Comprehensive Evaluation of Environmental Policies for Energy Infrastructure Transformation by Promoting Renewable Energy Development with Carbon Tax to Reduce Greenhouse Gas Emission in China

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ABSTRACT

Due to the rapid economic growth and coal-dominant energy system, China's greenhouse gas (GHG) emission continues to rise after it overtook the United States to become the world's largest GHG emitter in 2007. Currently China is facing great pressure in the international climate negotiations to combat global climate change. Transformation of the existing coal-dominant energy system into a low carbon one is an effective way to coordinate the economic development and GHG mitigation in China.

China's GHG emission was 7,217.06 $MtCO_2$ e in 2010, accounting for 23.8% of the world's total GHG emission. And nearly half of China's GHG emission was from the sector of electricity and heat production. So demand of electricity is the largest driver of the rise in China's GHG emission. As to China's electricity demand, it was 4,228.1 TWh in 2010, almost tripled the amount of 2000. Moreover, coal-fired power generation is dominant in China's energy system, representing over 80% of the total electricity generation for the recent years. Therefore, the key to mitigation in China is to develop renewable energy to transform the existing coal-dominant energy system. However, although China has abundant renewable energy resources, the main technological, financial, and institutional risks associated with China's renewable energy development still remain, especially the high cost of renewable energy. Against the background, we propose the comprehensive policies of carbon tax and subsidy to promote the renewable energy development, in order to transform the coal-dominant energy system and coordinate the economic development, energy consumption and GHG mitigation in China.

In this study, we construct an integrated model for China's energy and environmental policy analysis, into which the principles of commodity flow balance, energy flow balance, and value flow balance are embedded in order to comprehensively evaluate the effects of environmental policies including promotion of renewable energy development on improving trade-off between economic development and GHG mitigation by transforming the energy system.

The simulation was completed using LINGO, an optimization modeling software. The objective function is to maximize the sum of discounted GDP from 2007 to 2020, subject to a series of specific formulations. The simulation results prove that the integrated model can reflect the development of China's economy with high reliability. Therefore, the integrated modeling approach is a useful and effective method in policy evaluation.

From comprehensive simulation towards environmental policies evaluation with an emphasis on energy infrastructure transformation, we find that the proposed environmental policies of introducing carbon tax and new energy industry are effective to coordinate the relationship among China's economy, energy and GHG mitigation. Based on consideration of trade-off between GHG mitigation and economic development, we identify the optimal case in which GHG emission constraint is set as 1.8 times more than the base year along with introduction of 30 Yuan/tCO_2e carbon tax. Not only because it has the lowest GHG intensity and best investment effect on GDP, but it is the most efficient in energy consumption among all the cases.

The simulation results of optimal case prove that the comprehensive proposed policies are effective to promote the economic development, GHG mitigation, and energy system transformation in China. In the aspect of economic development, China's GDP will reach 70.79 Trillion Yuan in 2020, and the annual growth rate of GDP is 7.91%. As to GHG mitigation, China's GHG intensity will be reduced by 43.13% relative to 2005 by 2020, and China's climate commitment can be realized with introduction of the proposed policies. Moreover, with the subsidy from 30 Yuan/tCO_2e carbon tax, the total electricity of wind power, solar power, and biomass power is 3,574.03 TWh from 2007 to 2020. The share of renewable energy power generation in the total electricity generation has increased to 24.17% in 2020, and China's target of renewable energy development will be realized. Furthermore, it indicates that electricity substitution and industrial structure adjustment are two main approaches to achieve the optimization of economic growth and GHG mitigation in China.

This study makes a systematic attempt to coordinate China's economic growth and GHG mitigation by transforming the coal-dominant energy system. The comprehensive policies are proven to be very effective to promote the renewable energy development by introducing carbon tax and subsidy in China. It can offer a useful approach to evaluate the other environmental issues, and provide some recommendations in GHG mitigation to the policy makers in order to form the scientific basis of policy decision-making for sustainable development in China.

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GLOSSARY OF VARIABLES

$X_u(t)$: production of usual industry in term t (endogenous variable);

$X_m(t)$: production of thermal power industry in term t (endogenous variable);

$X_r(t)$: production of hydropower industry in term t (endogenous variable);

$X_n(t)$: production of new energy industry in term t (endogenous variable);

A_{uu}: input coefficient to usual industry i by usual industry (exogenous variable);

A_{um}: input coefficient to thermal power industry by usual industry (exogenous variable);

A_{ur}: input coefficient to hydropower industry by usual industry (exogenous variable);

A_{un}: input coefficient to new energy industry by usual industry (exogenous variable);

$C_u(t)$: household consumption of usual industry in term t (endogenous variable);

G_{u_d}: government consumption of usual industry in base year (exogenous variable);

Q_{uu}: investment demand to usual industry induced by one unit capital formation in usual industry (exogenous variable);

Q_{um}: investment demand to usual industry induced by one unit capital formation in thermal power industry (exogenous variable);

Q_{ur}: investment demand to usual industry induced by one unit capital formation in hydropower industry (exogenous variable);

Q_{un}: investment demand to usual industry induced by one unit capital formation in new energy industry (exogenous variable);

$\Delta K_u(t)$: capital stock formation of usual industry in term t (endogenous variable);

$\Delta K_m(t)$: capital stock formation of thermal power industry in term t (endogenous variable);

$\Delta K_r(t)$: capital stock formation of hydropower industry in term t (endogenous variable);

$\Delta K_n(t)$: capital stock formation of new energy industry in term t (endogenous variable);

E_{u_d}: export of usual industry in base year (exogenous variable);

$M_u(t)$: import of usual industry in term t (endogenous variable);

b: rate between production and electricity generation (exogenous variable);

$X_e(t)$: production of electricity industry (endogenous variable);

A'_{eu}: electricity consuming factor of usual industry (exogenous variable);

A'_{em}: electricity consuming factor of thermal power industry (exogenous variable);

A'_{er}: electricity consuming factor of hydropower industry (exogenous variable);

A'_{en}: electricity consuming factor of new energy industry (exogenous variable);

$C'_e(t)$: electricity consumption by households (endogenous variable);

E'_{e_d}: export of electricity in base year (exogenous variable);

$M'_e(t)$: import of electricity (endogenous variable);

A_{e_u}: input coefficient to usual industry by electricity industry (exogenous variable);

A_{em}: input coefficient to thermal power industry by electricity industry (exogenous variable);

A_{er}: input coefficient to hydropower industry by electricity industry (exogenous variable);

A_{en}: input coefficient to new energy industry by electricity industry (exogenous variable);

$C_e(t)$: household consumption of electricity industry (endogenous variable);

E_{e_d}: export of electricity in value in base year (exogenous variable);

$M_e(t)$: import of electricity in value (endogenous variable);

$P_u(t)$: price rate of usual industry in term t (endogenous variable);

$P_e(t)$: price rate of electricity in term t (endogenous variable);

$Y_{hu}(t)$: household income of usual industry (endogenous variable);

δ_u: depreciate rate of usual industry (exogenous variable);

$K_u(t)$: capital stock of usual industry (endogenous variable);

ζ_u: indirect tax rate of usual industry (exogenous variable);

$Y_{hm}(t)$: household income of thermal power industry (endogenous variable);

δ_m: depreciate rate of thermal power industry (exogenous variable);

$K_m(t)$: capital stock of thermal power industry (endogenous variable);

ζ_m: indirect tax rate of thermal power industry (exogenous variable);

ζ_c: carbon tax rate (exogenous variable);

$Y_{hr}(t)$: household income of hydropower industry (endogenous variable);

δ_r: depreciate rate of hydropower industry (exogenous variable);

$K_r(t)$: capital stock of hydropower industry (endogenous variable);

ζ_r: indirect tax rate of hydropower industry (exogenous variable);

σ_n: subsidy rate of new energy industry in term t (endogenous variable);

$Y_{hn}(t)$: household income of new energy industry (endogenous variable);

δ_n: depreciate rate of new energy industry (exogenous variable);

$K_n(t)$: capital stock of new energy industry (endogenous variable);

