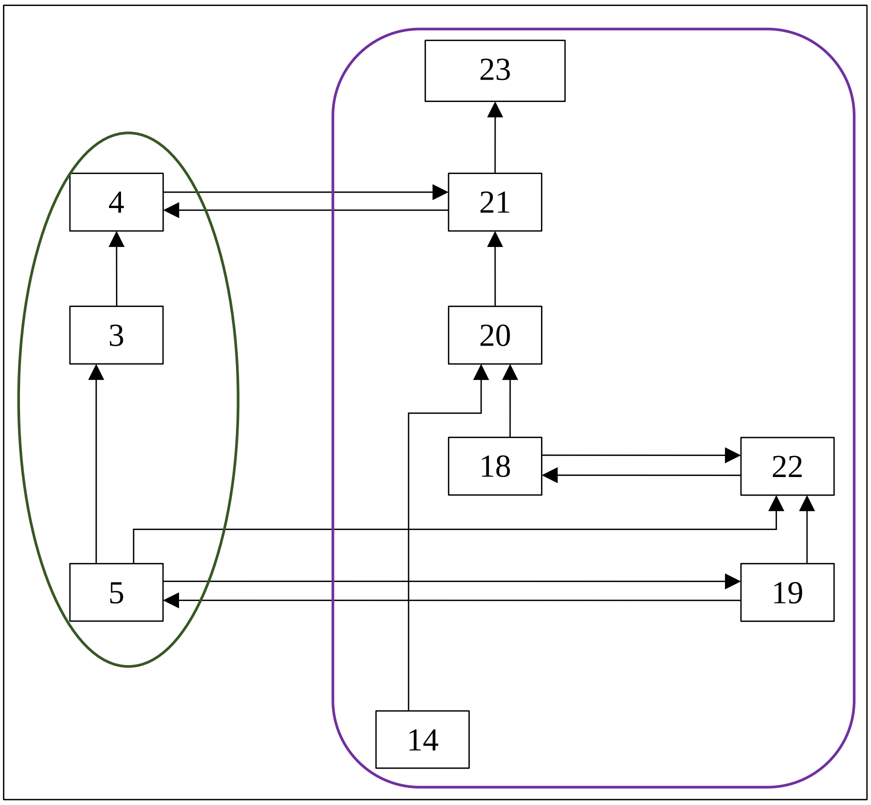

Figure 4-7 The Simplified Logical Relational Model of Simplification Based on the Causal Relationships among the Factors

Constructed from Figure 4-5, this simplified logical relational model (Figure 4-7) presents three processes: the effect of interactions among the three industrial policies (Factors 3, 4 and 5) (brown part), the approach for the industry to achieve sustainable development when the industrial policies (Factors 4 and 5) are stable (purple part), and the methods by which the three industrial policies support and manage the progress of sustainable development in the industrial low-carbon economy. Therefore, this simplified model could be further simplified and segmented into two models, referring to the rules presented in section 3.4.8 (3) (simplification based on causal relationships among factors) and 3.4.8 (4) (simplification based on the factors' stability).

The brown part shows that the industrial policy for low-carbon emission (Factor 5) influences the fiscal and monetary policy for industrial economy (Factor 4), through directly determining the industrial policy for structural adjustment (Factor 3), and Factor 3 directly determining Factor 5. This part therefore is recognised as the decision-making model for industrial fiscal and monetary policy (Figure 4-9).

The purple part represents how industrial sustainable development could be achieved when Factor 23 (industrial net profit in the low-carbon economy) is maintained larger than zero, with the assumption that the industrial policies (Factor 4 and 5) are stable. In this part, the industrial net profit (Factor 23) is determined by the industrial income tax payable (Factor 21) and the total profit for industry in the low-carbon economy (Factor 20), while Factor 20 is determined by the industrial GDP (Factor 14) and the industrial cost of reducing CO_2 emissions (Factor 18). Factor 18 is determined by its interaction with the industrial target for CO_2 emissions (Factor 22), which is affected by Factor 19 (amount of CO_2 emissions from industrial production), under a certain industrial policy for low-carbon emission (Factor 5). This part represents the process for achieving industrial sustainable development in the low-carbon economy under stable industrial policies, therefore it is identified as the model for industrial sustainable development in a low-carbon economy (Figure 4-10).

The three industrial policies affect industrial sustainable development through two methods, which are the direct influence from the interaction between Factor 5 (industrial policy for low-carbon emission) and Factor 19 (amount of CO_2 emissions from industrial production); and the direct influence from the interaction between Factor 4 (fiscal and monetary policy for industrial economy) and Factor 21 (income tax payable by industry in the low-carbon economy). Therefore, they suggest that the government could either make appropriate fiscal and monetary policies for the industrial economy (Factor 4) to reduce industrial income taxation (Factor 21), or determine a more rational industrial low-carbon policy (Factor 5) and industrial target for CO_2 emissions (Factor 22) for reducing the cost of low-carbon emission (Factor 18), for maintaining the industrial net profit (Factor 23) and supporting the industrial sustainable development in the low-carbon economy.

4.8.4 The Decision-Making Models for Industrial Low-carbon Emission Policy and Industrial Fiscal and Monetary Policy

Constructed in section 4.8.3 (Figure 4-5), the decision-making model for industrial low-carbon emission policy (Figure 4-8) shows the approach and the factors considered by the government in its industrial policy for low-carbon emission (Factor 5). The industrial factors providing the industrial information to the policy maker for this decision-making are: natural resources required in industrial production (Factor 15), capital employed in industrial production (Factor 16), quantity of labour involved in industrial production (Factor 17), and industrial production technology (Factor 12), which determine the industrial GDP (Factor 14). The industrial GDP (Factor 14) interacts with other macro factors, which are fiscal and monetary policy for macro-economy (Factor 2), GDP (Factor 6), GDP growth rate (Factor 7), national income per capita (Factor 9) and disposable income per capita (Factor 10), together affecting policy and law in the improving the educational level and cultural standards (Factor 1) and educational level and cultural standards (Factor 11). Finally, Factors 1 and 11 together determine the industrial policy for low-carbon emission (Factor 5). The root causes in this model is still population (Factor 8), and industrial production technology (Factor 12), which means human and industrial technology are still the fundamental factors when making low-carbon policy for one industry.

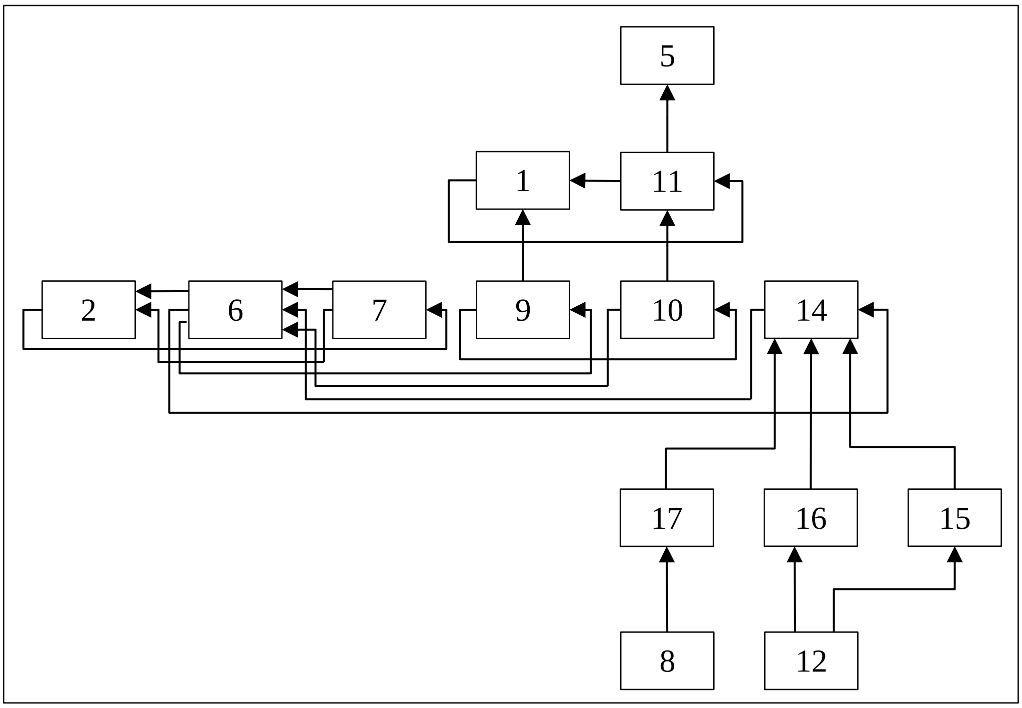

Figure 4-8 The Decision-Making Model for Industrial Low-carbon Emission Policy

The decision making model for industrial fiscal and monetary policy (Figure 4-9), constructed in section 4.8.3 (Figure 4-6), presents the pathway by which the fiscal and monetary policy for industrial economy (Factor 4) is determined. The fiscal and monetary policy is determined by industrial policy for structural adjustment (Factor 3), which in turn is influenced by industrial policy for low-carbon emission (Factor 5). This model suggests that the application for the industrial policy for low-carbon emission affects the low-carbon procedure, both through its own effect on Factor 19, and through its impact on the fiscal and monetary policy for industrial economy. Therefore, an appropriate fiscal and monetary policy for industrial economy could support sustainable development in the industrial low-carbon economy.

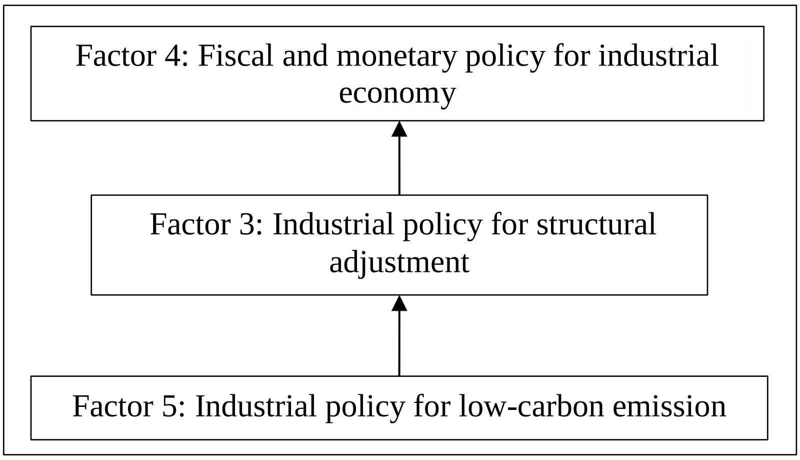

Figure 4-9 The Decision-Making Model for Industrial Fiscal and Monetary Policy

The decision-making models for industrial low-carbon emission policy and for industrial fiscal and monetary policy focus on the construction process of the policies. Moreover, the factors contained within these two models are mainly macro-variables related to the policy and law, macro-economy, and society dimensions, which could not be validated from the industrial data. However, these two models provide a method for further adjustments to these two policies.

4.8.5 The Model for the Sustainable Development in an Industrial Low-carbon Economy

Constructed in section 4.8.3 (Figure 4-6), the model for sustainable development in an industrial low-carbon economy (Figure 4-10) represents the approach for industry to achieve sustainable development, when the industrial policies (Factor 3, 4 and 5) are stable in certain periods, which is through maintaining the industrial net profit in the low-carbon economy (Factor 23). The environmental request (industrial target for CO_2 emissions Factor 22) impacts industrial economic development through containing the industrial cost for reducing CO_2 emissions (Factor 18) within the production cost, as the production function constructed in section 4.2 suggested. The industrial cost of low-carbon emission directly affects the total profit for industry (Factor 20).

Once the total profit for industry can afford both the industrial cost of reducing CO_2 emissions and the industrial income tax payable (Factor 21), meaning the industrial net profit in the low-carbon economy (Factor 23) is greater than zero, this industry could achieve sustainable development. Otherwise, it indicates that the industry could not afford the cost of reducing CO_2 emissions, or after affording the low-carbon cost, it would be impossible for this industry to pay its income tax. In this case, the industry could not achieve sustainable development by itself, so it would be time for the government to become involved and support the industry.

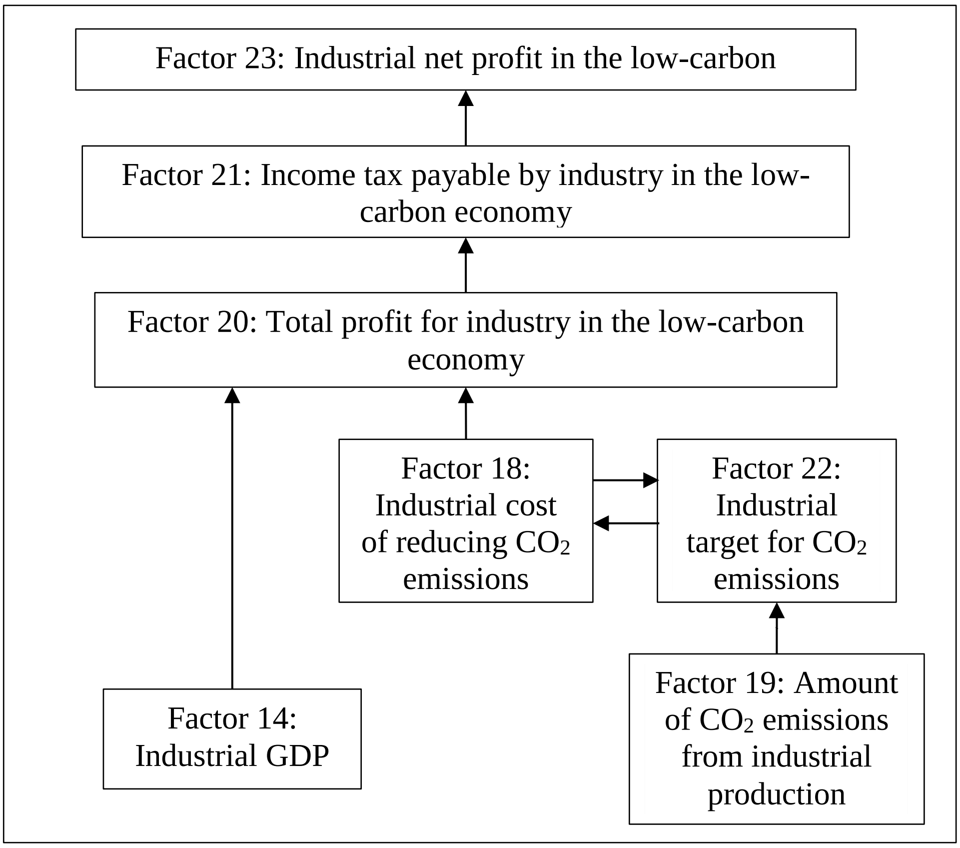

Figure 4-10 The Model for the Sustainable Development in an Industrial Low-carbon Economy

Moreover, because the factors involved in this model could be quantified, therefore this model could quantitatively present the approach for industry to achieve its sustainable development. This model also could be validated through the real time industrial data. In summary, this model for industrial sustainable development can qualitatively and quantitatively support both the government and the industry to assess the industry's capability and manage the industrial procedure for achieving sustainable development in the low-carbon economy.

4.8.6 The Model for the Optimal Approach to Low-carbon Emission in an Industrial Low-carbon Economy

Constructed in section 4.8.3, this model (Figure 4-11) represents the causal relationships among the process for producing, releasing and curbing CO_2 emissions. It indicates that the amount of CO_2 emissions from industrial production (Factor 19) is determined by the natural resources (Factor 15) and the industrial production technology (Factor 12); and Factor 19 reciprocally impacts and restrains the industrial policy for low-carbon emission (Factor 5). This model also shows that the amount of natural resources required depends on the industrial production technology. As the factors (Factor 12, 15 and 19) regarding the production of CO_2 emissions could be quantified, this model could both qualitatively and quantitatively present the process for producing and controlling CO_2 emissions.

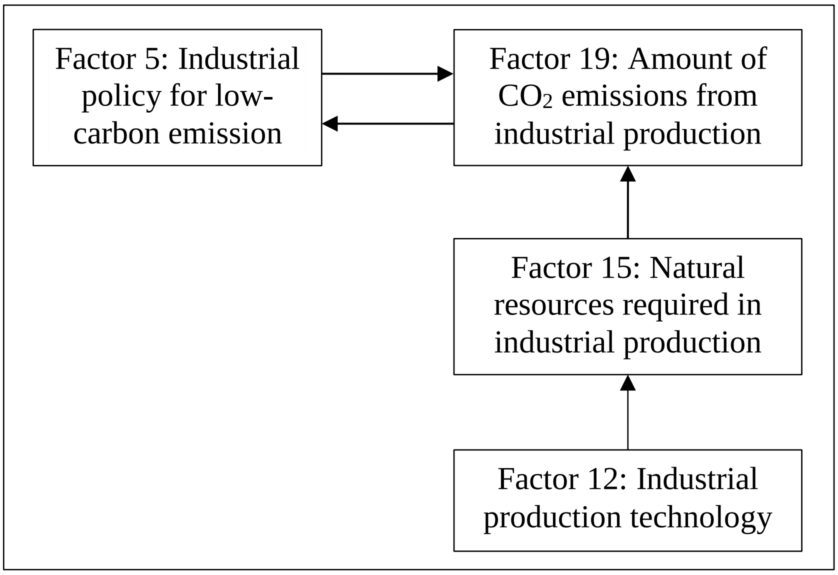

Figure 4-11 The Model for the Optimal Approach to Low-carbon Emission for the Industrial Low-carbon Economy

This model indicates that industry can reduce the amount of CO_2 emissions (Factor 19) through updating the industrial production technology (Factor 12) and improving efficiency in the use of natural resources, to reduce their consumption (Factor 15).

However, this procedure of upgrading technology may increase the cost of industrial production, and therefore the industry may require support from the industrial policy for low-carbon emission (Factor 5). Nevertheless, if production is based on an industrial production technology, which consumes natural resources not containing carbon, then the amount of CO_2 emissions from this type of industrial production (Factor 19) will be zero. Therefore, this model identifies and supports the industry in managing the optimal approach for achieving low-carbon and even no-carbon emission. This model also supports the policymaker in formulating the appropriate industrial policy for low-carbon emission.

4.8.7 The Theoretical Model for Economic Growth and CO_2 Emissions

Constructed in section 4.8.3, this model (Figure 4-12) represents the causal relationships among factors related to economic growth and CO_2 emissions.

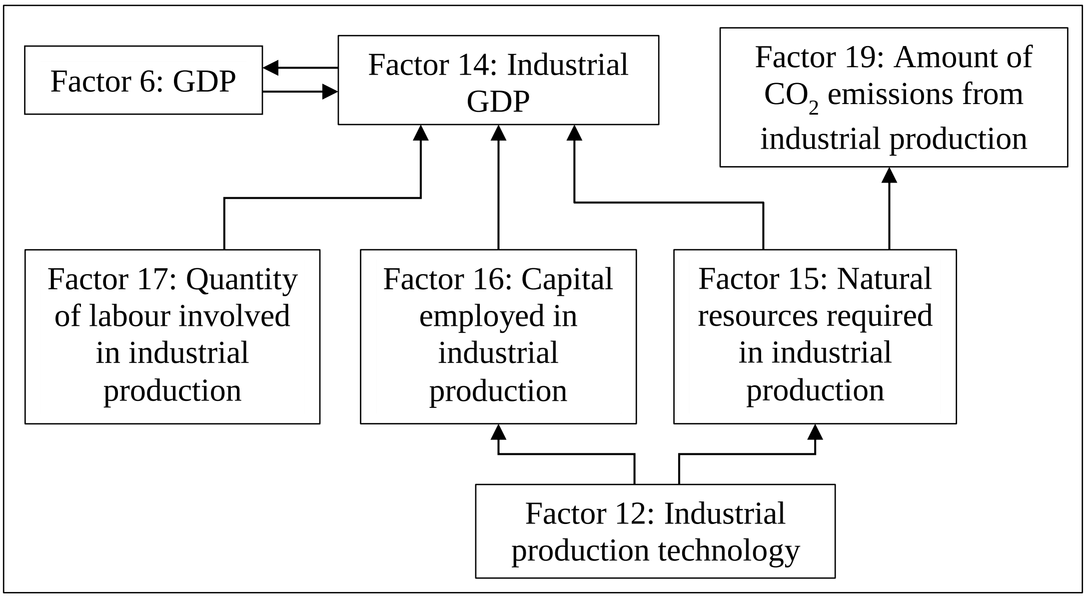

Figure 4-12 The Theoretical Model for Economic Growth and CO_2 Emissions

This model indicates that the industrial economic production requires natural resources, capital, labour, and production technology as input, and the industrial GDP and the CO_2 emissions are the economic and environmental output. In detail, the model shows that the industrial GDP (Factor 14) is determined by natural resources required in industrial production (Factor 15), capital employed in industrial production (Factor 16), quantity of labour involved in industrial production (Factor 17) and industrial production technology (Factor 12); on the other hand, industrial production technology and the natural resources required determine the amount of CO_2 emissions (Factor 19). Therefore, there is positive correlation between the industrial GDP and the amount of CO_2 emissions by industry.

The industrial GDP (Factor 14) and national GDP (Factor 6) directly influence each other, as national GDP is the sum of every industries' GDP, and are determined by factors from the bottom levels (Factors 15, 16, 17 and 12). However, as there is no causal relationship between the amount of CO_2 emissions from industrial production (Factor 19) and industrial GDP, neither is there a causal relationship between the amount of CO_2 emissions from industrial production and national GDP (Factor 6). Therefore, there is no causal relationship between GDP and the sum of each industry's CO_2 emissions, which is sum of Factor 19 from different industries.

4.9 Chapter Summary

This chapter implemented the research methodology for a low-carbon economy system and constructed the production function for an industrial low-carbon economy. It described the selection of the dimensions and factors for the system, and the construction of the dimensional structure model, the factors' relational model, the hierarchical structure model and the logical relational model for the industrial low-carbon economy. Through simplification of the logical relational model, the following were established: the model for industrial sustainable development, the model for the optimal approach to low-carbon emission, the theoretical model for economic growth and CO_2 emissions, the decision-making model for industrial low-carbon emission policy and the decision-making model for industrial fiscal and monetary policy.

The model for industrial sustainable development indicates that the sustainable approach to achieving both the low-carbon emission target and economic development is that the cost of reducing CO_2 emissions must be afforded within the total profit for industry, under a given industrial fiscal and monetary policy and industrial low-carbon emission policy. It also indicates that if sustainable development could not be achieved, the government could then support the industry either through a supportive fiscal and monetary policy for industry reducing its income tax, or by a more reasonable industrial policy of low-carbon emission reducing the cost for the CO_2 emissions reduction. The model for the optimal approach to low-carbon emission indicates that to reduce CO_2 emissions during the production process, the industrial production technology must be improved to increase the efficient use of natural resources or by updating the technology to use the non-carbon resources. The theoretical model for economic growth and CO_2 emissions indicates that there is no causal relationship between (industrial) economic growth and CO_2 emissions. The next chapter will apply these three theoretical models to the Chinese thermal electricity generation industry, to validate them and the research methodology established in chapter 3.

The decision-making models for the industrial low-carbon emission and industrial fiscal and monetary policies, contain the macro-factors related to policy and law, macro-economy, and society dimensions, and indicate the construction process for these policies. These two models could support further adjustments, if required, although they could not be validated based on the industrial data. Instead, their validation would require further research into the system that is beyond the scope of a study at the industrial level, and will be carried out at the national level.

Chapter 5 The Theoretical Models for the Industrial Low-carbon Economy System for the Chinese Thermal Electricity Generation Industry

5.1 Introduction

Referring to the research methodology introduced in chapter 3, this chapter mainly applies the theoretical models constructed in chapter 4 into the Chinese thermal electricity generation industry. In order to do so, this chapter first defines and introduces this Chinese industry, and then explains the factors' meanings specifically for this industry, referring to their selection and analysis in pervious chapters. After clarifying the dimensions and factors meaning in the low-carbon economy system regarding this industry, this chapter then develops the logical relational model, the model for industrial sustainable development in a low-carbon economy, the model for the optimal approach to low-carbon emission, and the model for economic growth and CO_2 emissions, for this Chinese industry.

5.2 Data Source and Illustration

5.2.1 Data Source

The data used in this chapter were collected from the National Bureau of Statistics of the Peoples' Republic of China, the China Electricity Council, the China Carbon Trade Network, the China Industry Statistical Yearbook, the Macro China Database, the China Taxation Yearbook and the Electric Power Planning and Engineering Institute, which are the authoritative data sources provided by the corresponding government sectors in China.

First, the macroeconomic data, like GDP and industrial economic data are collected from the National Bureau of Statistics, the China Industry Statistical Yearbook, the Macro China Database, and the China Taxation Yearbook. Secondly, the data related to the production of electricity in the Chinese thermal electricity generation industry are collected from the China Electricity Council. Thirdly, the environmental data related to

CO_2 based on the energy balance sheet (physical quantity), are also collected from the National Bureau of Statistics. Then, the data related to carbon trade in China are collected from the China Carbon Trade Network. Finally, the data related to industrial technology improvement is collected from the publications of the Electric Power Planning and Engineering Institute (2014).

5.2.2 Data Illustration

Inevitably, there are statistical differences among the data collection processes of the National Bureau of Statistics and the China Electricity Council. However, as the National Bureau of Statistics represents national-level statistical data guaranteed by the government, this study prefers its data when both sources available for a given factor.

However, the industrial data from the National Bureau of Statistics is based on the industrial category for electricity generation (EG), combining the different methods of generation and hot water production. Therefore, this study will use this combined industrial data calculating the data for thermal electricity generation as the proportion of its market share.

This study has been proposed to use the international system of units: 1 kiloton (kt) = 1000 tonnes (t) = 10^6 kilogram (kg) = 10^9 gram (g); 1 billion = 10^9, 1 million = 10^6; 1 m^{-3} = 1 cubic metre; 1 terajoule (TJ) = 10^9 kilojoule (kJ) = 10^{12} joule (J). For the thermal power generator 1MW = 1000 KW = 10^6 W. At 15ºC, 1 kcal = 29307.6 kJ, which is the converting standard used in the Chinese thermal electricity generation industry.

5.3 General Statement of the Chinese Thermal Electricity Generation Industry

In this section, this study will present the definition and three analyses regarding the Chinese thermal electricity generation industry to briefly introduce this industry. The production scale, market position and power plants' capacity will be analysed, indicating that the thermal electricity generation industry is taking a strong position in the continuously growing market for Chinese electricity. Moreover, the capacity of the power plants' in this industry is generally over the capacity of 6000KW.

5.3.1 Definition of the Chinese Thermal Electricity Generation Industry

In thermal electricity generation (thermal power generation), the heat energy from burning fossil fuels, like coal, oil and gas, is converted into electrical energy through thermal power plants. This industry presents this thermal electricity generation proceeding, where it also produces district heating and hot water using the heat energy produced (National Bureau of Statistics of the Peoples' Republic of China, 2011).

5.3.2 Economic Scale and Market Position

To indicate the scale of production and the market position of the Chinese thermal electricity generation industry, this section draws on data from the National Bureau of Statistics, finding that the total production of electricity increased each year from 2000 to 2013 (Figure 5-1), as did that of the thermal electricity generation. Hydroelectricity, nuclear power and wind power also increased but with a higher growth rates.

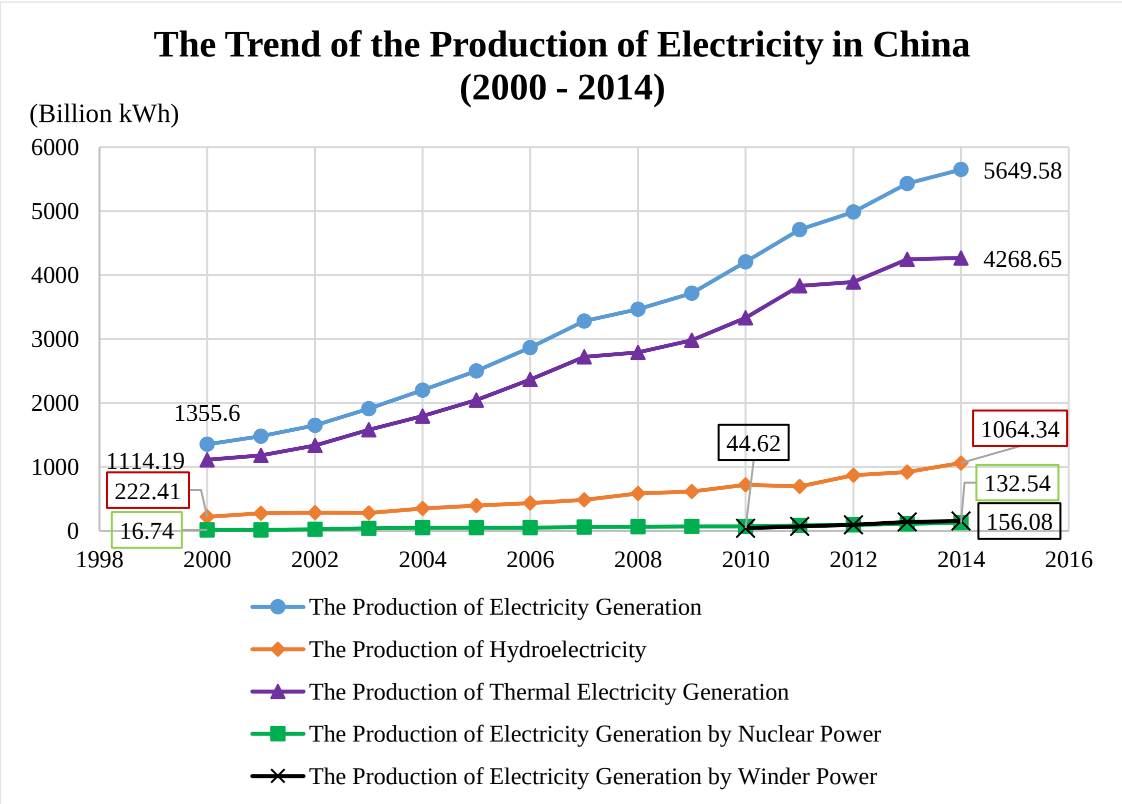

Figure 5-1 The Trend of the Production of Electricity in China (2000 – 2014)

The thermal electricity generation industry's market share remained stable at around 80.88% throughout these years (Figures 5-1 and 5-2). Thermal power stations produced the majority of electricity in China, and their production rapidly increased to meet national demand. Electricity generated by all renewable sources remained at around 20%. Nevertheless, thermal electricity's market share has slowly and uncertainly decreased since 2007 (Figure 5-2).

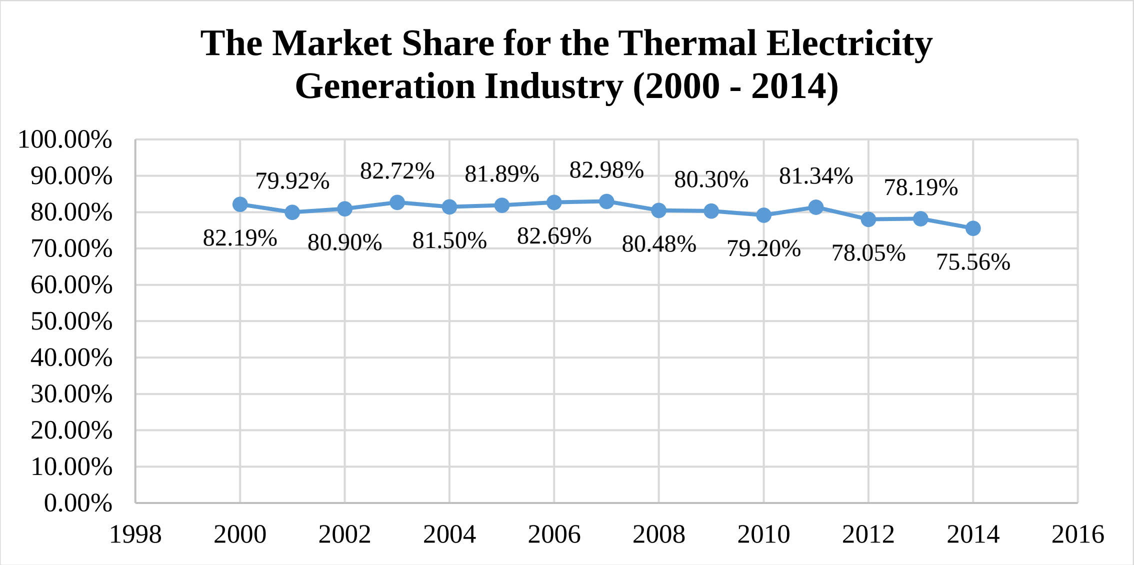

Figure 5-2 The Market Share for the Thermal Electricity Generation Industry (2000 - 2014)

5.3.3 The Percentage of Thermal Power Plants with 6000kW Capacity or above

From 2008 to 2014, an average of 99.77% of Chinese thermal electricity was generated by power plants whose capacity was more than 6000kw (Figure 5-3) through the calculation. Therefore, this research uses this data for the thermal power plants with 6000kW capacity or more from the China Electricity Council, to represent the entire thermal electricity generation industry.

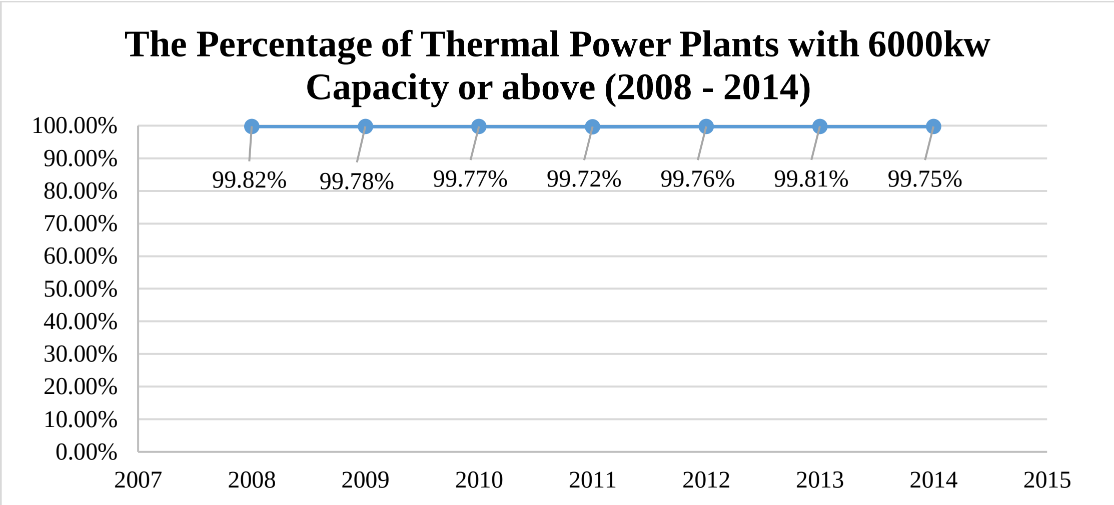

Figure 5-3 The Percentage of Thermal Power Plants with 6000kW Capacity or above (2008 – 2014)

5.4 The Industrial Low-carbon Economy System for Chinese Thermal Electricity Generation Industry

5.4.1 Selection of the Dimensions and Factors for Industrial System

The dimensions for Chinese thermal electricity generation industry are based on those in the logical relational model developed in section 4.7: policy and law (P), macro-economy (E), society (S), industrial technology (T_i), industrial economy in the low-carbon economy (E_i), carrying capacity (N_e), and development goal for industrial low-carbon economy (G_{ce}). Moreover, the factors in each dimension are also based on the model in section 4.7.

These applied as follows:

- P involves improving the educational level and cultural standards, fiscal and monetary policy for macro-economy, industrial policy for structural adjustment, fiscal and monetary policy for industrial economy, and industrial policy for low-carbon emission.
- The selected factors for E are GDP and GDP growth rate.
- For S, they are population, national income per capita, disposable income per capita, and educational level and cultural standards.

- For T_i they are industrial production technology and industrial technology for CO_2 pollution treatment.
- For E_i they are industrial GDP, natural resources required in industrial production, capital employed in industrial production, quantity of labour involved in industrial production, industrial cost of reducing CO_2 emissions, amount of CO_2 emissions from industrial production, total profit for industry in the low-carbon economy, and income tax payable by industry in the low-carbon economy.
- For N_e the selected factor is the industrial target for CO_2 emissions.
- For G_{ce} it is the industrial net profit in the low-carbon economy.

The symbols and numeral list for these dimensions and factors, originally presented in Table 4-1, is repeated below in Table 5-1.

Table 5-1 The Symbols and Numeral List for the Dimensions and Factors in the Industrial Low-carbon Economy System for Chinese Thermal Electricity Generation Industry

Factors' No.	**Dimensions**	**Factors**
1	Policy and Law Dimension (P)	Policy and law in improving the educational level and cultural standards
2		Fiscal and monetary policy for macro-economy
3		Industrial policy for structural adjustment
4		Fiscal and monetary policy for industrial economy
5		Industrial policy for low-carbon emission
6	Macro-economy Dimension (E)	GDP
7		GDP growth rate
8	Society Dimension (S)	Population
9		National income per capita
10		Disposable income per capita
11		Educational level and cultural standards
12	Industrial Technology Dimension (T_i)	Industrial production technology
13		Industrial technology for CO_2 pollution treatment
14	Industrial Economy Dimension in the low-carbon economy (E_i)	Industrial GDP
15		Natural resources required in industrial production

16		Capital employed in industrial production
17		Quantity of labour involved in industrial production
18		Industrial cost of reducing CO_2 emissions
19		Amount of CO_2 emissions from industrial production
20		Total profit for industry in the low-carbon economy
21		Income tax payable by industry in the low-carbon economy
22	Carrying Capacity Dimension (N_e)	Industrial target for CO_2 emissions
23	Development Goal for Industrial Low-carbon Economy Dimension (G_{ce})	Industrial net profit in the low-carbon economy

5.4.2 Factors for the Industrial Low-carbon Economy System in the Chinese Thermal Electricity Generation Industry

5.4.2.1 Factors for the Policy and Law Dimension

5.4.2.1.1 Analysis of the Policy and Law Factors in Improving the Educational Level and Cultural Standards

The policies and laws to improve the educational level and cultural standards in China since 2005 are listed below. There are 20 laws and policies current effectively maintain the improvement of educational level in China. Four laws are legislation foundation regarding education; another four policies relate to improving the standards of compulsory education, while three laws relate to improving the standards of higher education, two policies relate to improving the standards of national education, and another three policies regards to improving the standards of vocational education. Finally, there are four policies for improving the standards of education on environmental protection. On the other hand, there are eleven effective policies and laws in total concerning raising cultural standards. These policies and laws promote to improve the residents' educational level, satisfying their requirements of education, as well as influence the social behaviour and guide them into an energy saving society (Mackerras et al., 1998; Ao, 2013; Zhang, 2011).

(1) The effective laws related to improving the educational level are:

- 29 June 2013 – *Non-State Education Promotion Law of the People's Republic of China (2013 Amendment)*, issued by the Standing Committee of the National People’s Congress.
- 24 April 2015 – *Compulsory Education Law of the People's Republic of China*, issued by the Standing Committee of the National People’s Congress.
- 27 December 2015 – *Decision on Amending the Education Law of the People's Republic of China*, issued by the Standing Committee of the National People’s Congress.
- 27 December 2015 – *Higher Education Law of the People's Republic of China*, issued by the Standing Committee of the National People’s Congress.

(2) The effective policies related to improving the standards of compulsory education are:

- 25 May 2005 – *Some Opinions on Education on Further Promoting the Balanced Development of Compulsory Education*, issued by Ministry of Education.
- 24 December 2005 – *Circular on Deepening the Reform of the Guarantee Mechanism for Rural Compulsory Education Funds*, issued by the State Council.
- 24 November 2010 – *Several Opinions on Current Development of Preschool Education*, issued by the State Council.
- 27 September 2012 – *Some Opinions on Further Promoting the Balanced Development of Compulsory Education*, issued by the State Council.

(3) The effective laws related to improving the standards of higher education are:

- 28 October 2010 – *Circular on Printing and Distributing the Measures for the Administrating Special Funds for the Development of Local Colleges and Universities Supported by the Central Government*, issued by the Ministry of Finance and the Ministry of Education.
- 16 March 2012 – *Opinions on Improving the Quality of Higher Education (Jiao Gao [2012] No. 4)*, issued by the Ministry of Education.

- 2 March 2013 – *Opinions on Improving the Investment Mechanism of Postgraduate Education*, issued by the Ministry of Finance, the National Development and Reform Commission, and the Ministry of Education.

(4) The effective policies related to improving the standards of national education are:

- 15 November 2014 – *Notice on Printing and Distributing the Education and Scientific Research Plan for National Education (2014-2020)*, issued by the General Office of the Ministry of Education.
- 17 August 2015 – *Decision on Expediting the Development of Ethnic Education*, issued by the State Council.

(5) The effective policies related to improving the standards of vocational education are:

- 28 October 2005 – *Decision on Vigorously Developing Vocational Education*, issued by the State Council.
- 22 June 2014 – *Decision on Accelerating the Development of Modern Vocational Education*, issued by the State Council.
- 26 October 2015 – *Notice on Printing and Distributing the Guiding Opinions on Accelerating the Development of Vocational Education on Modern Tourism*, issued by China National Tourism Administration and the Ministry of Education.

(6) The effective policies related to improving the standards of education on environmental protection are:

- 14 September 2007 – *Notice on School-Based Actions for Energy Conservation and Emissions Reduction*, issued by the Ministry of Education.
- 31 January 2008 – *Notice on Printing and Distributing of the Main Points of the 2008 National Environmental Publicity and Education Works*, issued by the General Office of the Ministry of Environmental Protection.
- 22 October 2013 – *Notice on Printing and Distributing the Measures for the Nationwide Application and Administration of Social Practice Bases for Environmental Education in Primary and Secondary Schools (for Trial*

Implementation), issued by the General Office of the Ministry of Environmental Protection and the General Office of the Ministry of Education.

- 4 June 2014 – *Notice on Printing and Distributing the Administrative Measures on the Review and Acceptance of Pilot Projects for the Construction of an Energy-saving Supervision and Management System on Campus (for Trial Implementation)*, issued by the Ministry of Housing and Urban-Rural Development and the Ministry of Education.

Secondly, the policies and laws concerning cultural standards:

(1) The effective laws related to raising cultural standards are:

- 6 April 2005 – *Archives Law of the People's Republic of China*, issued by the Standing Committee of the National People's Congress.
- 29 December 2006 – *Decision on Ratifying the Convention on the Protection and Promotion of the Diversity of Cultural Expressions*, issued by the Standing Committee of the National People's Congress.
- 26 February 2010 – *Decision on Amending the Copyright Law of the People's Republic of China*, issued by the Standing Committee of the National People's Congress.
- 25 February 2011 – *Intangible Cultural Heritage Law of the People's Republic of China*, issued by the Standing Committee of the National People's Congress.

(2) The effective policies related to raising cultural standards are:

- 5 July 2009 – *Opinions on Promoting Ethnic Minorities' Cultural and Arts Undertakings*, issued by the State Council.
- 15 November 2011 – *Guiding Opinions on Further Strengthening the Establishment of Public Digital Culture*, the Ministry of Culture and Ministry of Finance.
- 2 February 2012 – *Guiding Opinions on Strengthening the Productive Protection of Intangible Cultural Heritage*, the Ministry of Culture.
- 14 January 2013 – *Circular on Printing and Distributing the Ministry of Culture's Implementation Framework of the Construction of a Public Culture*

Service System in the 12th Five-Year-Plan Period, issued by the Ministry of Culture.

- 14 January 2015 – *Opinions on Accelerating the Construction of a Modern Public Culture Service System*, issued by the General Office of the Communist Party of China and the General Office of the State Council.
- 5 May 2015 – *Notice on Suggestions on the Successful Accomplishment of the Governmental Purchasing of Public Cultural Services from Societal Sources*, forwarded by the General Office of the State Council to the Ministry of Culture and other relevant departments.
- 2 October 2015 – *Guiding Opinions on Promoting the Construction of Basic-Level Comprehensive Cultural Service Centres*, the General Office of the State Council.

5.4.2.1.2 Analysis of Fiscal and Monetary Policy for Macro-economy

First, the fiscal policy for the macro-economy stimulates or constrains the macro-economic trends mainly through taxation and subsidies. Specifically, these could maintain the macro-economic growth rate at a certain level, keep a low unemployment rate, preserve a low or stable inflation rate, and balance in imports and exports. The stable and growing macro-economy is essential for this industrial development. In 2008, because of the financial crisis, this industry results in an immediate minus total profit, seen in later analysis. Therefore, the related fiscal policy for maintaining the macro-economic development is necessary. The effective fiscal policies for Chinese macro-economy since 2005 are listed here:

- 15 December 2008 – *Detailed Rules for the Implementation of the Interim Regulations of the People's Republic of China on the Consumption Tax*, issued by the Ministry of Finance and the State Administration of Taxation.
- 28 October 2011 – *Decision on Amending the Detailed Rules for the Implementation of Provisional Regulations on the Value-Added Tax and the Detailed Rules for the Implementation of the Interim Regulations on the Business Tax of the People's Republic of China*, issued by the Ministry of Finance.

- 28 October 2011 – *Detailed Rules for the Implementation of the Interim Regulations of the People's Republic of China on the Resource Tax*, issued by the Ministry of Finance.
- 4 July 2014 – *Supplementary Circular on Issues Concerning Preferential Policies for the Enterprise Income Tax for Public Infrastructure Projects*, issued by the Ministry of Finance and the State Administration of Taxation.
- 1 August 2014 – *Announcement on the Exemption of the Purchase Tax on New Energy Vehicles*, issued by the Ministry of Finance, the State Administration of Taxation, and the Ministry of Industry and Information Technology.
- 6 August 2014 – *Guiding Opinions of the State Council on Further Piloting the Paid Use and Trading of Emissions Permits*, issued by the General Office of the State Council.
- 8 October 2014 – *Notice on Adjusting the Import Tariff Rates of Coal*, issued by the Customs Tariff Commission of the State Council.
- 9 October 2014 – *Notice on the Implementation of Coal Resource Tax Reform*, issued by the Ministry of Finance and the State Administration of Taxation.
- 9 October 2014 – *Notice on Adjusting the Relevant Policies on Crude Oil and Natural Gas Resource Taxes*, issued by the Ministry of Finance and the State Administration of Taxation.
- 18 November 2014 – *Notice on the Reward Policy for Constructing Charging Facilities for New Energy Vehicles*, issued by the Ministry of Finance, the Ministry of Science and Technology, the Ministry of Industry and Information Technology, and the Development and Reform Commission;
- 25 November 2014 – *Notice on Adjusting Consumption Tax Policies*, issued by the Ministry of Finance and the State Administration of Taxation;
- 26 December 2014 – *Notice on Issues Concerning the Adjustment of Preferential Tax Policies for Imported Natural Gas*, issued by the Ministry of Finance, the General Administration of Customs, and the State Administration of Taxation; and
- 12 January 2015 – *Notice on Continuous Increase the Consumption Tax on Oil Products*, issued by the Ministry of Finance and the State Administration of Taxation.

Secondly, the monetary policy for macro-economy controls the money supply and withdrawal through the interest rate. This policy also regulates the demand and supply in product market through the policies on monetary aggregates and the credit polices of financial institutions. Monetary policy also regulates the supply of foreign currency through the foreign exchange policy. The effective monetary policies for the Chinese macro-economy since 2005 are listed here:

- 3 July 2007 – *Notice on Printing and Distributing the Guidelines on Risk-Based Loan Categorization*, issued by the China Banking Regulatory Commission.
- 12 March 2008 – *Guiding Opinions on Banking and Financial Institutions to Support the Acceleration of the Development of the Service Sector*, issued by the China Banking Regulatory Commission.
- 18 March 2009 – *Guiding Opinions on Further Strengthening the Adjustment of Credit Structure to Promote the Rapid but Steady Development of the National Economy*, issued by The People's Bank of China and the China Banking Regulatory Commission.
- 12 February 2010 – *Interim Measures for the Administration of Working Capital Loans*, issued by the China Banking Regulatory Commission.
- 14 November 2013 – *Administrative Measures for Pilot Consumer Finance Companies*, issued by the China Banking Regulatory Commission.

5.4.2.1.3 Analysis of Industrial Policy for Structural Adjustment

The trend of the industrial policy for structural adjustment in the thermal electricity generation industry is to remove those enterprises that are high-energy consumers and high-pollution releasers. Specifically, these industrial policies involve accelerating the upgrading of current power units to reduce emissions, and upgrading or closing small-scale thermal power plants with high coal consumption and heavy pollution in local situations. These policies also promote the integrating production of coal and electricity, accelerating the construction of large-scale coal-electricity production bases, and encouraging the development of combined the heat and electricity production. The effective industrial policies for structural adjustment since 2005 are listed here:

- 2007 – *Notice of Opinions on Accelerating the Closure of Small Thermal Power Generating Units (Guo Fa [2007] No. 2)*, promulgated by the State Council.
- 2011 – *Administrative Measures on Power Generating Units Entering and Exiting Business Operations*, promulgated by the State Electricity Regulatory Commission.
- 9 March 2012 – *The Electricity Generation Industry's 12th Five-Year Plan Research Report*, issued by the China Electricity Council.
- 2012 – *Notice on Further Strengthening the Elimination of Outdated Production Capacity (Guo Fa [2010] No.7)*, issued by the State Council.
- 2012 – *The 12th Five-Year Plan on Renewable Energy Planning Objectives*, issued by the National Energy Administration.
- 2013 – *Notice on the Adjustment of Renewable Energy Electricity Additional Charging Standards and the Environmental Protection Electricity Charging Standards*, issued by the National Development and Reform Commission.
- 6 January 2014 – *Notice on Printing and Distributing the Interim Measures for the Promotion and Management of Energy-Saving and Low-Carbon Technology*, issued by the National Development and Reform Commission.
- 12 September 2014 – *Action Plan on Energy-saving, Emissions Reduction, and the Upgrading of Coal-Fired Power Generation (2014-2020)*, jointly issued by the National Development and Reform Commission, the Ministry of Environmental Protection, and the National Energy Administration.
- 2 December 2015 – *Notice on Issues Related to the Implementation of Policies Supporting the Electricity Fee Structure of Ultra Low Emissions Coal-Fired Power Plants*, issued by the National Development and Reform Commission, the Ministry of Environmental Protection and the National Energy Administration.

The *Action Plan on Energy-saving, Emissions Reduction, and the Upgrading of Coal-Fired Power Generation (2014-2020)*, requires the average coal consumption per unit of electricity supply by newly constructed coal-fired generating units throughout China to be less than 300 g/kWh. By 2020, the average coal consumption for the upgraded coal-fired generating units should be less than 310 g/kWh and for power plants with a capacity of 600,000 kW or above it should be less 300g/kWh. Moreover, new projects to construct thermal power stations are required to select the ultra-supercritical (USC) units with a capacity of 600,000 kW or above; simultaneously, efficient desulphurisation, denitrification and soot-removing facilities are required. In the eastern regions, newly constructed plants must meet the emission limits for turbines; in the central regions, they should approach or reach the emission limits in principle; and the western regions are encouraged to approach or meet the emission limits. This action plan also requires accelerating the elimination of conventional small-scale thermal power plants with a capacity of 50,000 kW or less, and the other outdated production capacity.

5.4.2.1.4 The Fiscal and Monetary Policy for Industrial Economy

The fiscal policy for control and regulation of industry's economic trends through tax and subsidies will adjust industrial demand, eventually achieving a balance between this industry and others and maintaining balance in the macro-economy. The effective fiscal policies for industrial economy since 2005 are listed here.

- 7 January 2014 – *Announcement on the Collection and Management of the Business Income Tax and the Implementation of the Preferential Policy for Energy Conservation Service Enterprises with the Energy Management Contract Project*, issued by the State Administration of Taxation and the National Development and Reform Commission. This announcement was to encourage enterprises to adopt the contract energy management model to provide energy-saving services and increase efforts on energy saving and emissions reduction. It clearly stipulated that enterprises meeting the conditions would enjoy a preferential policy of "three years of exemptions and another three years of half" for their business income tax.
- 29 September 2014 – The State Council decided during its 64th executive meeting that from 1 December 2014, the coal resource tax under *ad valorem* reform would be implemented and the relevant fees and funds would be rationalised. Tax rates under this plan would be limited to 2-10%. The governments of provinces, autonomous regions and municipalities directly under the central government would formulate the applicable tax rate. Prior to their

announcement, the tax rates should be reported to the Ministry of Finance and the State Administration of Taxation for review and approval.

- 12 May 2015 – *Interim Measures for the Management of Energy Conservation and Emissions Reduction Subsidy Funds*, issued by the Ministry of Finance. According to these measures, the budget of the central government would include special subsidies for energy conservation and emissions reduction.
- 19 January 2016 – *Notice on Issues Concerning the Collection of Special Funds for the Structural Adjustment of Industrial Enterprises*, promulgated by the Ministry of Finance. This notice supported the structural adjustment of industrial enterprises in China, and indicated that the Ministry of Finance would begin to levy monthly special funds for industrial enterprises' restructuring from 1 January 2016 onwards.

The monetary policy for the industrial economy regulates the demand and supply relationship of the industry, mainly through the credit policies of financial institutions. The effective monetary policies for industrial economy since 2005 are listed here.

- 23 November 2007 – *Notice on Printing and Distributing the Guiding Opinions on Credit Granting for Energy Conservation and Emissions Reduction*, issued by the China Banking Regulatory Commission.
- 19 April 2010 – *Notice on Opinions of Supporting Policies and Measures of Circular Economy Development*, issued by the National Development and Reform Commission, the People's Bank of China, and the China Banking Regulatory Commission.
- 28 May 2010 – *Opinions on Further Improving Financial Support for Energy Conservation, Emissions Reduction, and the Elimination of Outdated Production Capacity*, issued by the People's Bank of China and the China Banking Regulatory Commission.

5.4.2.1.5 Analysis of the Industrial Policy for Low-carbon Emission

Chinese natural resources determine that the main source of energy is coal-based. According to the 2005 National Development and Reform Commission Document (Guo Fa) No. 39, it is required that "the achievements of development and environmental protection should be scientifically evaluated. A method for green national economic accounting should be developed, in which the resource consumption, environmental damages, and environmental benefits will be gradually included in the evaluation system of economic development"(State Council, 2005).

In 2005, the Chinese government signed the Kyoto Protocol. In 2007, it issued the *Long-Term Renewable Energy Development Plan* and the *National Response to Climate Change Program*. During the *Copenhagen Summit (United Nations Climate Change Conference)*, it made a commitment to cut its CO_2 emissions per unit of GDP by 40% to 45% by 2020, compared to the emission level in 2005. Moreover, in the Chinese *12th and 13th Five-Year Plan*s (State Council, 2012; National Development and Reform Commission, 2016), the government added restraints on the increase of new thermal power stations, and specifically made provisions regarding the average standard coal (SC) consumption per unit of electricity supply during the thermal power production process. The effective industrial policy for low-carbon emission since 2005 are listed here.

- 2011 – *Emission Standard of the Air Pollutants for Thermal Power Plant (GB13223-2011)*, issued by the Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine.
- 2012 – *Notice on Printing and Distributing the 12th Five-year Development Plan on Energy Saving and Emissions Reduction (Guo Fa [2012] No.40)*, issued by the State Council.
- 2012 – *Notice on Printing and Distributing the Industrial Action Plan on Addressing Climate Change (2012-2020)*, issued by the Ministry of Industry and Information Technology, the National Development and Reform Commission, the Ministry of Science and Technology, and the Ministry of Finance.
- 2012 – *Notice on Printing and Distributing the 12th Five-Year Development Plan on Air Pollution Prevention and Treatment in Key Regions*, issued by the Ministry of Environmental Protection, the National Development and Reform Commission, and the Ministry of Finance.
- 2013 – *Notice on Printing and Distributing the 12th Five-Year Development Plan on National Environmental Protection Standards*, issued by the Ministry of Environmental Protection.

- 2013 – *Notice on Printing and Distributing the 12th Five-Year Special Development Plan on National Carbon Capture and Storage Technology*, issued by the Ministry of Science and Technology.
- 2013 – *Notice on Printing and Distributing the Air Pollution Prevention and Treatment Action Plan (Guo Fa [2013] No.37)*, issued by the State Council.
- 2013 – *National Strategies for Adaptation to Climate Change*, issued by the National Development and Reform Commission, the Ministry of Finance, the Ministry of Housing and Urban-Rural Development, the Ministry of Transport, the Ministry of Water Resources, the Ministry of Agriculture, the State Forestry Administration, China Meteorological Administration, and the State Oceanic Administration.
- 13 January 2014 – *Interim Measures for the Promotion and Management of Energy-Saving and Low-Carbon Technologies*, issued by the National Development and Reform Commission.
- 30 April 2014 – *Notice on Printing and Distributing the Assessment Methods for the Implementation of the Action Plan for the Prevention and Control of Atmospheric Pollution (for Trial Implementation) (Guo Ban Fa [2014] No.21)*, issued by the General Office of the State Council. On 21 July 2014, the *Detailed Rules* for these *Assessment Methods* were issued by the Ministry of Environmental Protection, the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Finance, the Ministry of Housing and Urban-Rural Development, and the National Energy Administration.
- 15 May 2014 - *Notice on Printing and Distributing the 2014-2015 Action Plan for Energy Conservation and Emission Reduction (Guo Ban Fa [2014] No.23)*, issued by the General Office of the State Council.
- 21 June 2014 – *Engineering Technical Specifications for Dust Removal of Thermal Power Plants (HJ2039-2014)*, issued by the Ministry of Environmental Protection.
- 21 June 2014 – *Management technical specification of the operation of flue gas treatment facilities of thermal power plant (HJ2040-2014)*, issued by the Ministry of Environmental Protection.

- 13 November 2014 – *National Climate Change Action Programme (2014-2020)*, issued by the National Development and Reform Commission.
- 18 November 2014 – *Implementation Plan for the Comprehensive Improvement of Coal-Fired Boiler Energy Saving and the Environmental Protection Programme*, issued by the National Development and Reform Commission, the Ministry of Environmental Protection, the Ministry of Finance, the General Administration of Quality Supervision, Inspection and Quarantine, the Ministry of Industry and Information Technology, the National Government Offices Administration, and the National Energy Administration.
- 29 December 2014 – *Interim Measures on the Alternative Management of Coal Consumption Reduction in Key Areas*, issued by the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Finance, the Ministry of Environmental Protection, the National Bureau of Statistics and the National Energy Administration.
- 31 December 2014 – *Implementation Plan for the Key Resource Recycling Project (Technology Promotion and Equipment Industrialisation)*, issued by the National Development and Reform Commission, the Ministry of Science and Technology, the Ministry of Industry and Information Technology, the Ministry of Finance, and the Ministry of Environmental Protection.
- 15 April 2015 – *Clean Production Evaluation Index System for the Electric Power (Coal-Fired Power Generation Enterprises) Industry*, issued by the National Development and Reform Commission, the Ministry of Environmental Protection, and the Ministry of Industry and Information Technology.
- 27 April 2015 – *Action Plan on the Clean and Highly-Efficient Utilisation of Coal (2015-2020)*, issued by the National Energy Administration.
- 31 December 2015 – *Guiding Opinions on Promoting Third-party Environmental Pollution Control in Coal-Fired Power Plants (Fa Gai Huan Zi [2015] No.3191)*, issued by the National Development and Reform Commission, the Ministry of Environmental Protection, and the National Energy Administration.
- 7 November 2016 - *The Thirteenth Five-Year Plan for the Development of Electricity Industry*, issued by the National Development and Reform Commission, and the National Energy Administration.

5.4.2.2 Factors for the Macro-economy Dimension for this Chinese Industrial System

5.4.2.2.1 Analysis of the Trends for GDP

The nominal GDP data is collected from National Bureau of Statistics of China (2015). The real GDP is calculated based on the data of the GDP_{2000} and the index for GDP (constant prices) (1978 as base year). The calculation is $GDP_t = GDP_{2000} \times (Index_t / Index_{2000})$, where the $index_t$ provided with the basis year of 1978, t presents the year (Figure 5-4).

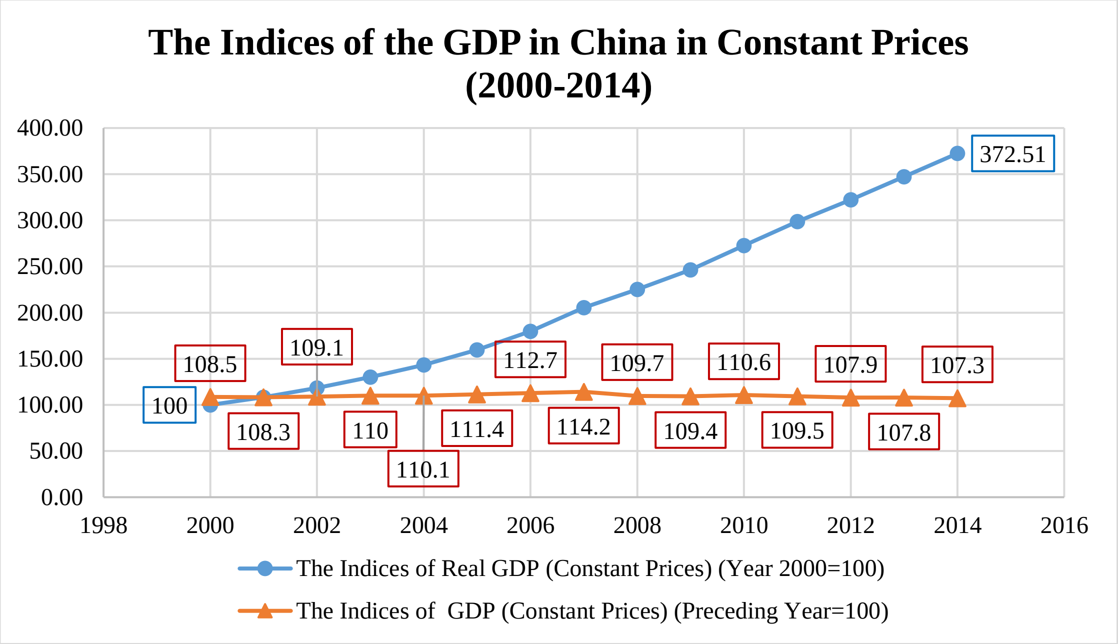

Figure 5-4 The Indices of the GDP in China in Constant Prices (2000 - 2014)

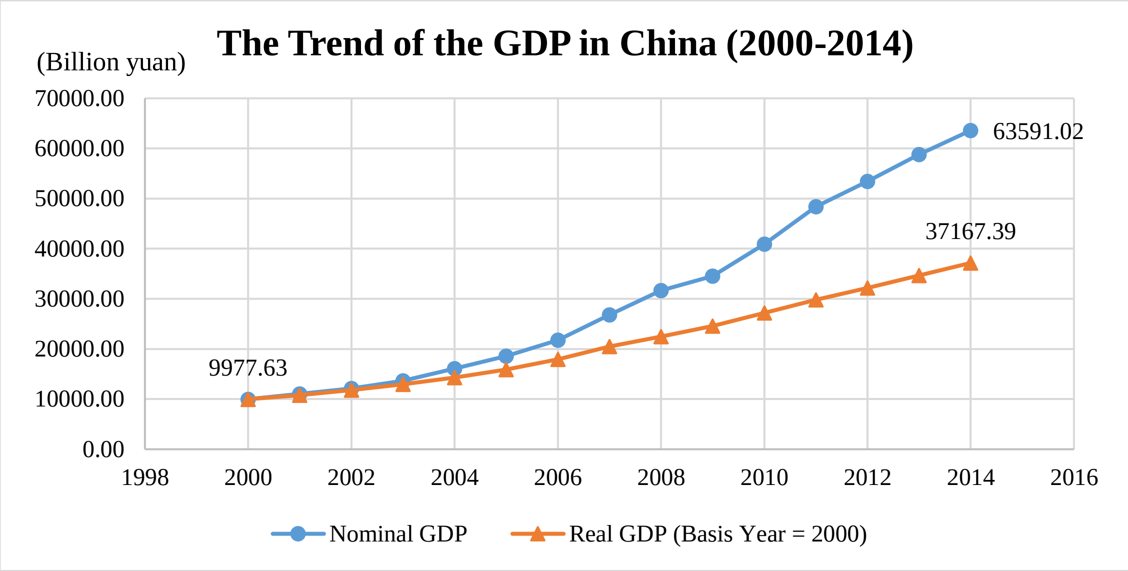

Figure 5-5 The Trend of the GDP in China (2000-2014)

From 2000 to 2014, the nominal GDP of China rapidly increased from 9,977.63 Billion Yuan to 67,670.8 Billion Yuan, while the real GDP from 2000 increased from 9,977.63 to 37,167.39 Billion Yuan (Figure 5-5). Both Figure 5-4 and Figure 5-5 show that the Chinese economy was growing rapidly and steadily, with the total scale of the economy increasing by 6.3 times from 2000 to 2014.

5.4.2.2.2 Analysis of the Trend for GDP Growth Rate

First, based on Figure 5-4, the overall Chinese economy rapidly growth from 2000 to 2014, as the indices of GDP (constant prices) increased from 100 in 2000 (base year) to 372.51 in 2014. However, shown by the indices of GDP (Preceding Year = 100), during 2000 to 2014, the Chinese economy first rapidly growth until 2007, when the indices reached the peak point of 114.2; after the financial crisis in 2008, the growth of the economy was slow down, as the indices gradually decreased to 107.3 in 2014.

Based on Figure 5-5, the CAGRs of nominal GDP and real GDP from 2000 to 2014 are calculated, with 2000 as the base year. The CAGR of nominal GDP from 2000 to 2014 is 14.14%, while the CAGR of real GDP in this period was smaller, 9.85%.

This study also analyses the trend of GDP growth in China since the *Reform and Opening* from 1978, shown in Figure 5-6.

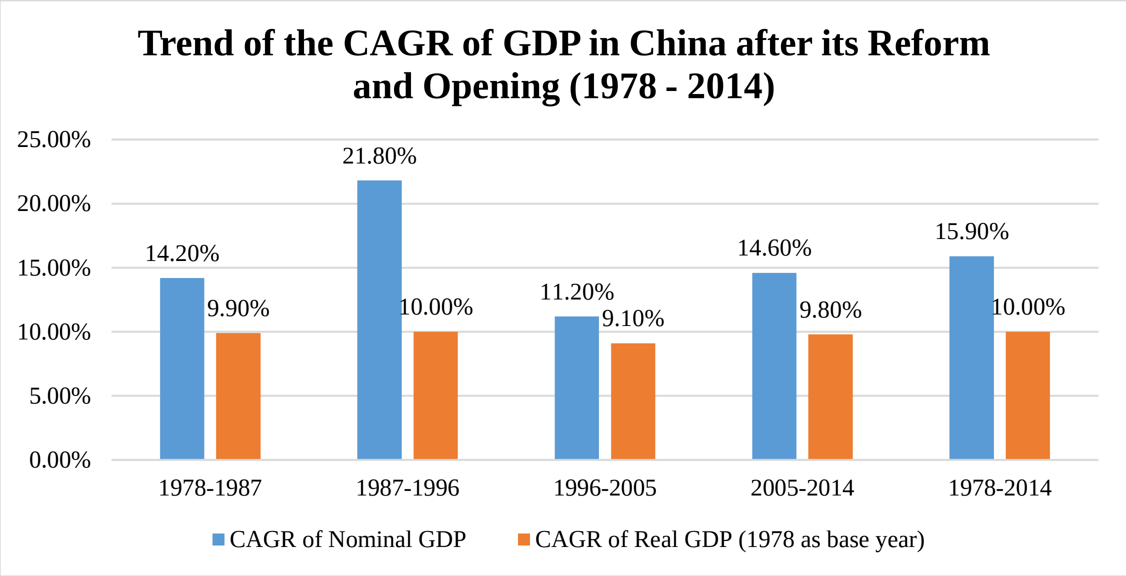

Figure 5-6 Trend of the CAGR of GDP in China after its Reform and Opening (1978 – 2014)

In general, the CAGR of nominal GDP is larger than the GAGR of real GDP as the price effects. The CAGR of real GDP over these four periods keeps constant with an overall rate as 10%, while that of nominal GDP over the period is fluctuant and the rate over time is about 15.9%, all indicating that the continuously growth in Chinese economy. Especially, the CAGR of nominal GDP increased from 14.2% to the peak point of 21.8%, and then rapidly decreased to 11.2%, finally increased to 14.6%. It means that during 1987 to 1996, the prices of goods rapidly increased compared with the early period of the Reform and Opening. After the Asian financial crisis in 1997, the general prices decreased and then rose back along with the economic development.

5.4.2.3 Factors for the Society Dimension

5.4.2.3.1 Analysis of the Trend for Population

From 2000 to 2014, the total population of China increased from 1.267 billion to 1.368 billion, with an average growth rate at 0.546%. The natural growth rate declined from 0.76% to 0.48% in 2010 and 2011. There was slow growth after 2012, and in 2014, the natural growth rate reached 0.52% (Figure 5-7).

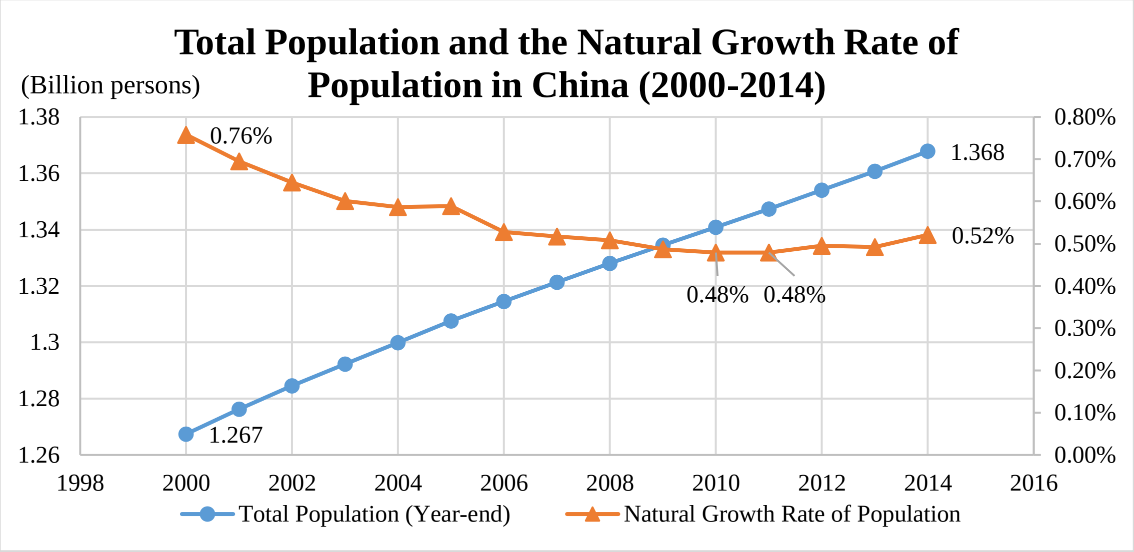

Figure 5-7 The Total Population and the Natural Growth Rate of Population in China (2000-2014)

During 2000 to 2014, the composition of the population gradually changed, except for the composition of the urban population (Figure 5-8). Along with the process of the urbanisation in China, the proportion of urban population rapidly increased from 36.22% to 54.77%; but the proportion of employed persons remained almost the same, with a very slow decrease from 56.9% to 56.5% over the 14 years. The trends for each age group were generally stable. However, in 2010, there was a decrease in the 0-14 age group, and an increase of the percentage of people aged 15-64, probably caused by the Chinese population policy during 1980s to the 2012. The proportion of older people slowly increased during the 14 years, indicating an aging population trend in China.

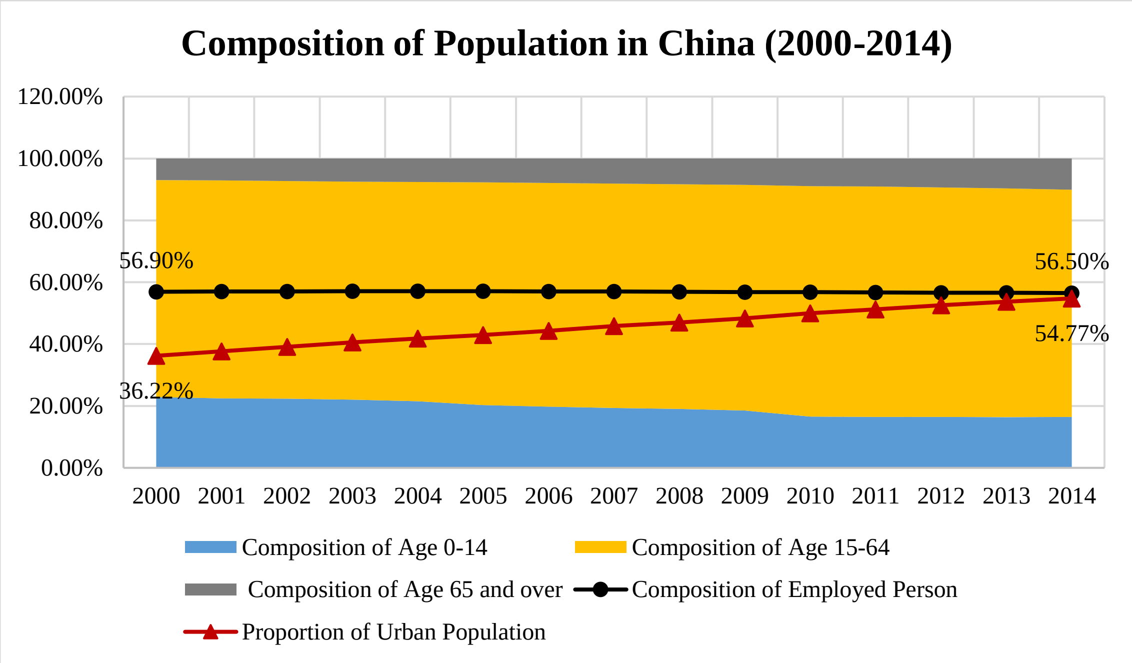

Figure 5-8 The Composition of Population in China (2000-2014)

5.4.2.3.2 Analysis of the Trend for National Income per Capita

From 2000 to 2014, the national income per capita (current prices) increased from 7,816.3 yuan to 47,140.05 yuan with a CAGR of 13.7%, while based on the price in 2000, the national income per capita (constant prices) increased from 7,816.3 yuan to 27,344.53 yuan a CAGR of 9.36% (Figure 5-9).

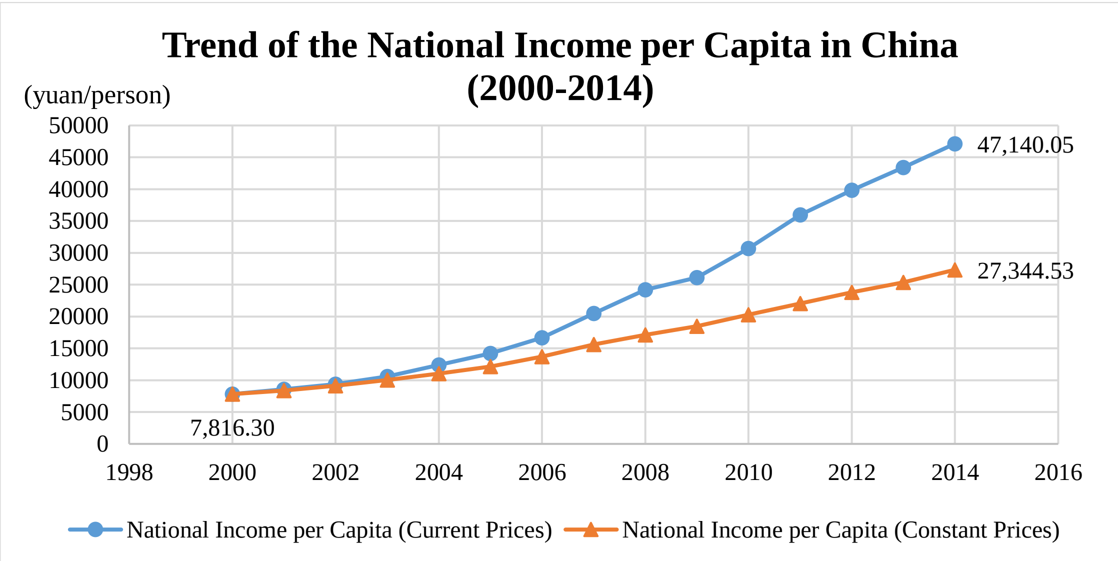

Figure 5-9 Trend of National Income per Capita in China (2000-2014)

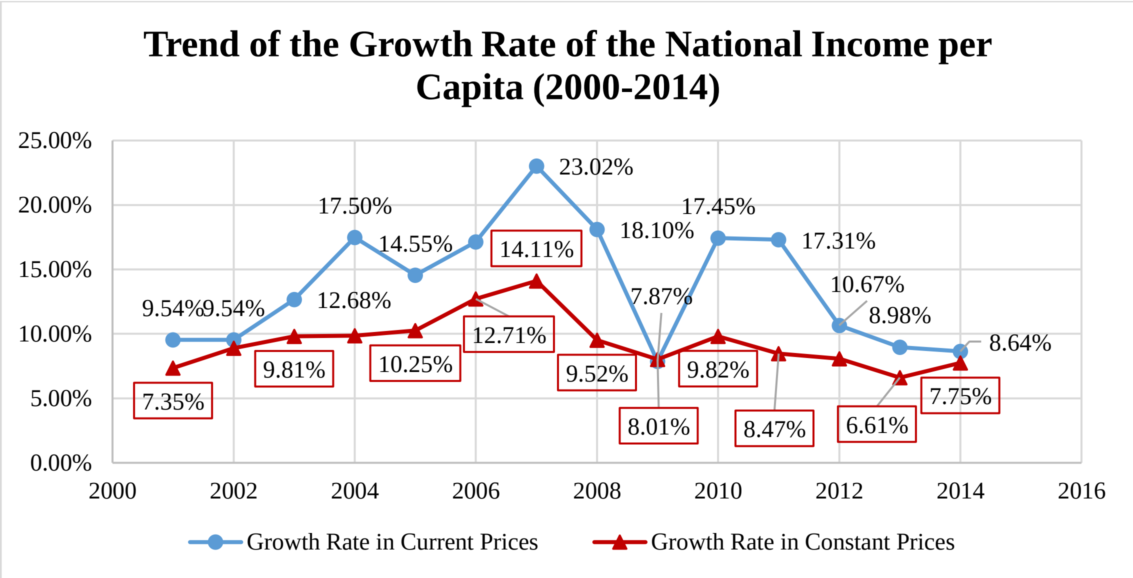

Figure 5-10 Trend of the Growth Rate of the National Income per Capita in China (2000-2014)

Figure 5-10 shows that the movement of national income per capita in current prices is fluctuant compared with that in constant prices. In constant prices, the growth rate smoothly increased from 7.35% to 14.11% in 2007 as the economic growth, and then gradually decreased to 7.75% in 2014, under the influence of the financial crisis and the slowdown of Chinese economy. Under the same effects, the growth rate in current prices reached its first peak at 17.5% in 2004 with a small decrease then met the second peak of 23.02% in 2007. With a big drop in 2009 when it was 7.87%, the growth rate rose back around 17.4% in 2010 and 2011. Finally, it decreased to 8.64% in 2014.

5.4.2.3.3 Analysis of the Trend for Disposable Income per Capita

Until 2013, the data for disposable income per capita was collected separately for urban and rural households, under the statistical variable of the per capita disposable income of urban households and the per capita net income of rural households (National Bureau of Statistics of China, 2015) (Figure 5-11).

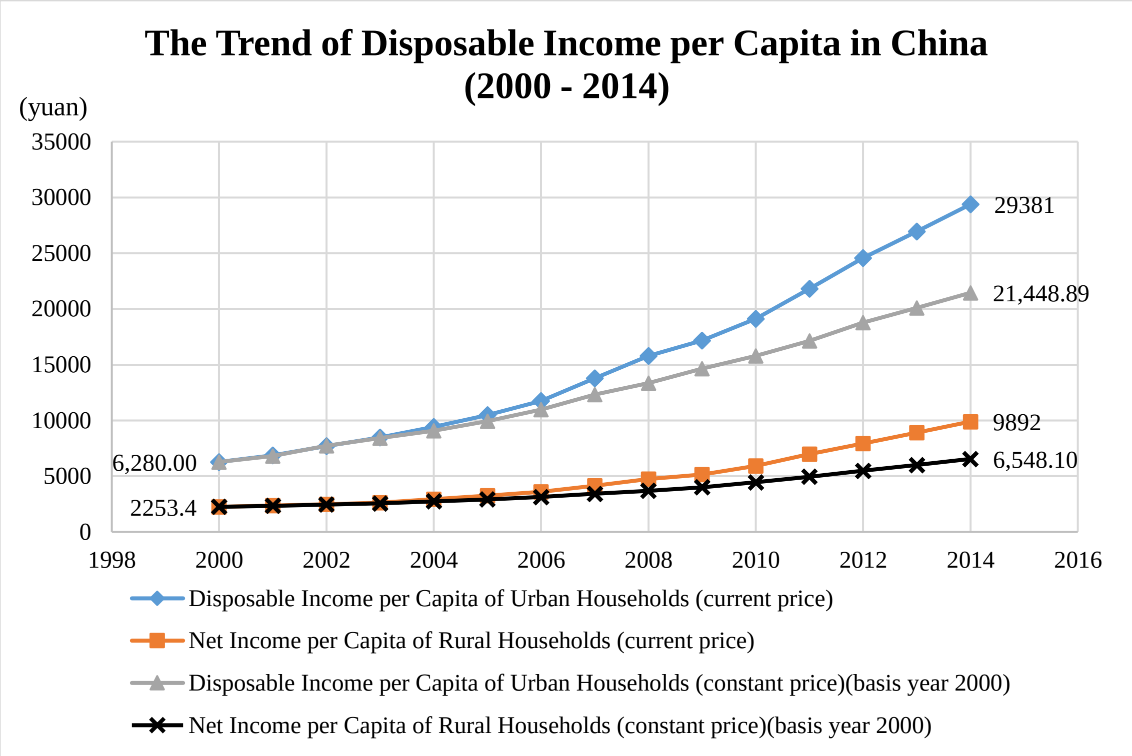

Figure 5-11 The Trend of Disposable Income per Capita in China (2000 – 2014)

From Figure 5-11, the general disposable income per capita in China increased during these 14 years, although that of urban households was generally around three times of the net income per capita of rural households for both current and constant price data. The income gap between urban and rural households did not change much. Although the price or inflation effects increased the disposable income for both urban and rural households, these effects were especially stronger for the urban households.

Based on the data of current price, the disposable income per capita of urban households rapidly increased from 6,280 to 29,381 yuan with a CAGR of 11.65%, while the net income per capita of rural households increased more smoothly from 2,253.4 to 9,892 yuan with a CAGR of 11.14%. Based on the data of constant price, where 2000 is the base year, the disposable income per capita of urban households increased from 6,280 to 21,448.89 yuan with a CAGR of 9.17%, while the net income per capita of rural households increased from 2,253.4 to 6,548.1 yuan with a CAGR of 7.92%.