GHG(t): GHG emission in term t (endogenous variable);

ef_u: GHG emission factor of usual industry (exogenous variable);

ef_m: GHG emission factor of thermal power industry (exogenous variable);

ef_n: GHG emission factor of new energy industry (exogenous variable);

ef_c: GHG emission factor of household consumption (exogenous variable);

ef_w: GHG emission factor of crop straw in the open-burning process (exogenous variable);

W(t): quantity of crop straw treated by open-burning (endogenous variable);

A_{wu}: disposed coefficient of crop straw by usual industry (exogenous variable);

A_{wn}: treated coefficient of crop straw by new energy industry (exogenous variable);

$y_u(t)$: income rate of usual industry (exogenous variable);

$y_m(t)$: income rate of thermal power industry (exogenous variable);

$y_r(t)$: income rate of hydropower industry (exogenous variable);

$y_n(t)$: income rate of new energy industry (exogenous variable);

$Y_d(t)$: disposable income of households (endogenous variable);

ζ_d: direct tax rate (exogenous variable);

β: household saving rate (exogenous variable);

α_u: share of usual industry's consumption in the total household consumption (exogenous variable);

α_e: share of electricity's consumption in the total household consumption (exogenous variable);

Sh(t): household saving in term t (endogenous variable);

Sg(t): government saving in term t (endogenous variable);

φ_{min}: minimum share of net export in total saving (exogenous variable);

φ_{max}: maximum share of net export in total saving (exogenous variable);

h_u: capital input coefficient (capital input amount per unit production) in usual industry (exogenous variable);

h_m: capital input coefficient in thermal power industry (exogenous variable);

h_r: capital input coefficient in hydropower industry (exogenous variable);

h_n: capital input coefficient in new energy industry (exogenous variable);

ρ: social discount rate (exogenous variable) ;

GDP(t): China’s gross domestic production in term t (endogenous variable);

V_u: added value rate of usual industry (exogenous variable);

V_m: added value rate of thermal power industry (exogenous variable);

V_r: added value rate of hydropower industry (exogenous variable);

V_n: added value rate of new energy industry (exogenous variable);

$\overline{GHG(t)}$: restriction of GHG emission at time t (exogenous variable).

CHAPTER 1 INTRODUCTION

1.1 Background

Climate change, as one of the hottest topics for discussion on a global scale, has brought great influence on the human socio-economic development. A growing body of evidence has established on warming of the climate system, including observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Average Arctic temperatures have increased at almost twice the global average rate in the past 100 years, and some extreme weather events have changed in frequency and intensity over the last 50 years. Moreover, climate change has far-reaching environmental consequences on ecosystems, food security, coasts, water resources, and human health etc (Figure 1-1).

In regard to the causes of climate change, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse-gas concentrations” (IPCC, 2007). The language “very likely” has been upgraded from “likely”, which was used six years earlier in the Third Assessment Report, thus confirming the broad acceptance by scientists of the link between greenhouse-gas (GHG) emissions and global climate change. According to Doha Amendment to the Kyoto Protocol, which is the 18th session of the Conference of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC) opened in 2012, GHG listed in Annex A includes Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF_6), and Nitrogen trifluoride (NF_3). The lifetimes and global warming potential relative to CO_2 (GWP) are shown in Table 1-1.

The greenhouse effect of GHG is necessary to keep the temperature of the earth suitable for human beings. However, excessive emissions of GHG in recent years reinforce the greenhouse effect overly, leading to the global warming. In 2010, the total GHG emission in the world was increased to 30,276.14 million tons of CO_2 equivalent ($MtCO_2e$), in which 23.8% was emitted by China.

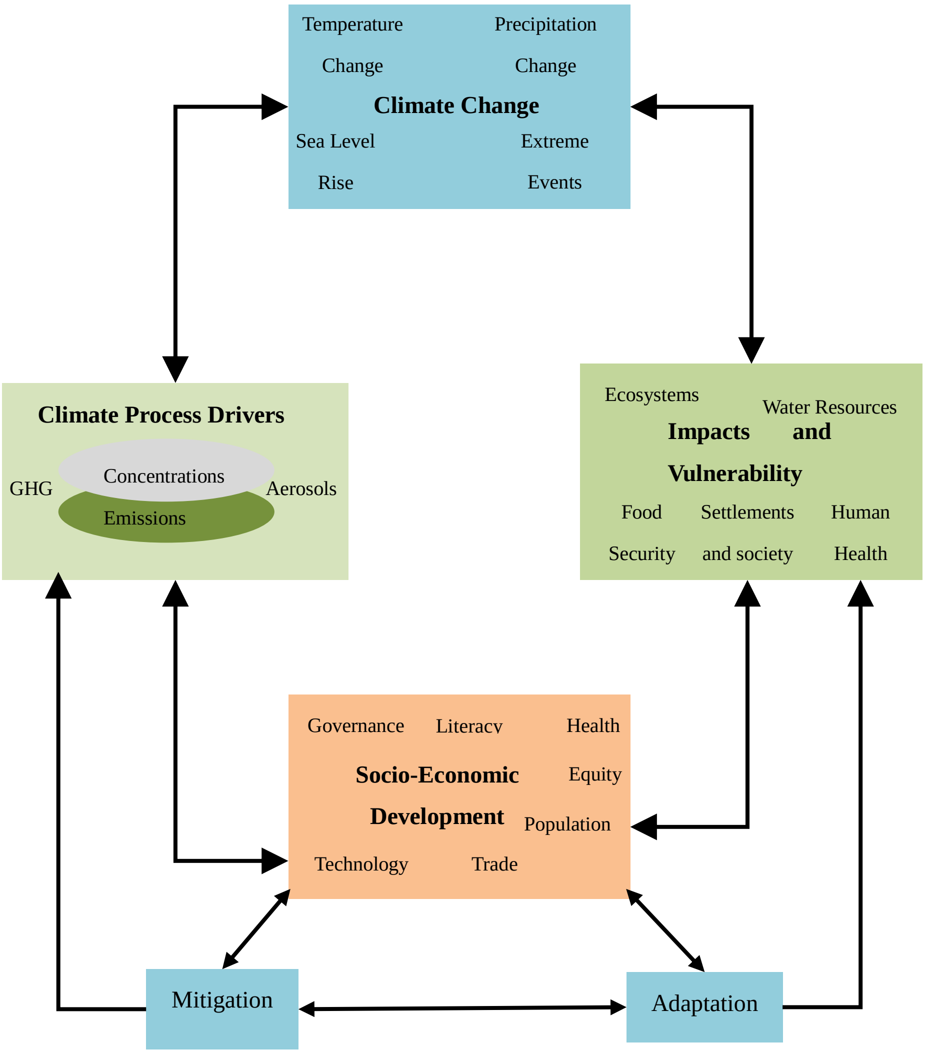


Figure 1-1 Causes and impacts analysis of climate change (IPCC, 2007)

Table 1-1 Lifetimes and GWPs of GHG (IPCC, 2007)

Common name	Chemical formula	Life time (years)	100-yr GWP
Carbon dioxide	CO_2	See the Note	1
Methane	CH_4	12	21
Nitrous oxide	N_2O	114	310
HFC-23	CHF_3	270	11,700
PFC-14	CF_4	50,000	6,500
Sulphur hexafluoride	SF_6	3,200	23,900
Nitrogen trifluoride	NF_3	740	12,300

Note: The CO_2 response function used in IPCC report is based on the revised version of the Bern Carbon Cycle Model using a background CO2 concentration value of 378 ppm.

In order to alleviate global warming, worldwide reductions in GHG emissions are needed. Recognizing that developed countries are principally responsible for the current high levels of GHG emissions in the atmosphere as a result of more than 150 years of industrial activity, UNFCCC places a heavier burden on developed nations under the principle of “common but differentiated responsibilities”. The Kyoto Protocol was adopted on 11 December 1997 and entered into force on 16 February 2005. During its first commitment period which started in 2008 and ended in 2012, 37 industrialized countries and the European Community committed to reduce GHG emissions to an average of five percent against 1990 levels. On 8 December 2012, the “Doha Amendment to the Kyoto Protocol” was adopted, which establishes the new commitments in a second commitment period from 1 January 2013 to 31 December 2020. The Kyoto Protocol offers three market-based mechanisms to help Parties meet their emission targets in cost-effective way, including International Emissions Trading, Clean Development Mechanism (CDM), and Joint implementation (JI).

As a developing country, China is currently undergoing a significant transformation. This has led to spectacular growth of the Chinese economy, with an annual growth rate of 11.2% of GDP during the period 2006-2010. Meanwhile, energy consumption rose from 2,475.62 million tons of coal equivalent (Mtce) in 2006 to 3,249.39 Mtce in 2010. The corresponding GHG emission grew from 5,602.95 $MtCO_2e$ to 7,217.06 $MtCO_2e$ during the same period (IEA, 2012). In fact, China overtook the United States to become the world's largest annual emitter of energy-related CO_2 in 2007, although in cumulative and per capita terms the United States remains the largest (IEA, 2012). Facing the mounting mitigation pressure, the Chinese government promised to reduce its GHG emissions per unit of GDP by 40 to 45 percent by 2020 compared to the 2005 level prior to the Copenhagen Climate Summit in 2009. However, there are many debates about the credibility and stringency of this climate commitment (Zhang, 2010), which focuses on whether such a commitment is truly a challenge or merely represents business as usual.

Regardless of China's climate commitment, GHG emission in China is very likely to increase continually with the rapid economic development in the future, while China is the world's largest populous country and largest coal-producer and consumer. In order to reduce the GHG emission in China, Therefore, the transformation of China's coal-dominant energy system into a low carbon one is of great influence on future global GHG emission. China's Renewable Energy Law has recognized the strategic role of renewable energies in optimizing China's energy supply mix, which was passed on 28 February, 2005 and took effect on 1 January, 2006. Besides, the government has established a serious of laws, regulations and policies to promote the renewable energy development, listed in Table 1-2. It clearly shows the efforts the Chinese government has made to shape an integrated policy framework for renewable energy development in China, including national renewable energy development targets, a feed-in tariff, a special fiscal fund, tax relief, and public R&D support as well as education and training.

Table 1-2 Laws, policies and plans related to renewable energy in China

Issued by	Issue/effective data	Document
NPC	February 2005	Renewable energy law
NDRC	November 2005	National guidance catalogue for renewable energy industry development
SCC	June 2007	China's national climate change program
NDRC	August 2007	Medium and long-term development plan for renewable energy
NDRC	March 2008	The 11th five-year plan of the development of renewable energy
MOF	October 2008	Temporary management regulations on the financial subsidy for power generation from the crop straw
NDRC	January 2006	Regulations on the administration of power generation from renewable energy
NDRC	January 2007	Provision management regulations on renewable energy surcharge balancing
NDRC	April 2007	The 11th five-year plan for the biomass power industry
NDRC	January 2006	Provisional management measures on renewable electricity tariffs and cost sharing program
SCC	June 2009	Policies to promote the development of the biomass power industry
NDRC	August 2009	Notice on improvements to the wind power feed-in pricing policy
MOF	April 2008	Circular on value-added tax (VAT) and import tariff rebate on key wind turbine components

Note: NPC-the National People's Congress of China; NDRC-National Development and Reform Commission; SCC-the State Council of China; MOF-Ministry of Finance.

However, the main technological, financial, and institutional risks associated with China’s renewable energy development still remain. Especially the high cost of renewable energy should not be neglected. At present, all the renewable energy power plants are developed with the fiscal support from the government (Fan, 2013). However, it still cannot compete with traditional energy equally in the market. Taking the solar power for example, the cost of solar power is about approximately 4 Yuan/kWh, which is over ten times higher than that of coal-fired power plants (Liu et al., 2011). Which policies and strategies should be taken to promote the development of renewable energy in China? What are the impacts of proposed policies on the socio-economic development? To which extent will renewable energies contribute to China’s sustainable energy system transition? Although some of these questions have been addressed by a number of studies in the past (Zhang et al., 2010; Kahrl et al., 2011; Wang and Chen, 2010; Liu et al., 2011), yet those studies were not able to take the context of China’s economic-energy-environmental development into account.

Against the background, our research proposes the new policies of carbon tax and subsidy to promote the renewable energy development in China, in order to transform the energy structure and coordinate the economic development, energy consumption and GHG mitigation.

1.2 Literature Review

As the world’s largest GHG emitting country, China is in urgent need of effective policies to transform the energy system and reduce its GHG emission. There are a lot of studies carried out to give some recommendations for the policy-makers. In this part, the literature review is summarized in five aspects, such as quantitative analysis of GHG emission, qualitative analysis of the renewable energy development, research on carbon tax, comprehensive modeling approaches, and input-output model.

1.2.1 Quantitative Analysis of China’s GHG Emission

Prior to analyze China’s GHG emission, we introduce two kinds of criterions in accounting GHG emission, production-based and consumption-based GHG emission. The production-based GHG emission includes the emissions from resident institutional units analogous to GDP, while the emissions embodied in exports are excluded and the emissions embodied in imports are included in the consumption-based GHG emission. The current accounting system used in Kyoto Protocol is production-based. But some authors have argued that consumption-based GHG emission inventory is “fairer” than production-based inventory (Kondo et al., 1998; Munksgarrd and Pedersen, 2001; Munksgarrd et al., 2005, 2007; Lenzen et al., 2007; Peters and Hertwich, 2008). Table 1-3 gives an overview of the key differences between the production-based and consumption-based GHG emission. Key advantages of consumption-based GHG emission include eliminating carbon leakage through imports, and consistency between consumption and environmental impacts. However, production-based GHG emission is much closer to the statistical sources and hence they have less uncertainty. Therefore, we use the production-based GHG emission in our study.

Table 1-3 Comparison of production-based and consumption-based emission

	Production-based	Consumption-based
Emissions covered	Administered territory	Global
Allocation	Domestic production	Domestic consumption
Allocation of trade	Includes exports, not imports	Includes imports, not exports
Transparency	High	Low
Uncertainty	Lower	Higher

In regards to China’s GHG emission, Zhang et al. (2009) used the complete decomposition method to find the energy intensity effect is the dominant contributor to the decline in energy-related CO_2 emission and CO_2 emission intensity during the period 1991-2006. Chen et al. (2010) built a biophysical balance model to calculate the embodiment of natural resources and GHG emissions in Chinese economy 2005. Chen and Zhang (2010) presented the total GHG emission by the Chinese economy in 2007 to reveal the emission embodiment in final consumption and international trade. Chen estimated that the total direct GHG emission amounted to 7,456.12 $MtCO_2e$ by the commonly referred IPCC global warming potentials, and China is a net exporter of embodied GHG emissions, with emissions embodied in exports of 3,060.18 $MtCO_2e$, in magnitude up to 41.04% of the total direct emission. Ji et al. (2011) investigated GHG emissions of Chinese economy in 2007 by producing sectors from production-based and consumption-based perspectives, and the results showed that electric and heat power sector contributed the most direct emission.

Besides, there are some international institutions providing the GHG emission database for countries, including China. International Energy Agency (IEA) provides the CO_2 emission from fuel combustion from 1971 to 2010 (IEA, 2012). World Resources Institute has developed the Climate Analysis Indicators Tool (CAIT) to estimate the international emissions (CAIT, 2012). The Carbon Dioxide Information Analysis Center (CDIAC) is the primary climate-change data and information analysis center of the U.S. Department of Energy, including the World’s Data Center for Atmospheric Trace Gases (CDIAC, 2012). However, all the studies above only calculate GHG emission in some historic year, does not give some insight for the future.

1.2.2 Qualitative Analysis of China’s Renewable Energy Development

Many papers have focused on the potential analysis of China’s renewable energy development, and found that China has plenty of renewable energy resources to revolutionize its energy system. But there are still many barriers in the process of renewable energy development. Wang and Chen (2010) presented a reserves assessment, the current status, and barriers for further development of renewable power generation (hydropower, wind power, solar energy, biomass energy, ocean energy and geothermal) together with nuclear power for China. Liao et al. (2010)

reported on the technical and economic potentials of wind power, the recent development, existing obstacles, and related policies in China. Kahrl et al. (2011) examined the challenges to China’s transition to a low carbon electricity system, in which renewable energy would play a significant role, and forecasted the share of non-coal generation would shift from 22% in 2009, to 35% in the lower demand case and 21% in the high demand case in 2020.