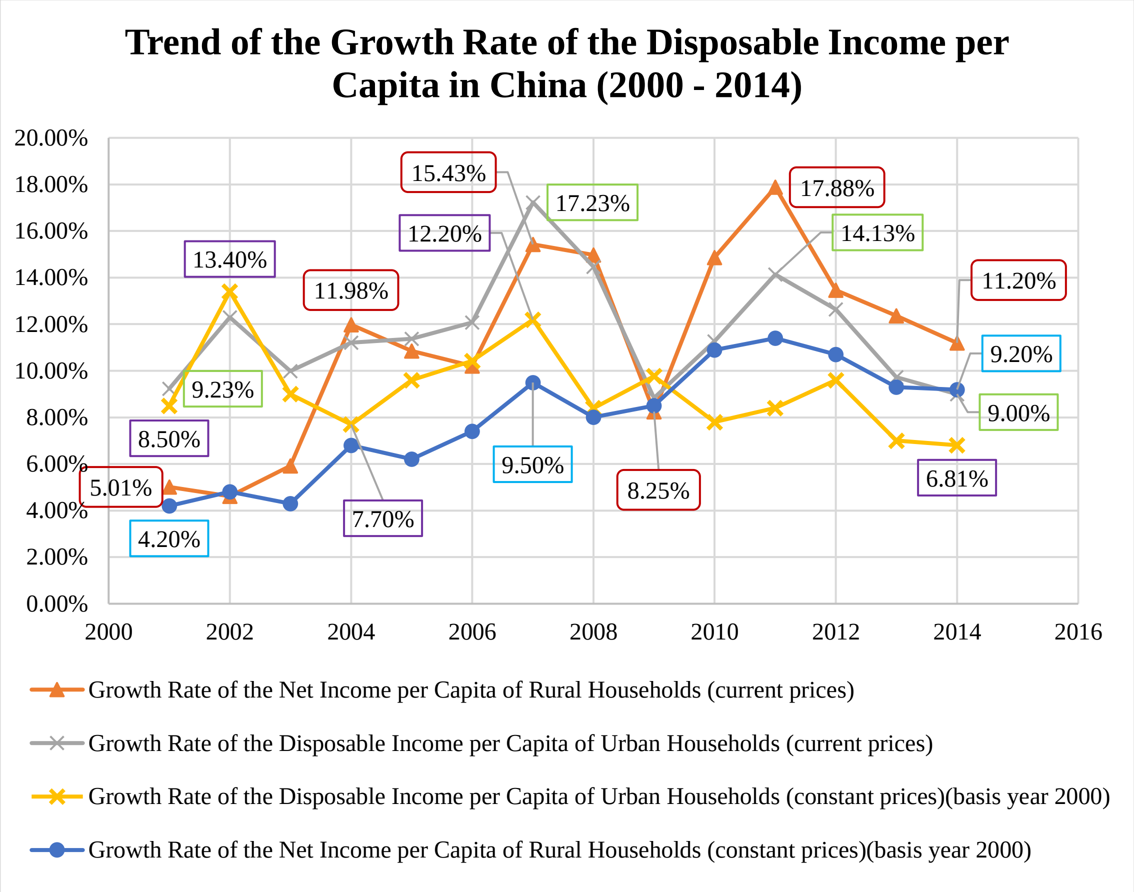

Figure 5-12 Trend of the Growth Rate of the Disposable Income per Capita in China (2000 - 2014)

Figure 5-12 shows that the growth rate of the disposable income per capita of urban households in both constant and current prices slightly decreased over the years, while that of the net income per capita of rural households in both prices increased. This indicates the slowdown of the growth rate of the disposable income per capita of urban households, but an increase for rural households under the related political promotion. The movement of the growth rate of the net income per capita of rural households in constant prices is more stable than the rest three rates, with an increase from 4.2% to 9.2%. That in current price is fluctuant, which rapid increased from 5.01% to 11.98% then slightly dropped in 2005 and 2006, and rose to 15.43% in 2007 with another downwards to 8.25%, finally an increase to reach the highest peak point of 17.88% with a drop to 11.2%. The growth rate of the disposable income per capita of urban households in both constant and current prices were synchronous moving and reaching the peak point in 2002, and 2007, except a few years.

5.4.2.3.4 Analysis of the Trend for Educational Level and Cultural Standards

In this section, the statistical data indicated that the general social situation in education and culture in China. They improved during these 14 years, and evidences were found of the government continuously promoting ways for these improvements, detailed in following sub-sections.

5.4.2.3.4.1 <u>The Analysis of the Trend for Educational Level</u>

In order to indicate the educational level one of a country, the scale, structure and quality of education should be analysed (Wang and Niu, 2009). This research used the average number of students enrolled at each level of education per one million residents to analyse the educational level in China (Figure 5-13).

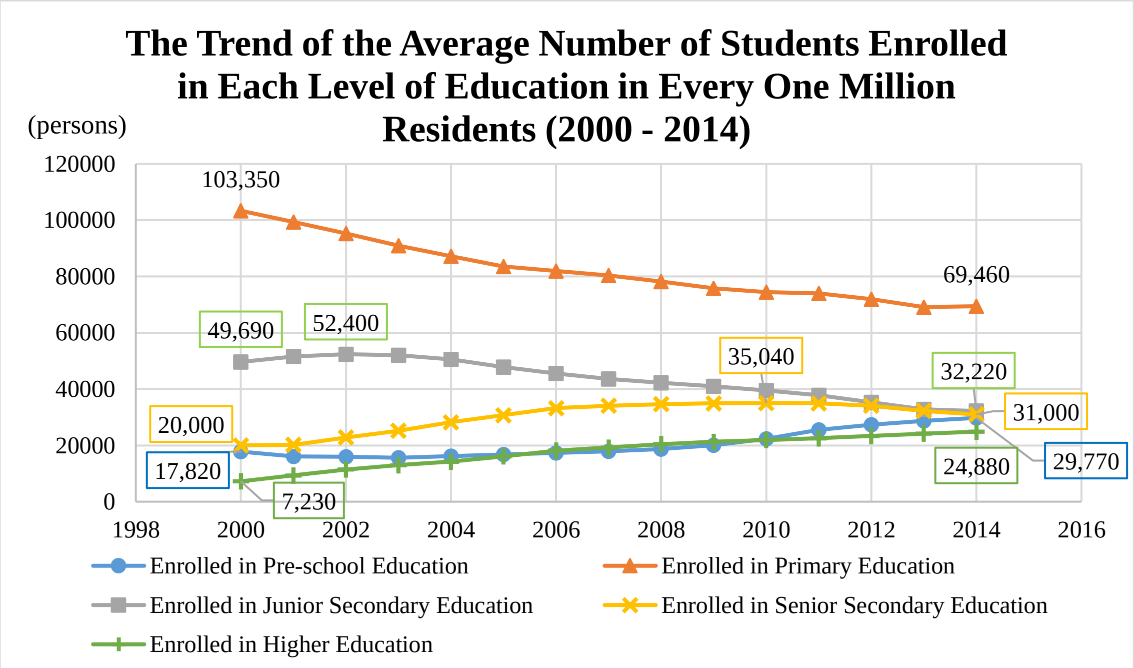

Figure 5-13 The Trend of the Average Number of Students Enrolled in Each Level of Education in Every One Million Residents (2000 - 2014)

The number of students in primary and middle school (junior secondary education) generally decreased, as an effect of the *One Child Policy*. The average number enrolled in primary education decreased from 103,350 to 69,460 per million residents, and in junior secondary education increased from 49,690 to a peak of 52,400 per million residents in 2002, after which it decreased to 32,220 in 2014. As these young residents grew older, the average number of students enrolled in senior secondary education and higher education, generally increased over this period. The number enrolled in high school increased from 20,000 to 35,040 in 2010, but then slowly decreased to 31,000 in 2014. The number enrolled in higher education continuously increased from 7,230 in 2000, to 24,880 in 2014, reflecting the higher education policy throughout these years (Ministry of Education, 1998). The average number of children enrolled in pre-school institutions first slightly decreased from 17,820 to 15,600 in 2003, and then smoothly increased to 29,770 with a growth rate at 6.1%.

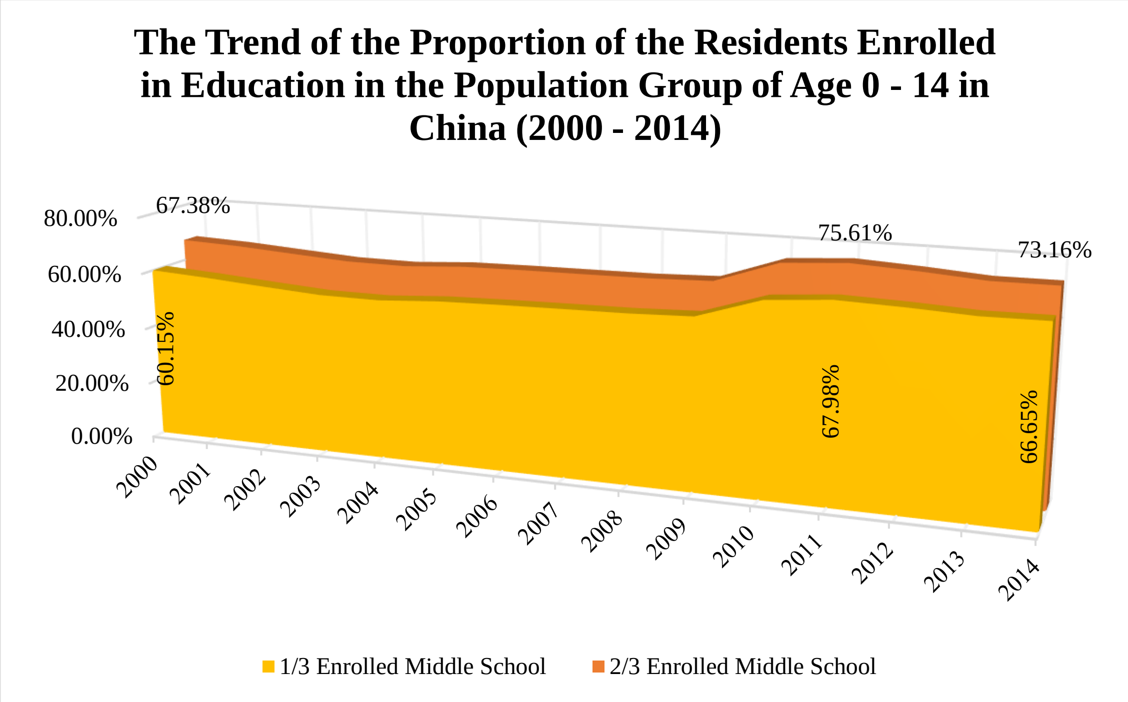

Figure 5-14 The Trend of the Proportion of the Residents Enrolled in Education in the Population Group of Age 0 - 14 in China (2000 – 2014)

Combining the analysis of the population structure in China in section 5.4.2.3.1, with the analysis of the proportion of residents enrolled in education within 0-14 age group, the education level for this group is calculated (Figure 5-14). The age group 0 -14 normally covers pre-school, primary and part of the junior secondary education, indicating a country's basic education status; this nine-year period is also that of compulsory education in China. For example, in 2000, there were around 229,000 persons in a million residents in the 0-14 age group with the total number of students at each level in every one million resident calculated in Figure 5-13. Because junior secondary school generally takes three years, to age 13 or 14 around one- to two-thirds of the enrolled students are in the 0-14 category. The figure decreased from 60.15% -

67.38% to 55.94% - 63.79% in 2004, but increased to 66.65% - 73.16% in 2014, indicating that the educational level, especially basic education, increased over the years.

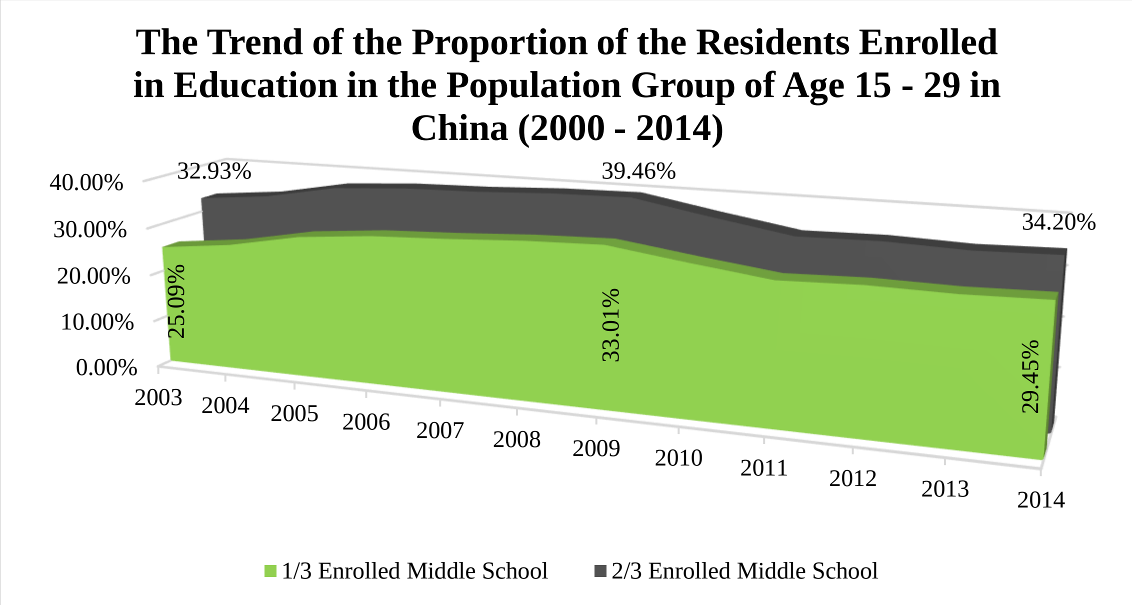

Figure 5-15 The Trend of the Proportion of the Residents Enrolled in Education in the Population Group of Age 15-29 in China (2000 - 2014)

More significantly, based on the annual population sample from 2003 to 2014, this enables calculation of the proportion of students enrolled in education in the population group of age 15 - 29, which generally includes the second year and/or the final year of middle school, senior secondary education, and higher education (Figure 5-15). Although the proportions in this figure increased from 2003 to 2009, the rapid decrease in the number of students in junior secondary education led to a decrease in the proportion of the population enrolled in the 15 - 29 group, from 33.01% - 39.46% in 2009 to 29.45% - 34.2% in 2014. However, compared with the proportion in 2000, the overall proportion of residents enrolled in education in 15-29 age is increasing. It indicates that the improvement of junior secondary education and higher education in China.

5.4.2.3.4.2 The Analysis of the Trend for the Cultural Standards

In identifying national cultural standards, data on cultural institutions, public libraries, national comprehensive archives, and publications can be used (Cai, 2009). These variables are analysed below.

(1) The Analysis of the Trend for the Cultural Institutions in China

Basing on the data from the National Bureau of Statistics of China (2015), the data of cultural institutions is listed in Table 5-2.

Table 5-2 The Number of Cultural Institutions in China (2000-2014) (unit)

Year	Public Libraries	National Comprehensive Archives	Cultural Centres	Museums	Art Performance Groups
2000	2675	3319	45321	1392	2619
2001	2696	3325	43379	1461	2605
2002	2697	3237	42516	1511	2587
2003	2709	3196	41816	1515	2601
2004	2720	3194	41402	1548	2759
2005	2762	3191	41588	1581	2805
2006	2778	3170	40088	1617	2866
2007	2799	3161	40601	1722	4512
2008	2820	3154	41156	1893	5114
2009	2850	3142	41959	2252	6139
2010	2884	3127	43382	2435	6864
2011	2952	3121	43675	2650	7055
2012	3076	3110	43876	3069	7321
2013	3112	3100	44260	3473	8180
2014	3117	3070	44423	3658	8769
Average Growth Rate	1.1%	-0.55%	-0.12%	7.28%	9.81%

The number of public libraries, museums and art performance groups generally increased over these years, while the number of national comprehensive archives and cultural centres slightly decreased. Specifically, the number of performing arts groups increased slowly before 2007, and rapidly afterwards, with an average growth rate of 9.81%. The number of museums increased steadily with an average growth rate of 7.28% in these years, and the number of public libraries increased slowly with an average rate of 1.1%. However, the number of the cultural centres decreased from 45,321 units in 2000 to 40,088 in 2006, although it rose again to 44,423 units in 2014, it with an overall decrease over the period. The national comprehensive archives also decreased with an average rate of 0.55% from 2000 to 2014.

(2) The Analysis of the Trend of the Total Collections and Circulation in Public Libraries, and Archives in National Comprehensive Archives

The total number of the archives (items) in the national comprehensive archives, and the total size of collections and figures for circulation in public libraries are shown in Figure 5-16.

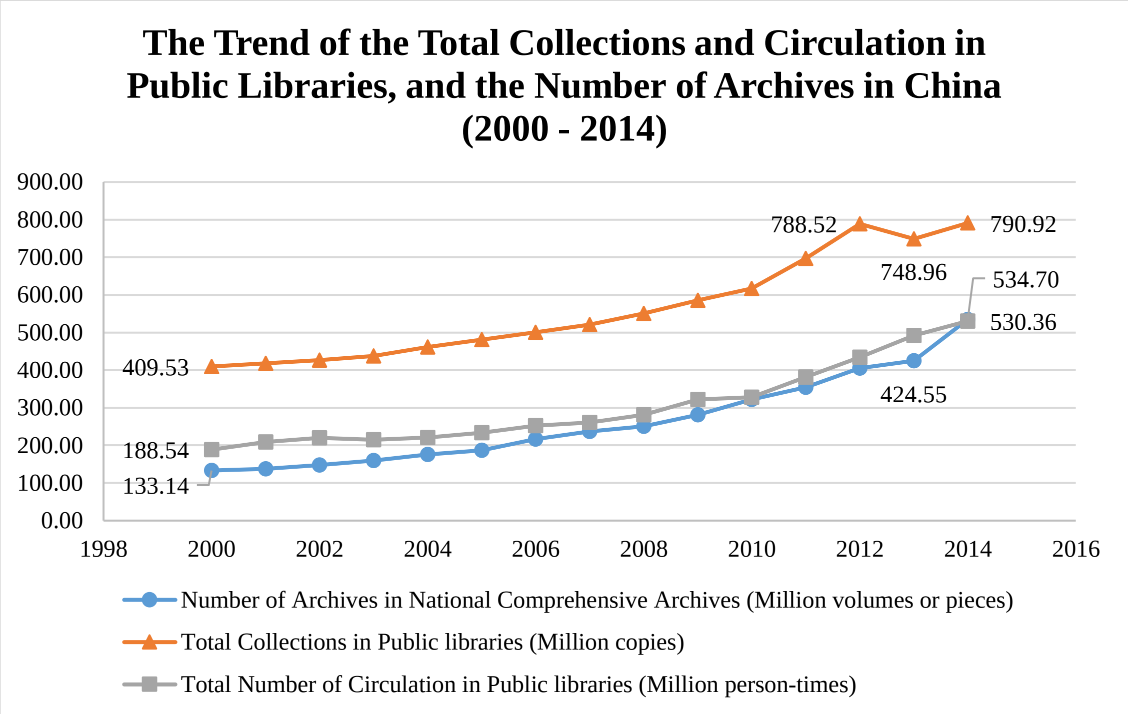

Figure 5-16 The Trend of the Total Collections and Circulation in Public Libraries, and the Number of Archives in National Comprehensive Archives (2000 - 2014)

The number of items held in public libraries was 3.08 times that in the in national archives in 2000, although only 1.59 times the number the archives in 2014. The national archives' collections increased smoothly from 133.14 to 534.7 million items, despite a dip 2010. In public libraries, the total size of collections increased from 409.53 million to 790.92 copies, with a small drop in 2013. Finally, the circulation in public libraries, the circulations of the visiting of the residents, increased from 188.54 million person-times in 2000 to 534.70 million person-times in 2014.

(3) The Trend of the Publication of Book, Magazines, Newspapers

From Table 5-3 and Figure 5-17, the information regarding publications in China is presented.

Table 5-3 The Trend of the Publication of Books, Magazines, Newspapers (2000 - 2014)

Year	Number of Publication of Books (titles)	Number of New Publication of Books (titles)	Total Printed Copies of Magazines (titles)	Number of Publication of Newspapers (titles)
2000	143376	84235	8725	2007
2001	155000	91416	8889	2111
2002	171000	100693	9029	2137
2003	190000	110812	9074	2119
2004	208000	121597	9490	1922
2005	222473	128578	9468	1931
2006	233971	160757	9468	1938
2007	248283	136226	9468	1938
2008	274123	148978	9549	1943
2009	301719	168296	9851	1937
2010	328387	189295	9884	1939
2011	369523	207506	9849	1928
2012	414005	241986	9867	1918
2013	444427	255981	9877	1915
2014	448431	255890	9966	1912
Average Growth Rate	8.53%	8.63%	0.96%	-0.30%

In the number of books and magazines published increased over the 14 years: books with an increasing rate at 8.53%, but magazines only with a growth rate of 0.96%. The figure for books in 2014 is 3.13 times that for 2000 indicating the especially rapid growth. A similar figure for new published books is illustrated. Although newspapers' publication increased during 2000 - 2002, there was a large fall in 2004, when the effects of the Internet and related digital products began to be felt (Han and Qin, 2007; Gentzkow, 2007).

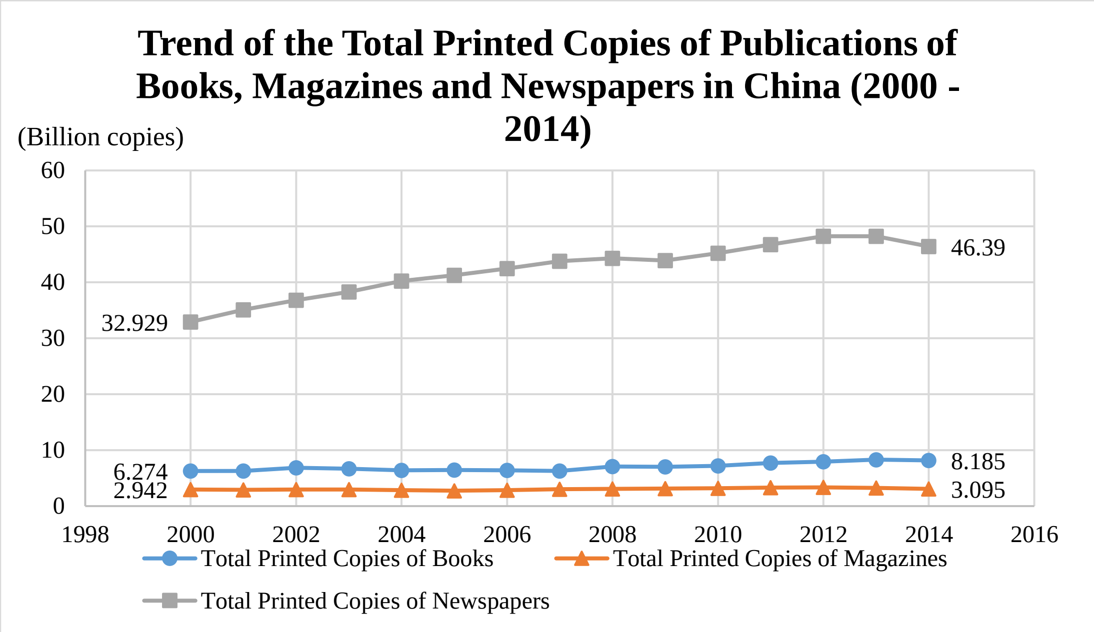

Figure 5-17 Trend of the Total Printed Copies of Publications of Books, Magazines and Newspapers in China (2000 - 2014)

The total number of printed copies of books, magazines and newspapers generally increased during these 14 years (Figure 5-17). The figure for books rose from 6.274 to 8.185 billion copies, an average growth rate of 2.02%, while the number of magazines slowly increased from 2.942 billion copies to 3.095 billion copies, a small growth rate of 0.41%. Although the number of newspapers' titles fell, the total number of copies printed rapidly increased to 46.39 billion, its growth rate of 2.51% exceeding that of books and magazines.

All in all, above analysis of educational level an cultural standards indicated that the Chinese residents have improved their educational level and raised the cultural standards, which promote the achievement of low-carbon economy (Cai, 2009; Zhang, 2011; Ao, 2013).

5.4.2.4 Factors for the Industrial Technology Dimension for this Chinese Industrial System

5.4.2.4.1 Analysis of the Industrial Production Technology

Generally, thermal electricity generation collectively refers to the process of using the energy contained in combustibles to produce electricity. It can be divided into generation by coal-fired steam turbine plants, by oil-fired steam turbine plants, by gas-steam combined-cycle power plants (CCPP), and internal combustion engine power plants. As these production technologies determining the method and amount of natural resources used for electricity generation, this research focuses on the consumption of natural resources under one particular technology and on the different consumptions under various technologies, to identify the influence of each technology on CO_2 emissions.

5.4.2.4.1.1 The Technical Process of Production for this Thermal Electricity Generation Industry

The technical procedures for thermal electricity generation production includes the combustion subsystem (boiler), the steam-water subsystem, electrical generating subsystem (turbine and generator), and control subsystem (British Electricity International, 1991a).

(1) The Combustion System

This system consists of the combustion chamber (the boiler furnace), air supply device (combustion air intake), coal (or oil or natural gas) conveyor device, ash discharge device, and other components. The main function is to complete the fuel combustion process, releasing the energy contained in the fuel through heating up the water in the boiler to create steam. The main processes include the boiler, the flue gas procedure, ventilation, and the process for collecting and discharging ash. The basic requirements of the combustion system are as follows: to achieve complete combustion, as much combustion as possible, with the boiler achieving a combusting efficiency over 90%; the ash emissions should meet the required standards (Central Electricity Generating Board, 1971; British Electricity International, 1991b; Xie et al., 2008; Moran and Shapiro, 2008; Ghosh and Prelas, 2009; 2011).

(2) The Steam and Water System

The steam and water system consists of the feedwater pump, circulation pump, feedwater heater, high- and low- pressure heater, steam separators and dryers, turbine, condenser, deaerator, water wall and piping systems. Its function is to use fuel combustion to turn water into high-temperature and high-pressure steam and to maintain the circulation of water and steam. The main processes are the combined reheat and regenerative Rankine cycle. This Rankine cycle consists of four phases of vapour power: the feed-water process, water-steam process (water heating), steam passing through the turbine, and the steam condensing process. This cycle also contains the regenerative and steam reheat process to improve energy efficiency and deal with "the droplets at the low-pressure side of the turbines" (Moran and Shapiro, 2008; Ghosh and Prelas, 2009). The basic requirements for this system are to minimise the loss of water and steam, heating the condensed water using the extracted steam in order to increase the feedwater temperature (British Electricity International, 1991a; 1991b; Xie et al., 2008; Zeng and Wang, 2008; Zhou, 2011).

(3) The Electrical Generation System

The electrical generation system includes the main plant wiring, turbine generators, main transformers, power distribution equipment, switching equipment, generator leads, factory ties, factory transformers and reactors, factory motors, security power, battery direct-current systems and communication equipment, lighting equipment, and other components. It ensures the electricity supply, and guarantees that loads meet the power quality requirements. The main processes include the power generating procedure, based on the turbine generator, electricity supply process and the factory's self-consumption of electricity. The basic requirements from this system are the security and reliability of the power supply; the scheduling flexibility; good adjustment and operational functionality to ensure the agreed supply of electricity; and the ability for fast troubleshooting to avoid the expansions of accident (British Electricity International, 1991a; 1991b; Xie et al., 2008).

(4) The Control System

This system controls the boiler and its auxiliary system, the turbine and its auxiliary system, generators and electrical equipment, and other ancillary systems. The control system performs automatic adjustment and control of the various procedures of the thermal power plant in order to coordinate all its parts. Finally, this system helps maintain the safe, appropriate and economic operation of the thermal electricity generation plant, reduces labour intensity, and improves productivity. If there is failure, the control system quickly and correctly deals with issues to avoid accidents. The main work processes are the self-starting and self-stopping processes of the steam turbine, the automatic speed-up control, the combustion control of the boiler, the fire protection process, thermal monitoring and control, automatic troubleshooting of electrical or gas problems, and automatic dust and soot removal (British Electricity International, 1991a; Xie et al., 2008; Baggini and Sumper, 2012).

5.4.2.4.1.2 The Thermal Power Units and the Related Technology

Currently, the technology for coal-fired power generation is vigorously developing in two main directions. The first area is the development and utilisation of new high-efficiency power generation technology, such as the integrated gasification combined cycle (IGCC). The second area is the conventional power generation system with improvement in the combustion, and steam and water system, in which the steam parameter for the unit is improved, for example reaching the level of an ultra-supercritical power plant (USC). The research contribution of IGCC is still at the demonstration stage. Therefore, improving the steam parameter becomes the important method of increasing energy efficiency and reducing emissions for the conventional coal-fired power plants. As its economic efficiency of upgrading equipment in conventional power generation, this method is also the main direction of upgrading coal-fired power generation technology in China, detailed below. In order to efficiently use the energy released during the electricity generation, technologies for cogeneration within the power station are also being developed (Zeng and Wang, 2008; Ghosh and Prelas, 2009; Zhou, 2011; Zhang, 2013).

(1) The Units for Improving the Steam Parameter and Cycling Efficiency

a) Supercritical and ultra-supercritical technology

The supercritical (SC) technology is the steam temperature and pressure within the furnace higher than the critical pressure of water (around 374.3ºC and 22.129 MPa) (Tian et al., 2006), but not as high as with the ultra-supercritical (USC). The USC unit is the most advanced equipment for thermal electricity generation, in which the temperature of the steam within the furnace is higher than 600 ºC, normally around 600ºC - 700 ºC, and the steam pressure is greater than 31MPa. The high temperature and high pressure lead to increased thermal efficiency, with the USC unit around 4%

higher than that of a subcritical unit, and around 1.5% higher than SC. In China, as its economic and environmental features, the SC unit is a mature technology widely applied in the thermal electricity generation industry. The USC units, especially with capacity of 600MW and 1000MW are applied in the newly constructed power plant. By the end of 2014, 69 million-kilowatt USC units had been put into operation in China, which is the largest number of million-kilowatt USC units in the world (Xie et al., 2008; Zeng and Wang, 2008; Ghosh and Prelas, 2009; Zhou, 2011; Zhang, 2013; Ma, 2015).

b) The combined cycle gas turbine (CCGT) plant

The CCGT plant is one type of combined-cycle power plant (CCPP), where the steam turbine of the Rankine cycling works at low temperatures and the gas turbine of the Brayton cycle works at high temperatures, combined to form one energy utilisation system. The thermal energy is achieved through a hierarchical process. This system improves the steam parameter, as does the design of steam-reheated, three-dimensional and multi-stage heat recovery. As a result, CCGT achieves high-energy efficiency, even exceeding 60% (Xie et al., 2008; Tao, 2012; Zhou, 2012; Han, 2015).

(2) The Technology for Total Energy Utilisation in the Electricity Generation Process

a) The combined heat and power plant

The combined heat and power generation (CHP) or cogeneration plant refers to the production approach using the extracted or exhaust steam from the backpressure unit to supply steam and heat while simultaneously generating electricity in thermal power units. The cascade utilisation of heat energy reduces losses due to condensation. The total energy efficiency reaches 70% - 80%. If the combined cycle unit is also involved in this heat and power cogeneration, then the total energy efficiency can reach 80% -90% (Kreith and Goswami, 2007; Kang et al., 2008; Wang, 2011; Pickard and Strobelt, 2016).

b) The combined cooling, heat and power plant

The combined cooling, heat and power generation (CCHP) or tri-generation plant is based on cogeneration, with extracted or exhausted steam passing through absorption chillers to produce not only heat and power but also cooling or cold water for use in air conditioning or cooling processes. The advantage of the tri-generation plant is that after power generation, the steam does not directly go through the condensation and decompression process, but is extracted or exhausted and used to meet the demand for heating or cooling. Therefore, the energy efficiency of this type of production is high. It can also increase the load rate of the back pressure units in summer and improve the energy efficiency of the cogeneration (Yan et al., 2003; China Association for Science and Technology, 2016).

c) The combined heat, power and coal-gas production

After heating, the volatile components in coal will vaporise, producing the coal-gas for domestic or other consumptions. The coke produced can be sent to the circulating fluidised bed boiler for combustion and production the steam for cogeneration (China Association for Science and Technology, 2016).

(3) The Technology of the Coal Gasification for both Electricity Generation and Coal Chemical Production for Comprehensive Energy Utilisation System

a) Large-scale circulating fluidised bed combustion technology

Circulating fluidised bed combustion (CFBC) technology is incorporated in atmospheric circulating fluidised bed combustion (ACFBC) technology for coal-fired power stations, and is more widely used than the bubbling fluidised bed combustion technology (BFBC) of ACFBC in China. "In the fluidized beds of these technologies, solid fuels are suspended by upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids allowing more effective chemical reactions and heat transfer. Moreover, normally combined with subcritical steam turbines, together sorbent injection for SO_2 reduction and removal of particulates from flue gases, fluidized bed systems can reduce sulphur dioxide by 90% - 95% and nitrogen oxides by 90% or more. CFBC is principally of value for low-grade, high-ash coals which are difficult to pulverize, and which may have variable combustion characteristics. It is also suitable for co-firing coal with low grade fuels, including some waste materials." (Ghosh and Prelas, 2009). China has developed advanced technology in CFBC units. In 2014, 91.5% of the coal-fired power generators had added flue-gas desulphurisation units, while the rest generators used CFBC boilers (Xie et al., 2008; Zeng and Wang, 2008; Zhang, 2013; Ma, 2015).

b) The pressurised fluidised bed combustion boiler

The pressurised fluidised bed combustion (PFBC) boiler-combined cycle (PFBC-CC) plant is generally based on CFBC, which allows PFBC to use “low-grade, high-ash coal” for combustion; both “provide same power output with a small size of unit” (Ghosh and Prelas, 2009). Unlike CFBC, PFBC uses “a sorbent and jets of air to suspend the mixture of sorbent and burning coal during combustion” to further elevate the stream pressure within the bed to reach about 1MPa-1.6MPa, with the temperature controlled at around 850ºC - 950ºC; this leads to a higher “efficient combined cycle system” than CFBC (Ghosh and Prelas, 2009). The efficiency of PFBC for power generation is 3% higher than ordinary equipment, and its cycle efficiency is up to 41%. The desulphurisation and denitrification rates of PFBC are as high as with CFBC technology, which can “reduce sulphur dioxide by 90% - 95% and nitrogen oxides by 90% or more” (Ghosh and Prelas, 2009). Based on the first generation, the second generation of PFBC technology (advanced pressurised fluidised bed combustion or APFBC) is being developed. APFBC additionally involves “the pressurized carbonizer to convert coal into fuel gas and char”, and “another combustion of fuel gas from the carbonizer to meet the turbine’s rated firing temperature”, which is approximately 1,350ºC. Moreover, the “heat recovered from the gas turbine exhaust to produce steam, which is used to drive a conventional steam turbine”, means that APFBC conducts with a higher efficiency than PFBC (Zhou, 2000; Wang et al., 2004; Xie et al., 2008; Zeng and Wang, 2008; Ghosh and Prelas, 2009; Zhang, 2013).

c) Integrated gasification combined cycle

The integrated gasification combined cycle (IGCC) technology is a clean coal-fired power generation technology. It “departs from the direct coal combustion, but first converts the coal into synthetic gas (syngas), which is cleansed from its impurities and almost to the same level as natural gas” (Ghosh and Prelas, 2009). The thermal efficiency of IGCC can exceed 40%, and the key emission and water consumption indicators are 10% and 50% that of common electricity generators. IGCC technology “removes 95% - 99% of the sulphur and nitrogen impurities in the coal gas”, which not only significantly reduces the relative pollution, but also makes possible “converting these pollutants into usable products, such as chemicals and fertilizers” (Ghosh and Prelas, 2009). However, this technology is not yet mature in the market. China has constructed an IGCC plant with a capacity of 250, 000 kW to develop this technology (Zeng and Wang, 2008; Zhang, 2013).

In summary, the most representative clean-coal power generation technologies currently on the market in China are USC power generation, CFBC-CC technology, PFBC-CC technology, and IGCC technology. They have different advantages, and this research systematically compares the four technologies for their units’ efficiency, environmental performance (based on desulphurisation rate and the emission of nitrogen oxides), reliability (based on maximum capacity of a single unit), technological maturity, the standard coal consumption per unit of electricity supply, and investment in equipment (Table 5-4).

Table 5-4 The Comparison of Relative Technology Units for Thermal Power Generation

Technology	**Units’ Efficiency (%)**	**Environmental Performance**	**Reliability**	**Technological Maturity**	**Standard Coal Consumption per unit of Electricity Supply**	**Equipment Investment**
USC	43 - 47	Good	High	Mature	285.6 g/kWh	Medium
CFBC	36 - 41	Medium	Medium	Very mature	350 g/kWh	Low
PFBC	1st: 40 – 42 2nd: 45 - 47	Good	Low	1st: Mature 2nd: Not yet to mature	Lower than CFBC (339g/kWh for P800 by ABB Company)	Second highest
IGCC	42 - 47	Very Good	Low	Not yet to mature	240 g/kWh	Highest

The resources from Huang (1998); Zhao (1999); Zhou (2000); Zeng and Wang (2008); Ghosh and Prelas (2009); Zhou (2011); Zhang (2013).

(4) The Technology for Improving the Reliability of Thermal Power Units

The technologies to improve the reliability of thermal power units address the design and construction of the power units, the operation of power plant equipment, the diagnosis of power plant fault, and optimisation of power plant operation. The optimisation technology is applied to the operation of boiler, turbine, single unit and entire plant (British Electricity International, 1991a; Xie et al., 2008).

(5) The Technology for Intelligent Thermal Power Plant

The intelligent power plant, also called the smart power station (SPS), is based on the physical power plant, integrating the technology of intelligent control, fieldbus control, modern advanced sensing measurement, and information technology. It is intelligent, information-intensive, integrated, economical, and environmentally friendly. The technological core of the intelligent thermal power station is intelligent control technology implemented through integrated technologies for advanced sensing, control, plant-level optimisation, and deep data mining (Kreith and Goswami, 2007; Baggini and Sumper, 2012; Chen et al., 2013).

5.4.2.4.2 Analysis of the Treatment Technologies for CO_2 in this Chinese Industry

There are three technical approaches to achieving low-carbon development in the thermal electricity generation industry. The first is an efficient and clean coal-fired power generation technology, which focuses on pollution treatments to remove the traditional pollutants, such as SO_2, NO_x, smoke and dust particles. It also aims to improve combustion efficiency to reduce coal consumption per unit of electricity, leading to a decrease in carbon dioxide emissions (Zhou, 2011). The second process is carbon capture and storage technology (CCS) (Working Group III, 2005a; IPCC, 2015). Although several CCS pilot sites have been established, this technology remains at the experimental stage (Zeng and Wang, 2008; Zhang, 2013). The third approach is through artificial reforestation to absorb and store carbon dioxide (IPCC, 2015). Carbon trading is based on the forest's capacity to absorb and store carbon dioxide, to balance global CO_2.

5.4.2.4.2.1 Analysis of the Clean Coal Technology in Electricity Generation

The high efficiency of clean coal-fired power generation is the leading technology addressing the problem of CO_2 emissions in the thermal power industry. It includes power generation through USC units, IGCC, CFB, and other related technologies, to significantly reduce CO_2 emissions (Xie et al., 2008; Zeng and Wang, 2008; Ghosh and Prelas, 2009; Zhou, 2011).

5.4.2.4.2.2 Analysis of the Carbon Capture and Storage

CCS refers to "a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere" (Working Group III, 2005a; 2005b). IPCC (2015) believes that CCS technology will largely support the reduction of CO_2 in the 2030s to 2050s. There are four methods of CO_2 storage: "geological storage (in geological formations, such as oil and gas fields, un-minable coal beds and deep saline formation), ocean storage (direct release into the ocean water column or onto the deep seafloor), industrial fixation of CO_2 into inorganic carbonates, and the application of carbon dioxide in industry"(Working Group III, 2005b). However, as IPCC (Working Group III, 2005b) reports, the industrial use of liquid or gas of CO_2 will not promote the reduction of CO_2 emissions. CCS technologies are mainly still at the research and partial pilot phases, with only parts of the technology in practical application (Working Group III, 2005b). The United States and Germany are the leaders in this field, while China has also conducted research in related technologies. In 2008, the first pilot project in China to capture CO_2 on the flue-gas of a coal-fired power plant was launched at the Huaneng Beijing Thermal Power Station, marking the first application of CCS technology in the country.

5.4.2.5 Factors for the Industrial Economic Dimension for this Chinese Industrial System

5.4.2.5.1 Analysis of the Trend of the Industrial GDP of the Chinese Thermal Electricity Generation Industry

Based on the data for industrial GDP at current prices, this industry's GDP grew from 399.2 billion yuan in 2005 to 1044.2 billion yuan in 2013, then decreased to 980.2 billion yuan in 2014 (Figure 5-18). The annual growth rate for this industry's GDP at current prices is also calculated and presented in Figure 5-19.