In terms of hydropower, the theoretical potential of hydropower resources in China is 694 GW, annual power output 6,080 TWh, technical exploitable capacity 542 GW, technical exploitable annual power output 2,470 TWh, economic exploitable capacity 402 GW and economic exploitable annual power output 1,750 TWh (Li and Shi, 2006). However, the development of hydropower remains controversial in the issues of environment (Stone, 2008), security (Pan, 2004), and social impact (Tan and Yao, 2006).

As to wind power, there is a huge wind power potential in China, around 700-1,200 GW (Li et al., 2007). The main barrier in the development of wind power is technical bottle neck for integration, because wind power impacts frequency control of power grid, voltage regulation, power supply quality, fault level and stability of power grid (Wang and Chen, 2004).

In regard to solar power, China is abundant in the solar resource. More than two-third of China receive an annual radiation of more than 5,000 MJ/m^2 and more than 2,000 h of sunshine (CWERA, 2009). However, the cost of solar power is the most and obvious barrier. In 2007, the average on-grid electricity price of solar power plants is 4 Yuan/kWh (Liu et al., 2011), compared to the average on-grid electricity price of wind power 0.617 Yuan/kWh, nuclear power 0.436 Yuan/kWh, and coal-fired plant 0.346 Yuan/kWh (CEC, 2008). It is difficult to enable solar power generation to advance on a large scale before the technological advancement substantially reduces the cost of solar power generation.

Last is biomass power. The total exploitable biomass energy in China is around 7×10^8 ton of standard coal equivalent (tce), about 3.5×10^8 tce of crop straw accounting for more than 50%. The employment of biomass energy in China includes biological chemical transformations (marsh gas and fuel alcohol), biomass gasification (power generation or thermal power co-production), biomass liquefaction (bio-diesel) and direct burning (boiler burning, dense burning and garbage burning). In this paper, we only consider biomass power, and the biomass waste is referred to crop straw. The main barrier in the development of biomass power is the material. In the rural areas, the price of crop straw has increased from 200 Yuan/ton in 2007 to 310 Yuan/ton in 2008. Moreover, the quality of crop straw has decreased as farmer added water and even sand into the crop straw to increase its weight so as to make more money (Liu and Jiang, 2009).

Although the papers above have analyzed the potential and barriers in China's renewable energy development thoroughly, few studies provide feasible policy proposals to overcome the obstacles. In our study, we propose the policies of carbon tax and subsidy to promote the renewable energy development.

1.2.3 Research on Carbon Tax

In order to reduce GHG emissions, a lot of policy methods have been implemented which include emission trading systems, emission standards, carbon tax and energy tax (Liu and Wang, 2009). Among these mitigation measures, carbon tax is a cost-effective instrument in achieving a given abatement target and highly recommended by economists and international organizations (EEA, 1996).

Carbon tax is levied on fossil fuels and related products such as coal, jet fuel and natural gas depending on their carbon contents in order to reduce the fossil fuel consumption and carbon emissions. The effects of carbon tax are two sided. On the one hand, it can promote the substitution of fuel products and therefore changes the structures of energy production and consumption, encourage energy saving as well as investment in energy efficiency improvement (Baranizini et al., 2000; Wang and Yan, 2009). On the other hand, it influences investment and consumption behaviors through the recycling of the collected carbon tax revenue. For example, it can promote the development of renewable energy by subsidizing the environmental protection projects or the technological development of energy saving and emission reduction while reinforcing the previous effects (Baranizini et al., 2000).

However, carbon tax inevitably has its own defects. Firstly, in the short run, carbon tax may raise the prices of related products, increase the costs of enterprises, weaken the competitiveness of energy intensive industries and impose negative impacts on economic growth (Liang et al., 2007a). Secondly, the mitigation impacts of carbon tax are uncertain. The enterprises may shift increased cost to consumers via higher prices, thus, carbon tax will only lead to the increase of fiscal revenue rather than emission reduction. Higher price elasticity implies more difficulty in shifting carbon tax costs to consumers and therefore gaining better mitigation impacts; otherwise, carbon tax costs will be shifted and the mitigation effectiveness will be lowered. Finally, the recycling framework of carbon tax revenue will influence the public acceptability of carbon tax. Carbon tax revenue can be recycled to lower the income tax or indirect tax, or be returned as subsidies to the technological advancement. If the carbon tax revenue is not recycled, it will impose a higher cost to the enterprises than other mitigation measures, which may decrease the public acceptability.

Currently, only a few countries have implemented carbon tax due to its negative impacts on competitiveness of domestic industries, including Finland, Netherlands, Norway, Sweden, and Denmark as well as followers like Italy, New Zealand, Switzerland, Canada and Colorado in America. Table 1-4 gives the information of main countries levying carbon tax. Research on the impacts and problems of carbon tax implementation in these countries will provide great practical significance as well as caution for countries that are to levy carbon tax, such as China (NDRC, 2010). Lin and Li (2011) estimated the mitigation effects of five north European countries and it indicates that the externality of environment requires a flat tax rate for different sectors which is also the reason why Finland’s carbon tax works better than other countries although it imposed generally lower nominal tax rates. And he also pointed that the mitigation effects of carbon tax were weakened due to the tax exemption policies on certain energy intensive industries in these countries.

Table 1-4 Situations of main countries levying carbon tax (CR, 2011)

Country	Starting year	Annual carbon tax revenue (billion dollars)	Recycling of the revenue
Finland	1990	0.75	Reducing the income tax
Netherlands	1990	4.82	Reducing other taxes, and supporting climate change project
Norway	1991	0.90	Used as government’s budget
Sweden	1991	3.67	Used as government’s budget
Denmark	1992	0.91	Used as environmental subsidy
Canada	2007	0.19	Supporting climate change project

Carbon tax has sparked a lively controversy in China. Lu (2009) argues that it is still too early for China to impose carbon tax because introduction of carbon tax will bring huge impacts on energy sector and the whole economy. Chen and Zhang (2009) argue that carbon tax should be designed to meet specific needs of China, and many concerns need to be addressed before the tax is introduced. The concerns include how to balance the short-run benefits of energy sector and long-run sustainable development, how carbon tax affects economic growth, whether carbon tax will enlarge the income gap, whether the tax will weaken China’s competitive ability, and whether the tax can harmonize with current policies. Liang et al. (2007a) suggests to protect China’s energy- and trade-intensive sectors from the negative impacts of carbon tax through properly relieving or subsidizing production sectors. Using a computable general equilibrium (CGE) model, they simulate the impacts of carbon taxation policy on Chinese economy, especially on energy and trade-intensive sectors. They show that the quasi-Denmark pattern scheme could be a relatively idea tool to alleviate the negative impact of carbon tax on the macro economy of China.

In addition to Liang’s study, there have been some studies exploring the impacts of different carbon taxation schemes on Chinese economy. With the general equilibrium model, Wei and Glomsrod (2002) computed the energy consumption in production sectors and residential sector, covering 19 commercial energy products, including coal, oil, and natural gas. They conclude that carbon tax will slow down economic growth and largely reduce carbon emissions. Lu et al. (2010) explores the impact of carbon tax on Chinese economy, as well as the cushion effects of the complementary policies, including reducing indirect tax and giving price subsidy to households, by constructing a dynamic recursive general equilibrium model. The simulation results show that carbon tax is an effective policy tool because it can reduce carbon emissions with a little negative impact on economic growth; reducing indirect tax in the meantime of imposing carbon tax will help to reduce the negative impact of the tax on production and competitiveness; in addition, giving households subsidy in the meantime will help stimulate household consumptions. Yang et al. (2011) analyzed the impacts of carbon tax on Chinese macroeconomics by establishing a multi-objective optimal carbon tax model. Under the first set of constraints, the optimal fixed carbon tax should be 8.84 Yuan/t CO_2, and the environmental benefits from CO_2 emission reductions should be 3.92%, going with economic costs from 0.99% decline of gross output and 2.96% rise of CPI. Under the second set of constraints, the optimal fixed carbon tax is identified as 17.99 Yuan/t CO_2. Liang and Wei (2012) compares the impacts of different carbon tax schemes on household disposable income, household welfare, economic growth, and CO_2 emissions with a recursive dynamic CGE model. Results show that, given the current social security system that obviously favors urban households and the current investment-driven economic growth pattern, without complementary measures for protecting households, a carbon tax will not only widen the urban–rural gap, but also reduce the living standards of both urban and rural households.