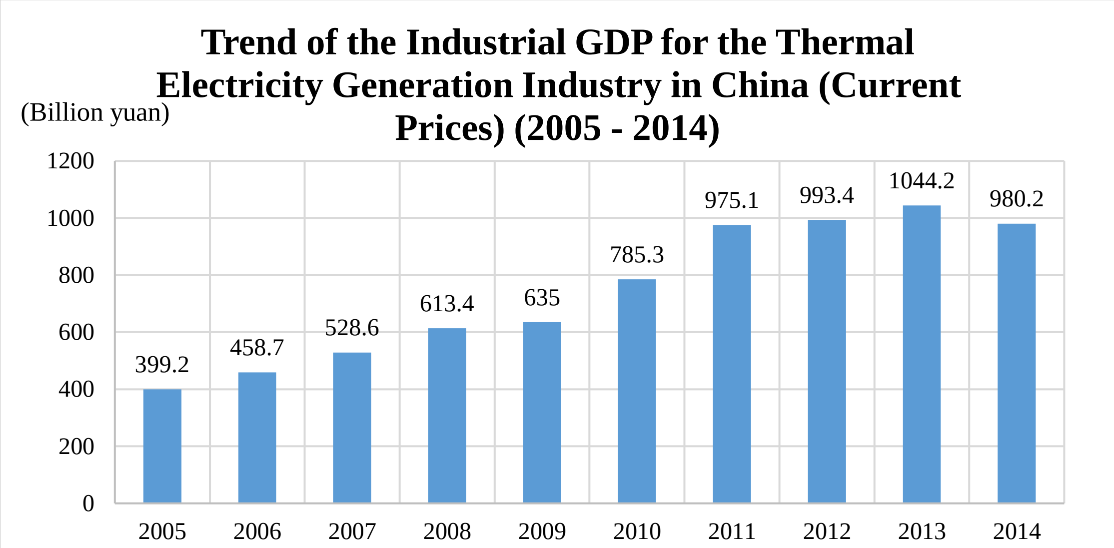

Figure 5-18 Trend of the Industrial GDP for the Thermal EG Industry in China (Current Prices) (2005 - 2014)

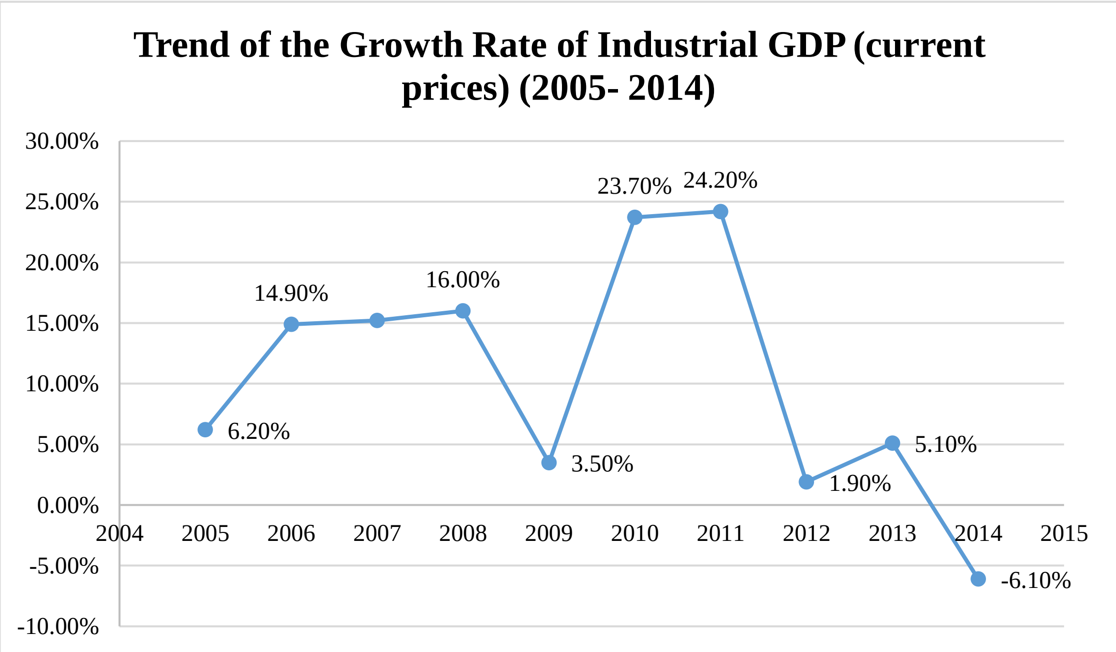

Figure 5-19 Trend of the Growth Rate of Industrial GDP (current prices) (2005- 2014)

From 2005 to 2014, the annual growth rate of the industrial GDP fluctuated, increasing from 6.2% in 2005 to reach the first peak at 16% in 2008, and then rapidly dropped to 3.5% in 2009, but reaching a second peak of around 24.2% in 2011, and continued downwards to -6.1% in 2014. Moreover, the CAGR of industrial GDP in 2014 is 10.5% with the base year of 2005, indicating the overall growth of this industrial GDP.

5.4.2.5.2 Analysis of the Trend of the Natural Resources Required in this Industrial Production

The natural resources required during thermal electricity generation production in China are chiefly water and coal, although natural gas, oil and other energy resources are also required but at less than 20% proportion compared with coal (Ghosh and Prelas, 2009). This research focuses not only on the total amount of natural resources required, but also on the resources required per unit of GDP.

5.4.2.5.2.1 Analysis of the Trend of the Total Amount of Water Resources Required by this Chinese Industry

Gu et al. (2013) in their report *The Evaluation of Water Saving Effect of Energy Conservation Policy in China* calculated the regression expression of the relationship between the amount of water required by Chinese thermal electricity generation and the quantity of electricity produced.

$Y=0.012X+355.61$, where X represents the electricity production (10^8 kWh), and Y represents the water consumed for this (10^8 m^3).

Based on this expression, this researcher calculated the amount of water consumed by the thermal power industry from 2005 to 2014 (Figure 5-20). During these years, water consumption by this industry increased from 601.29 $\times10^8$ m^3 to 867.85 $\times10^8$ m^3, along with the growth in electricity generation from 20,473.4 $\times10^8$ kWh to 42,686.5 $\times10^8$ kWh. Based on this water consumption data, the proportion of this industrial consumption was also calculated (Figure 5-21).

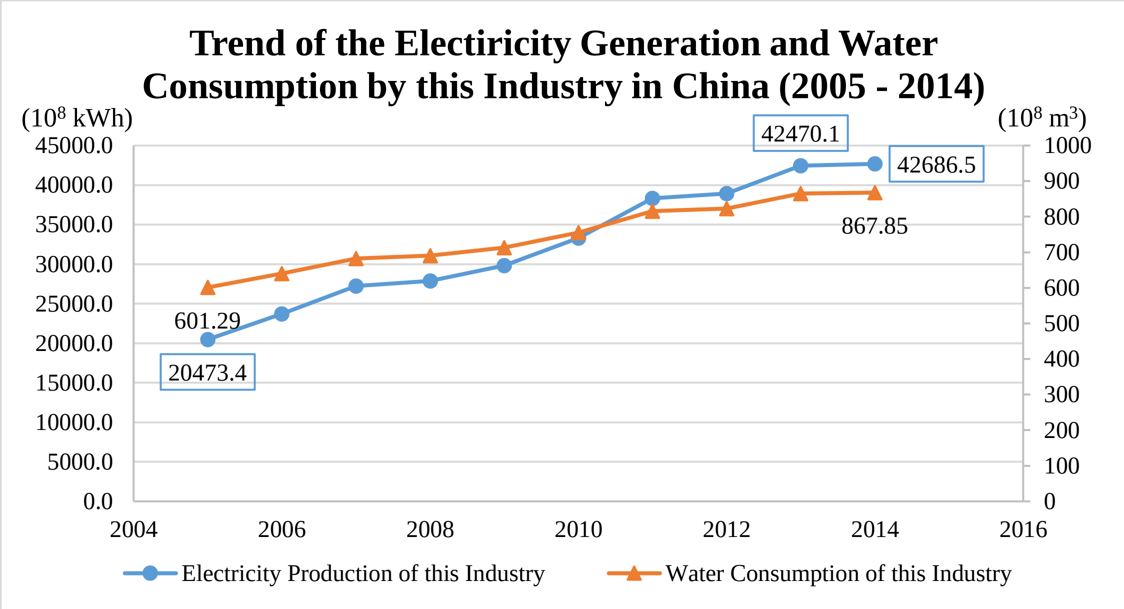

Figure 5-20 Trend of the Electricity Generation and Water Consumption by this Industry in China (2005 - 2014)

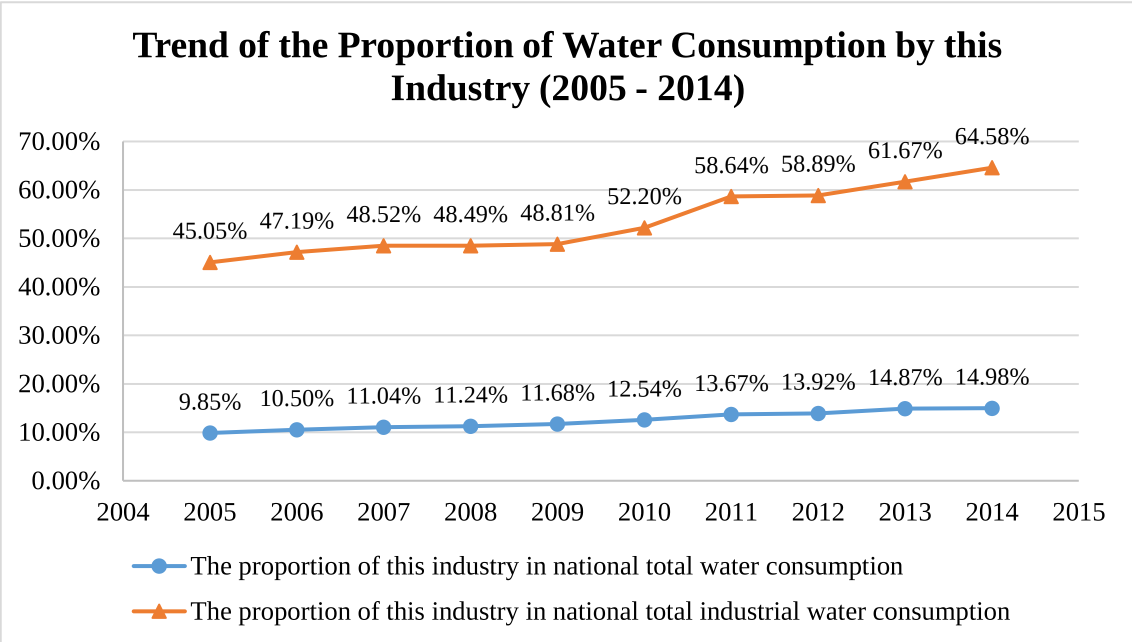

Figure 5-21 Trend of the Proportion of Water Consumption by this Industry (2005 - 2014)

From the calculation, the proportion of water consumption by this industry in the total national water consumption gradually increased from 9.85% to 14.95%, while the proportion of this industry in the total national industrial consumption rose rapidly from 45.05% to 64.58%. Thermal electricity generation industry consumes half of the total industrial consumption, and water is one of the core resources constraining this industrial development.

5.4.2.5.2.2 Analysis of the Trend of the Total Amount of Coal Resources Required by this Chinese Industry

The consumption of coal and coal products, which is the other core resource in this Chinese industry, is analysed from both the national and industrial perspectives.

(1) Analysis of the Trend of the Total Production and Consumption of Coal in China

Referring to the data (National Bureau of Statistics of China, 2015) in Figure 5-22, the total production of coal and coal products in China, represented by standard coal equivalent (SCE), increased from 1.773 billion tonnes to 2.663 billion tonnes. The corresponding consumption rose from 1.892 billion tonnes to 2.793 billion tonnes, while the gap between consumption and production averaged around 0.137 billion tonnes, filled by imports and existing reserves.

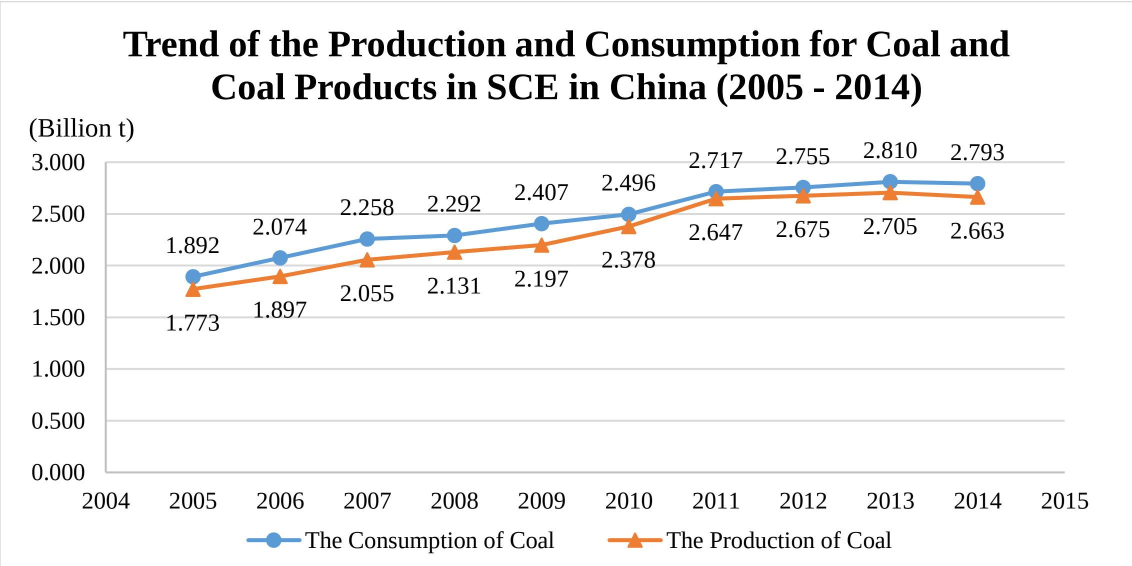

Figure 5-22 Trend of the Production and Consumption for Coal and Coal Products by SCE in China (2005 - 2014)

(2) Analysis of the Trend of Total Consumption of Coal in by this Chinese Industry

As represented by the SCE value (Figure 5-23), the total consumption by this Chinese industry rapidly doubled from 757.04 million tonnes to 1,430.51 million tonnes in 2013, then slightly dropped back to 1,360.86 million tonnes in 2014. However, the electricity production remained almost constant in 2014, indicating that this reduction was a result of the reduction in coal consumption per unit of electricity production, caused by the improvement in production technology.

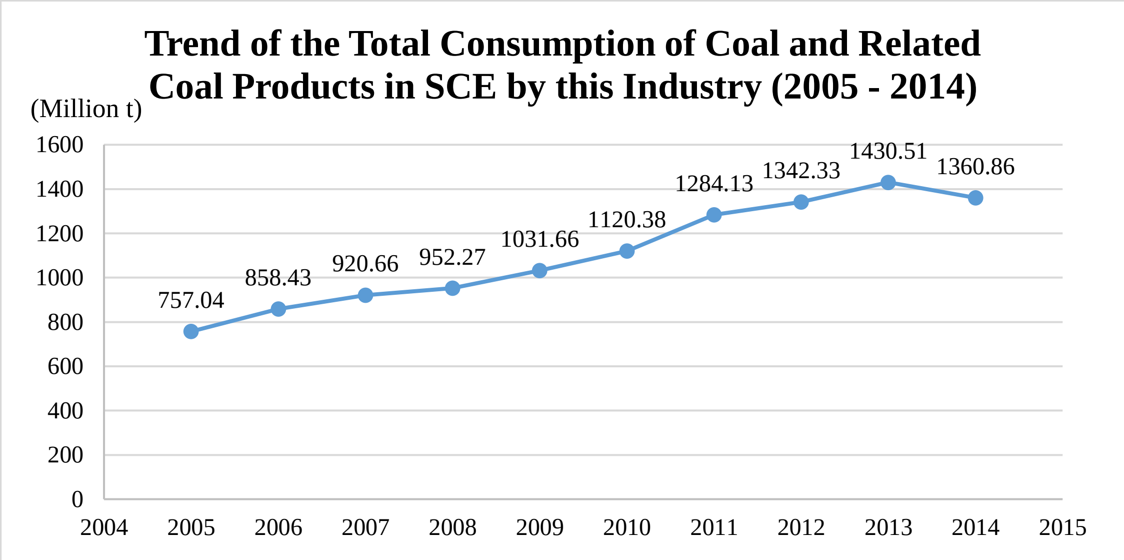

Figure 5-23 Trend of the Total Consumption of Coal and Related Coal Products by SCE by this Industry (2005 - 2014)

5.4.2.5.3 Analysis of the Trend of the Capital Employed by this Industrial Production

Based on the available data (Figure 5-24), the total investment in fixed assets in thermal electricity generation industry first decreased from 325.36 billion yuan in 2005, to 200.41 billion yuan in 2011, then increased to 326.55 billion yuan in 2014. Generally, around 41.04% of the investment was in construction and installation works, and around 47.78% in purchasing equipment, and leaving around 11.18% for other purposes. The trend for investment in construction and installation works also was decline from 142.01 billion yuan in 2005 to 79.84 billion yuan in 2011, rising again to 141.95 billion yuan within three years. Taking the largest proportion, investment in equipment also fluctuated and decreased from 2005 to 2011, but unlike the other two investments, which declined around 50%, it only dropped from 146.89 to 97.77 billion yuan, after which it rapidly rose to 155.22 from 2012. Finally, taking the smallest proportion of investment, the money for other purposes also fluctuated and fell from 36.45 billion yuan in 2005 to 19.96 billion yuan in 2012. Although it was back to 29.48 billion yuan by 2014, this is still less than the level in 2005. As this category of investment is normally to supply the other two types, there seems be a one-year delay on the movement of this investment compared with the other two.

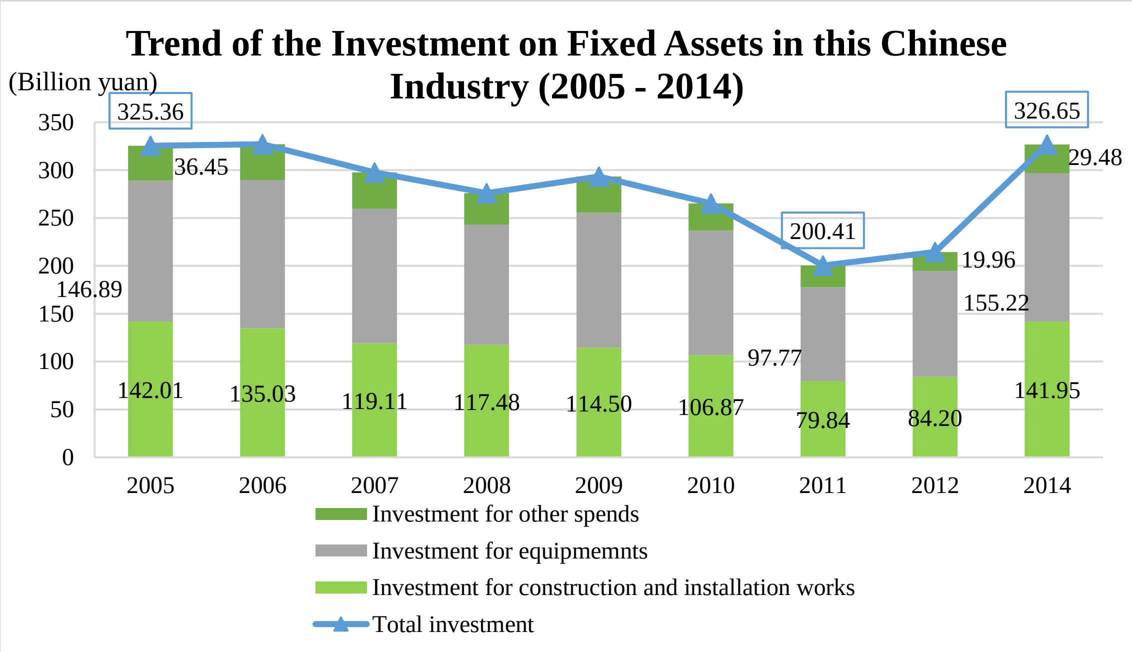

Figure 5-24 Trend of the Investment on Fixed Assets in this Chinese Industry (2005 - 2014)

5.4.2.5.4 Analysis of the Trend of the Labour Involved in this Industrial Production

As shown in Figure 5-25, the labour employed in the thermal power industry first increased from 69.5 × 10^4 persons to a peak of 75.2 × 10^4 persons in 2008. It fluctuated downwards to 65 × 10^4 persons in 2012, but rose to 70.4 × 10^4 persons in 2014.

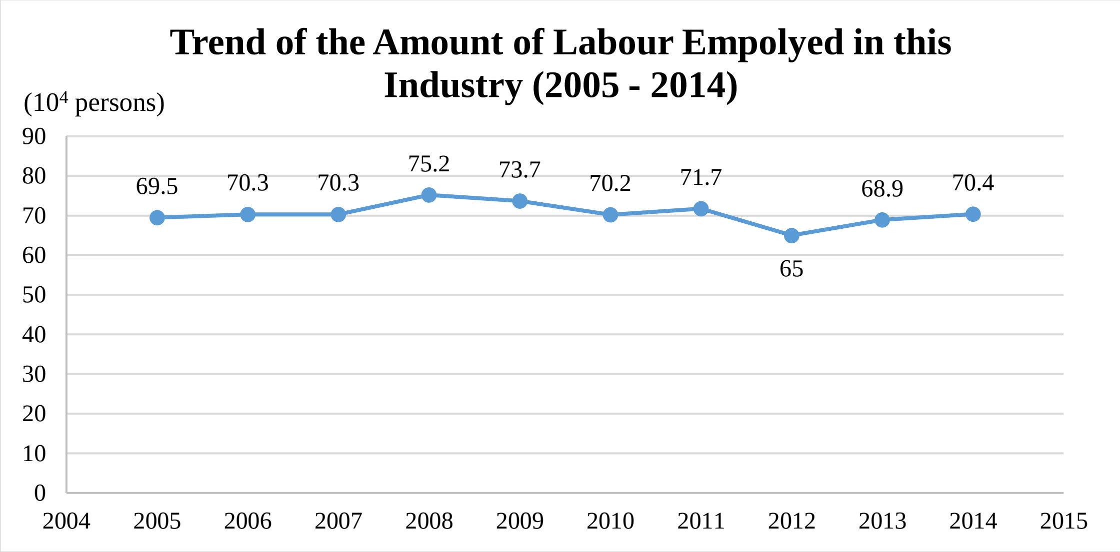

Figure 5-25 Trend of the Amount of Labour Employed in this Industry (2005 - 2014)

5.4.2.5.5 Analysis of the Industrial Cost of Reducing CO_2 Emissions in this Industrial Production

The cost of reducing CO_2 emissions in this industrial production is the amount spent during industrial procedures to achieve development in the low-carbon economy. There are two main approaches to achieving an industrial low-carbon economy (see the analysis in section 4.3.5.2.5). The first approach is the model for the optimal approach to low-carbon emission for an industrial low-carbon economy, described in section 4.8.6, which indicates that industrial CO_2 emissions from this industry could be reduced through improving production technology, to increase the efficiency of utilising the natural resources, and then through reducing the CO_2 emissions from production. In this approach, the cost of improving the technology of industrial production is the industrial cost of reducing CO_2 emissions. The second approach is through carbon trading, to move the responsibility of reducing CO_2 emissions to maintain the global balance of emissions. In this approach (see section 4.3.5.2.5), the cost of reducing CO_2 emissions for this industry is the cost of carbon trading. The calculation expression is: Industrial Cost of Reducing CO_2 Emissions = the Reduction Target of CO_2 emissions × the Price in Carbon Trading, where the reduction target is the nationally regulated reduction standard, the responsibility that this Chinese industry must adopt; the price of carbon trading is the price per unit ton of CO_2 determined in the carbon trading market.

5.4.2.5.6 *Analysis of the Amount of CO_2 Emissions from this Industrial Production*

In analysing the amount of CO_2 emissions released by this industry, this study focuses on the trend of CO_2 emissions during production, both under and not under the low-carbon economy.

5.4.2.5.6.1 Analysis of the Trend of the Amount of CO_2 Emissions by this Industry not under the Low-carbon Economy

In 2005, the thermal electricity generation industry was not under a low-carbon economy, which means it did not consider low-carbon emission at all during their production. The 2005 production technology consumed 370 g standard coal per unit of electricity supply. If this industry is continuously under this economy, the CO_2 emissions from this industry are calculated as follows: CO_2 emissions from this industry not under low-carbon economy = production of electricity in that year × 370 × 3.14, where 3.14 is the coefficient of converting standard coal to CO_2 (IPCC, 2006).

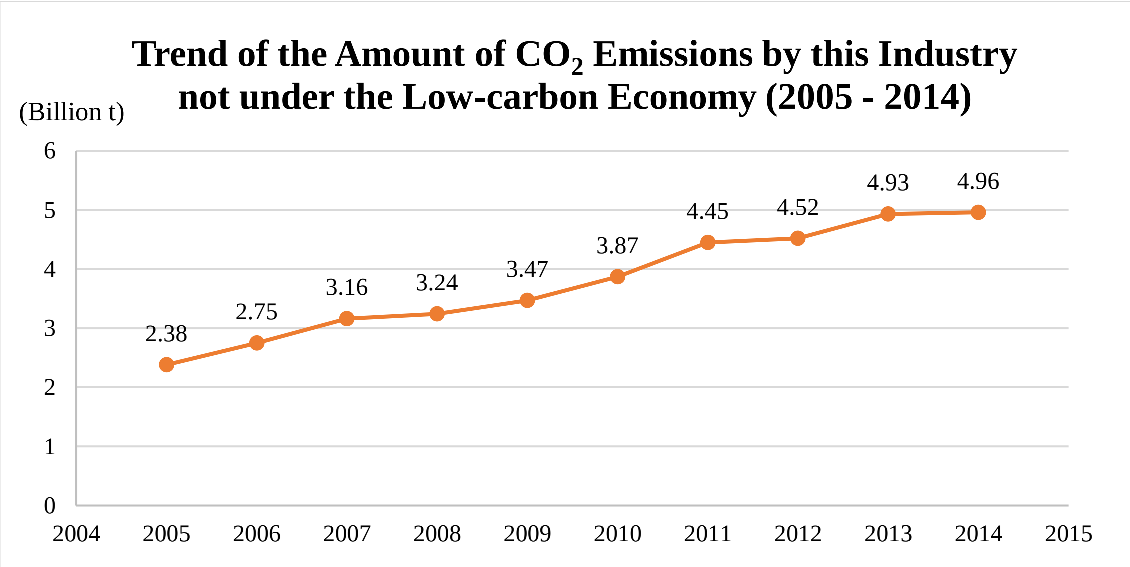

Figure 5-26 Trend of the Amount of CO_2 Emissions by this Industry not under the Low-carbon Economy (2005 - 2014)

The total amount CO_2 emissions by this industry, when not under the low-carbon economy over the years (Figure 5-26), continuously increased from 2.38 billion tonnes in 2005 to 4.96 billion tonnes in 2014, doubling the amount of CO_2 emissions.

5.4.2.5.6.2 Analysis of the Trend of the Amount of CO_2 Emissions by this Industry under the Low-carbon Economy

Since 2005, this industry has begun to improve production technology to reduce air pollution and reduce the consumption of coal, leading to a reduction in CO_2 emissions. Therefore, the amount of CO_2 emissions from this industry under the low-carbon economy is also in practice the actual amount of CO_2 released over these years, which can be calculated from following expression. CO_2 emissions from this industry = total consumption of energy resources in SCE by this industry × 3.14, where 3.14 is the coefficient of converting standard coal to CO_2 (IPCC, 2006).

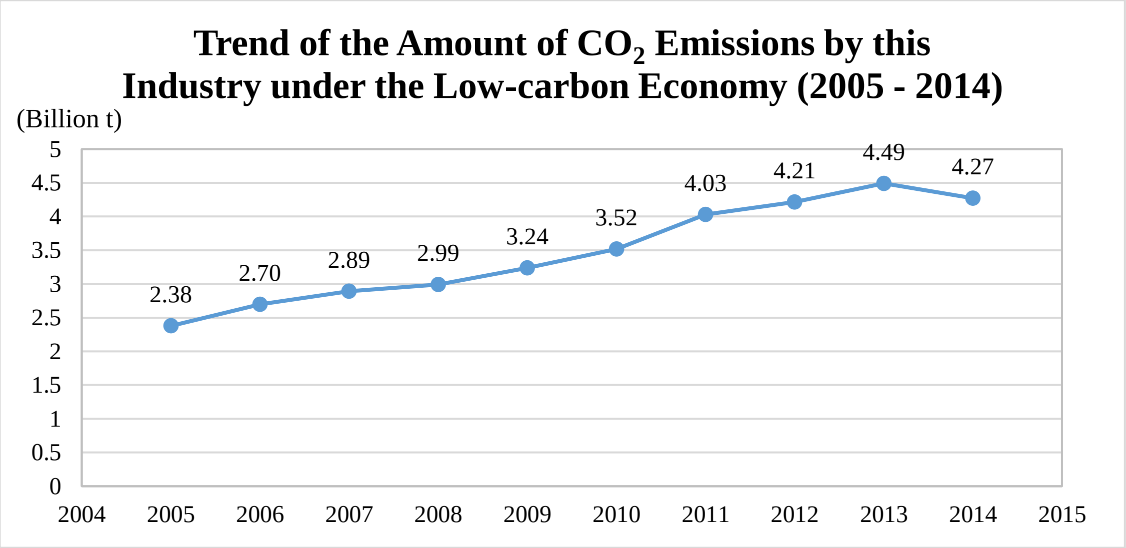

Figure 5-27 Trend of the Amount of CO_2 Emissions by this Industry under the Low-carbon Economy (2005 - 2014)

Figure 5-27 shows that the total amount of CO_2 released by this industry during these years increased from 2.38 to 4.27 billion tonnes. When compared with Figure 5-26, it shows that from 2006, this Chinese industry reduced the CO_2 emissions each year. Over these years, thermal electricity generation reduced 3.01 billion tonnes of CO_2 emissions in total. From 2005 to 2013, the total amount of CO_2 emissions continuously increased, after which it began to decrease. In 2014, 0.22 billion tonnes of less of CO_2 was emitted into the atmosphere. Moreover, compared with the increase in electricity production, this CO_2 emissions reduction in 2014 indicates that the increase in emissions caused by the growth of electricity could be deducted by the implementation of a low-carbon economy.

Table 5-5 The Total Amount of CO_2 Emissions by this Industry in the Low-carbon Economy (2005 – 2014) (Million tonnes)

Year	Summary	Coal	Oil	Natural Gas	Other Energy Sources
2005	2377.12	2313.88	58.81	1.15	3.28
2006	2695.46	2646.96	41.99	2.19	4.31
2007	2890.89	2849.78	32.43	3.08	5.61
2008	2990.14	2960.02	22.79	3.12	4.2
2009	3239.42	3211.4	17.81	5.12	5.09
2010	3517.99	3481.01	16.46	15.42	5.1
2011	4032.16	3994.5	13.4	18.4	5.86
2012	4214.92	4178.15	12.06	17.67	7.03
2013	4491.81	4458.63	6.81	17.64	8.72
2014	4273.1	4233.66	10.5	18.39	10.55

Table 5-5 presents the amount of CO_2 released by this industry using different energy resources. The amount of CO_2 from coal follows the same trend as the summary, with an increase before 2014 and then a rapid decrease from 4,458.63 to 4,233.66 million tonnes. The CO_2 emitted from using oil decreased from 58.81 million tonnes to the bottom point of 6.81 million tonnes, with a slightly increase in 2014 to around 10.5 million tonnes. The CO_2 emissions through the consumption of natural gas increased continuously from 1.15 million tonnes to 18.39 million tonnes. Finally, the emissions from other energy sources increased from 3.28 million tonnes to 10.55 million tonnes.

Table 5-6 The Proportion of CO_2 Emissions for Each Energy Resources (2005 – 2014)

Year	Coal	Oil	Natural Gas	Other Energy
2005	97.34%	2.47%	0.05%	0.14%
2006	98.20%	1.56%	0.08%	0.16%

2007	98.58%	1.12%	0.11%	0.19%
2008	98.99%	0.76%	0.10%	0.14%
2009	99.14%	0.55%	0.16%	0.16%
2010	98.95%	0.47%	0.44%	0.14%
2011	99.07%	0.33%	0.46%	0.15%
2012	99.13%	0.29%	0.42%	0.17%
2013	99.26%	0.15%	0.39%	0.19%
2014	99.08%	0.25%	0.43%	0.25%

Table 5-6 presents the proportion of CO_2 emissions from consuming different energy sources. Significantly, the CO_2 emitted through the consumption of coal is generally more than 97%, topping out at 99.26% in 2013. Oil was in second place until 2011, when it was overtaken by natural gas. There was a slight increase of consumption from other sources. This indicates that coal-fired production is still the main approach for thermal electricity generation in China, although natural gas for generation is being promoted, with oil less interest. Finally, thermal power generation using other sources has not yet to be fully explored in China.

5.4.2.5.7 Analysis of Industrial Total Profit Chinese Thermal Electricity Generation Industry

The cost of technological innovations since 2005 has already been accounted in the industrial production cost. Therefore, the data for the total profit for industry of this industry before 2005, represents the total profit from the traditional, non-low-carbon economy), while the data since 2005 represents the industry's total profits in the low-carbon economy. The calculation of these two total profits are based on the method presented in section 4.3.5.2.7, which is Industrial Total Profit in the Low-carbon Economy = Industrial Total Profit in Traditional Economy ± Industrial Cost of Reducing CO_2 Emissions. Therefore, this research will directly use the data of industrial total profit since 2005, as the total profit in the low-carbon economy for this industry.

5.4.2.5.8 Analysis of Income Tax Payable by the Chinese Thermal Electricity Generation Industry

Based on the definition of income tax payable presented in section 4.3.5.2.8, this industry's income tax payable is the sum of all income tax payable within this industry;

similarly, the data for total profit. The data is provided by the National Bureau of Statistics of China (2015).

5.4.2.6 Factor of Carrying Capacity Dimension for Chinese Industrial System

The reduction target of CO_2 emissions for this Chinese industry firstly calculated from the national reduction target, and then is regulated as the industrial policy on low-carbon emission for the thermal electricity generation industry in China. In the *Action Plan on Energy-saving, Emissions Reduction, and the Upgrading of Coal-Fired Power Generation (2014-2020)* (2014a), the National Development and Reform Commission, the Ministry of Environmental Protection, and the National Energy Administration regulated that the new introduced thermal electricity generators should be constructed with the efficient desulphurisation, denitrification and soot-removing facilities. The average standard coal consumption per unit of electricity supply of the re-constructed generators should be less than 310 g/kWh. For the current generators with the capacity of 600,000 kWh or above, except their air-cooling units, their average standard coal consumption per unit of electricity supply must lower than 300 g/kWh. These regulations curb the final energy consumption, which therefore ensured the CO_2 emissions level from this industry. Therefore, the factor for this dimension, the industrial target for CO_2 emissions, is defined as the average standard coal consumption per unit of electricity supply. It is calculated as Standard Coal Consumption per unit of Electricity Supply = Standard Coal Consumption by this Industry / Production of Electricity (final goods).

5.4.2.7 Factor for the Development Goal Dimension for this Chinese Industrial System

Referring to the factor analysis and calculation method in section 4.3.7.2, the industrial net profit in the low-carbon economy in G_{ce} dimension is calculated based on total profit for industry in the low-carbon economy and income tax payable by industry in the low-carbon economy.

Industrial net profit in the low-carbon economy = Industrial total profit in the low-carbon economy - Income tax payable by industry in the low-carbon economy.

This factor represents the capacity of the sustainable development in Chinese thermal electricity generation industry. When this industrial net profit is above zero, it means that this industry has the capacity to achieve sustainable development in low-carbon economy. However, if the net profit is below zero, it means the industry does not have the capacity for achieving sustainable development. The more detail standards of judgements for this issue will be presented in later section.

5.4.3 The Logical Relational Model for the Industrial Low-carbon Economy System for the Chinese Thermal Electricity Generation Industry

The logical relational model for the industrial low-carbon economy system, constructed in section 4.7, is applied into this Chinese industry (Figure 5-28).

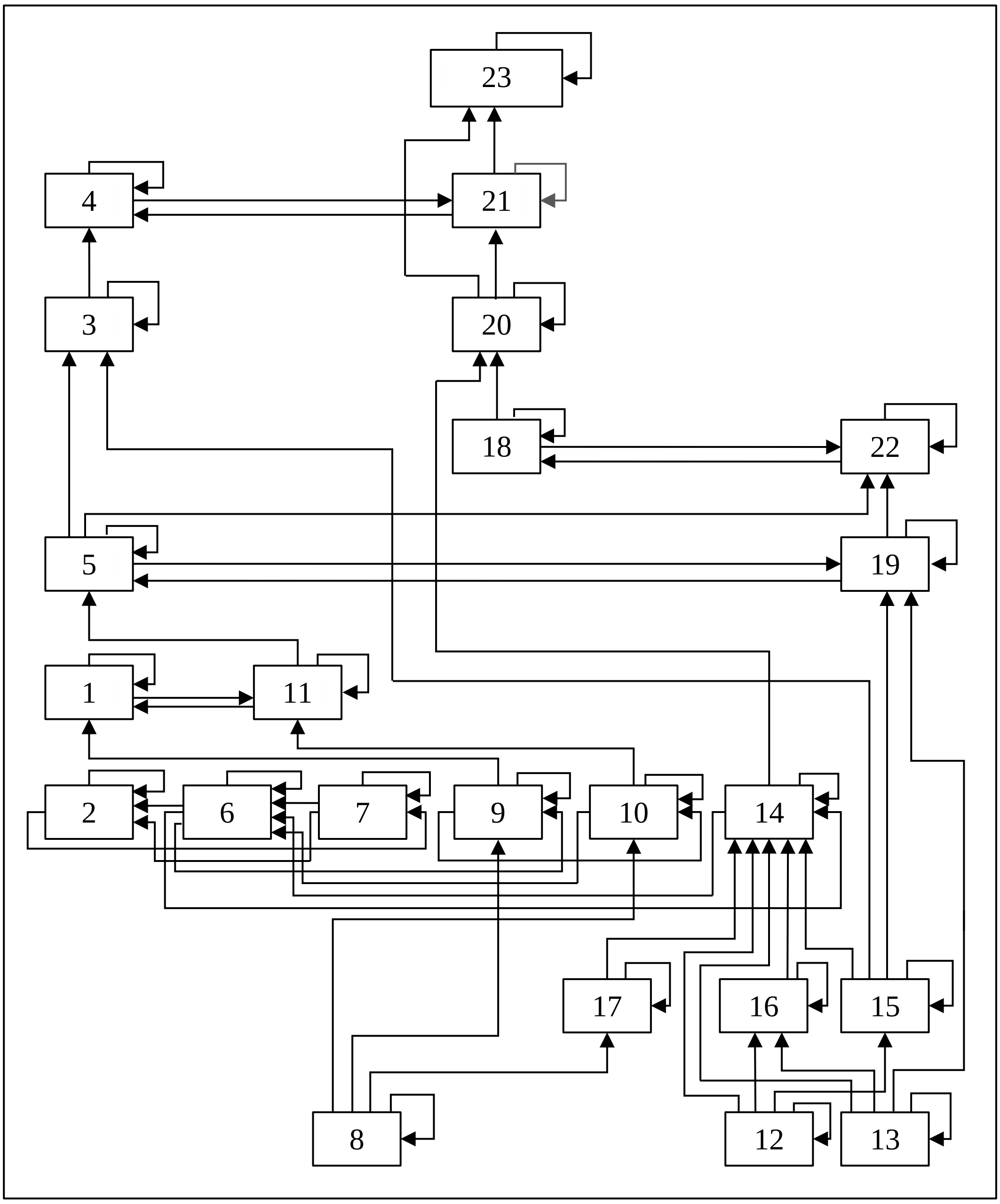

Figure 5-28 The Logical Relational Model for the Industrial Low-carbon Economy System for the Chinese Thermal Electricity Generation Industry

In this model, the factors are defined as in section 5.4.2. Population (Factor 8), industrial production technology (Factor 12), and industrial technology for CO_2 pollution treatment (Factor 13) are still the bottom factors, which are the root causes in achieving the system's goal (Factor 23). Referring to the methods in section 3.4.8 (1), (2), (3) and (4), is given a specific industrial policy (Factors 3, 4 and 5), the causal relationships affecting and determining these factors can be deducted. As presented in section 5.4.2.4.2.2, the CCS and other related CO_2 treatment technologies are still at the experimental stage and cannot be applied to commercial activities. Therefore, Factor 13 is deducted. After the simplification of this model, the root factor for the logical relational model is Factor 12, industrial production technology, which indicates that the production technology of this Chinese industry determines its economic development and its CO_2 emissions. Therefore, Factor 12 is also the fundamental factor for both the model for industrial sustainable development and the model for the optimal approach to low-carbon emission.

5.4.4 The Model for the Sustainable Development in the Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

This section applies the model in section 4.8.5 to construct the model for this Chinese industry (Figure 5-29).

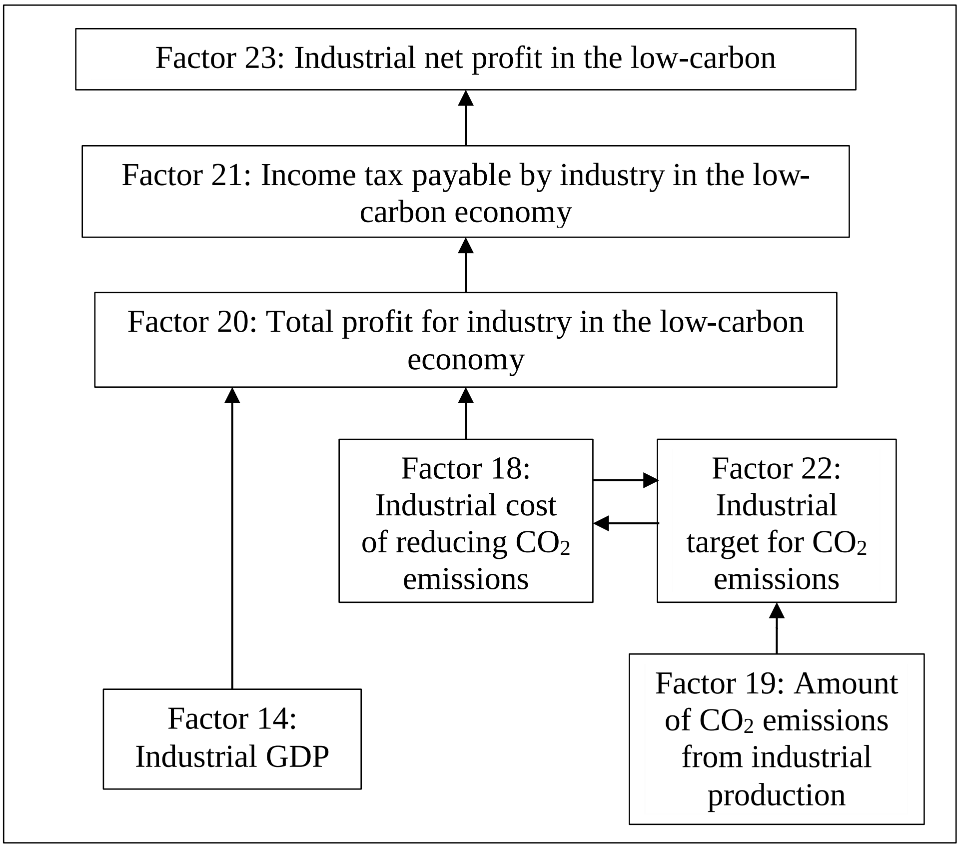

Figure 5-29 The Model for the Sustainable Development in the Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

In this model, the industrial production process is represented by Factor 14 (industrial GDP) as the economic output and Factor 19 (the amount of CO_2 emissions from industrial production) as the environment output. Based on the discussion in section 5.4.3, under certain policies, the industrial production technology (Factor 12) determines the industrial production (Factor 14) and industrial CO_2 emissions (Factor 19), which means that sustainable development in the low-carbon economy for Factor 23 is achieved based on improving industrial production technology (Factor 12), through the impact of Factors 14 and 19. The system's goal, industrial net profit in the low-carbon economy (Factor 23), is achieved through balancing the economic and environmental aspects, meeting the environmental and economic concerns. In detail, this model indicates that whether the industry could achieve sustainable development or not, depends on whether or not the total profit for the industry in the low-carbon economy (Factor 20) can afford the industrial cost of reducing CO_2 emissions (Factor 18). In other words, if Factor 23 is larger than zero, then this industry can afford Factor 18, and it can achieve sustainable development in the low-carbon economy. Otherwise, it cannot afford Factor 18 and cannot be sustainable. However, given a deduction in total profit for the industry in the low-carbon economy (Factor 20), government could adjust its income tax rate, to reduce the tax payable by industry in the low-carbon economy (Factor 21), for promoting the sustainable development in this industry.