In sum, the design of China’s carbon tax scheme is still in discussion, and the impacts of carbon tax on the Chinese socio-economic development are not clear.

1.2.4 Research on Comprehensive Modeling Approaches

There are two wide-spread modeling approaches for the quantitative assessment of economic impacts induced by energy policies: bottom-up models of the energy system and top-down models of the broader economy. The bottom-up models emphasis the technological details of the energy system, while the top-down models lay stress on the comprehensiveness of endogenous market adjustments.

Bottom-up energy system models are partial equilibrium representations of the energy sector, including Long-range Energy Alternatives Planning System (LEAP), MARKet ALocation (MARKAL), and AIM model. They feature a large number of discrete energy technologies to capture substitution of energy carriers on the primary and final energy level, process substitution, or efficiency improvements. Such models often neglect the macroeconomic impact of energy policies. Bottom-up energy system models are often used in the optimization problems which compute the least-cost combination of energy system activities to meet a given demand for final energy or energy services subject to technical restrictions and energy policy constraints.

In regard to the application of bottom-up models, Cai et al. (2007) adopted LEAP model to predict GHG emission by China's electricity sector from 2000 to 2030. Mckinsey (2009) analyzed China's GHG emissions across ten industries based on technology abatement potential and cost by 2030. IEA (2009) developed a large-scale bottom-up mathematical model with six supply and demand modules for 24 regions, including China individually. China Energy Group of Lawrence Berkeley National Laboratory (Zhou et al., 2011a) used LEAP which is a technology and end-use based accounting model to assess the role of energy efficiency, structural change in industry, and new supply options for transitioning China's economy to a low CO_2 emissions trajectory by 2050. There are five end-use sectors and ten supply-side and transformation subsectors in the LEAP model. The findings from this research suggest that the common belief that "China's CO_2 emissions will continue to grow throughout this century and will dominate global emissions" will not necessarily be the case because saturation in ownership of appliances, construction of residential and commercial floor area, roadways, railways, fertilizer use, and urbanization will peak around 2030 with slowing population growth.

Top-down models adopt an economy-wide perspective taking into account initial market distortions, pecuniary spillovers, and income effects for various economic agents such as households or government. Endogenous in economic responses to policy shocks typically comes at the expense of specific sectoral or technological details. Input-output model, macroeconomic approach, and CGE model belong to the top-down models. Conventional top-down models of energy-economy interactions have a limited representation of the energy system. Energy transformation processes are characterized by smooth production functions which capture local substitution possibilities through constant elasticity of substitution. As a consequence, top-down models usually lack detail on current and future technological options which may be relevant for an appropriate assessment of energy policy proposals. In addition, top-down models may not assure fundamental physical restrictions such as the conservation of energy.

As to the application of top-down models, World Bank (1996) developed China GHG model, including macroeconomic model and Input-output model to analyze the impacts of different exogenous GDP growth rate on the GHG emission by 2020. Zhang (1996) used a dynamic time-recursive CGE model to evaluate the macroeconomic effects on China’s GHG mitigation. Li (2003) constructed an integrated econometric model consisting of macroeconomic sub-model, energy sub-model, and environment sub-model to perform a long-term simulation study for China towards 2030. The results showed that more comprehensive measures should be adopted to promote the sustainable development, including improvements in energy efficiency, more rapid energy switching from coal to natural gas and renewable energy resources, imposing carbon tax, development of clean coal technology, establishment of strategic petroleum stockpiling, enforcement of air protection, etc. Li (2005) built an Input-ouput model to evaluate the comprehensive effects of carbon tax on CO_2 emission curtailment from the viewpoint of advancement of alternative energy, and derived the optimal carbon tax rate required to attain the mitigation target as 85.25 Yuan/t CO_2.

In addition, the hybrid models using bottom-up and top-down approaches together are widely adopted in the recent studies. China's Energy Research Institute (CERI, 2009) developed integrated policy assessment model of China (IPAC) which is composed of multi approaches including top-down models such as CGE, and bottom-up models such as AIM technology assessment model, to forecast the energy consumption and GHG emission outlook to 2050 in China. Dai et al. (2011) used a hybrid static AIM/CGE model in which the electricity sector is disaggregated into 12 generation technologies, to analyze the effects and impacts of policies that could help to achieve China's Copenhagen commitments.

In sum, there are many kinds of economic modeling approaches available to evaluate the impacts of environmental policies on the Chinese socio-economic development. Due to the limitations of CGE model, such as the lack of empirical validation (Borges, 1986), we finally choose Input-output model together with macroeconomic approach as our evaluating tool. This choice has been motivated by the wide recognition of Input-output model as an appropriate tool for such a purpose. In the following part, we will illustrate the input-output model specifically.

1.2.5 Research on Input-output Model

Input-output model, developed by Wassily Leontief (1936), has been recognized as a useful top-down approach for policy analysis and resources accounting (Wiedmann et al., 2007a, 2007b; Wiedmann, 2009). It provides a consistent framework of analysis and can capture the contribution of related activities through inter-industry linkages in the economy. Thus input-output model is a popular tool for policy evaluation in many nations (Wei, 2006; Oloveira and Antunes, 2004). For Australia, Lenzen (1998) described the direct and indirect primary energy and GHG embodied in the final consumption. For Japan, Higano and Uchida (2000) constructed an extended input-output table including virtual industries and developed a comprehensive methodology in three view points of value balance, energy balance and material balance to evaluate the impacts of policies such as taxes and subsidies. For India, Tiwari (2000) used an input-output framework to calculate energy intensities for different sectors in the economy. For Portugal, Oliveira and Antunes (2004) built an economy-energy-environment multiple objective model based on the input-output analysis. For Korea, Chung et al. (2009) developed an energy input-output approach to estimate the energy and GHG emission intensity caused by energy consumption. For Greece, Hristu-Varsakelis et al. (2010) explored the reallocation of production and posed a constrained optimization problem, in order to meet overall demand constraints and GHG emissions targets.

As to China, there are two main directions of input-output model application. The first direction of input-output model application is decomposition analysis. Wei (2006) used an input-output model to assess how socio and economic changes will affect energy requirements, and found that technological advancement had the strongest impact on energy intensity. Liang et al. (2007b) established a multi-regional input-output model for energy requirements and CO_2 emissions in China, and recommended that continuing efforts should be taken to advance improvements of energy end-use efficiency in each region. Liu et al. (2010) evaluated the energy embodied in goods produced in China during 1992-2005 and used input-output structural decomposition analysis to identify five key factors causing the changes of energy embodied in exports. The second direction is the accounting of GHG emission and energy resources. Chen and Zhang (2010) estimated the total direct GHG emission by the Chinese economy in 2007 with an input-output analysis. Liang et al. (2010) proposed a hybrid physical input-output model to calculate energy resources in both energetic and mass units in Suzhou, China. Zhu et al. (2012) built an input-output model to calculate the indirect carbon emissions from residential consumption. However, there is no study focused on the interrelationship among energy, economy, and environment in China using input-output model until now.

In sum, we compare the achievements and limitations of all the previous studies in Table 1-5.