5.4.5 The Model for the Optimal Approach to Low-carbon Emission for the Chinese Thermal Electricity Generation Industry

In this section, the model for the optimal approach to low-carbon emission from section 4.8.6 is implemented to construct the model for this industry (Figure 5-30).

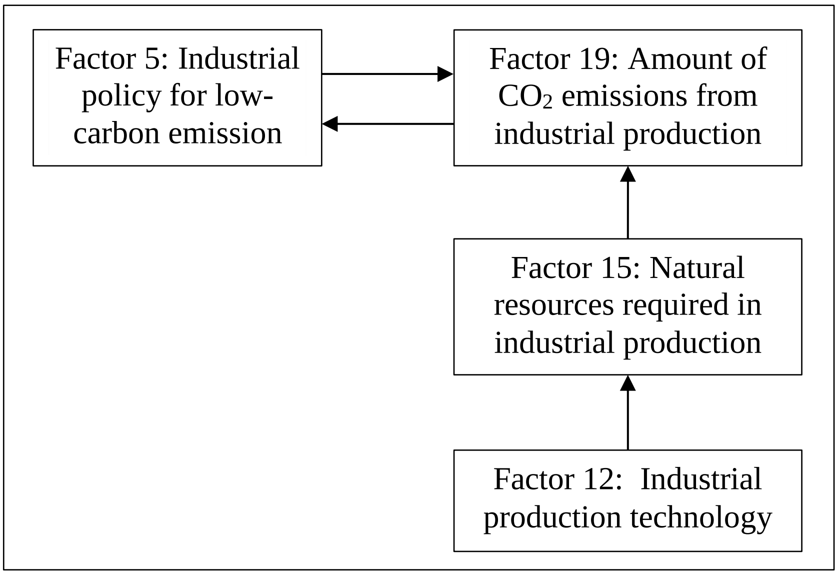

Figure 5-30 The Model for the Optimal Approach to Low-carbon Emission for Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

In this model, the industrial production technology (Factor 12) is the root cause, indicating that only through improving the production technology (Factor 12) and then through affecting the natural resources required in industrial production (Factor 15), can control of the amount of CO_2 emissions from industrial production (Factor 19) be achieved. The improvement of Factor 12 would occur either through increasing the efficiency of the utilisation of resources or by using non-carbon resources. On the other hand, the interaction between the industrial policy for low-carbon emission (Factor 5) and Factor 19 indicates that the government affects the industrial emissions (Factor 19) through legislating for the related low-carbon policy (Factor 5). The industrial emission level (Factor 19) influences decision making for the low-carbon policy (Factor 5).

5.4.6 The Theoretical Model for Chinese Economic Growth and the Industrial CO_2 Emissions

The theoretical model for economic growth and industrial CO_2 emissions from section 4.8.7 is applied to the Chinese industry to construct the theoretical model (Figure 5-31).

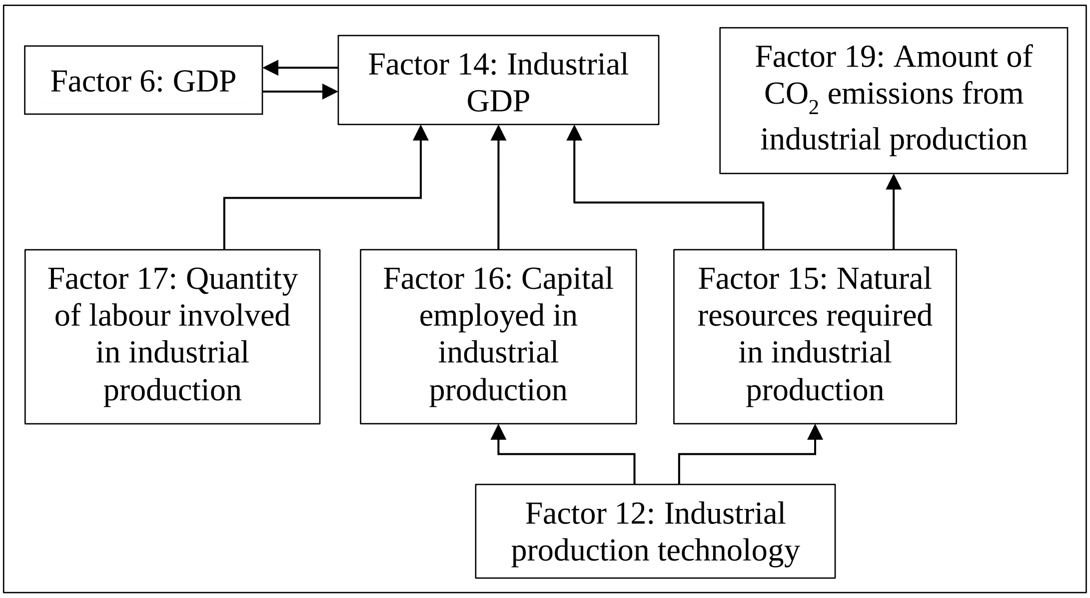

Figure 5-31 The Theoretical Model for Economic Growth and the Industrial CO_2 Emissions by the Chinese Thermal Electricity Generation Industry

In this model, natural resources required in industrial production (Factor 15), capital employed in industrial production (Factor 16), quantity of labour involved in industrial production (Factor 17), and industrial production technology (Factor 12), all represent the production process in the Chinese thermal electricity generation industry, determining the industrial GDP (Factor 14). The Chinese GDP (Factor 6) interacts with the industrial GDP of this industry (Factor 14). The CO_2 emitted (Factor 19) is determined by the consumption of natural resources (Factor 15) and production technology of this (Factor 12) industry. Therefore, there is a positive correlation between this industrial GDP and its CO_2 emission, but no causal relationship between them. Moreover, there is no causal relationship between the Chinese GDP (Factor 6) and the industrial CO_2 emissions (Factor 19).

5.5 Chapter Summary

This chapter applied the theoretical models constructed in chapter 4 to the Chinese thermal electricity generation industry, building up further models for this industry. In order to do so, the dimensions and factors were explained regarding their contents in this thermal electricity generation industry, and the quantifiable factors were analysed on their trend of movements. With the illustrations of factors, this chapter applied the logical relational model and the three sub-model constructed based on this model to this industry, identifying that the model for sustainable development, for the optimal approach to low-carbon emission, and for Chinese economic growth and industrial CO_2 emissions, in an industrial low-carbon economy. These models will then be quantified and validated in the next chapter.

Chapter 6 Validation of the Theoretical Models for the Industrial Low-carbon Economy System with data from Chinese Thermal Electricity Generation Industry

6.1 Introduction

Based on the model constructed in chapter 5, and the information about the factors in this Chinese industrial low-carbon economy system, this chapter validated the models constructed in chapter 5, and the corresponding models in chapter 4 together with the research methodology constructed in chapter 3. This chapter will first present the data resources and related explanations. Secondly, this chapter will calculate and assess the national and industrial low-carbon emission targets. Based on these calculations and assessments, this chapter will then validate the theoretical models constructed in previous chapter through the mathematical expressions and logical criterions for the models. Then, referring to the validation of models in chapter 5, this chapter is able to validate the models built in chapter 4, as well as the research methodology for these modelling.

6.2 The National Standard for the Chinese Low-carbon Economy and the Industrial Standard for the Low-carbon Emission for Chinese Thermal Electricity Generation Industry

6.2.1 The National Standard for Low-carbon Emission in the Chinese Low-carbon Economy

The *Special Planning for Medium and Long Term Energy Conservation*, issued by the National Development and Reform Commission (2004), "regulates to achieve the energy-saving target with reducing 240 million tonnes of standard coal, during the 'eleventh five-year' period". The State Council (2006) proposed "at the end of the 'eleventh five year', to reduce the energy consumption in per unit of 10000 yuan GDP into 0.98 ton of standard coal". In 2009, the Chinese government promised, "by 2020 reducing the CO_2 emissions per unit of GDP by 40%-45% compared with 2005 level".

The Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine (2011) issued *Plan (GB13223-2011)*, and the General Office of the State Council (2014b) issued *Plan (Guo Ban Fa [2014] No.23)*, both regulated the emission allowances and related environmental standards.

Referring to the policies and standards presented in section 5.4.2.1.5 and here, this section examines the Chinese national standard for low-carbon emission in low-carbon economy, which is "by 2020 reducing the CO_2 emissions per unit of GDP by 45% compared with 2005 level". Based on the targets in related government plan (2014b), this research assumes that during the 15 years from 2005 to 2020 the national standard for low-carbon emission is equally allocated to each year. Therefore, during these 15 years, the CO_2 emissions per unit of GDP should be reduced 3% per year compared with the 2005 level. Therefore, the calculations for reduction standard for CO_2 emissions per unit of GDP and the allowance of CO_2 emissions per unit of GDP for one targeted year N are as follows:

Equation 6-1: $RS_{CN} = CO_{2\ (GDP2005)} \times 3\% \times N$, where RS_C presents the reduction standard (RS) of CO_2 emissions per unit of GDP for China (C) for a targeted year N; $CO_{2\ (GDP2005)}$ represents the CO_2 emissions per unit of GDP in 2005; N represents the serial number of the year from 2005, i.e. N = 0, 1, 2,…, 15.

Equation 6-2: $EA_{CN} = CO_{2\ (GDP2005)} \times (1 - 3\% \times N)$, where EA_C represents the emission allowance (EA) of CO_2 emissions per unit of GDP for China for a targeted year N.

6.2.1.1 Calculation of the Amount of CO_2 Emissions by Chinese Energy Consumption in 2005

The calculation for CO_2 emissions in 2005 can be calculated from energy consumption and related coefficients. The calculation process is shown in Table 6-1, while the amount of CO_2 emissions from the four types of energy is shown in Figure 6-1.

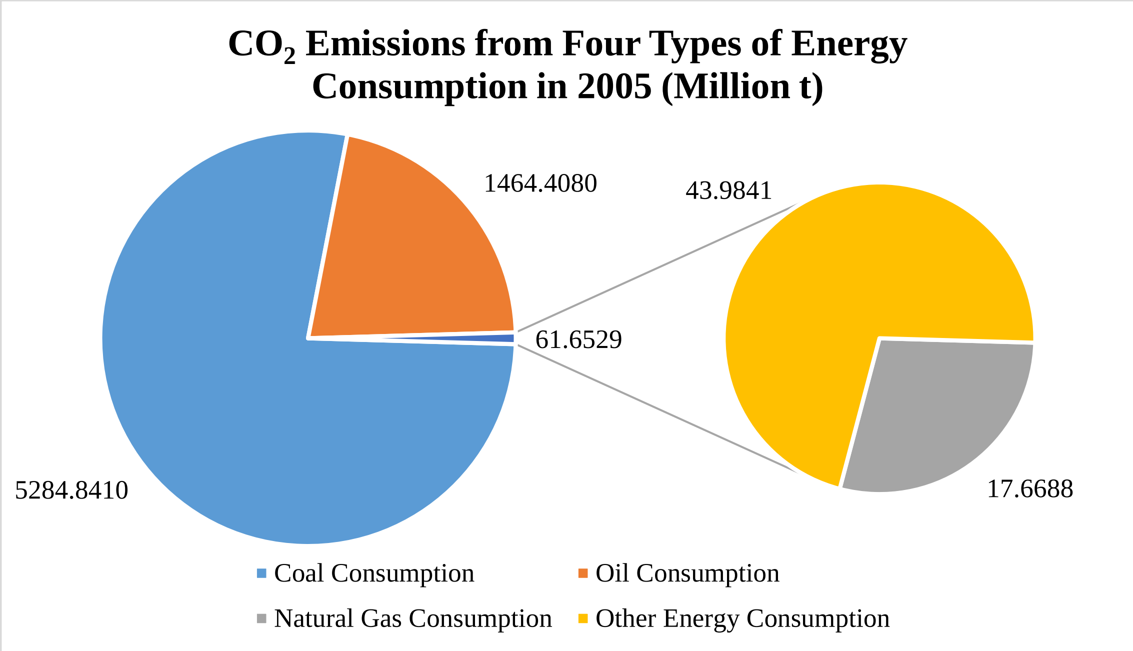

Figure 6-1 CO_2 Emissions from Four Types of Energy Consumption in 2005

From Figure 6-1, the around 78% of CO_2 emissions in China were produced by the consumption of coal or coal-based products, and 22% by oil consumption. The CO_2 emissions from natural gas and other sources of energy were less than 1%.

From Table 6-1, first, we use the coefficients to covey all the energy consumption into a standard coal equivalent (SCE). CO_2 emissions are therefore calculated using the SCE consumption.

Table 6-1 CO_2 Emissions by Type of Energy Consumption in 2005

Items	**Energy Consumptions (10000t)**	**Coefficient for the Conversion into Standard Coal (kgce/kg)**	**Coefficient for the Conversion from Standard Coal to CO_2 (kg/kgce)**	**CO_2 Emissions (Million t)**
Coal Total				5284.8410
Raw Coal	235526.53	0.7143	3.14	5282.6293
Cleaned Coal	-21.76	0.9000	3.14	-0.6149
Other Washed Coal	1.02	0.2850	3.14	0.0091
Briquette	1.90	0.6000	3.14	0.0358
Coke	-1427.26	0.9714	3.14	-43.5342
Other Coal Gas	247.521 (Billion m^3)	0.5798 (kgce/m^3)	3.14	45.0591

Other Coking Products	30.79	1.3000	3.14	1.2568
Petroleum Products Total				1464.4080
Crude Oil	30089.17	1.4286	3.14	1349.7412
Gasoline	-578.29	1.4714	3.14	-26.7181
Kerosene	63.54	1.4714	3.14	2.9357
Diesel Oil	-117.61	1.4571	3.14	-5.3810
Fuel Oil	2469.85	1.4286	3.14	110.7926
Liquefied Petroleum Gas	619.50	1.7143	3.14	33.3471
Other Petroleum Products	-7.04	1.4000	3.14	-0.3095
Natural Gas Total				17.6688
Natural Gas	46.351 (Billion m^3)	1.2140 ($kgce/m^3$)	3.14	17.6688
Other Energy Summary				43.9841
Other Energy	3269.00 (10000t SCE)	0.4285	3.14	43.9841
Total CO_2 Emissions from Energy Consumption (Million t)				6810.9018

Note: The data in Table 6-1 is based on the *China Overall Energy Balance Sheet (Physical Quantity)*; the negative value table indicates the inventory increase at the end of the year. The coefficient for the conversion from energy to standard coal is from the *General Principles for Calculation of the Comprehensive Energy Consumption* (2008). The coefficient for the conversion from standard coal to CO_2 is 3.14 kg/kgce, which is calculated from the default emission factors provided by IPCC (2006). Standard coal is defined as 1kg consumption releasing 7000 kcal energy, which is close to the energy provided by coke (6300 − 7500kcal/kg). Moreover, the coefficient for converting coke into standard coal is 0.9714, near 1. Thus, this study used data for the default emission factor for coke from the IPCC (2006) to represent the data for standard coal, which is 107000 kg of CO_2 per TJ on a net calorific basis. As illustrated in section 5.2.2, at 15ºC, 1 kcal = 4.1868 kJ. Therefore, the consumption of 1kg of standard coal will release 7000 kJ, as 29307.6 kJ, which will lead to $107000 \times 29307.6 / 10^9 = 3.1359$ kg ≈ 3.14 kg of CO_2 emissions. Therefore, the coefficient for the conversion from standard coal to CO_2 is 3.14 kg/kgce.

6.2.1.2 The Calculation for the Reduction Standard of CO_2 Emissions per unit of GDP in China

Referring to the Equation 6-1, $RS_{CN} = CO_{2\ (GDP2005)} \times 3\% \times N$, the calculation for the reduction standard of CO_2 emissions per unit of GDP uses the CO_2 emissions per unit of GDP in 2005 ($CO_{2\ (GDP2005)}$). $CO_{2\ (GDP2005)}$ is the CO_2 emissions in 2005 derived from section 6.2.1.1 and the GDP in 2005.

$CO_{2\ (GDP2005)}$ = CO_2 emissions / GDP = 366.38 g/yuan.

Therefore, the reduction standard of CO_2 emissions per unit of GDP from 2005 to 2020 is calculated and shown in Figure 6-2.

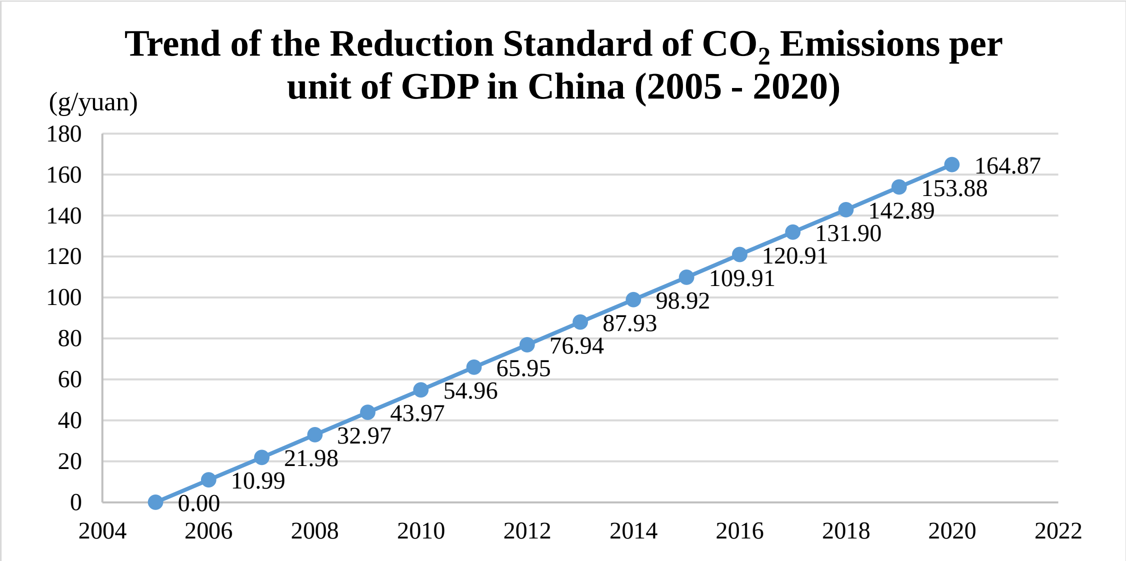

Figure 6-2 Trend of the Reduction Standard of CO_2 Emissions per unit of GDP in China (2005 - 2020)

By 2020, the CO_2 emissions per unit of GDP in China should reduce 164.87 g/yuan from the 366.78 g/yuan in 2005.

6.2.1.3 Calculation of the Allowance of CO_2 Emissions per unit of GDP in China

Referring to the Equation 6-2, $EA_{CN} = CO_{2\ (GDP2005)} \times (1-3\% \times N)$, the calculation for the allowance of CO_2 emissions per unit of GDP uses the CO_2 emissions per unit of GDP in 2005 ($CO_{2\ (GDP2005)}$). As shown above, $CO_{2\ (GDP2005)}$ = 366.38 g/yuan.

Therefore, the reduction standard of CO_2 emissions per unit of GDP from 2005 to 2020 is calculated and shown in Figure 6-3.

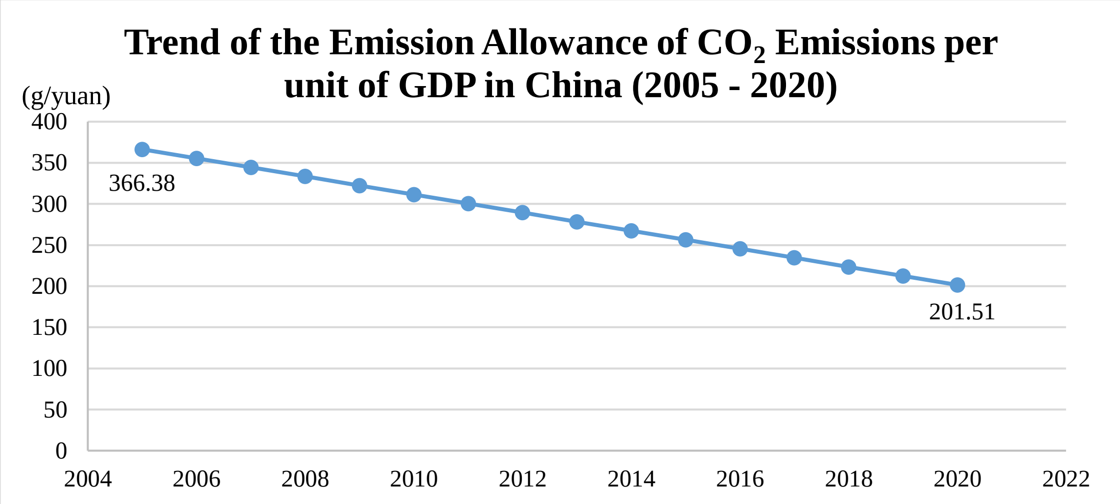

Figure 6-3 Trend of the Allowance of CO_2 Emissions per unit of GDP in China (2005 - 2020)

By 2020, the CO_2 Emissions per unit of GDP in China should be less than 201.51 g/yuan.

6.2.2 The Industrial Standards for Low-carbon Emission in the Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

Referring to the national plan for economic development in the eleventh, twelfth and thirteenth “five-year” periods, the industrial standards for low-carbon emission of the Chinese thermal electricity generation industry rely on regulation of the standard coal consumption per unit of electricity supply. It is stipulated that “the standard coal consumption per unit of electricity supply of this industry should be reduced from 370 g/kWh to 310 g/kWh from 2005 to 2020” (State Council, 2012; National Development and Reform Commission, 2016). As this research assumes the standard coal consumption per unit of electricity supply is reduced by the same level each year, reduction is 4 g/kWh every year. Based on it, the calculations for the reduction standard and emission allowance of CO_2 emissions per unit of electricity generation for this industry in the low-carbon economy are as follows:

Equation 6-3: $RS_{IN} = 3.14 \times 4 \times N$, where RS_{IN} represents the reduction standard of CO_2 emissions per unit of electricity generation for this industry in year N, where N is the serial number of the year N = 0, 1, 2,… 15, from 2005 to 2020. 4 is the average reduction of standard coal consumption per unit of electricity supply for each year; while 3.14 is the coefficient for the conversion from standard coal to CO_2 (IPCC, 2006).

Equation 6-4: $EA_{IN} = 3.14 \times (F_{15(2005)} - 4 \times N)$, where EA_{IN} is the allowance of CO_2 emissions per unit of electricity generation for this industry in year N. $F_{15(2005)}$ is the standard coal consumption per unit of electricity supply in this industry in 2005, and 4 and 3.14 are as in the previous equation (IPCC, 2006).

The standard coal consumption per unit of electricity supply and the CO_2 emissions per unit of electricity generation for both the emission allowance and the reduction standard are calculated below.

6.2.2.1 Calculation for the Reduction Standard for the Chinese Electricity Generation Industry

Referring to the analysis above, the reduction standard for coal consumption per unit of electricity supply is assumed to be 4 g/kWh per year. The trend of the reduction standard is shown in Figure 6-4.

Referring to the Equation 6-3, $RS_{IN} = 3.14 \times 4 \times N$, as the reduction standard of the standard coal consumption per unit of electricity supply for each year is known (= 4), the reduction standard of CO_2 emissions per unit of electricity generation is calculated and shown in Figure 6-4.

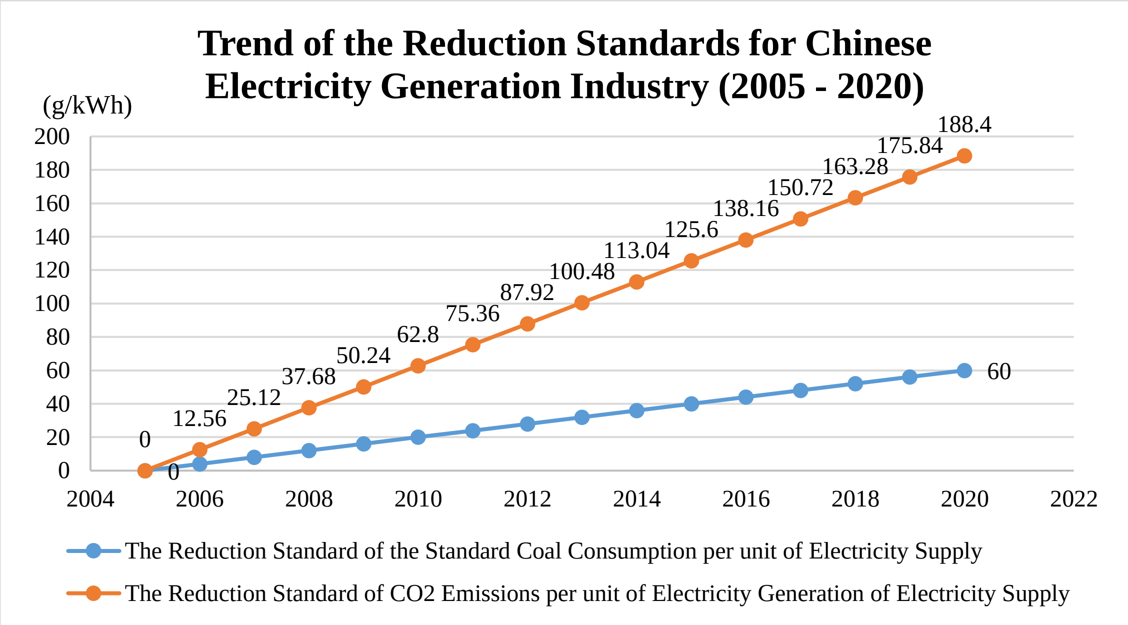

Figure 6-4 Trend of the Reduction Standards for Chinese Electricity Generation Industry (2005 – 2020)

By 2020, CO_2 emissions per unit of electricity supply for this Chinese industry should reduce 188.4 g/kWh from level in 2005, while the standard coal consumption per unit of electricity supply must reduce 60 g/kWh from the level of 2005.

6.2.2.2 Calculation of the Emission Allowance for the Chinese Electricity Generation Industry

Referring to the reduction standard, the allowance for the standard coal consumption per unit of electricity supply equals $F_{15\ (2005)}$ minus the reduction standard (Figure 6-5).

Referring to the Equation 6-4, $EA_{IN} = 3.14 \times (F_{15\ (2005)} - 4\times N)$, where $F_{15(2005)}$ is the standard coal consumption per unit of electricity supply in this industry in 2005, equal to 370 g/kWh. Therefore, the allowance of CO_2 emissions per unit of electricity supply (2005 - 2020), is calculated and shown in Figure 6-5.

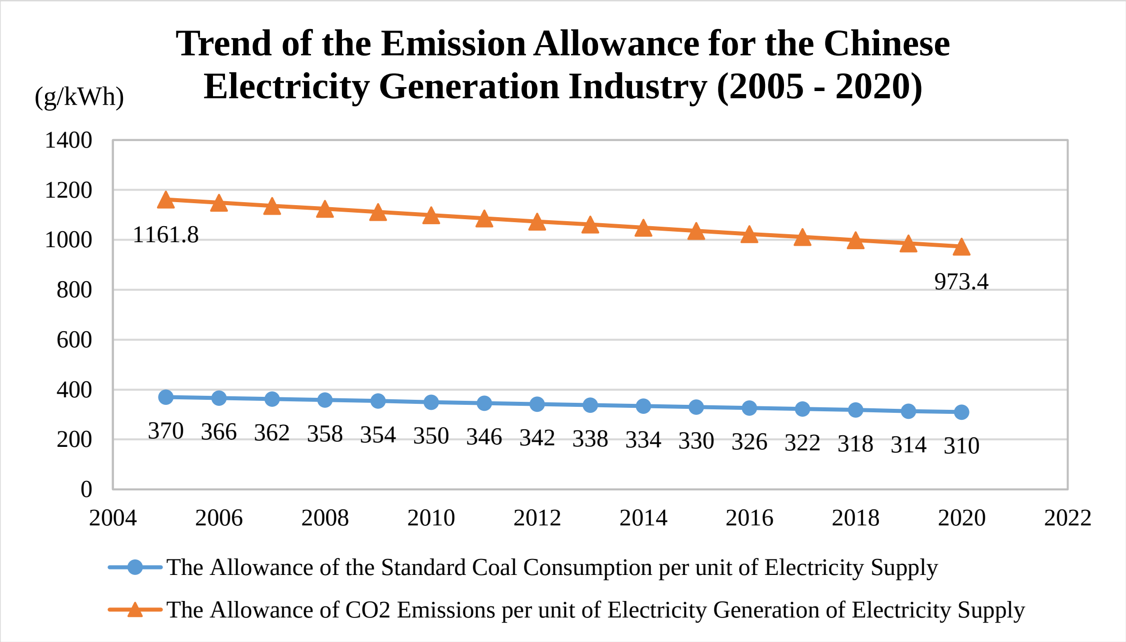

Figure 6-5 Trend of the Emission Allowances for the Chinese Electricity Generation Industry (2005 – 2020)

By 2020, CO_2 emissions per unit of electricity supply by this industry must decrease from 1161.8 g/kWh (2005) to 973.4 g/kWh, while the standard coal consumption per unit of electricity supply must be lower than 310 g/kWh.

6.3 Comparison between National Emission Allowance and Real CO_2 Emissions in this Low-carbon Economy in China

6.3.1 Analysis of the Trend of GDP in China from 2005 to 2020

Based on China's *Thirteenth Five-Year Plan* (National Development and Reform Commission, 2016), the GDP (current price) in China should reach around 92714.86 billion yuan, and from 2016 to 2020, the GDP's annual growth rate should be around 6.5%. Moreover, based on data from the GDP index (current price), this research sets the base year as 2005 to calculate the real GDP in constant price from 2005 to 2020 (Figure 6-6). As the real GDP represents the GDP's trend without the influence of prices (detail in section 4.3.2.2.1), the real GDP during 2005 to 2020 was first calculated and estimated. With the base year of 2005, the real GDP grows from 18589.58 billion yuan to 63214.82 billion yuan in 2020. Eliminating the effects of prices, the GDP growth in China is steady and continuous during these 16 years.

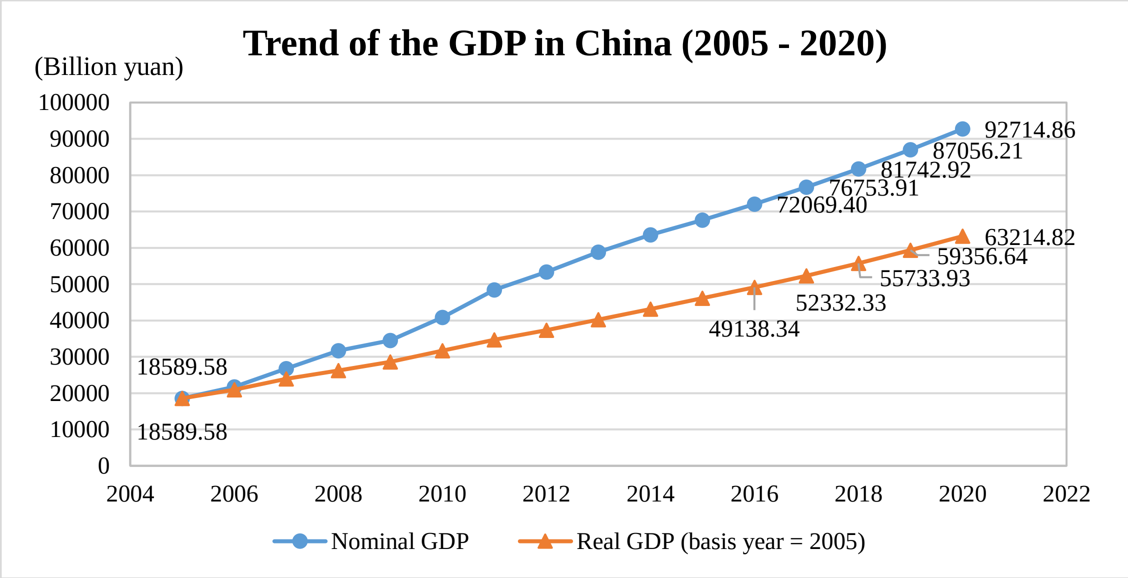

Figure 6-6 Trend of GDP in China (2005-2020)

6.3.2 The Practical CO_2 Emissions per unit of GDP in China

Based on the data of real GDP (base year 2005) and energy consumption from 2005 to 2014, the actual CO_2 emissions per unit of GDP in China are calculated for the period 2005 to 2014. The CO_2 emissions per unit of GDP during 2015 to 2020 are also estimated based on the average growth rate over the previous 10 years. The trend of the practical CO_2 emissions per unit of GDP in China from 2005 to 2020 is shown in

Figure 6-7.

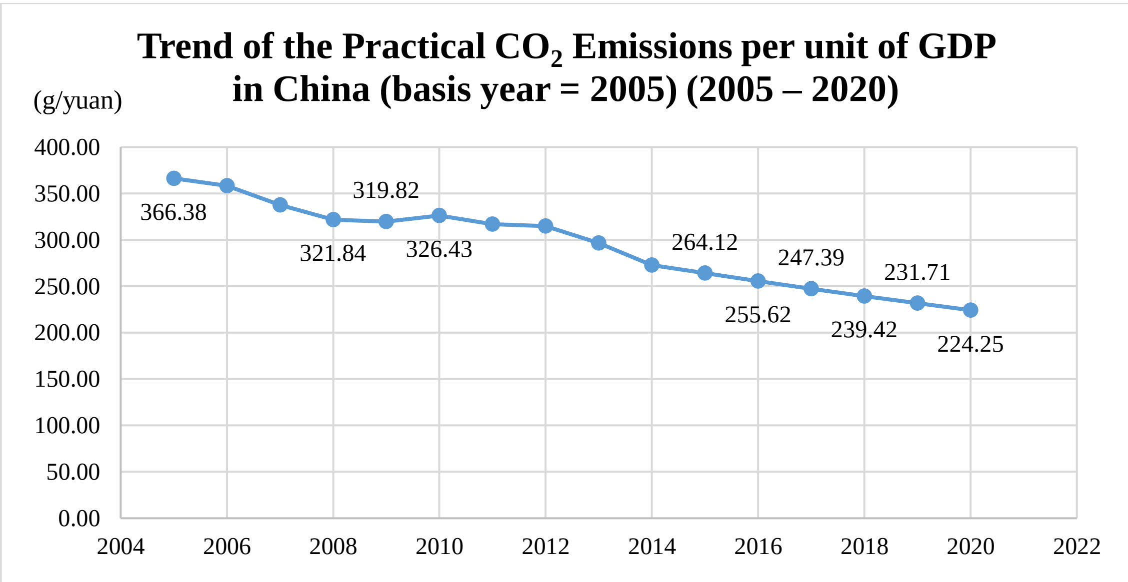

Figure 6-7 Trend of the Practical CO_2 Emissions per unit of GDP in China (basis year = 2005) (2005 - 2020)

As discussed in section 4.3.2.2.1, the real GDP deducting the effects of price, could provide more accurate information about production than the nominal GDP. Moreover, the huge influence of prices leads to a nominal GDP 33% greater the real GDP on average, so the calculated CO_2 emissions per unit of GDP will shift because of using the nominal GDP data. Therefore, this researcher calculated the CO_2 emissions per unit of GDP based on the real GDP data instead of the nominal GDP data. From Figure 6-7, the CO_2 emissions per unit of GDP are seen to decrease from 366.38 g/yuan to 319.82 g/yuan in 2009, with a slight increase in 2010 to 326.43 g/yuan, and estimated to decline to 224.25 g/yuan by 2020.

6.3.3 Comparison between National Emission Allowance and Practical CO_2 Emissions per unit of GDP in China

Comparing the national emission allowance from section 6.2.1.3 and the actual emissions in section 6.3.2 (Figure 6-8), this study finds that China could not achieve its national target for reducing CO_2 emissions by 2020.

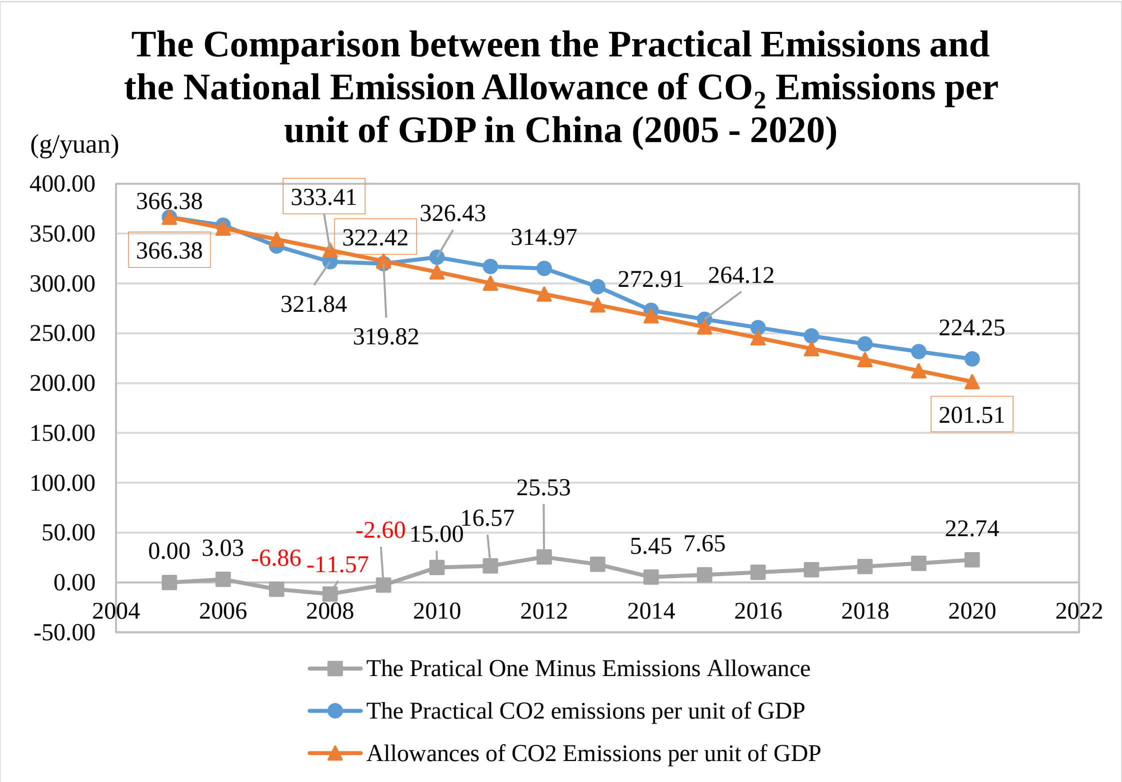

Figure 6-8 The Comparison between the Practical Emissions and the National Emission Allowance of CO_2 Emissions per unit of GDP in China (2005 - 2020)

In detail, Figure 6-8 shows that in 2007, 2008 and 2009, the actual emissions of China were less than the national allowance; however, in all the other years, they exceeded the allowance. By 2020, the estimated actual emission is about 61.2% of the level in 2005, which is 1.2% over the minimised national target for 2020. Therefore, the current procedure of reducing CO_2 emissions cannot achieved with the Chinese national carbon reduction standard by 2020. In order to achieve the target, China must speed up the process of reducing CO_2 emissions during the period 2015 to 2020. Furthermore, there were nine years between 2005 and 2014 when the actual emission exceeded the allowances. Even by 2020, if the national target is achieved, the cumulative emissions from these nine years have to be considered and treated to minimise the cumulative CO_2 released during these 15 years.

6.4 Comparison between Industrial Standards for CO_2 Emissions and Practical CO_2 Emissions by the Chinese Thermal Electricity Generation Industry

In the logical relational model in section 5.4.3, under a given industrial policy for low-carbon emission, industrial production technology is root cause. Using the logical approach of improving industrial production technology (Factor 12) to reduce the natural resources required in industrial production (Factor 15), then reducing the amount of CO_2 emissions from industrial production (Factor 19) and eventually achieving the industrial target for CO_2 emissions (Factor 22), this study applies the industrial data. The application will suggest whether this industry could achieve its industrial standards target through improving its production technology, and finally show whether the logical relational model can support this industry to meet the industrial standards for low-carbon emission.

According to the analysis in section 5.4.2, China began to reduce its CO_2 emissions in 2005, as did the thermal electricity generation industry. The reduction in this approach is through improvement of production technology (section 5.4.2.4.1). Therefore, the actual emissions and energy consumption data from this industry are applied to the logical relational model. This section therefore compares this practical data with the industrial standards for low-carbon emission, to investigate whether the logic is correct.

6.4.1 Analysis of the Trend in Thermal Electricity Generation

Referring to *Made in China 2025* and the *Thirteenth Five-year Plan* (State Council, 2015; National Development and Reform Commission, 2016; 2016), the maximum increase in production for thermal electricity generation is 900 billion kWh in 2020 over the level of 2015. Therefore, the maximum production of thermal electricity in 2020 is 5110.2 billion kWh. This study assumes stable growth in the production of thermal electricity from 2016 to 2020, with a CAGR of 3.95%. This production is estimated based on the CAGR and shown in Figure 6-9.

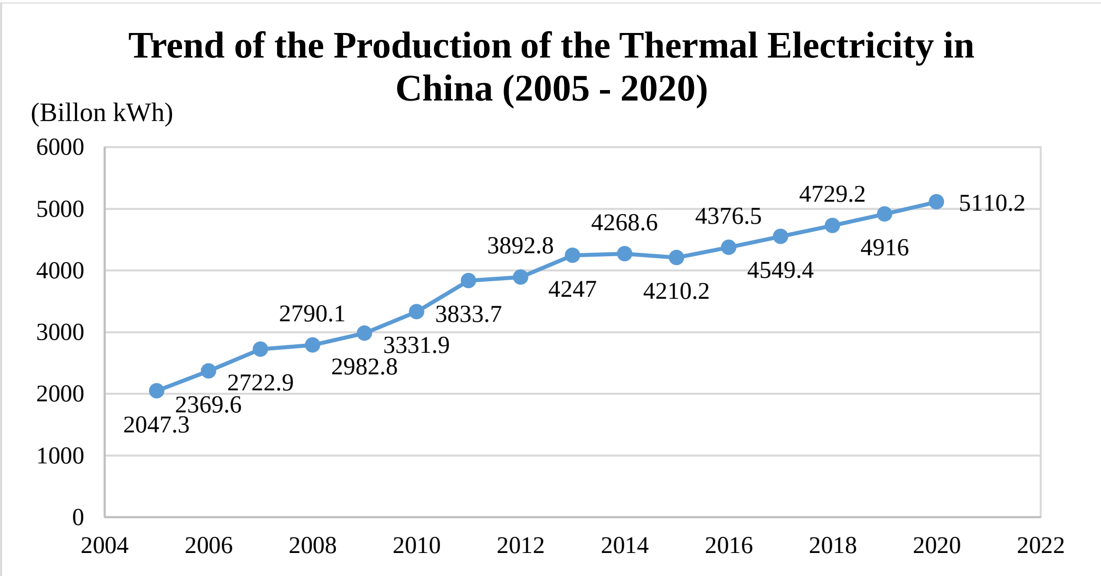

Figure 6-9 Trend of the Production of the Thermal Electricity in China (2005-2020)

Figure 6-9 shows that a growth in production from 2047.3 billion kWh in 2005 to 5110.2 billion kWh in 2020, generally continuous and steady over the 15 years.

6.4.2 The Practical Standard Coal Consumption per unit of Electricity Supply in the Chinese Thermal Electricity Generation Industry

The practical standard coal consumption per unit of electricity supply during 2005 to 2014 is calculated by the equation in section 5.4.2.6: Practical Standard Coal Consumption per unit of Electricity Supply = Practical Standard Coal Consumption by this Industry / Production of Electricity (final goods). The practical standard coal consumption is based on data from the *China Overall Energy Balance Sheet (Physical Quantity)* (National Bureau of Statistics of China, 2015). For 2015 to 2020, it is estimated based on the average growth rate for the previous years (Figure 6-10).

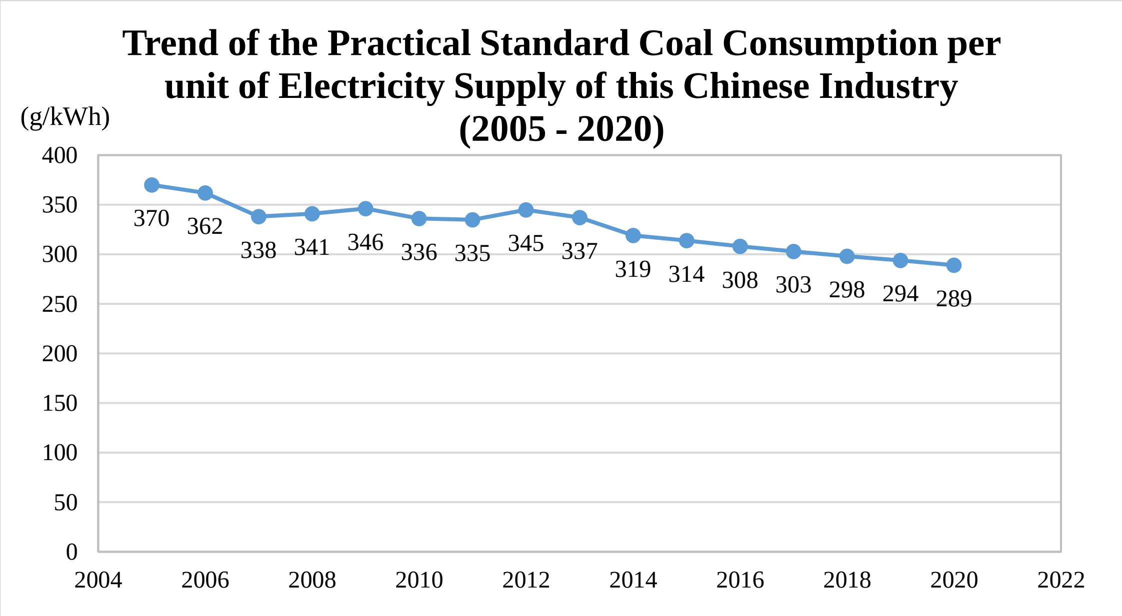

Figure 6-10 Trend of the Practical Standard Coal Consumption per unit of Electricity Supply of this Chinese Industry (2005 - 2020)

Figure 6-10 shows that the standard coal consumption per unit of electricity supply of this industry decreased from 370 g/kWh in 2005 to 319 g/kWh in 2014, along with technological improvement, from subcritical units to supercritical units. The figure for 2015 to 2020 is estimated to decrease from 314 g/kWh to 289 g/kWh.

6.4.3 Practical CO_2 Emissions per unit of Electricity Supply in the Chinese Thermal Electricity Generation Industry

Referring to the analysis in section 6.4.2, this section calculates and estimates the practical CO_2 emissions per unit of electricity supply for this industry from 2005 to 2020 (Figure 6-11). The CO_2 Emissions per unit of Electricity Supply = 3.14 × Standard Coal Consumption per unit of Electricity Supply, where 3.14 is the coefficient for the conversion from standard coal to CO_2 (IPCC, 2006).

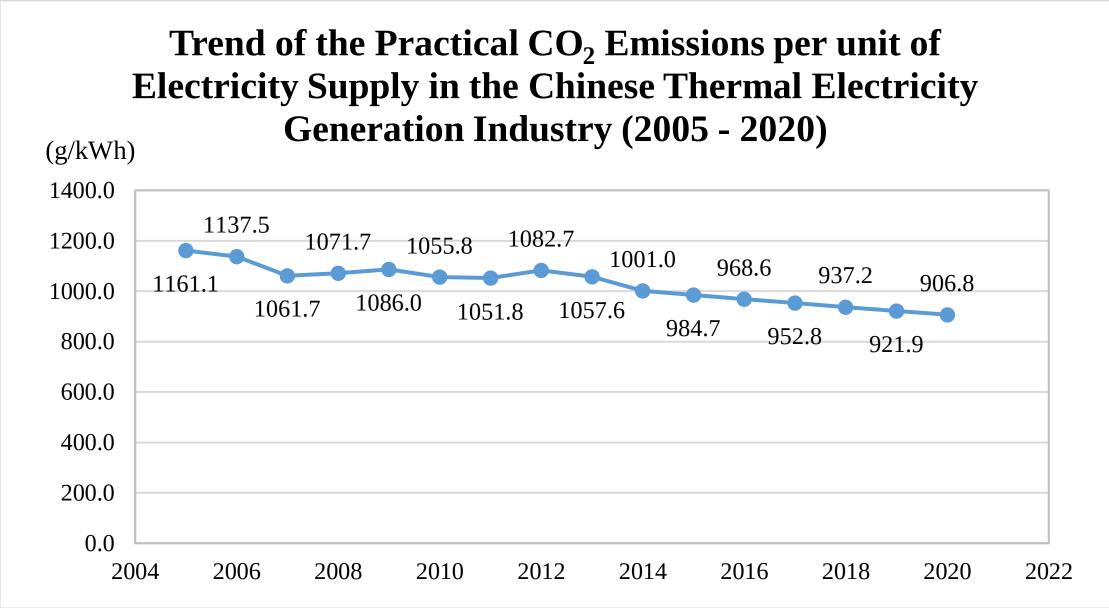

Figure 6-11 Trend of the Practical CO_2 Emissions per unit of Electricity Supply in the Chinese Thermal Electricity Generation Industry (2005 - 2020)

Along with the decline in the standard coal consumption per unit of electricity supply, the practical CO_2 emissions per unit of electricity supply decreased from 1161.1 g/kWh in 2005 to 1001 g/kWh in 2014, and are estimated to reduce to 906.8 g/kWh by 2020, because of the upgrade in industrial production technology.

6.4.4 Comparison between the Industrial Standards for CO_2 Emissions and the Practical CO_2 Emissions per unit of Electricity Supply in the Chinese Industry

Based on the calculations in section 6.2.2.2 and 6.4.3, the comparison between the industrial standard for CO_2 emissions and the actual CO_2 emissions is investigated (Figure 6-12).

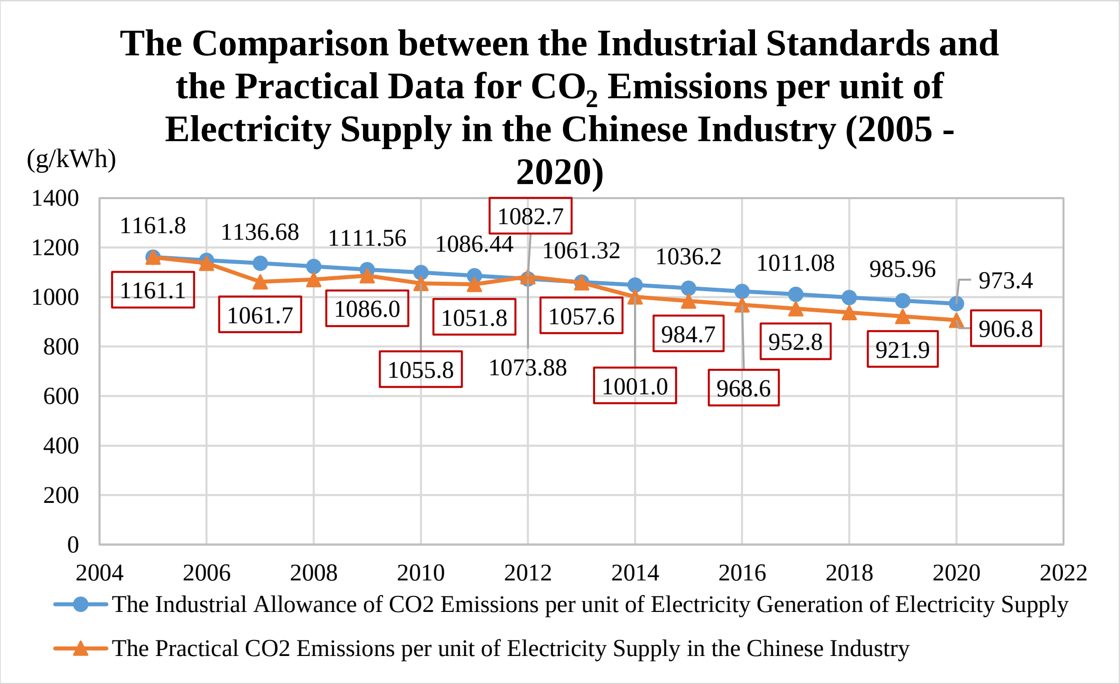

Figure 6-12 The Comparison between the Industrial Standards and the Practical Data for CO_2 Emissions per unit of Electricity Supply in the Chinese Industry (2005 - 2020)

Figure 6-12 shows that most of the actual emissions are lower than the industrial standards over these 15 years, except in 2012, meaning that the industry generally can achieve its targets. In 2012, the actual emission was 1082.7 g/kWh, exceeding the allowance by about 8.82g/kWh. Moreover, the industrial target for 2020 (973.4 g/kWh) could be reached by 2016, when the industrial practical emission is estimated at about 968.6 g/kWh. Consequently, the Chinese thermal electricity generation industry can achieve its 2020 industrial target for CO_2 emissions by 2016.

This comparison indicates that the industry can meet its industrial standard through improving its production technology. The logical approach of improving technology (Factor 12) to reduce resource consumption (Factor 15), and then reducing the CO_2 emissions (Fact 19) to meet the industrial target (Factor 22) is proved to be correct. This logical approach represents the process by which the industry attains its CO_2 reduction and its standards for CO_2 emissions. The logical relational model in section 5.4.3 can support the industry in accomplishing the low-carbon emission in the low-carbon economy.

6.5 Validation of the Theoretical Models for the Industrial Low-carbon Economy System for Chinese Thermal Electricity Generation Industry

6.5.1 Validation for the Model for the Sustainable Development in the Industrial Low-carbon Economy for this Chinese Industry

Referring to the result in section 6.4, this industry could match its allowance for low-carbon emission through improving its production technology. This section therefore applies industrial data to the model for industrial sustainable development in section 5.4.4, to determine whether this industrial sustainable development could be achieved based on improvement in its technology, eventually validating the model. In implementing the model, this section first represents it by mathematical expression to calculate the cost of reducing CO_2 emissions, and then analyses the sustainability of this industry in the low-carbon economy based on this model.

6.5.1.1 The Mathematical Expression for the Model for the Sustainable Development in the Industrial Low-carbon Economy for this Chinese Industry

Referring to the model in section 5.4.4, Figure 5-29, the following sub-sections represent the model with mathematical expressions, in order to quantify it and supply it with the industrial data.

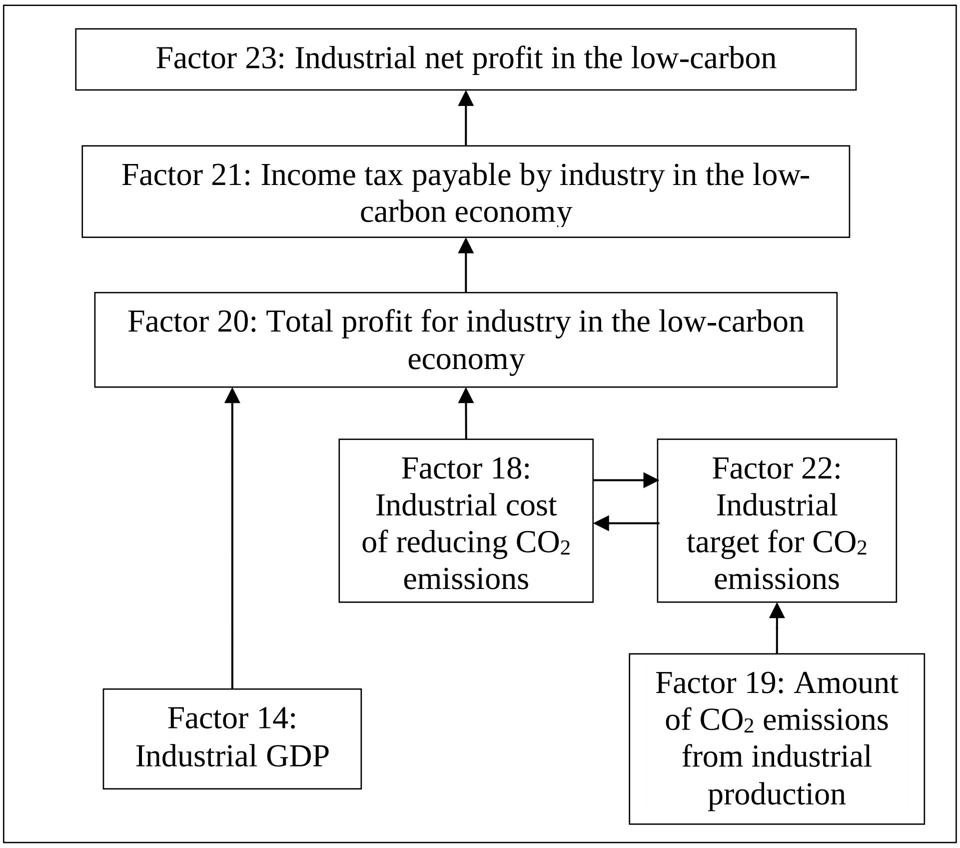

Figure 5-29 The Model for the Sustainable Development in the Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

Based on the model shown in Figure 5-29, the industrial cost of reducing CO_2 emissions (Factor 18) and the industrial GDP (Factor 14) together determine the total profit for the industry in the low-carbon economy (Factor 20). Therefore, this study first determines the mathematical expressions for Factor 18, and then similarly expresses the entire model.

6.5.1.1.1 The Mathematical Expressions for the Industrial Cost of Reducing CO_2 Emissions in the Low-carbon Economy for this Chinese Industry

Based on this model (Figure 5-29) and the analysis in section 5.4.2.5.5, the industrial target for CO_2 emissions can be met through carbon trading and improving the industrial production technology. Both methods will result in determining the industrial cost of reducing CO_2 emissions, increasing the cost of production and deducting the total profit for the industry. This section presents the mathematical expressions for the industrial cost of reducing CO_2 emissions caused by these two methods, as follows:

(1) The Low-carbon Economy through Carbon Trading

Equation 6-5: $F_{18CN} = (F_{19U\ (2005)} - F_{22SN}) \times P_{FN} \times P_{PN}$

In Equation 6-5, F_{18CN} represents the industrial cost of reducing CO_2 emissions through carbon trading by this industry in year N. $F_{19U\ (2005)}$ represents the CO_2 emissions per unit of electricity supply in 2005 for this industry. F_{22SN} represents the industrial standards of the CO_2 emissions per unit of electricity supply in year N. P_{FN} represents the annual production of electricity by this industry in year N. P_{PN} represents the average traded price of CO_2 in the carbon trading market (unit: yuan/t) in year N. N is the serial number of the year N = 0, 1, 2,… 15, from 2005 to 2020.

However, carbon trading balances global CO_2 emissions through trading the allowance, a process of redistributing the economic benefits among companies, industries or nations. This only increases the cost of production rather than directly reducing the real CO_2 emissions from production. Although the carbon trading market started trial trading in 2011, a mature national trading market was not expected to be established before the end of 2016. Therefore, given the practical status and the research purpose of promoting the direct reduction of CO_2 emissions by industry, carbon trading is not considered here.

(2) The Low-carbon Economy through the Improvement of the Industrial Production Technology

As proved in section 6.4, following the logic from the relational model can achieve the industrial standard for CO_2 emissions, which is improving Factor 12 to reduce Factor 15, then reducing Factor 19 and finally achieving Factor 22. In particular, referring to the analysis of related industrial policies in sections 5.4.2.1.3 and 5.4.2.1.5, and the analysis of industrial production technology in section 5.4.2.4.1, the current main approach for technology improvement in this industry is upgrading existing subcritical units to SC or USC unit (Wu and Shu, 2010; Ding and Ran, 2013; Zhou, 2011). Generators with capacity less than 300MW are scheduled to be closed gradually. By 2010, the proportion of generators with 300MW capacity or above was over 70% (Zhou, 2011). The 300MW subcritical generators within this 70% were largely constructed in the 1980s and 1990s, with a capacity for 40 years operation, facing the environmental challenges and requiring to be shut down or upgraded (Wu and Shu, 2010), while the large-scale generators, with capacity of 600MW and 1000MW, were generally constructed after 2000 and with advanced production technology, like SC and USC. Therefore, this study focuses on the upgrading of the 300MW subcritical units to SC units, because of the economic advantage and technological maturity of SC units. Moreover, most of the technology for these 300MW units, related to the efficiency of their structural features, is on the same level as that of the 600MW and 1000MW units, except for technology regarding the efficiency of the heat cycle, which could be improved by advancing the initial steam parameter (Wu and Shu, 2010; Ding and Ran, 2013). Through the partial improvement of the technology of units in relation to the efficiency cycle, this industry could not only achieve its environmental target, but also derive get economic benefit with at a lower cost than constructing new units with the same advanced technology. The industrial cost of reducing CO_2 emissions through this method is therefore represented as:

Equation 6-6: $F_{15N} = (F_{15(2005)} - F_{15TN}) \times P_{FN} = F_{15(2005)} \times P_{FN} - F_{15TN} \times P_{FN}$

Equation 6-7: $P_C = (370\ g/kWh - 310\ g/kWh) \times P_{A(300MW)}$

Equation 6-8: $EQ_{(300MW)N} = F_{15N} / P_C$

Equation 6-9: $EQ_{(300MW)AN} = EQ_{(300MW)N} - EQ_{(300MW)(N-1)}$

Equation 6-10: $F_{18N} = EC_{(300MW)} \times EQ_{(300MW)AN}$

In Equation 6-6, F_{15N} represents the total amount of standard coal consumption reduced by this industry in year N. $F_{15\,(2005)}$ represents the standard coal consumption per unit of electricity supply in 2005, equalling 370 g/kWh. F_{15TN} represents the standard coal consumption per unit of electricity supply after the improvement of production technology in year N. P_{FN} represents the annual production of electricity by this industry in year N. N is the serial number of the year N = 0, 1, 2,… 15, from 2005 to 2020.

In Equation 6-7, P_C represents the average reduction in the amount of standard coal consumption by one 300MW generator after upgrading to supercritical technology. 370 g/kWh represents the standard coal consumption per unit of electricity supply by a subcritical unit with 300MW capacity, while 310 g/kWh represents that of a supercritical unit with 300MW capacity. $P_{A(300MW)}$ represents the average annual production of electricity by one 300MW supercritical generator.

In Equation 6-8, $EQ_{(300MW)N}$ represents the cumulative number of the 300MW generators upgraded from subcritical to supercritical technology in year N. F_{15N} and P_C are as in the Equation 6-6 Equation 6-7. N is also as in previous equations.

In Equation 6-9, $EQ_{(300MW)AN}$ represents the annual number of the 300MW generators newly upgraded from subcritical to supercritical technology in year N. $EQ_{(300MW)N}$ and $EQ_{(300MW)(N-1)}$ represent the cumulative number of the 300MW generators upgraded from subcritical to supercritical technology in year N and in year N-1. N is as in the previous equations.

In Equation 6-10, F_{18N} represents the industrial cost of reducing CO_2 emissions for this thermal electricity generation industry, through improving production technology in year N. $EC_{(300MW)}$ represents the cost of upgrading one 300MW generator from subcritical to supercritical technology. $EQ_{(300MW)AN}$ is as in Equation 6-9. N is still as in the previous equations.

6.5.1.1.2 The Mathematical Expression for Sustainable Development in the Industrial Low-carbon Economy for this Chinese Industry

Based on the industrial cost of reducing CO_2 emissions expressed in the previous section, and referring to the model for the sustainable development in section 5.4.4 sustainability for this industry can be presented and examined by the industrial net profit in the low-carbon economy. The information of Factor 14 (industrial GDP) is represented by the total profit for industry in the low-carbon economy (Factor 20), while the calculated Factor 18 deducts Factor 20. Therefore, the mathematical expression for this model is:

Equation 6-11: $F_{20lowN} = F_{20N} - F_{18N}$

Equation 6-12: $F_{23N} = F_{20lowN} - F_{21N}$

In Equation 6-11, the F_{20lowN} represents the total profit for this industry in the low-carbon economy in year N, while F_{20N} represents its total profit in the traditional economy in year N. F_{18N} represents the industrial cost of reducing CO_2 emissions for this industry, by improving its production technology in year N. N is the serial number of the year N = 0, 1, 2,… 15, from 2005 to 2020, as in the previous equations.

In Equation 6-12, F_{23N} represents the industrial net profit for this Chinese thermal electricity generation industry in the low-carbon economy in year N, while F_{20lowN} is as in Equation 6-11. F_{21N} represents the income tax payable by this industry in the low-carbon economy in year N. N is as in the previous equations.

Based on these mathematical expressions for this model, the logic meaning and criteria for validating this low-carbon emission method are presented here.

First, for Equation 6-11:

When $F_{20N} > 0$ and $F_{18N} > 0$, and assuming when $F_{20N} > F_{18N}$, if $F_{20lowN} > 0$, then the logic from Factor 19 to Factor 20 is correct, and the industrial cost of reducing CO_2 emissions could be afforded. When $F_{20N} > 0$ and $F_{18N} > 0$, and assuming when $F_{20N} < F_{18N}$, if $F_{20lowN} > 0$, then the logic from Factor 19 to Factor 20 is wrong.

When $F_{20N} > 0$ and $F_{18N} > 0$, and assuming when $F_{20N} > F_{18N}$, if $F_{20lowN} \leq 0$, then the logic from Factor 19 to Factor 20 is wrong. When $F_{20N} > 0$ and $F_{18N} > 0$, and assuming when $F_{20N} < F_{18N}$, if $F_{20lowN} \leq 0$, then the logic from Factor 19 to Factor 20 is correct; however, the industrial cost of reducing CO_2 emissions could not be afforded by this Chinese industry, which indicates that F_{22}, the industrial target for CO_2 emissions (Factor 22), is not appropriate.

Therefore, in Equation 6-11, this research only needs to prove: when $F_{20N} > 0$, $F_{18N} > 0$, and $F_{20N} > F_{18N}$, then $F_{20lowN} > 0$; and then this it can be shown that the logic from Factor 19 to Factor 20 is correct, and the industrial cost of reducing CO_2 emissions can be afforded.

Secondly, for Equation 6-12:

When $F_{20lowN} > 0$ and $F_{21N} > 0$, and assuming $F_{20lowN} > F_{21N}$, if $F_{23N} > 0$, then the logic from Factor 20 to Factor 23, when industry benefits from the effects of low-carbon emission actions, is correct; and it also indicates that this industry could see sustainable development in this low-carbon economy. When $F_{20lowN} > 0$ and $F_{21N} > 0$, and assuming $F_{20lowN} < F_{21N}$, if $F_{23N} > 0$, then the logic from Factor 20 to Factor 23 after the industry takes low-carbon actions, is wrong.

When $F_{20lowN} > 0$ and $F_{21N} > 0$, and assuming $F_{20lowN} > F_{21N}$, if $F_{23N} \leq 0$, then the logic from Factor 20 to Factor 23 after the industry takes low-carbon emission actions, is wrong. When $F_{20lowN} > 0$ and $F_{21N} > 0$, and assuming $F_{20lowN} < F_{21N}$, if $F_{23N} \leq 0$, then this industry could not achieve sustainable development, and indicating that F_{21}, income tax payable by the industry in the low-carbon economy (Factor 21), is not appropriate. The government should adjust its fiscal and monetary policy for industry (Factor 4) to reduce the income tax payable F_{21}.

Therefore, in Equation 6-12, this research only needs to prove: when $F_{20lowN} > 0$, $F_{21N} > 0$, and $F_{20lowN} > F_{21N}$, then $F_{23N} > 0$; this would show that the logic from Factor 20 to Factor 23 in the industrial low-carbon economy is correct, and the industry can achieve sustainable development in a low-carbon economy.

Consequently, only when both the criteria for Equation 6-11 and Equation 6-12 are met (i.e. when $F_{20N} > 0$, $F_{18N} > 0$, and $F_{20N} > F_{18N}$, then $F_{20lowN} > 0$ and when $F_{20lowN} > 0$, $F_{21N} > 0$, and $F_{20lowN} > F_{21N}$, then $F_{23N} > 0$) can the model for this industrial sustainable development in a low-carbon economy can be proved to be correct.

6.5.1.2 Analysis of the Cost of Reducing CO_2 Emissions for this Chinese Industry in the Low-carbon Economy

Referring to the analysis in section 6.4 and the expressions in section 6.5.1.1.1 (2), the industrial standard for low-carbon emission could be achieved through improving industrial production technology, where the cost of upgrading the technology is the industrial cost of reducing CO_2 emissions. This section therefore calculates both the practical cost and the standard cost of reducing CO_2 emissions for this industry.

6.5.1.2.1 Analysis of the Cost of Upgrading One 300MW Generator and its Production

Referring to the analysis in section 6.5.1.1.1 (2), technological improvement based on upgrading the 300MW subcritical units is considered. The total cost of the upgrade (F_{18N}) relies on the cost per unit of the boilers to be upgraded and the number of subcritical generators upgraded (Equation 6-10). This section therefore analyses the cost per unit of boiler upgrade ($EC_{(300MW)}$) and the annual production of electricity by one

300MW supercritical generator ($P_{A(300MW)}$) for calculating $EQ_{(300MW)AN}$ (the annual number of the 300MW generators newly upgraded from subcritical to supercritical technology) in a later section.

(1) Analysis of the Cost of Upgrading One 300MW Generator from Subcritical Unit to Supercritical Unit

Based on the data from the Electric Power Planning and Engineering Institute (2014), in 2008 to 2013 the cost of a subcritical boiler spends was only about 11.79% of the average total cost of constructing an entire 2×300MW generator, while the cost of a SC boiler was 20.79% higher than that of a subcritical one, and 14.24% of the total cost on average (Table 6-2). 2×300MW units is represented because the industry normally constructs two generators together as a pair for one station.

Table 6-2 Analysis of the Cost of the 300MW Subcritical Boiler and that of the Supercritical Boiler (2008 - 2013)

Year	**Total Price for Constructing the Entire 2×300MW Subcritical Units (Million yuan)**	**Price of the 300MW Subcritical Boiler (Million yuan/unit)**	**Price of the 300MW Supercritical Boiler (Million yuan/unit)**
2008	1341.6	178	230
2009	1323.6	172	223
2010	1332.9	165	195
2011	1329	150	175
2012	1304.7	140	165
2013	1318.2	133	145
Average	1325	156.33	188.83
The Average Gaps between the Price of the 300MW Subcritical Boiler and that of the Supercritical Boiler (Million yuan)		32.50	

Table 6-2 indicates that the cost per boiler only considers the amount for constructing an entire unit. Moreover, along with the technology improvement in general, the price of the boiler for both subcritical and SC technology decreased over time; specifically, the price of the SC technology decreased about 37% from 2008 to 2013. The average difference between these two technologies is about 32.5 million yuan. Moreover, the price of a 300MW SC unit also increased by around 2.15 million yuan over the price of other equipment related to the heat system, excluding the boiler. An additional 6.2 million yuan on the water system, compared with the subcritical unit, also is required for this upgrade. Therefore, the cost of upgrading one 300MW generator from subcritical to SC technology, $EC_{(300MW)}$, is 40.85 million yuan.

(2) Analysis of the Production of Electricity by one unit of 300MW Thermal Generator

The production of electricity by one 300MW thermal generator ($P_{A(300MW)}$) is estimated based on the average working hours of thermal generators in China. As presented in section 5.3.3, the data for electricity generators with capacity above 6000KW represents the data for the entire Chinese thermal electricity generation industry. Therefore, the average working hours for generators with a capacity of 6000kW or above is the industry's average working hours. The Production of Electricity by One 300MW Thermal Power Generator ($P_{A(300MW)}$) = the Industry's Average Working Hours × 300MW (Figure 6-13).

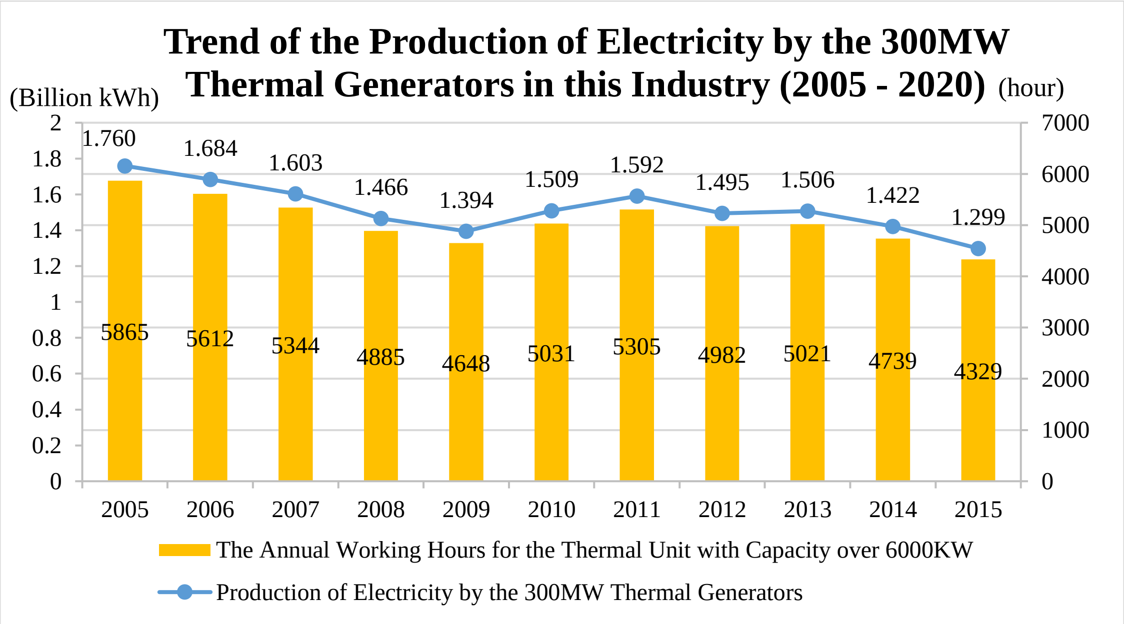

Figure 6-13 Trend of the Production of Electricity by the 300MW Thermal Generators in this Industry (2005 - 2020)

From 2005 to 2015, although there was an increase from 2009 to 2011 and a peak in 2011, the average working hours for this industry decreased from 5,865 to 4,329, a reduction of about 26.19%. The average working hours for thermal power generator in

China over these years was 5,069 hours, while the average electricity generated by one 300MW unit in China was 15.2075 billion kWh. These two average figures are used in the next two sections to estimate the annual output of a 300MW generator newly upgraded from subcritical to supercritical technology ($EQ_{(300MW)AN}$).

6.5.1.2.2 Calculation of the Practical Cost of Reducing CO_2 Emissions for this Chinese Industry through Improving Technology in the Low-carbon Economy

(1) Analysis of the Trend of the Total Amount of Standard Coal Consumption for Electricity Supply Reduced by this Industry through Technological Improvement

The calculation for the total reduction in standard coal consumption through industrial technological improvement is based on Equation 6-6 from section 6.5.1.1.1 (2). First, the standard coal consumption for electricity supply by this industry without improvement of production technology is calculated based on the data for $F_{15\ (2005)}$, equalling 370 g/kWh, and P_{FN} (the annual production of electricity by this industry) during 2005 to 2020 (Figure 6-14).

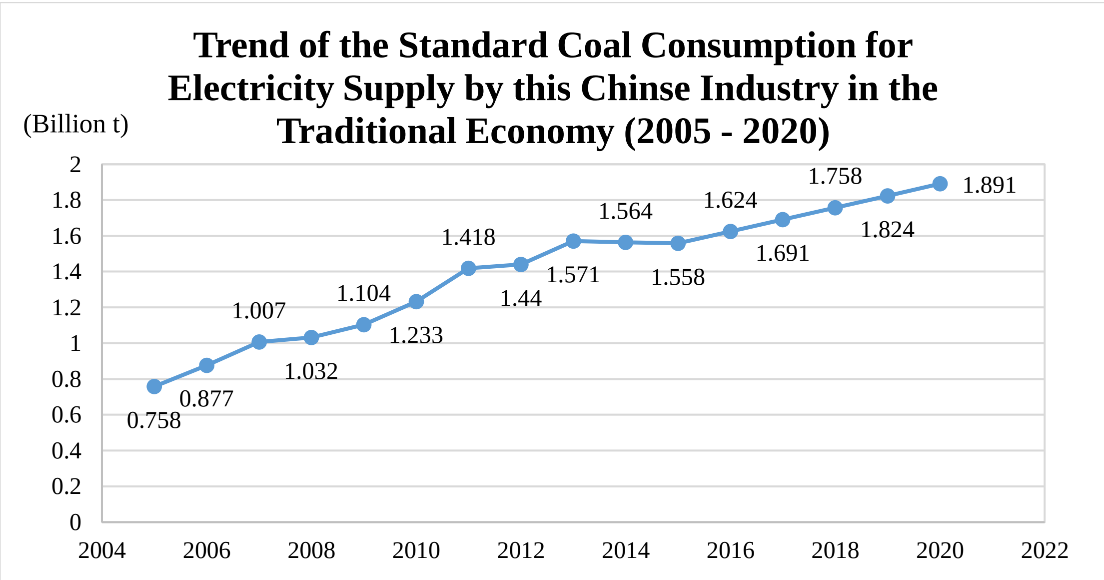

Figure 6-14 Trend of the Standard Coal Consumption for Electricity Supply by this Chinse Industry in the Traditional Economy (2005 - 2020)

Figure 6-14 shows that the standard coal consumption for electricity supply increased from 0.758 billion tonnes in 2005 to 1.564 billion tonnes in 2014, in the traditional economy, in which the standard coal consumption per unit of electricity supply did not change because of the lack of concern about low-carbon emission. Based on the estimated electricity production for 2015 to 2020, the consumption is estimated to reach 1.891 billion tonnes by 2020.

The practical standard coal consumption for electricity supply by this industry after the improvement of production technology is calculated, based on F_{15TN}, standard coal consumption per unit of electricity supply after the improvement of production technology (section 6.4.2), and P_{FN} (annual production of electricity by this industry) (Figure 6-15).

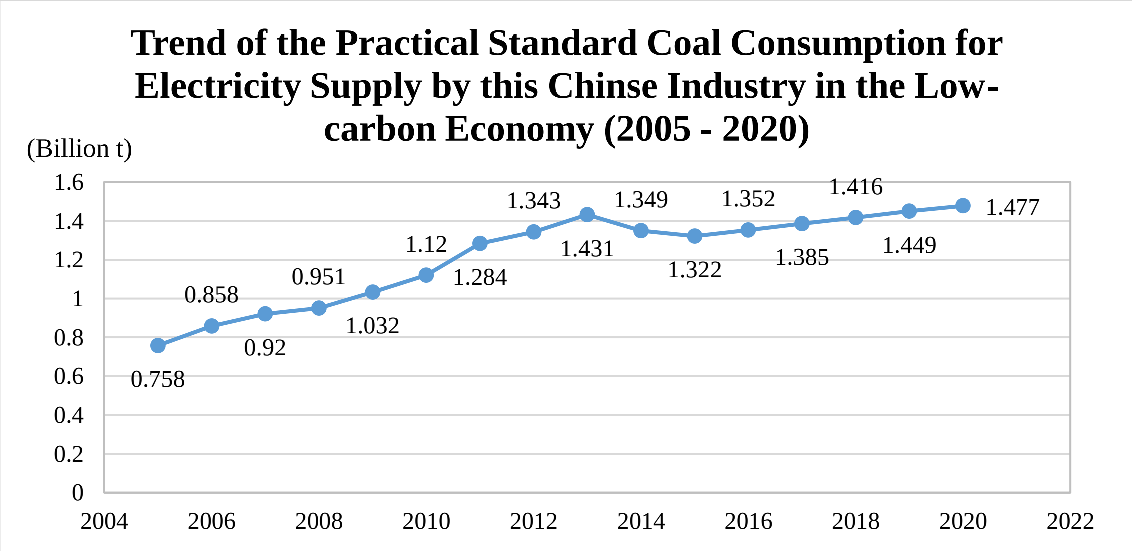

Figure 6-15 Trend of the Practical Standard Coal Consumption for Electricity Supply by this Chinse Industry in the Low-carbon Economy (2005 - 2020)

Figure 6-15 shows that the actual standard coal consumption for electricity supply increased from 0.758 billion tonnes in 2005 to 1.349 billion tonnes in 2014, while in the other six years it was estimated to increase from 1.322 billion tonnes to 1.477 billion tonnes.

Therefore, based on the above calculations, the total amount of standard coal consumption reduced for electricity supply, in calculating the practical cost of reducing

CO_2 emissions by technological improvements (F_{15N}), is calculated and shown in Figure 6-16.

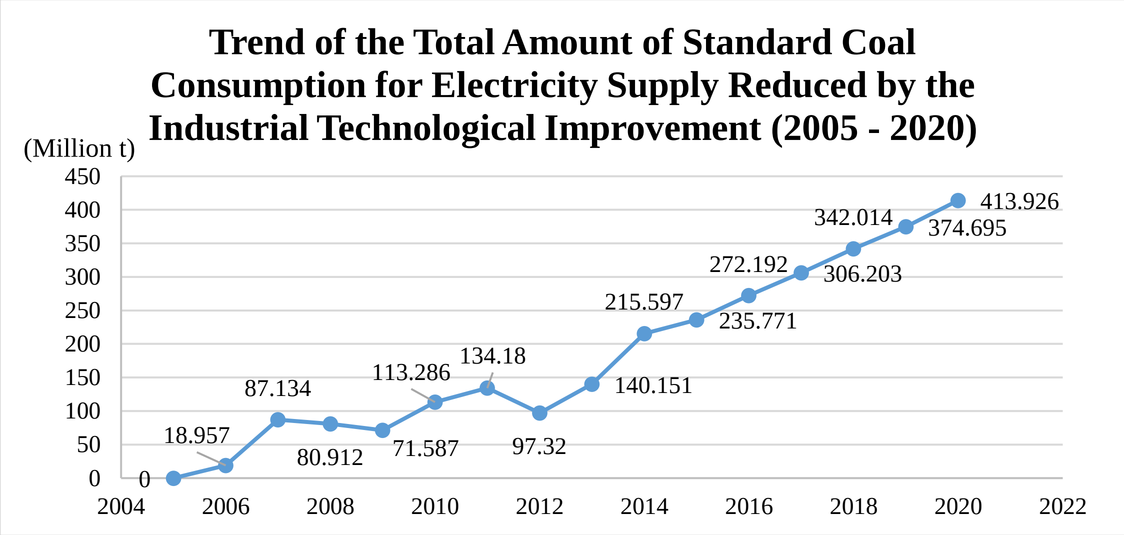

Figure 6-16 Trend of the Total Amount of Standard Coal Consumption for Electricity Supply Reduced by the Industrial Technological Improvement (2005 - 2020)

Figure 6-16 shows that along with improvement in industrial production technology, F_{15N} continuously increased over these years, and it is estimated to save 413.926 million tonnes of standard coal by this industry by 2020.