Table 1-5 Literature Review

	Authors	Year	Achievements	Limitations
Quantitative analysis of China’s GHG emission	Chen	2010	Calculated GHG emission in Chinese economy 2007	Only status analysis of GHG emission, lack of mitigation policy proposals.
	IEA	2012	Provided the GHG database for countries, including China	
Qualitative analysis of China’s renewable energy development	Wang	2010	Presented a reserves assessment and barriers of renewable energy development in China	Despite of abundant barrier analysis in the renewable energy development, they did not propose some policies to overcome the obstacles.
	Kahrl	2011	Examined the challenges to China’s transition to a low carbon electricity system	
	Liu	2011	Predicted the potential of renewable energy in China	
Research on carbon tax	Liang	2007	Analyzed the impacts of carbon tax policy on energy and trade-intensive sectors.	Did not incorporate the renewable energy development into the carbon tax scheme design.
	Lu	2010	Explored the impacts of carbon tax scheme in which carbon tax is used to reduce the indirect tax.	
Research on Input-output model	Wei	2006	Assessed how economic changes would affect energy requirements	Lack of comprehensive policy evaluation in macroeconomic view.
	Liu	2010	Identified five key factors causing the changes of energy embodied in exports	
	Zhu	2012	Used for indirect GHG emission calculation	

Based on the analysis of previous studies, the innovations of our research are drawn as follows: 1) offering a dynamic integrated approach to estimate the impacts brought by policies and technologies introduction; 2) developing a comprehensive model for the comprehensive policy evaluation in the view of energy, economy, and GHG mitigation together; 3) designing a carbon tax scheme with attempts to promote the renewable energy development and transform the coal-dominant energy system.

1.3 Objectives of This Study

Based on the analysis above, it is urgent to transform the coal-dominant electricity system in China, and few studies have focused on Chinese mitigation policy evaluation in the view of energy-economy-environment till now. Therefore, in this study we construct a comprehensive model to evaluate the impacts of carbon tax for sustainable development in China. The carbon tax is levied on the largest GHG emission source - thermal power industry, and the revenue will be used as subsidy to give incentives to develop the renewable energy industry. The simulation is finished in LINGO, which is an optimization modeling software for linear, nonlinear, and integer programming developed by LINDO Systems.

The purposes of this study are three-fold:

(1) to grasp the main problems in China’s GHG mitigation based on familiar with the current situation of GHG emission and energy system;

(2) to construct an integrated model to evaluate the impacts of proposed policies. In the original model, the industries are further subdivided into 21 sectors, and we simulate the development of every sector considering the commodity flow balance, value flow balance, energy balance, and macroeconomic balance;

(3) to assess the comprehensive impacts of proposed policies which emphasizes on energy infrastructure transformation by promoting renewable energy development with carbon tax, and provide some specific recommendations to the policymakers.

A robust and credible model will play a key role in informing policymakers by assessing policy impacts on the socio-economic development. This is especially true for developing countries such as China, where uncertainties are greater while the economy continues to undergo rapid growth and industrialization. Therefore, it is very necessary to construct a comprehensive model considering the interrelationship among economy, energy and environment in China. However, the previous studies just calculated the GHG emission and energy consumption in China, cutting the relationship in economy, energy and environment (Wei, 2006; Liang et al., 2007b; Liu et al., 2010; Chen and Zhang, 2010; Zhu et al., 2012). In our study, the interaction between environmental and socioeconomic activities can be analyzed by simulating the precise socio-economic trends, energy supply and demand balance, GHG emission, and renewable energy technologies during the modeling period (2007- 2020).

Another contribution of this study is about the design of carbon tax scheme which is still in controversy in China. Because of the considerable negative impacts of carbon tax on the economic growth, it is necessary to evaluate the impacts of carbon tax on the socio-economic development as well as the GHG mitigation. Therefore, we construct an integrated model to assess the impacts of carbon tax on the socioeconomic development in China. This study also offers a useful method for mitigation policy evaluation in China as well as the other countries facing the similar issues.

1.4 Outline of the Dissertation

This study is a systematic attempt to deal with the economic implications of GHG mitigation for Chinese economy in the light of a comprehensive model.

The dissertation consists of five chapters. Chapter 1 first introduces the background of this study and raises the question of how to coordinate the economic development with GHG mitigation in China. And then the work of literature review is carried out in five aspects, and we find the innovations of our research by comparing the achievements and limitations of previous studies. At last, we introduce our research purposes.

Chapter 2 deals with the current situation of energy system and GHG emission in

China. By examining the challenges of China’s GHG mitigation and characteristics of China’s energy system, we restate the necessity of promoting the renewable energy development, and propose to introduce carbon tax policy to transform the coal-dominant energy system.

For macroeconomic analysis of GHG mitigation in China, a comprehensive model of the Chinese economy has been designed and is described in Chapter 3. The comprehensive model operates by simulating the activities of industries, household, government, with equations specifying supply and demand behaviors across all the markets. The model includes 21 sectors, aggregated into four industries. The model is made up of the following blocks: objective function, production function, commodity flow balance, value flow balance, energy balance, household income and expenditure, government income and expenditure, investment and saving balance, foreign trade, and GHG emission. Moreover, we set up three cases to analyze the impacts of the proposed policy.

Chapter 4 is devoted to analyze the simulation results to evaluate the comprehensive effects of the environment policy on the economy, energy, and environment. The simulation results give specific information on the economic growth, GHG emission, GHG intensity, and energy consumption in each case. By comparing the simulation results among cases, we can identify the optimal carbon tax for China.

Finally, Chapter 5 summarizes the conclusions of this study and points out some areas where there is a need for further methodological and empirical work to enrich the policy recommendations of this study.

CHAPTER 2 CURRENT SITUATION OF ENERGY SYSTEM AND GHG EMISSIONS IN CHINA

2.1 Introduction

As a result of soaring energy demand from a staggering pace of economic growth and the related growth of energy-intensive industry, China overtook the United States to become the world's largest contributor to GHG emissions in 2007. At the same time, China has taken serious actions to reduce its energy and GHG intensity by setting both short-term energy intensity reduction goal for 2006 to 2015 as well as long-term GHG intensity reduction goal for 2020. However, China still emitted 7,217.06 Mt CO_2e in 2010, amounting for 23.8% of global CO_2 emissions. In order to reduce the GHG emission effectively, it is necessary to analyze the current situation of energy system and GHG emission in China. This chapter is devoted to serving such a purpose by examining some aspects of the Chinese energy system. At the same time, it sheds light on the implications for China's future GHG emissions.

The structure of this chapter is as follows. Section 2.2 analyzes China's energy system, emphasizing on the development of energy resources and the electricity system. In section 2.3, China's historic GHG emissions are characterized, and the future emissions are presented. This chapter ends with some concluding remarks.

2.2 China's Energy System

We will introduce China's energy system from two aspects, the development of energy resources and the electricity system. First of all, an overview of China's energy supply, energy consumption and economic growth in the past 30 years will be presented. As indicated in Figure 2-1, China's energy demand has been stimulated tremendously by the rapid development of economy and society. And renewable energy has been developed steadily and has begun to play a role in the energy structure. However, China's energy supply and consumption structure which is dominated by fossil fuel, especially coal, has basically remained.

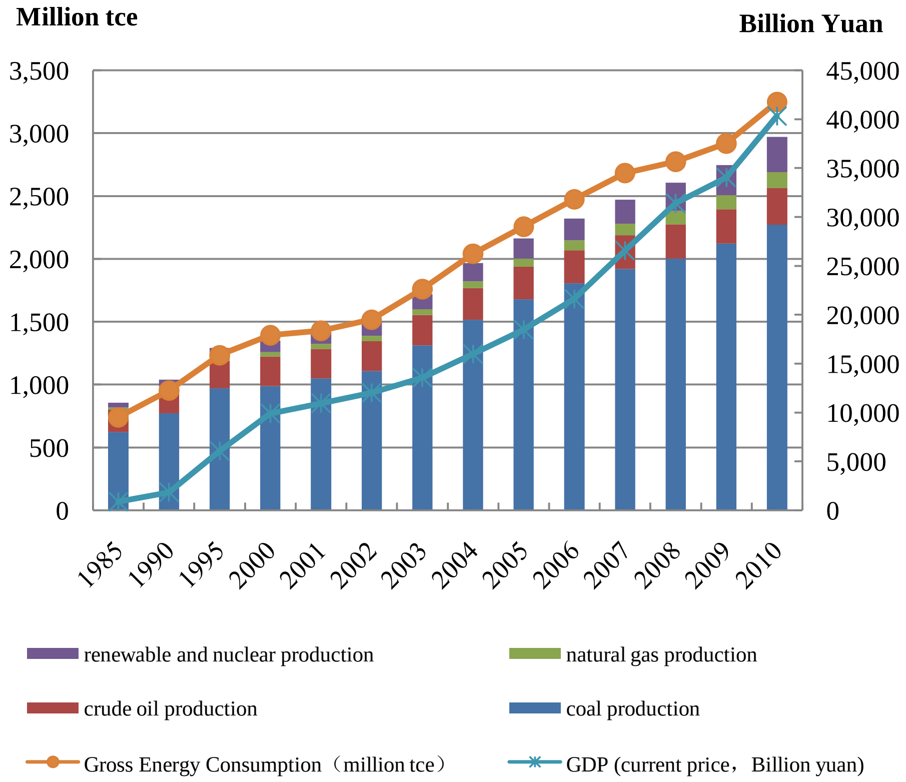


Figure 2-1 China's primary energy consumption and economic development

2.2.1 Energy Resources and Their Development

In this section, we will discuss the resources and their development of coal, oil, natural gas, nuclear power, and renewable energy in China.