(2) Analysis of the Practical Number of the Generator Required to be Upgraded by this Chinese Industry in the Low-carbon Economy

Based on Equation 6-7, Equation 6-8 and Equation 6-9, and on the calculations for F_{15N} and $P_{A(300MW)}$ in the previous two sections, $EQ_{(300MW)N}$ and $EQ_{(300MW)AN}$ are estimated. In detail, the average reduction in the amount of standard coal consumption by a single 300MW generator after upgrade to supercritical technology is calculated as: P_C = 60 g/kWh × 15.2075 billion kWh = 91245.3 t, where each 300MW generator reduced 60 g/kWh after its upgrade. Then, the total reduction in standard coal consumption by this industry in year N (F_{15N}) divided by P_C, calculates the cumulative number of the 300MW generators upgraded from subcritical to supercritical technology in year N, $EQ_{(300MW)N}$. $EQ_{(300MW)N}$ minus this value in year N-1 is the annual number of generators required to be upgraded in year N (Figure 6-17).

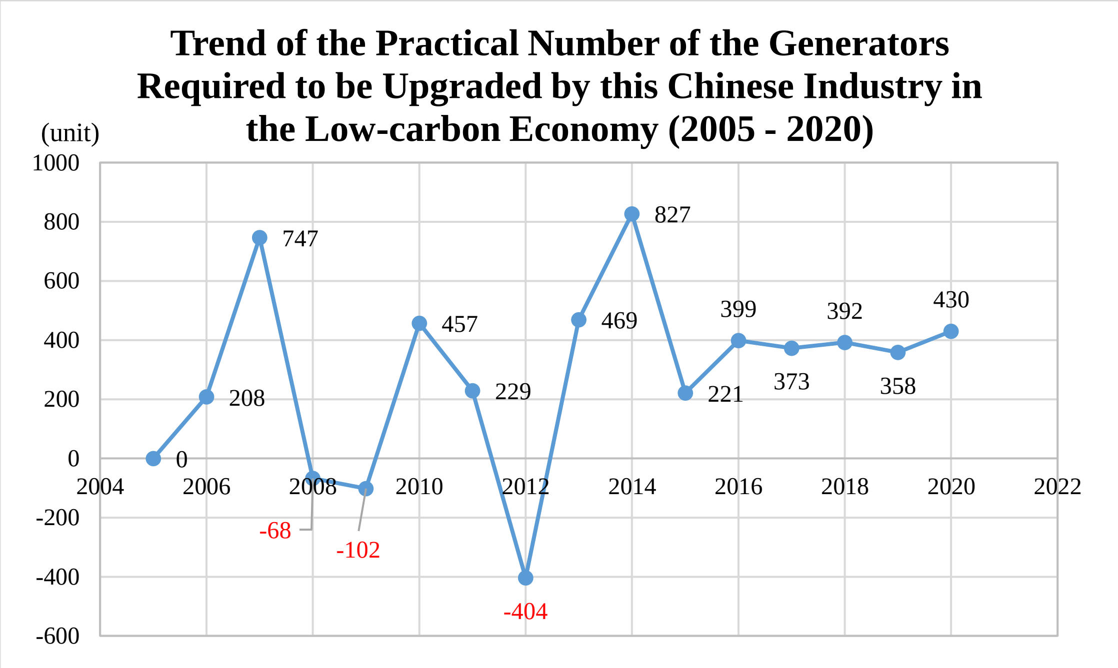

Figure 6-17 Trend of the Practical Number of the Generators required to be Upgraded by this Chinese Industry in the Low-carbon Economy (2005 - 2020)

Figure 6-17 shows that $EQ_{(300MW)N}$ fluctuated over the early years, peaking in 2007, 2010 and 2014, indicating that the upgraded units were not insufficient to work along with the reduction of standard coal consumption in those years, therefore the generators needed to be upgraded. In 2008, 2009 and 2012, $EQ_{(300MW)N}$ was below zero, which means that the units upgraded in previous years were sufficient to support the reduction in standard coal consumption in those years. Referring to the actual CO_2 emissions in section 6.4.3, this industry was on course to achieve its industrial target of CO_2 emissions by 2016, when the cumulative amount of required generators would be 2,983. The total number of generators upgraded over these 15 years was 4536, which would result in the actual standard coal consumption per unit of electricity supply reaching 289 g/kWh by 2020.

(3) Analysis of the Practical Cost of Reducing CO_2 Emissions by Upgrading the Production Technology for this Industry

Referring to the calculation of the $EQ_{(300MW)AN}$ and $EC_{(300MW)}$ (equals to 40.85 million yuan), this section estimates the actual cost of reducing CO_2 emissions for this industry by improving its production technology based on Equation 6-10, shown in Figure 6-18.

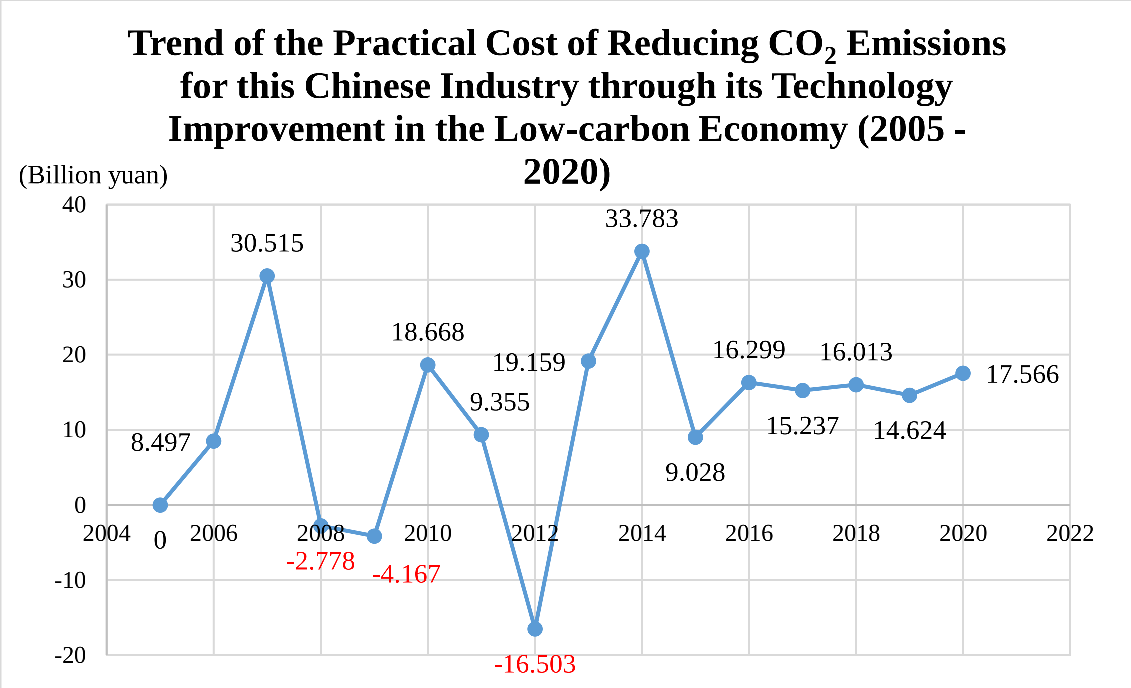

Figure 6-18 Trend of the Practical Cost of Reducing CO_2 Emissions for this Chinese Industry in the Low-carbon Economy (2005 - 2020)

Figure 6-18 shows that, along with fluctuation in $EQ_{(300MW)AN}$, the actual cost of reducing CO_2 emissions by this industry rapidly changed over these years. In 2007, 2010 and 2014, the actual cost of reducing CO_2 emissions rapidly increased, while in 2008, 2009 and 2012 it was negative. The cumulative amount of the practical cost of reducing CO_2 emissions for this industry over these years is 185.296 billion yuan.

6.5.1.2.3 Calculation of the Standard Cost of Reducing CO_2 Emissions for this Chinese Industry in the Low-carbon Economy

Referring to the equations in section 6.5.1.1.1 (2), the standard cost of reducing CO_2 emissions is the cost of reducing the emissions according to the industrial standards for low-carbon emission. Therefore, in Equation 6-6: $F_{15N} = (F_{15(2005)} - F_{15TN}) \times P_{FN} = F_{15(2005)} \times P_{FN} - F_{15TN} \times P_{FN}$, where F_{15TN} represents the industrial allowance for the standard coal consumption per unit of electricity supply in year N instead of the actual one. Accordingly, the standard cost of reducing CO_2 emissions for this industry is calculated as follows:

(1) Analysis of the Number of the Generators Required to be Upgraded by this Chinese Industry under the Industrial Standards for Low-carbon Emission

Based on Equation 6-6, Equation 6-7, Equation 6-8 and Equation 6-9, the related variables P_{FN}, F_{15N}, P_C, $EQ_{(300MW)N}$ and $EQ_{(300MW)AN}$ are calculated in Table 6-3. The number of generators needing to be upgraded to meet the industrial standards is also shown in Figure 6-19.

Table 6-3 Trend of the Number of the Generators Required to Upgraded by this Chinese Industry under the Industrial Standards for Low-carbon Emission (2005 - 2020)

Year	**P_{FN} (Billion kWh)**	**$F_{15\ (2005)}$ - F_{15TN} (g/kWh)**	**F_{15N} (t)**	**P_C (t)**	**$EQ_{(300MW)N}$ (unit)**	**$EQ_{(300MW)AN}$ (unit)**
2005	2047.3	0	0	0	0	0
2006	2369.6	4	9478400	91245.3	104	104
2007	2722.9	8	21783440	91245.3	239	135
2008	2790.1	12	33480960	91245.3	367	128
2009	2982.8	16	47724480	91245.3	523	156
2010	3331.9	20	66638600	91245.3	730	207
2011	3833.7	24	92008800	91245.3	1008	278
2012	3892.8	28	108998680	91245.3	1195	187
2013	4247.0	32	135904320	91245.3	1489	294
2014	4227.4	36	152186328	91245.3	1668	179
2015	4210.2	40	168408000	91245.3	1846	178
2016	4390.2	44	193168800	91245.3	2117	271
2017	4570.2	48	219369600	91245.3	2404	287
2018	4750.2	52	247010400	91245.3	2707	303
2019	4930.2	56	276091200	91245.3	3026	319
2020	5110.2	60	306612000	91245.3	3360	334
Cumulate	-	-	-	-	-	3360

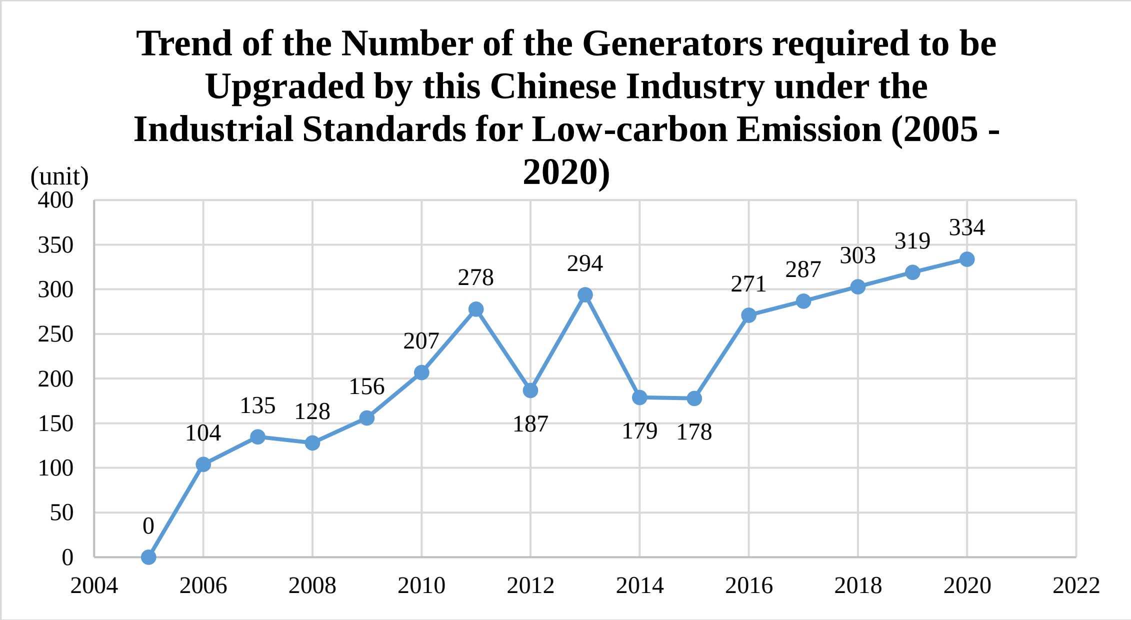

Figure 6-19 Trend of the Number of the Generators required to be Upgraded by this Chinese Industry under the Industrial Standards for Low-carbon Emission (2005 - 2020)

Figure 6-19 shows that $EQ_{(300MW)AN}$ smoothly increases, compared with that in calculating the practical cost. In 2011 and 2013, the required amount peaked, while the required amount was comparatively low in 2012, 2014 and 2015. The total number of generators needing to be upgraded over the period is 3,360, which indicates that after upgrading 3,360 units of 300MW subcritical generators, the industry could meet its standard coal and the CO_2 emission allowances. Compared with the practical cumulative number of generators required, this total is larger as result of the advanced upgrade in practice. Along with the increase in P_{FN} and then in F_{15N}, with the same P_C, then $EQ_{(300MW)N}$ and $EQ_{(300MW)AN}$ will increase. Therefore, the sooner the production technology is improved, the fewer generators will have to be upgraded, when P_{FN} continuously increases.

(2) The Standard Cost of Reducing CO_2 Emissions for this Chinese Industry in the Low-carbon Economy

Based on the calculation above and $EC_{(300MW)}$ (equalling 40.85 million yuan), the standard cost is worked out through Equation 6-10, and shown in Figure 6-20.

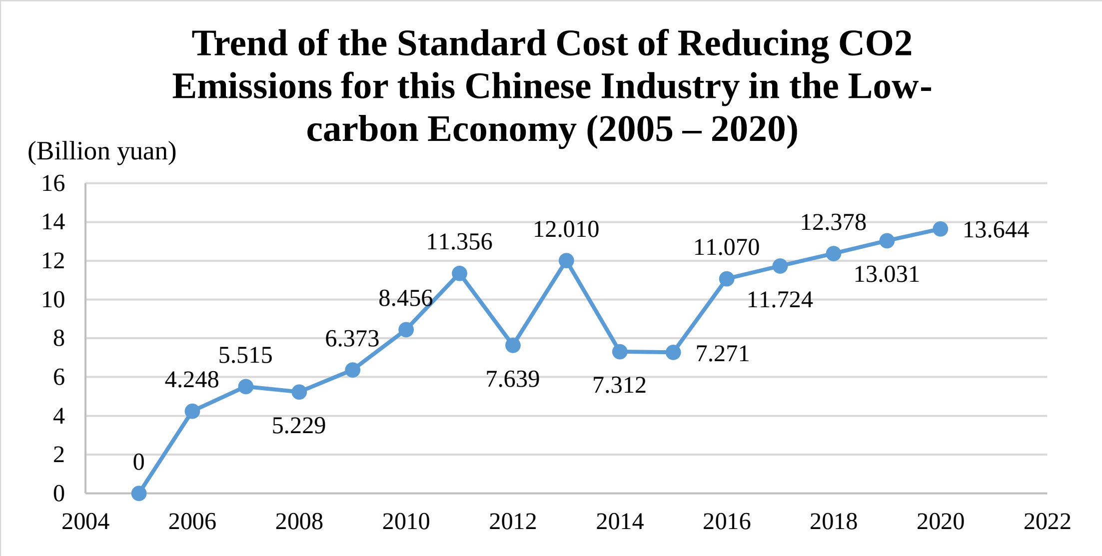

Figure 6-20 Trend of the Standard Cost of Reducing CO_2 Emissions for this Chinese Industry in the Low-carbon Economy (2005 – 2020)

Figure 6-20 shows that the standard cost of reducing CO_2 emissions for this industry continuously increased over time. In 2012, 2014 and 2015, the standard cost dropped, estimated to reach 13.644 billion yuan by 2020. The cumulative standard cost of reducing CO_2 emissions over these years is 137.256 billion yuan. Accordingly, this industry must spend about 137.256 billion yuan on upgrading its production technology before it can meet the industrial target for CO_2 emissions.

6.5.1.3 Analysis of the Factors for Examining the Sustainability for this Chinese Industry in the Low-carbon Economy

Referring to the model in section 5.4.4 and Equation 6-11 and Equation 6-12, sustainability for is examined by the industrial net profit in the low-carbon economy (Factor 23), as F_{23N} in Equation 6-12. Therefore, this study analyses the total profit for industry (Factor 20), represented by F_{20lowN}, and the income tax payable by industry in the low-carbon economy (Factor 21), represented by F_{21N}, to investigate industrial net profit. Moreover, as discussed in section 5.4.2.5.7, the practical data for this industry is the data for the low-carbon economy. The total profit for industry in the traditional economy (F_{20N}) is therefore calculated for comparison.

As explained in section 5.2.2, the data from the National Bureau of Statistics is for the industry of the production and supply of the electric and heat power, not for this thermal electricity generation industry. Given the lack of summarised accounting data for the thermal industry, the calculations are based on available data.

6.5.1.3.1 Analysis of the Trend of the Total Profit for this Chinese Industry in the Low-carbon Economy

For the total profit for this industry in the low-carbon economy (F_{20lowN}), the data for 2005 and 2011 was estimated by: Factor 20 = Market Share based on the Production for this Industry × Total Profit of the Industrial Enterprises above Designated Size in Electricity Production Industry, collected from the *China Industry Statistical Yearbook*. The data for 2006 to 2010 was collected from the China Electricity Council and figures for 2007 to 2010 estimated from the data for January to November in the respective years. Thus, Factor 20 = the Total Profit in the Low-carbon Economy from January to November in year N × 12 / 11. The data for 2012 to 2014 was collected directly from the *China Industry Statistical Yearbook*. Finally, the data for 2015 to 2020 was estimated from the data for 2005 to 2014: Factor 20 = the Average Profit per unit of Electricity Produced × the Annual Production of electricity by this industry in year N. The Average Profit per unit of Electricity Produced = Sum of Factor 20 from 2005 to 2014 / Sum of the Annual Production of electricity by this industry from 2005 to 2014. The total profit for this industry in the low-carbon economy over the years is shown in Figure 6-21.

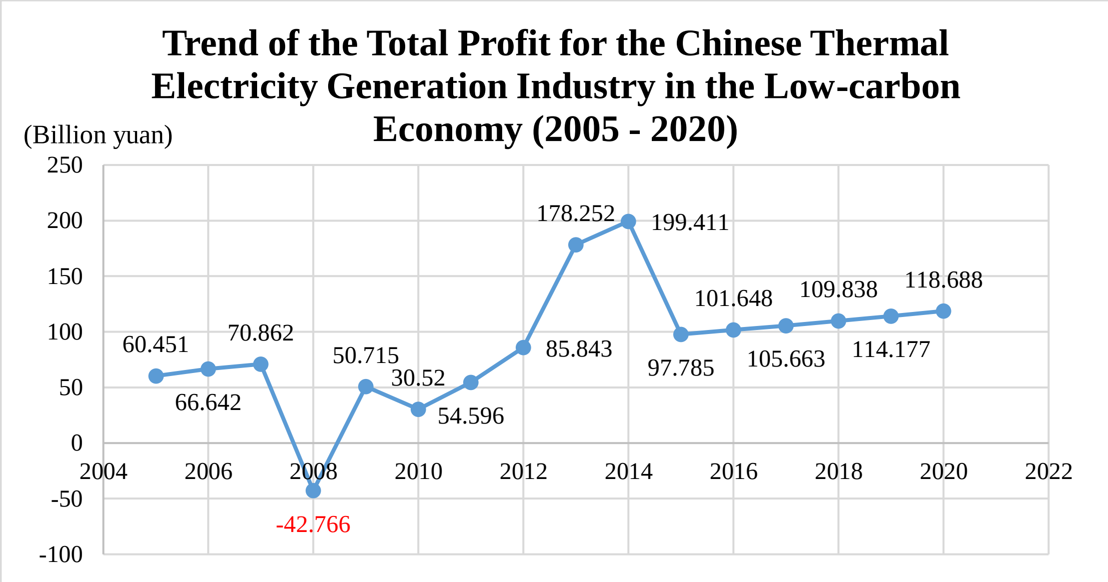

Figure 6-21 Trend of the Total Profit for the Chinese Thermal Electricity Generation Industry in the Low-carbon Economy (2005 - 2020)

Figure 6-21 shows that the total profit for this industry in the low-carbon economy is generally above zero, except in 2008, when Factor 20 was -42.766 billion yuan. Moreover, Factor 20 generally grew, except in 2008, 2010 and 2015. As the data for 2015 to 2020 was estimated from the average profit per unit of electricity produced over the first nine years, it shows the average value for total profit. That is, Factor 20 decreased from 199.411 billion yuan in 2010 to 97.785 billion yuan in 2015, after which it should increase along with the growth of annual production of electricity. In 2008 and 2010, Factor 20 decreased because of the related policy in Factors 3 and 5, the effects of the financial crisis in 2008 and the increase in the price of coal in 2010.

6.5.1.3.2 Analysis of the Trend of the Income Tax Payable by this Chinese Industry in the Low-carbon Economy

Referring to Equation 6-11, the income tax payable by this industry in the low-carbon economy is represented by the variable F_{21N}. The data for income tax payable by this industry from 2005 to 2011 is estimated from data from the *Macro China Database* and the *China Taxation Yearbook,* while that for 2012, 2013 and 2014. It follows Factor 21 (2005 to 2009) = Market Share based on the Production for this Industry × the Income Tax Payable by the Electricity Generation Industry, where the Income Tax payable by the Electricity Generation Industry = the Income Tax Payable by the Electric Power

Production and Supply Industry - the Income Tax Payable by the Electric Power Supply Industry. The Income Tax Payable by the Electric Power Production and Supply Industry = the Income Tax Payable by the Production and Supply of the Electric and Heat Power Industry - the Income Tax Payable by the Production and Supply of the Heat Power Industry. Specifically, for 2010 and 2011, the Income Tax Payable by the Electricity Generation Industry = Sum of the Income Tax Payable by the Electricity Generation Industry / Sum of the Income Tax Payable by the Production and Supply of the Electric Power Industry (2005 to 2009) × the Income Tax Payable by the Production and Supply of the Electric Power Industry (2010 or 2011). Data for 2012 to 2014 was collected directly from the *China Industry Statistical Yearbook*. Finally, the data for 2015 to 2020 is estimated frim the data from the previous nine years, following Factor 21 = the Average Income Tax Payable by the Industry per unit of Electricity Produced (2005 to 2014) × the Annual Production of Electricity by this Industry. The Average Income Tax Payable by the Industry per unit of Electricity Produced = Average Factor 21 (2005 to 2014) / Average of the Annual Production of Electricity by this Industry from 2005 to 2014. Factor 21 is shown in Figure 6-22.

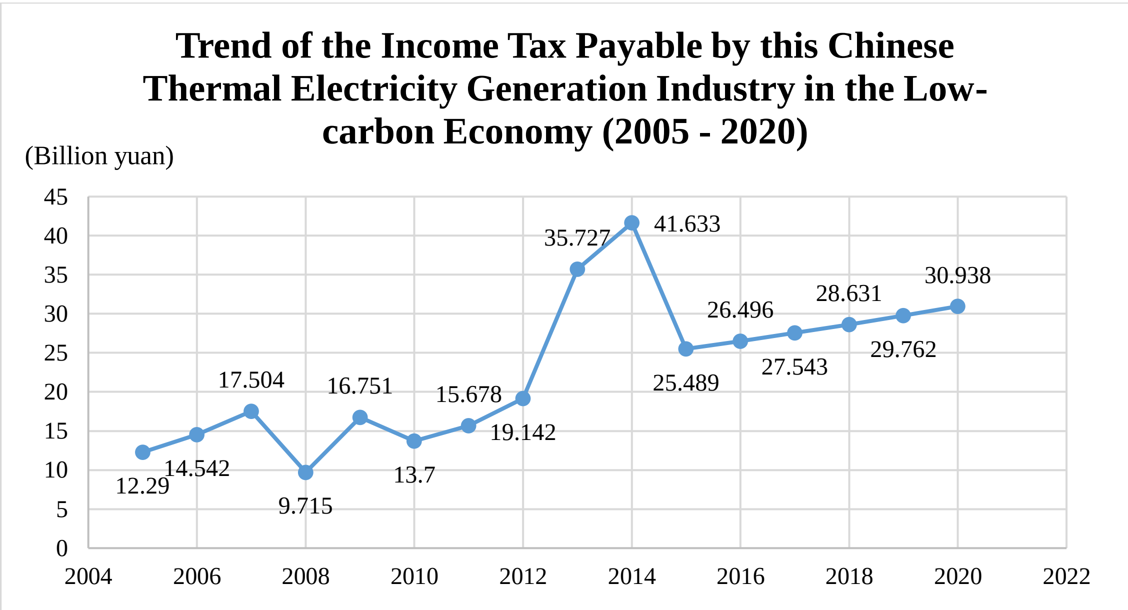

Figure 6-22 Trend of the Income Tax Payable by this Chinese Thermal Electricity Generation Industry in the Low-carbon Economy (2005 - 2020)

Figure 6-22 indicates that along with the growth in total profit for this industry, Factor 21 continuously increased from 12.29 billion yuan in 2005 to 30.938 billion yuan in

2012, with a decrease in 2008, 2010 and 2015. However, as this variable is the sum of the income tax payable for enterprises within this industry, the companies earning profit still pay income tax. Therefore, Factor 21 in 2008 was still above zero, even though Factor 20 was -42.766.

6.5.1.3.3 Analysis of the Trend of the Net Profit for this Chinese Industry in the Low-carbon Economy

Referring to the analysis of Factor 20 and Factor 21 in sections 6.5.1.3.1 and 6.5.1.3.2, the net profit for this Chinese industry in the low-carbon economy (F_{23N}), Factor 23, is calculated and presented in Figure 6-23.

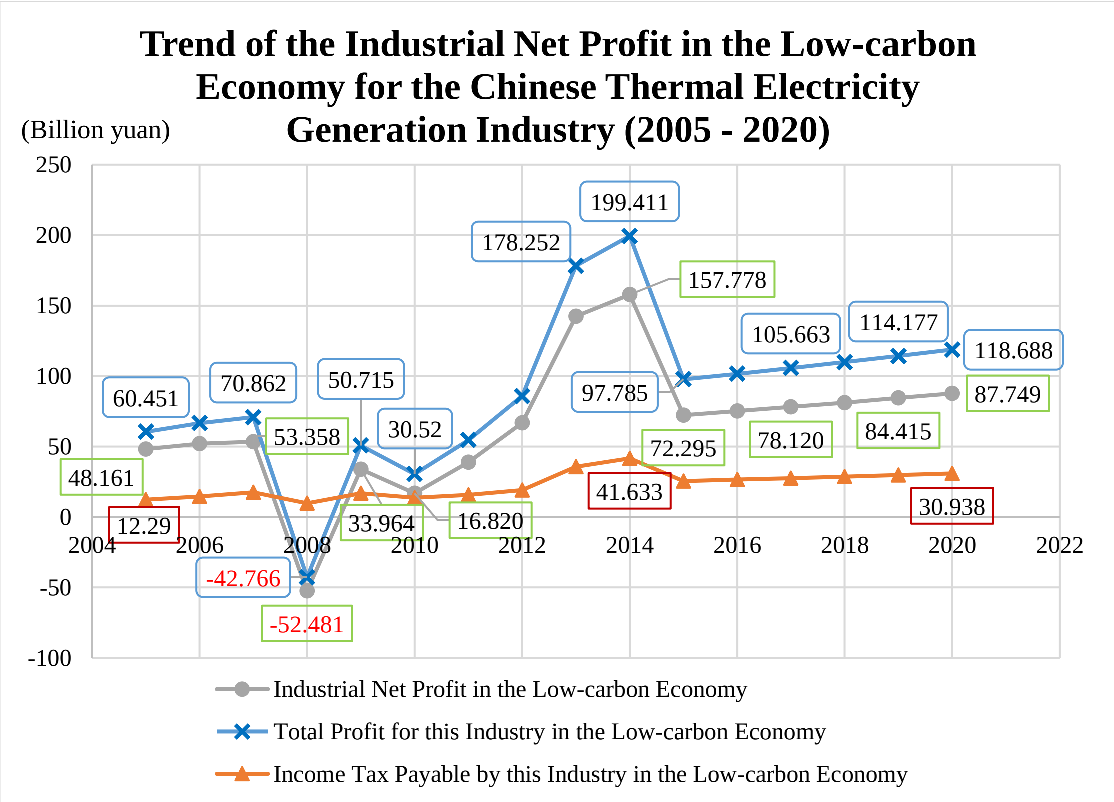

Figure 6-23 Trend of the Industrial Net Profit in the Low-carbon Economy for the Chinese Thermal Electricity Generation Industry (2005 - 2020)

Figure 6-23 shows that the trends in Factors 20, 21 and 23 are synchronous. In general, Factor 23 is larger than zero, indicating that this industry could maintain sustainable development from both the economic and environmental perspectives. However, the income tax payable for this industry averages 25.99% of Factor 20, which puts some pressure on industrial economic development, as in 2008, 2009 and 2010; Factor 23 was quite low.

6.5.1.3.4 Analysis of the Trend of the Total Profit for this Chinese Industry in Traditional Economy

Referring to the analysis of Factor 23 in section 6.5.1.3.3 and the analysis of Factor 18 (the practical cost of reducing CO_2 emissions) in 6.5.1.2.2, the total profit for this Chinese industry without low-carbon costs, that is the total profit for this industry in the traditional economy (F_{20N}), is presented in Figure 6-24 and Table 6-4.

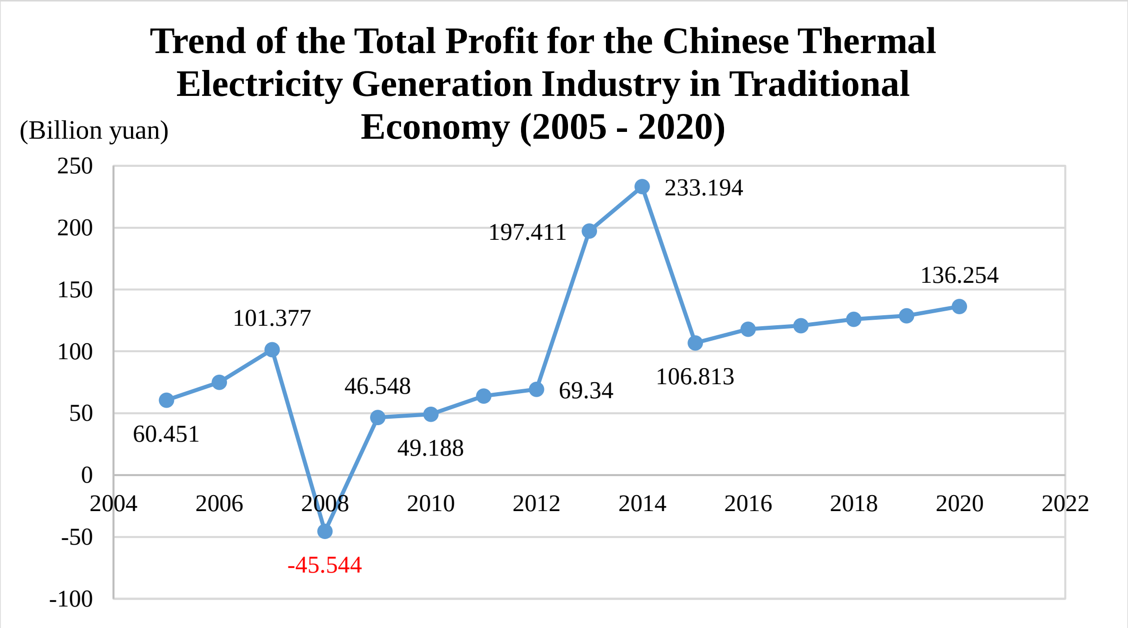

Figure 6-24 Trend of the Total Profit for the Chinese Thermal Electricity Generation Industry in Traditional Economy (2005 - 2020)

Figure 6-24 indicates that the total profit without the cost of the low-carbon emission generally increased from 60.451 billion yuan in 2005 to 136.254 billion yuan in 2020. However, in 2008, the operational performance of this industry was poor as its total profit was -45.544 billion yuan, which may have been affected by the financial crisis in that year. Since 2008, the gradual recovery of this industrial economic development is presented by the continuous increase of this total profit.

Table 6-4 Trend of the Total Profit for the Chinese Thermal Electricity Generation Industry in Traditional Economy (2005 - 2020)

Year	Factor 20 (Billion yuan)	Factor 18 (Practical Cost) (Billion yuan)	Total Profit in Traditional Economy (Billion yuan)
2005	60.451	0	60.451
2006	66.642	8.497	75.139
2007	70.862	30.515	101.377
2008	**-42.766**	**-2.778**	**-45.544**
2009	50.715	**-4.167**	46.548
2010	30.52	18.668	49.188
2011	54.596	9.355	63.951
2012	85.843	**-16.503**	69.34
2013	178.252	19.159	197.411
2014	199.411	33.783	233.194
2015	97.785	9.028	106.813
2016	101.648	16.299	117.947
2017	105.663	15.237	120.9
2018	109.838	16.013	125.851
2019	114.177	14.624	128.801
2020	118.688	17.566	136.254

Table 6-4 shows that Factor 20 can afford Factor 18 over the years, while in 2008 the total profit in the traditional economy was below zero and industrial economic performance was bad. On average, Factor 18 represents about 13.92% of Factor 20, while taking an average of around 10.21% of the total profit in the traditional economy. In 2008, 2009 and 2012, Factor 18 was below zero, meaning that the costs of reducing CO_2 emissions in previous years were sufficient to cover the CO_2 emissions target in these three years. Factor 18 in these years was earnings to total profits, increasing Factor 20's total profit in the traditional economy. Moreover, as Factor 18 only includes the cost of reducing CO_2 emissions caused by improving industrial production technology from section 6.5.1.1.1, when the mature carbon trading market is established in China, then this industry can also sell its remaining emission allowance (section 6.4.4) to the market to gain additional income for Factor 20.

6.5.1.4 Validation of the Model for Industrial Sustainable Development in the Low-carbon Economy for this Chinese Industry

First, based on the analysis in section 6.4.4, the Chinese industrial target for CO_2 emissions of 2020 could be achieved early by 2016, through improvement of the industrial production technology.

Secondly, referring to the criteria for Equation 6-11 in section 6.5.1.1.2, and based on the data in sections 6.5.1.2.2 and 6.5.1.3, for Factor 18 (F_{18N}), Factor 20 (F_{20lowN}) and F_{20N}, this study finds that during 2005 to 2020, when $F_{20N} > 0$, $F_{18N} > 0$, and $F_{20N} > F_{18N}$, then $F_{20lowN} > 0$ (except in 2008, the financial crisis, when $F_{20N} < 0$, therefore $F_{20lowN} < 0$), validating the logic from Factor 19 to Factor 20 and showing that the industrial cost of reducing CO_2 emissions can be afforded by this industry.

Thirdly, referring to the criteria for Equation 6-12, and based on the data in section 6.5.1.3, for Factor 20 (F_{20lowN}), Factor 21 (F_{21N}), and Factor 23 (F_{23N}), this study finds that in the period from 2005 to 2020, when $F_{20lowN} > 0$, $F_{21N} > 0$, and $F_{20lowN} > F_{21N}$, then $F_{23N} > 0$ (except in 2008 under the same influences, $F_{20lowN} < 0$, thus $F_{23N} < 0$), showing that the logic from Factor 20 to Factor 23 in the industrial low-carbon economy is correct, and that the Chinese industry can achieve sustainable development in the low-carbon economy.

Based on these conclusions that improving industrial production technology can promote the achievement of industrial standards for low-carbon emission, and that the criteria for Equation 6-11 and Equation 6-12 are met, this model for industrial sustainable development in the low-carbon economy for this Chinese industry (section 5.4.4) is validated by the industrial data. That is, the model for industrial sustainable development in a low-carbon economy proposed in section 4.8.6 is validated.

6.5.2 Validation of the Model for the Optimal Approach to Low-carbon Emission for this Chinese Industry in the Low-carbon Economy

6.5.2.1 The Mathematical Expression for the Model for the Optimal Approach to Low-carbon Emission for this Chinese Industry

Referring to the model for the optimal approach to low-carbon emission for this Chinese industry (section 5.4.5), Factor 12 determines Factor 15 then Factor 15 determines Factor 19. Factor 5 interacts with Factor 19 as they restrain each other (Figure 5-30). The mathematical expression for Factor 12 affecting Factor 19 is developed in Equation 6-13 and Equation 6-14.

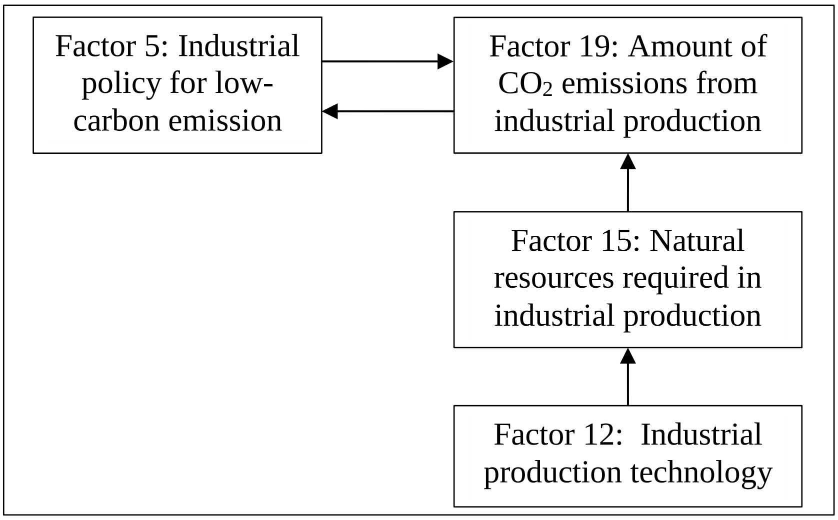

Figure 5-30 The Model for the Optimal Approach to Low-carbon Emission for Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

With a given industrial production technology (Factor 12), the amount of CO_2 emissions from industrial production is expressed as:

Equation 6-13: $F_{19N} = 3.14 \times F_{15N} \times P_{FN}$

Under different industrial production technologies, Factor 19 is:

Equation 6-14: $F_{19N} = 3.14 \times F_{15(F12K)N} \times P_{FN}$

In Equation 6-13, F_{19N} represents the total amount of CO_2 emissions from this industrial production in year N. F_{15N} represents the standard coal consumption per unit of electricity supply in a certain industrial production technology in year N. P_{FN} represents the annual production of electricity by this industry in year N. N is the serial number of the year N = 0, 1, 2,… 15, from 2005 to 2020.

In Equation 6-14, F_{19N}, P_{FN} and N are the same as in Equation 6-13. $F_{15(F12K)N}$ represents the standard coal consumption per unit of electricity supply in different industrial production technologies in year N, while F12K represents the different industrial production technologies, in which K equals 1 or 2. F121 represents the traditional industrial production technology, while F122 represents the SC technology.

Equation 6-14 indicates that along with the increase in the annual production of electricity from this industry (P_{FN}), the only way to reduce F_{19N} is effectively by reducing $F_{15(F12K)N}$, the standard coal consumption per unit of electricity supply.

6.5.2.2 Validation of the Model for the Optimal Approach to Low-carbon Emission for this Chinese Industry in the Low-carbon Economy

Based on the analysis above, the traditional production technology for this industry is taken as that in 2005, when the standard coal consumption per unit of electricity supply was 370 g/kWh, based on the calculation in 6.4.2. Therefore, $F_{15(F121)N}$ = 370 g/kWh. Since 2005, the industry has begun to improve its production technology, upgrading subcritical plant to SC technology. The average standard coal consumption per unit of electricity supply for SC technology is below 310 g/kWh, based on the technological standards for SC technology (Tian et al., 2006). Therefore, this study assumes that $F_{15(F122)N}$ = 310 g/kWh. With the comparison between the $F_{15(F121)N}$ and $F_{15(F122)N}$, improving the industrial production technology is shown to reduce the standard coal consumption per unit of electricity supply, and to reduce CO_2 emissions per unit of electricity supply, calculated through Equation 6-14. Furthermore, referring to the analysis in section 6.4.4, the industrial data indicates that the improvement of technology (Factor 12) supports this industry in achieving its target for CO_2 emissions by 2020.

Consequently, improvement in industrial production technology can reduce $F_{15(F12K)N}$ and achieve the industrial standard for CO_2 emissions. Therefore, based on the technological and industrial operational data, Equation 6-14 is validated and correct. The model for the optimal approach to low-carbon emission for this Chinese industry (section 5.4.5) is then validated. Therefore, the model for the optimal approach to low-carbon emission in an industrial low-carbon economy (section 4.8.6) is validated.

6.5.3 Validation of the Theoretical Model for Chinese Economic Growth and Industrial CO_2 Emissions from the Chinese Thermal Electricity Generation Industry

6.5.3.1 The Mathematical Expression for the Model of Chinese Economic Growth and CO_2 Emissions by this Chinese Industry

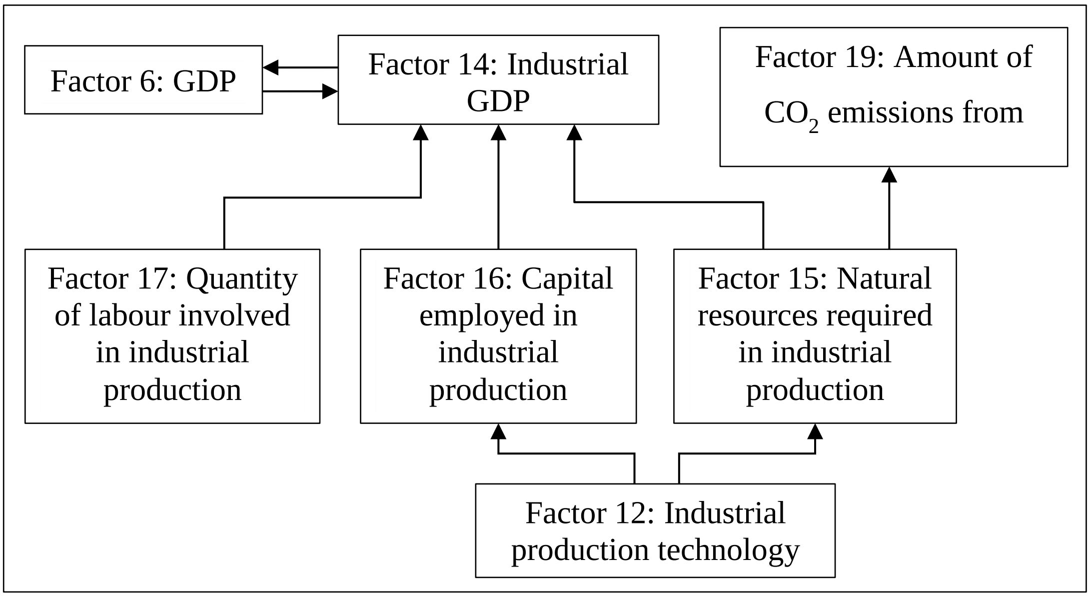

Figure 5-31 The Theoretical Model for Economic Growth and the Industrial CO2 Emissions by the Chinese Thermal Electricity Generation Industry

Referring to the model and analysis in section 5.4.6, Factor 14 (industrial GDP) is determined by factors related to industrial production: Factors 12, 15, 16 and 17. Factor 12, industrial production technology, determines the amount of Factor 15 (Natural resources required in industrial production) and Factor 16 (Capital employed in industrial production), while the affected Factor 15 determines the amount of CO_2 emissions from industrial production (Factor 19). There is interaction between Factors 14 and 6, as they restrain each other. There is no causal relationship between Factors 6 and 19; and therefore, no mathematical expression for it.

6.5.3.2 Validation of the Theoretical Model for Chinese Economic Growth and Industrial CO_2 Emissions from this Chinese Industry

Equation 6-14: $F_{19N} = 3.14 \times F_{15(F12K)N} \times P_{FN}$ (section 6.5.2.1), in which the optimal approach to low-carbon emission is expressed, indicates that Factor 19 is not determined by GDP, and that there is no causal relationship between the amount of CO_2 emitted by this industry and the GDP in China. Only Factor 19 is affected by P_{FN} and $F_{15(F12K)N}$. Because of the validation of Equation 6-14 (section 6.5.2.2), the non-causal relationship between Factors 19 and 6 is validated. Therefore, this theoretical model for Chinese economic growth and the industrial CO_2 emissions by the Chinese thermal electricity generation industry (section 5.4.6) is validated, meaning that the model in section 4.8.7 is validated.

6.5.4 Validation of the Logical Relational Model for the Industrial Low-carbon Economy System for this Chinese Industry

Consequently, the models in sections 5.4.4, 5.4.5 and 5.4.6 are validated. The model in section 5.4.4 refers to the model in section 4.8.5, that in section 5.4.5 to the model in section 4.8.6 and that in section 5.4.6 to the model in section 4.8.7. The model in section 5.4.3 refers to the model in section 4.7, whose simplification guides the construction of the models in section 4.8.5, 4.8.6 and 4.8.7. Therefore, the models in sections 5.4.4, 5.4.5 and 5.4.6 are based on the simplified model in section 5.4.3. As the three models in sections 5.4.4, 5.4.5 and 5.4.6 have been validated, the model in section 5.4.3 that is the logical relational model for the industrial low-carbon economy system for Chinese thermal electricity generation industry is also validated. In addition, the model in section 4.7, the logical relational model for the industrial low-carbon economy system, is validated, which means that the hierarchical structure model for the industrial low-carbon economy system is also validated.

6.6 Validation of the Research Methodology for Industrial Low-carbon Economy

As the logical relational model for the industrial low-carbon economy system for this Chinese industry was validated in section 6.5.4, the logical relational model constructed in section 4.7 is also validated. The hierarchical structure model for the industrial low-carbon economy system from section 4.6 is similarly validated. Consequently, the research methodology in section 3.4 is validated through implementation in Chinese thermal electricity generation industry.

6.7 Chapter Summary

Based on the model constructed in chapter 5, and the information about the factors in this Chinese industrial low-carbon economy system, this chapter first calculated the 2020 national and industrial targets for low-carbon emission, concluding that the Chinese national target cannot be achieved, however, the industrial target could be met by 2016, following current progress for low-carbon emission. The chapter then validated these industrial models through their mathematical expressions and the calculation on the industrial data. The results indicate, first, that the industrial target for CO_2 emissions for this industry can be achieved through the improvement of its production technology. Second, this industry generally can afford the cost of reducing CO_2 emissions, as it costs about 13.92% of the total profit for the industry in the low-carbon economy to reduce CO_2 emissions. Thirdly, there is no causal relationship between the growth of the Chinese economy and the amount of CO_2 emissions from this industrial production. Therefore, the relationship between GDP and the sum of CO_2 emissions from each industries' is not causal. Based on these results, the models for sustainable development, for the optimal approach to low-carbon emission, and for Chinese economic growth and Industrial CO_2 emissions, in the industrial low-carbon economy, were all validated. Thus, all the models constructed in chapter 5 were validated. Therefore, the corresponding models in chapter 4 were validated, including the logical relational model in section 4.7. Thus, the models for constructing this logical relational model were validated. Finally, the research methodology guiding this research was validated.

Chapter 7 Conclusion and Future Work

7.1 Overview of the Thesis

This thesis consists of seven chapters, which represents the research processes of answering the research question and addressing the research aim and objectives.

Chapter 1 provided the research background to the industrial low-carbon economy, and identified current research gaps, from which the research question, aim and objectives were provided. The aim of the study was *to develop a methodology to analyse the industrial low-carbon economy system, and then use this methodology to construct a multi-factor model for identifying critical factors related to low-carbon emission in industrial economies and a logical structure among these factors.* The first objective, *to determine the research scope and definition of an industrial low-carbon economy*, was initially addressed in this chapter.

Chapter 2 was a detailed literature review of related topics, including Pigouvian Tax Theory and the Coase Theorem, they are theoretical studies on curbing the amount of CO_2 emissions through economic methods like taxation, and the Environmental Kuznets Curve, the Theory of Coupling-Decoupling and the IPAT Function investigating the relationship between economic growth and CO_2 emissions. However, the published research could not directly guide industry to reduce CO_2 emissions or achieve their targets for low-carbon emission. They were also unable to provide a method that encapsulated all the factors regarding the industrial low-carbon economy system in a single, complex system. Therefore, this study viewed the industrial low-carbon economy from the perspective of systems thinking, and in chapter 3, developed a systematic research methodology.

Chapter 3 presented *systems philosophy* as the philosophic foundation of this research, as it is based on positivism and specifically supports the researcher in solving problems in complex systems. Guided by this philosophy, systems science and systems engineering were adopted as the theoretical foundation and analytical techniques for constructing the research methodology and theoretical models for the study. Then, as the research methodology was developed, the second objective, *to construct a research methodology, for constructing the multi-factor model for an industrial low-carbon economy system*, was satisfied; the methods for building up theoretical models were presented. Initial research scope and definition of the industrial low-carbon economy were also discussed and determined, addressing the objective one.

Chapter 4 addressed the third to fifth objectives, following the research methodology designed in chapter 3. Thus, the chapter built the production function for an industrial low-carbon economy, selected and optimised the dimensions and factors of the system, constructed the dimensional structure model, factors' relational model, hierarchical structure model and logical relational model for industrial low-carbon economy systems, and simplified the logical relational model. Through the simplification process, further sub-models with different emphasises were built and illustrated: for sustainable development and for optimal approach to low-carbon emission, and for economic growth and CO_2 emissions in an industrial low-carbon economy, and the decision-making models for industrial low-carbon emission policy and industrial fiscal and monetary policy.

Chapter 5 applied the multi-factor model constructed in chapter 4 to the Chinese thermal electricity generation industry, constructing the corresponding logical relational model, the models for the sustainable development and the optimal approach to low-carbon emission, and for economic growth and CO_2 emissions in the industrial low-carbon economy for this Chinese industry.

Chapter 6 used real data from this industry to validate these models. These four models for the industry were validated, thus the corresponding models in chapter 4 and the series of models for constructing the logical relational model were validated. Therefore, this chapter validated the research methodology for the industrial low-carbon economy, which is related to the sixth objective, *to validate the logical relational model and the simplified sub-models using the industrial data, and then validate the constructed research methodology*.

Chapter 7 presents the conclusions and evaluation of the thesis, with an outline of limitations and future work, addressing the seventh objective, *to conclude by presenting the research findings, contributions, and limitations of this research*.

As all ten objectives and the aim of the study has been achieved, this study constructed the research methodology and theoretical models for analysing and representing the industrial low-carbon economy.

7.2 Key Findings

The key findings of this research are the construction and validation of the research methodology and hierarchical structure model for an industrial low-carbon economy. Compared with previous research, which only involved partial factors of the industrial low-carbon economy system, this methodology systematically represented the entire system, following system philosophy. The integrated hierarchical structure model built referred to this methodology, systematically and quantitatively representing the system with all related factors within it and a hierarchical structure showing the inter-relationships of factors. Moreover, this model led to five simplified models: to identify the decision-making procedures for the policymaker to develop industrial low-carbon emission policy and the industrial fiscal and monetary policy; to recognise the optimal approach to low-carbon emission for industry, through improving industrial production technology; to suggest that sustainable development was only possible when industrial net profit could cover its cost for reducing CO_2 emissions; and to point out that no causal relationship was found between economic growth and CO_2 emissions.

7.3 Key Conclusions

This section identifies the key conclusions of the thesis. First, based on the literature view, Pigouvian Tax Theory (Pigou, 1920; Baumol, 1972) and the Coase Theorem (Coase, 1937; 1960; 1988; Medema and Zerbe, 2000), believe that the CO_2 emissions is externality, and environmental protection is the benefit balance between the pollution releasing industry and society (or the directly polluted sector). Moreover, neither believed that environmental protection should be the responsibility of the industrial entities during their economic activities, and neither analysed the direct effects and constraints, which the environment challenged the industrial sustainable development. In practice, the taxation regarding these theories increased the cost of production, promoting economic incentives, externally solving this problem, they did not settle the cost of reducing CO_2 emissions as one of the internal factors in the process of production. However, bases on our model for the optimal approach to low-carbon emission, this study identified that the optimal approach for the reduction in industrial CO_2 emissions could be addressed through the improvement of production technology, as the CO_2 treatment technology is not yet mature. Carbon trading just globally balances CO_2 emissions and allocates CO_2 emission allowance without directly reducing the emissions. Based on the model in section 4.8.3, and the two decision-making models for industrial low-carbon emission policy and industrial fiscal and monetary policy, this study found that these two policies did not directly determine the amount of CO_2 emissions reduction, although Factors 5 and 19 do restrain each other. Therefore, the theory for Pigouvian Tax Theory and the Coase Theorem cannot directly result in the reduction of CO_2 emissions.

Referring to the theories researching the relationship between economic growth and CO_2 emissions, such as the EKC, the Theory of Coupling-Decoupling, the IPAT Function, they tried to identify the relationship by using the macro or industrial data. Not only their conclusions were influenced by their data resources, but also they were unable to provide a method that encapsulated all the factors regarding the industrial low-carbon economy system in a single, complex system. Moreover, our theoretical model for economic growth and CO_2 emissions in a low-carbon economy indicated that there is no causal relationship between economic growth and CO_2 emissions; instead, the relationship between them is correlation. Therefore, none of the theories of EKC, Coupling-Decoupling and IPAT Function was tenable.

Based on the model for sustainable development in the industrial low-carbon economy indicated that the industrial sustainable development could be achieved when the net profit for this industry was above zero after affording the cost of reducing CO_2 emissions. However, this model is developed from the model in section 4.8.3, with the assumptions that the industrial low-carbon emission policy and industrial fiscal and monetary policy are given. It indicates that when under the given industrial polices, the sustainable development in an industrial low-carbon economy could not be achieved, and therefore, government could adjust their industrial low-carbon emission policy or industrial fiscal and monetary policy to support the industry, through reducing income tax rate or lowering CO_2 emissions target.

The decision-making models for industrial low-carbon emission policy and industrial fiscal and monetary policy presented approaches to determining industrial low-carbon emission policy and the industrial fiscal and monetary policy, supporting the policymaking in the future. Based on the model for the sustainable development in the industrial low-carbon economy, these current polices could be assessed and evaluated.

The hierarchical structure model for the industrial low-carbon economy system was validated based on the validation of three simplified models using Chinese industrial data. The validated hierarchical structure model then supported the validation of the constructed research methodology, indicating the validation of the whole theoretical framework for sustainable development in an industrial low-carbon economy.

With the implementation of these models, it was found that improvement in industrial production technology could lead to the achievement of both the industrial target for CO_2 emissions and the sustainable development for this Chinese industry. Although the 2020 industrial target for CO_2 emissions could be achieved as early as 2016, the national 2020 target for China would not be met following current processes. Moreover, there is no causal relationship between the growth of the Chinese economy and the amount of CO_2 emissions from this industrial production. Therefore, the relationship between GDP and the sum of CO_2 emissions from each industry is not causal.

Finally, the validated methodology and theoretical models constructed in the study provide research paradigm and theoretical support for future research and policymaking regarding the industrial low-carbon economy.

7.4 Research Contributions

7.4.1 Theoretical Contributions

This research clarified the scope and definition of an industrial low-carbon economy, and constructed a research methodology by referring to systems philosophy and systems theories. Applying systems techniques, this research constructed and validated an integrated hierarchical framework structure for investigating the relationships among the factors involved in sustainable development in an industrial low-carbon economy. This methodology fulfils gaps in the field of industrial low-carbon economy, and can be used as a research paradigm in this field. The hierarchical structure model represents the entire system qualitatively, filling the theoretical gaps in this field, and offering five simplified sub-models to qualitatively and quantitatively represent the system. These simplified sub-models identify an approach for sustainable development and for the optimal approach to low-carbon emission in an industrial low-carbon economy; and they scientifically analyse the relationship between economic growth and CO_2 emissions.

7.4.2 Practical Contributions

The integrated framework constructed here can be seen as a general paradigm for researching an industrial low-carbon economy, and methodologically and theoretically supporting government in establishing strategies for industry in such an economy. The validated hierarchical structure model shows the relationships among the factors involved in this system, offering five simplified sub-models, which can be widely used to support the activities of industrial low-carbon emission. Therefore, in practice, the government could directly implement the structure and factors' relationships identified for planning strategies and policies, as well as managing the progress of the low-carbon emission activities for individual industries. In particular, the model for the optimal approach to low-carbon emission can be used as an analytical and managerial method for proceeding towards the reduction of carbon emissions in a given industry; the model for sustainable development in an industrial low-carbon economy is an analytical method for industrial sustainable development, guiding policymaking.

In detail, the model in Figure 5-30 suggests that the policymaker could promote industrial low-carbon activities through Factor 5 or actions supporting the development and innovation for industrial production technology (Factor 12).

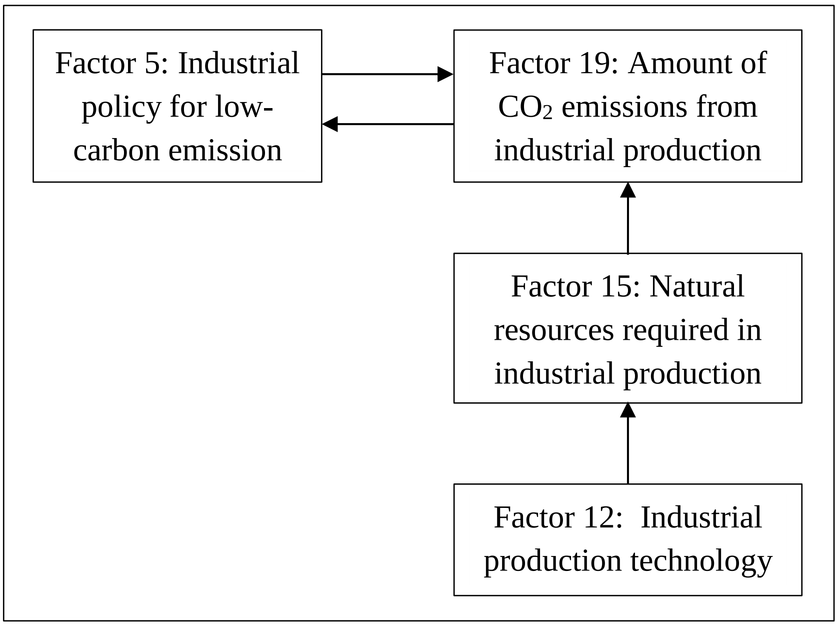

Figure 5-30 The Model for the Optimal Approach to Low-carbon Emission for Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

The model for sustainable development in Figure 5-29 suggests that Chinese government can promote the progress of low-carbon emission through legislating the industrial policy for low-carbon emission. The government also can support the industrial sustainable development through carrying out appropriate fiscal and monetary policy for industrial economy (Factor 4) to influence the income tax payable by industry in the low-carbon economy (Factor 21) and then maintaining the industrial net profit (Factor 23), which determining the industrial development. On the other hand, the industry itself can use this model to monitor and assess their own capability for achieving the required low-carbon emission targets, which is the foundation for their next step planning and negotiations.

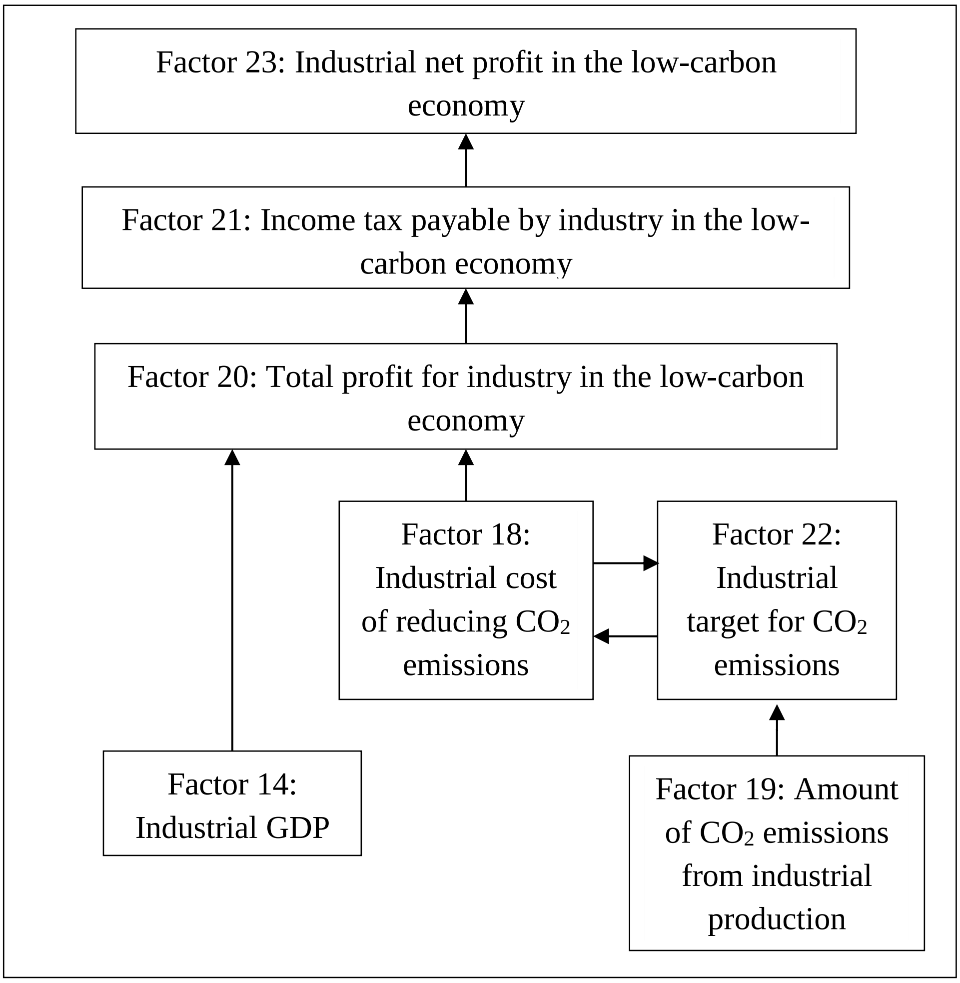

Figure 5-29 The Model for the Sustainable Development in the Industrial Low-carbon Economy for the Chinese Thermal Electricity Generation Industry

7.5 Limitations

The logic relationship (Factor 12 determines Factor 15) applied to construct the factors' relational model and all the following models, it was adopted to investigate whether improvement of production technology can reduce the consumption of natural resources (coal) per unit of production. Therefore, these models are not applicable in any industry, where fossil fuels or energy created by fossil fuel are not used, or where improving the industrial production technology cannot reduce its natural resources (coal) consumption per unit of production.

Moreover, the construction of the model for sustainable development in section 4.8.5 assumes that there are determined, stable industrial policies for structural adjustment (Factor 3) and for low-carbon emission (Factor 5), as well as the fiscal and monetary policy for industrial economy (Factor 4). Therefore, this model is not applicable in any industrial system that is insufficient in any of these assumptions.

7.6 Future Work

As explained in section 6.5, this study quantified models for sustainable development and for the optimal approach to low-carbon emission in the industrial low-carbon economy. Future work regarding the theoretical models for an industrial low-carbon economy system might be to further quantify the models, including time-series expressions of all the factors in the logical relational model, to construct dynamic theoretical models. For the policymaking purposes, the detailed process of the sustainable development and the optimal approach to low-carbon emission in the industrial low-carbon economy for all other industries consuming fossil fuel could be analysed by applying the models developed in chapter 4. Through the integration of those models, the national progress of sustainable development in the low-carbon economy may also be explored and identified.

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Appendix A: Calculation of the Reachability Matrix

First, input the Adjacency Matrix (A) and Identity Matrix (I) into Excel sheet.

The Adjacency Matrix for the Industrial Low-carbon Economy System (A)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
5	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
6	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
7	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0
14	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
15	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0
19	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

The Identity Matrix (I)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Start from k = 1, then (I ∪ A), $(I \cup A)^2$ and $(I \cup A)^4$ are calculated.

AA3 | {=MMULT(B3:X25,B29:X51)}

	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW
1												I ∪ A												
2		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
3	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
7	5	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
8	6	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
9	7	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	8	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
11	9	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
12	10	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13	11	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
14	12	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0
15	13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0
16	14	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
17	15	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
18	16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
19	17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
20	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0
21	19	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
22	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
23	21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
24	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
25	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

$(I \cup A)^2$ is calculated as following.

AA55 | {=MMULT(AA29:AW51,AA29:AW51)}

	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW
53													Step 1 for (I ∪ A)^2 = (I ∪ A) ∪ (I ∪ A)												
54			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
55		1	2	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
56		2	0	2	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57		3	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
58		4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1
59		5	0	0	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3	0
60		6	1	2	0	0	0	2	1	0	2	1	0	0	0	2	0	0	0	0	0	1	0	0	0
61		7	0	3	0	0	0	2	2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
62		8	1	0	0	0	0	1	0	1	2	3	1	0	0	1	0	0	2	0	0	0	0	0	0
63		9	2	0	0	0	0	1	0	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
64		10	1	1	0	0	1	2	0	0	1	1	2	0	0	1	0	0	0	0	0	0	0	0	0
65		11	2	0	1	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	1	0
66		12	0	0	1	0	0	1	0	0	0	0	0	1	0	4	2	2	0	0	1	1	0	0	0
67		13	0	0	0	0	1	1	0	0	0	0	0	0	1	3	0	2	0	0	2	1	0	1	0
68		14	0	1	0	0	0	2	0	0	1	0	0	0	0	2	0	0	0	0	0	2	1	0	1
69		15	0	0	2	1	1	1	0	0	0	0	0	0	0	2	1	0	0	0	2	1	0	1	0
70		16	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	1	0	0	0	1	0	0	0
71		17	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	0	0	1	0	0	0
72		18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	1	2	1
73		19	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3	0
74		20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	3
75		21	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
76		22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	2	0
77		23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

AA81 {=IF(AA55:AW77>1,1,AA55:AW77)}

Step 2 for (I ∪ A)^2 = (I ∪ A) ∪ (I ∪ A)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0
6	1	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0
7	0	1	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	1	0	1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
10	1	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0
11	1	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0
12	0	0	1	0	0	1	0	0	0	0	0	1	0	1	1	1	0	0	1	1	0	0	0
13	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	1	0	0	1	1	0	1	0
14	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	1	0	1
15	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1	0
16	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0
17	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

(I ∪ A)^4 is also calculated following the same steps.

(I ∪ A)^2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

AZ29 {=MMULT(AZ3:BV25,AZ3:BV25)}

Step 1 for ((I ∪ A)^2)^2 = ((I ∪ A)^2) ∪ ((I ∪ A) ^2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	2	0	2	1	3	0	0	0	0	0	2	0	0	0	0	0	0	1	2	0	0	2	0
2	1	3	0	0	0	3	3	0	2	1	0	0	0	2	0	0	0	0	0	1	0	0	0
3	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2
4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
5	0	0	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	2	3	4	2
6	4	5	0	1	2	6	3	0	5	3	3	0	0	4	0	0	0	0	0	3	2	0	2
7	2	4	0	0	0	5	3	0	4	2	1	0	0	3	0	0	0	0	0	2	1	0	1
8	6	3	1	0	3	6	1	1	5	4	5	0	0	5	0	0	2	0	1	3	1	1	1
9	5	2	1	0	3	3	1	0	3	3	4	0	0	2	0	0	0	0	1	1	0	1	0
10	5	4	2	1	4	5	2	0	4	3	4	0	0	3	0	0	0	1	2	2	1	2	1
11	2	0	4	2	4	0	0	0	0	0	2	0	0	0	0	0	0	3	3	1	1	4	0
12	1	2	4	3	2	5	1	0	2	1	0	1	0	5	2	2	0	1	3	6	3	2	2
13	1	2	2	2	3	4	1	0	2	1	0	0	1	4	0	2	0	3	3	6	2	4	2
14	2	3	0	2	0	4	2	0	3	2	1	0	0	2	0	0	0	0	0	3	3	0	4
15	1	2	4	5	3	3	1	0	2	1	0	0	0	3	1	0	0	3	3	5	4	4	3
16	1	2	0	1	0	3	1	0	2	1	0	0	0	3	0	1	0	0	0	4	2	0	2
17	1	2	0	1	0	3	1	0	2	1	0	0	0	3	0	0	1	0	0	4	2	0	2
18	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	3	2	4
19	0	0	3	2	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	2	2	4	1
20	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	4
21	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	2	2	2
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

AZ55 {=IF(AZ29:BV51>1,1,AZ29:BV51)}

Step 2 for ((I ∪ A)^2)^2 = ((I ∪ A)^2) ∪ ((I ∪ A) ^2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0
2	1	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	0	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	0	1	1	0	1
7	1	1	0	0	0	1	1	0	1	1	1	0	0	1	0	0	0	0	0	1	1	0	1
8	1	1	1	0	1	1	1	1	1	1	1	0	0	1	0	0	1	0	1	1	1	1	1
9	1	1	1	0	1	1	1	0	1	1	1	0	0	1	0	0	0	0	1	1	0	1	0
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	0
12	1	1	1	1	1	1	1	0	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	0	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	0	1	0	1	1	0	1	1	1	0	0	1	0	0	0	0	0	1	1	0	1
15	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	0	1	0	1	1	0	1	1	0	0	0	1	0	1	0	0	0	1	1	0	1
17	1	1	0	1	0	1	1	0	1	1	0	0	0	1	0	0	1	0	0	1	1	0	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

AZ81 {=IF(AZ55:BV77=AZ3:BV25,1,0)}

Comparing (I ∪ A)^2 and (I ∪ A)^4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1
2	0	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	0	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
6	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0
7	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	0
8	1	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
9	1	0	0	1	0	1	0	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1
10	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
11	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1
12	0	0	1	0	0	1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	0	0	0
13	0	0	0	0	1	1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	0	1	0
14	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
15	0	0	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	0	1	0
16	0	0	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0
17	0	0	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0
18	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Comparing $(I \cup A)^2$ and $(I \cup A)^4$.

Thus, $(I \cup A) \neq (I \cup A)^2 \neq (I \cup A)^4$. The calculation must be continued.

Then k = 2, repeat the three steps.

$(I \cup A)^8$ is also calculated following the same steps.

(I ∪ A)^4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0
2	1	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0

BY29 {=MMULT(BY3:CU25,AZ3:BV25)}

Step 1 for ((I ∪ A)^2)^3 = ((I ∪ A)^2) ∪ ((I ∪ A) ^2) ∪ ((I ∪ A) ^2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	2	0	4	3	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	2	3	5	2
2	4	5	0	1	2	6	3	0	5	3	3	0	0	4	0	0	0	0	0	3	2	0	2
3	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3
4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
5	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
6	5	5	2	4	4	6	3	0	5	3	4	0	0	4	0	0	0	1	2	3	4	2	5
7	5	5	1	2	3	6	3	0	5	3	4	0	0	4	0	0	0	0	1	3	3	1	4
8	6	5	4	4	5	8	3	1	6	4	5	0	0	6	0	0	2	3	3	5	4	4	4
9	5	5	4	3	5	6	3	0	5	3	4	0	0	4	0	0	0	3	3	4	3	4	2
10	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
11	2	0	4	5	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	3	5	5	4
12	4	5	5	6	5	9	3	0	5	3	3	1	0	7	2	2	0	4	4	8	6	5	6
13	4	5	3	5	5	8	3	0	5	3	3	0	1	6	0	2	0	4	3	7	6	5	6
14	5	5	1	3	3	6	3	0	5	3	4	0	0	4	0	0	0	0	1	3	4	1	5
15	4	5	4	6	5	7	3	0	5	3	3	0	0	5	1	0	0	4	3	6	6	5	6
16	4	5	0	3	2	7	3	0	5	3	3	0	0	5	0	1	0	0	0	4	4	0	5
17	4	5	0	3	2	7	3	0	5	3	3	0	0	5	0	0	1	0	0	4	4	0	5
18	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
19	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
20	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	4
21	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
22	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

BY55 {=IF(BY29:CU51>1,1,BY29:CU51)}

Step 2 for ((I ∪ A)^2)^3 = ((I ∪ A)^2) ∪ ((I ∪ A) ^2) ∪ ((I ∪ A) ^2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	0	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	0	1	1	0	1
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1
15	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	0	1	1	1	1	0	1	1	1	0	0	1	0	1	0	0	0	1	1	0	1
17	1	1	0	1	1	1	1	0	1	1	1	0	0	1	0	0	1	0	0	1	1	0	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Comparing $(I \cup A)^4$ and $(I \cup A)^8$.

BY81 | {=IF(BY55:CU77=BY3:CU25,1,0)}

Comparing (I ∪ A)^4 and (I ∪ A)^8

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
2	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1
7	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1
8	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
9	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	0
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
12	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1
15	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Thus, $(I \cup A)^4 \neq (I \cup A)^8$. The calculation must be continued.

Then k = 3, repeat the three steps.

$(I \cup A)^{16}$ is also calculated following the same steps.

(I ∪ A)^8

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	0	1	1	1	1	0	1	1	1	0	0	1	0	0	0	0	0	1	1	0	1

CX29 | {=MMULT(CX3:DT25,AZ3:BV25)}

Step 1 for ((I ∪ A)^2)^4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	2	0	4	5	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	3	5	5	5
2	5	5	2	4	4	6	3	0	5	3	4	0	0	4	0	0	0	1	2	3	4	2	5
3	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3
4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
5	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
6	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
7	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	3	3	4	5	4	5
8	6	5	4	5	5	8	3	1	6	4	5	0	0	6	0	0	2	4	3	6	6	5	6
9	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
10	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
11	2	0	4	5	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	3	5	5	5
12	5	5	6	6	6	9	3	0	5	3	4	1	0	7	2	2	0	4	5	8	6	6	6
13	5	5	4	5	6	8	3	0	5	3	4	0	1	6	0	2	0	4	4	7	6	6	6
14	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	3	3	4	5	4	5
15	5	5	5	6	6	7	3	0	5	3	4	0	0	5	1	0	0	4	4	6	6	6	6
16	5	5	2	4	4	7	3	0	5	3	4	0	0	5	0	1	0	1	2	4	4	2	5
17	5	5	2	4	4	7	3	0	5	3	4	0	0	5	0	0	1	1	2	4	4	2	5
18	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
19	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
20	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	4
21	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
22	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

CX55 | {=IF(CX29:DT51>1,1,CX29:DT51)}

Step 2 for ((I ∪ A)^2)^4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
15	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1
17	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Comparing $(I \cup A)^8$ and $(I \cup A)^{16}$.

CX81 | {=IF(CX55:DT77=CX3:DT25,1,0)}

Comparing (I ∪ A)^8 and (I ∪ A)^16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1
17	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Thus, $(I \cup A)^8 \neq (I \cup A)^{16}$. The calculation must be continued.

Then k = 4, repeat the three steps.

$(I \cup A)^{32}$ is also calculated following the same steps.

(I ∪ A)^16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1

DW29 | {=MMULT(DW3:ES25,AZ3:BV25)}

Step 1 for ((I ∪ A)^2)^5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	2	0	4	5	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	3	5	5	5
2	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
3	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3
4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
5	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
6	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
7	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
8	6	5	4	5	5	8	3	1	6	4	5	0	0	6	0	0	2	4	3	6	6	5	6
9	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
10	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
11	2	0	4	5	4	0	0	0	0	0	2	0	0	0	0	0	0	4	3	3	5	5	5
12	5	5	6	6	6	9	3	0	5	3	4	1	0	7	2	2	0	4	5	8	6	6	6
13	5	5	4	5	6	8	3	0	5	3	4	0	1	6	0	2	0	4	4	7	6	6	6
14	5	5	4	5	5	6	3	0	5	3	4	0	0	4	0	0	0	4	3	5	6	5	6
15	5	5	5	6	6	7	3	0	5	3	4	0	0	5	1	0	0	4	4	6	6	6	6
16	5	5	4	5	5	7	3	0	5	3	4	0	0	5	0	1	0	4	3	6	6	5	6
17	5	5	4	5	5	7	3	0	5	3	4	0	0	5	0	0	1	4	3	6	6	5	6
18	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
19	0	0	3	5	2	0	0	0	0	0	0	0	0	0	0	0	0	4	2	3	5	4	5
20	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	4
21	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3
22	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	4	2	5
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

DW55 | {=IF(DW29:ES51>1,1,DW29:ES51)}

Step 2 for ((I ∪ A)^2)^5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
15	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1
17	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Comparing $(I \cup A)^{16}$ and $(I \cup A)^{32}$.

{=IF(DW55:ES77=DW3:ES25,1,0)}

Comparing (I ∪ A)^16 and (I ∪ A)^32

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Thus, $(I \cup A)^8 \neq (I \cup A)^{16} = (I \cup A)^{32}$. The rule is met and the calculation is stopped. Therefore, the reachability matrix $M = (I \cup A)^{16}$.

Reachability Matrix M = (I ∪ A)^16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
3	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
5	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
11	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
13	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1
14	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1	1
15	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
16	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1
17	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1
18	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
19	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
20	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
21	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
22	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Appendix B: Level Partition of the Reachability Matrix

	FU	FV	FW	FX	FY
1		**Level Partition for Reachability Matrix**			
2	**Process 1**				
3	**Factor**	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Initial level**
4	**1**	1,3,4,5,11,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17	1,11	
5	**2**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
6	**3**	3,4,21,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17,3,5,19	3	
7	**4**	4,21,23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	4,21	
8	**5**	3,4,5,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17,5,19	5,19	
9	**6**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
10	**7**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
11	**8**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,8,17	8	8	A1
12	**9**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
13	**10**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
14	**11**	1,3,4,5,11,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17	1,11	
15	**12**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,12,15,16	12	12	A1
16	**13**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,13,16	13	13	A1
17	**14**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	
18	**15**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,15	12,15	15	
19	**16**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,16	12,13,16	16	
20	**17**	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,17	8,17	17	
21	**18**	4,18,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,22	18,22	
22	**19**	3,4,5,18,19,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,19	5,19	
23	**20**	4,20,21,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,22	20	
24	**21**	4,21,23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	4,21	
25	**22**	4,18,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,22	18,22	
26	**23**	23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23	23	R1

Process 2					
Factor	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Initial level**	**Factor**
1	1,3,4,5,11,18,19,20,21,22	1,2,6,7,9,10,11,12,13,14,15,16,17	1,11		**1**
2	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**2**
3	3,4,21	1,2,6,7,9,10,11,12,13,14,15,16,17,3,5,19	3		**3**
4	4,21	all-23	4,21	R2	**4**
5	3,4,5,18,19,20,21,22	1,2,6,7,9,10,11,12,13,14,15,16,17,5,19	5,19		**5**
6	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**6**
7	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**7**
9	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**9**
10	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**10**
11	1,3,4,5,11,18,19,20,21,22	1,2,6,7,9,10,11,12,13,14,15,16,17	1,11		**11**
14	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22	2,6,7,9,10,12,13,14,15,16,17	2,6,7,9,10,14		**14**
15	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,15	15	15	A2	**15**
16	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,16	16	16	A2	**16**
17	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,17	17	17	A2	**17**
18	4,18,20,21,22	1,2,5,6,7,9,10,11,12,13,14,15,16,17,18,19,22	18,22		**18**
19	3,4,5,18,19,20,21,22	1,2,5,6,7,9,10,11,12,13,14,15,16,17,19	5,19		**19**
20	4,20,21	1,2,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20,22	20		**20**
21	4,21	1,2,3,4,5,6,7,9,10,11,12,13,14,15,16,17,18,19,20,21,22	4,21	R2	**21**
22	4,18,20,21,22	1,2,5,6,7,9,10,11,12,13,14,15,16,17,18,19,22	18,22		**22**

Process 3					
Factor	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Initial level**	**Factor**
1	1,3,5,11,18,19,20,22,	1,2,6,7,9,10,11,14	1,11		**1**
2	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14,	2,6,7,9,10,14	A3	**2**
3	3	1,2,6,7,9,10,11,14,3,5,19	3	R3	**3**
5	3,5,18,19,20,22	1,2,6,7,9,10,11,14,5,19	5,19		**5**
6	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14	2,6,7,9,10,14	A3	**6**
7	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14	2,6,7,9,10,14	A3	**7**
9	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14	2,6,7,9,10,14	A3	**9**
10	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14	2,6,7,9,10,14	A3	**10**
11	1,3,,5,11,18,19,20,22	1,2,6,7,9,10,11,14	1,11		**11**
14	1,2,3,5,6,7,9,10,11,14,18,19,20,22	2,6,7,9,10,14	2,6,7,9,10,14	A3	**14**
18	18,20,22	1,2,5,6,7,9,10,11,14,18,19,22	18,22		**18**
19	3,5,18,19,20,22	1,2,5,6,7,9,10,11,14,19	5,19		**19**
20	20	1,2,5,6,7,9,10,11,14,18,19,20,22	20	R3	**20**
22	18,20,22	1,2,5,6,7,9,10,11,14,18,19,22	18,22		**22**

Process 4					
Factor	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Initial level**	**Factor**
1	1,5,11,18,19,22	1,11,	1,11	A4	**1**
5	5,18,19,22,	1,11,5,19	5,19		**5**
11	1,5,11,18,19,22	1,11,	1,11	A4	**11**
18	18,22	1,5,11,18,19,22	18,22	R4	**18**
19	5,18,19,22	1,5,11,19	5,19		**19**
22	18,22	1,5,11,18,19,22	18,22	R4	**22**

Process 5					
Factor	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Initial level**	**Factor**
5	5,19	5,19	5,19	5	**5**
19	5,19	5,19	5,19	5	**19**

Finally, the level partition for reachability matrix is summarised as following table.

Level Partition for Reachability Matrix				
Factors	**Reachability Set**	**Antecedent set**	**Intersection ∩**	**Level**
23	23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23	23	1
4	4,21,23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	4,21	2
21	4,21,23	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	4,21	2
3	3,4,21,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17,3,5,19	3	3
20	4,20,21,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,22	20	3
18	4,18,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,22	18,22	4
22	4,18,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,22	18,22	4
5	3,4,5,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17,5,19	5,19	5
19	3,4,5,18,19,20,21,22,23	1,2,5,6,7,8,9,10,11,12,13,14,15,16,17,19	5,19	5
1	1,3,4,5,11,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17	1,11	6
11	1,3,4,5,11,18,19,20,21,22,23	1,2,6,7,8,9,10,11,12,13,14,15,16,17	1,11	6
2	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
6	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
7	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
9	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
10	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
14	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23	2,6,7,8,9,10,12,13,14,15,16,17	2,6,7,9,10,14	7
15	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,15	12,15	15	8
16	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,16	12,13,16	16	8
17	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,17	8,17	17	8
8	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,8,17	8	8	9
12	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,12,15,16	12	12	9
13	1,2,3,4,5,6,7,9,10,11,14,18,19,20,21,22,23,13,16	13	13	9