(1) Coal

China is abundant in coal resources. As indicated in Figure 2-2, raw coal is mainly supplied by domestic production in China. 27 out of 31 provinces (including autonomous regions and municipalities) in mainland China produce raw coal. Only Tianjin, Shanghai, Guangdong, Hainan, and Tibet did not produce coal in 2007. The total production of coal nationwide was 2,691.61 million ton in 2007 (NBS, 2008a), and China exported 53.18 million ton of coal, 2% of production that year. Net coal exports have declined continuously as domestic demand has risen.

Raw coal is mainly consumed in three ways, such as used for final consumption, used for transformation including for power generation, for heating, for coking, for gas production, and loss in the consuming process. As indicated in Figure 2-3, coal consumption is increasing year by year and nearly half is used for power generation. In 2007, about 1,305.49 million ton raw coal was used for power generation, accounting for 48% of the total coal consumption.

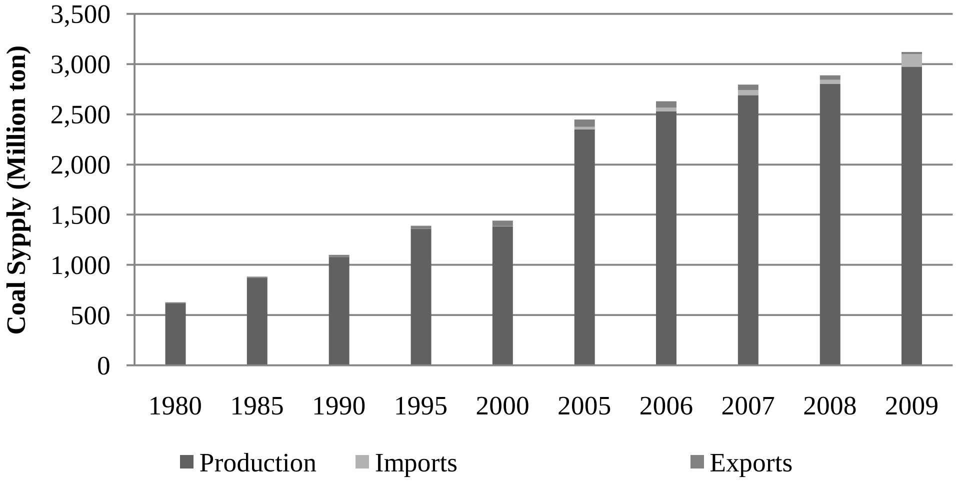


Figure 2-2 Production, imports and exports of coal in China

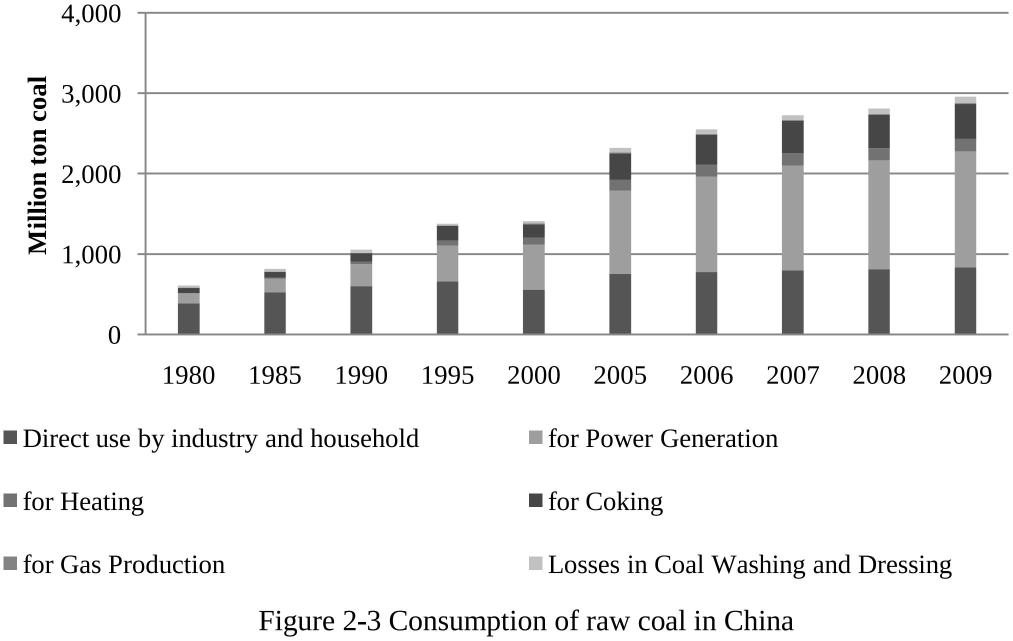


Figure 2-3 Consumption of raw coal in China

(2) Oil

Import plays a very important role in China’s crude oil supply. The total supply of crude oil was 340.03 million ton in 2007, while the domestic production was only 186.32 million ton (NBS, 2008a). As indicated in Figure 2-4, the dependency on imported oil was over 50% in 2007. Besides, about 93% of China’s domestic crude oil is produced by 15 oil fields or enterprises, a share that has not changed since 2000, which leads to the stable domestic production around 185 million ton from 2005 to 2009.

As to the consumption of crude oil, it is also divided into three ways, such as used for final consumption, used for transformation including for power generation, for heating, for petroleum refineries, and loss in oil field. As indicated in Figure 2-5, almost all the crude oil is used for petroleum refineries in China.

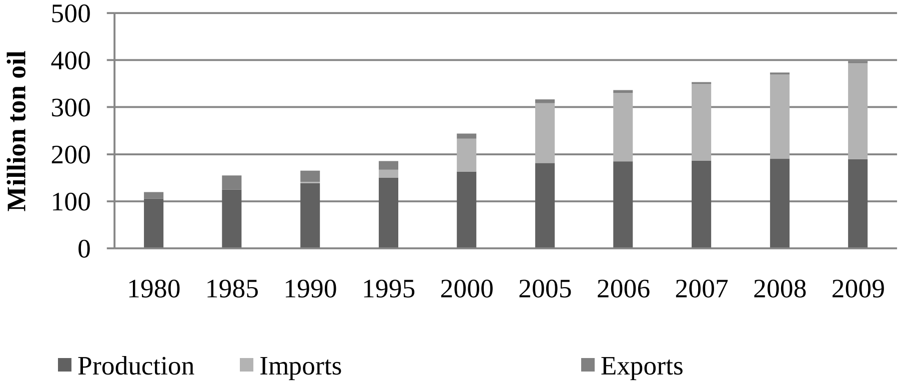


Figure 2-4 Production, imports and exports of oil in China

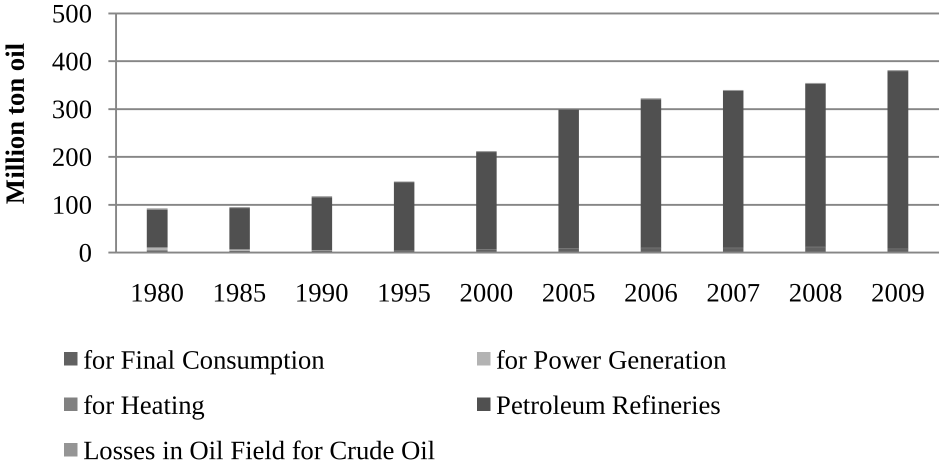


Figure 2-5 Consumption of crude oil in China

(3) Natural gas

Natural gas supply is depended on domestic production in China. The total supply of natural gas was 70.7 billion cubic meters in 2007, only 1% provided by imported (Figure 2-6). About 85% of natural gas is produced by 9 enterprises. Most gas fields are located in the western region of China. Gas is transported by long distance pipelines from west to east. At the end of 2008, China had 32,000 km of natural gas pipelines.

The consuming patterns of natural gas in China are composed of three main ways, such as used for final consumption, used for transformation including for power generation, for heating, for gas production, and loss in the consuming process. As indicated in Figure 2-7, most of the natural gas is directly used by industries and households. The consumption of natural gas was 69.52 billion cubic meters in 2007, 83% for final consumption and 10% for power generation.

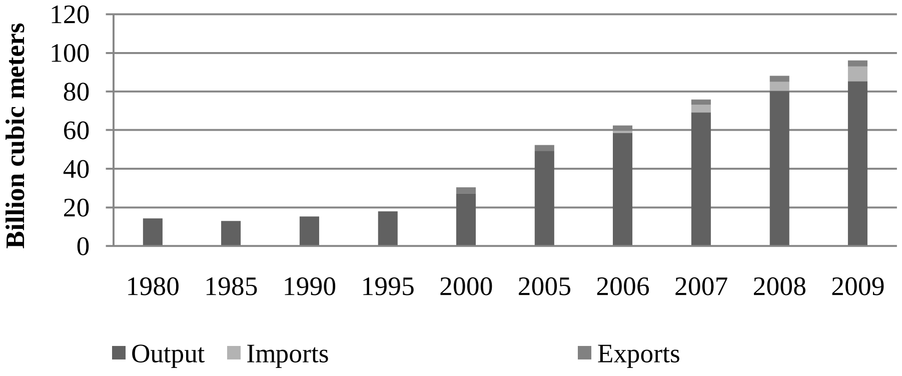


Figure 2-6 Production, imports and exports of natural gas in China

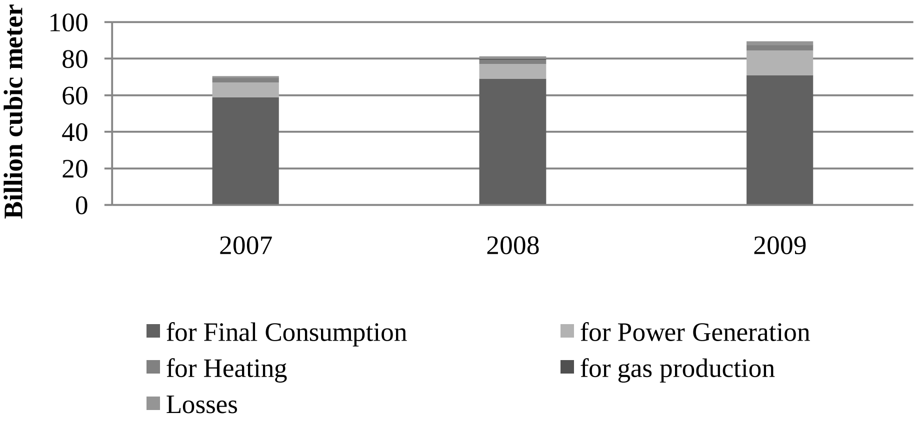


Figure 2-7 Consumption of natural gas in China

(4) Nuclear power

China's nuclear energy program has a relatively short history. In 1984, China National Nuclear Corporation began to construct its first indigenously designed and constructed nuclear power plant at Qinshan in Zhejiang Province, Southeast China. At the end of 2007, China has completed 11units in the coastal areas with their rapidly growing economy, with the total installed capacity of 8.6 GW (Table 2-1).

Meantime, the Chinese government approved an outline for the mid- and long-term development of nuclear power generation (2005-2020). It specified that by the end of 2020, 40 GW of nuclear power generations should be commissioned. However, Chinese ambitious nuclear power development will face the bottleneck of natural uranium fuel supply (Wang and Chen, 2010). Moreover, nuclear power is not suitable to be the main source of future power requirements because of safety limitations. The Chernobyl and Fukushima nuclear crises have made governments even more cautions about developing nuclear power. To be conservative, the nuclear power is not considered in our research.

Table 2-1 Operating nuclear power reactors at the end of 2007 (NDRC, 2007a)

Units	Province	Net capacity (each)	Operation year
Daya Bay-1 and 2	Guangdong	944 MW	1994
Qinshan-1	Zhejiang	279 MW	1994
Qinshan-2 and 3	Zhejiang	610 MW	2002, 2004
Lingao-1 and 2	Guangdong	935 MW	2002, 2003
Qianshan-4 and 5	Zhejiang	665 MW	2002, 2003
Tianwan-1 and 2	Jiangsu	1000 MW	2007
Total		8,587 MW	

(5) Hydropower

China has many substantial rivers, more than 5,000 of which cover a basin area of over 100 km^2, and 3,886 of which have a hydropower potential of over 10 MW. At the end of 2007, the total installed capacity of hydropower was 145.26 GW. Hydropower resources are widely distributed and mainly concentrated in the central and western regions. The exploitable hydropower resources in the Yangtze, Lancang, and Yellow Rivers as well as in their branches account for 60% of the country’s total. As indicated in Figure 2-8, China has planned to construct 13 hydropower bases according to the medium and long-term development for renewable energy. They are Jinshajiang River, Yalongjiang River, Daduhe River, Wujiang River, the Yangtze River Up Reaches, Qingjiang River, Nanpanjiang River and Hongshuihe River, Lancangjiang River, the Yellow River Up Reaches, the Yellow River Main, West Hunan, Fujian and Zhejiang and Jiangxi, the Northeast and Nujiang River. If the hydropower resources in these bases are completely developed, the installed capacity will amount to 275.77 GW (NDRC, 2007b).

Notes:
1. Northeast; 2. Yellow River Main (North); 3. Yellow River Up Reaches; 4. Yalongjiang River;5. Daduhe River;6. Yangtze Up Reaches; 7. Jinshanjiang River; 8. Nujiang River; 9. Wujiang River;10. West Hunan; 11. Fujian, Zhejiang, Jiangxi; 12.Lancangjiang River Main;13. Nanpanjiang River, Hongshuihe River

Figure 2-8 Locations of 13 hydropower bases in China (NDRC, 2007b)

Small hydropower in China refers to the hydropower generation with installed capacity of less than 50 MW (including 50 MW). At present, small hydropower plants are widely accepted as outlets of an environment-friendly energy resource in China. Giant hydropower plants, on the other hand, cause some indirect negative impact to the environment. For example, land submergence caused by building a large-scale reservoir can lead to changes in hydro-geological conditions and cause damage to wildlife environment. Due to the controversy of giant hydropower plants, we assume that China will not build large hydropower facilities by 2020 in this model.

(6) Wind power

China is a country with vast coastal and inland windy areas and there is a rich resource of wind energy with great development potential. According to the last national investigation, the technically exploitable land area is approximately 200,000 km^2. As indicated in Figure 2-9, the southeast coast and cast western regions, including Xinjiang, Inner Mongolia, Gansu Corridor and some areas of the Qinghai-Tibet Plateau, comprises the main wind-rich areas.

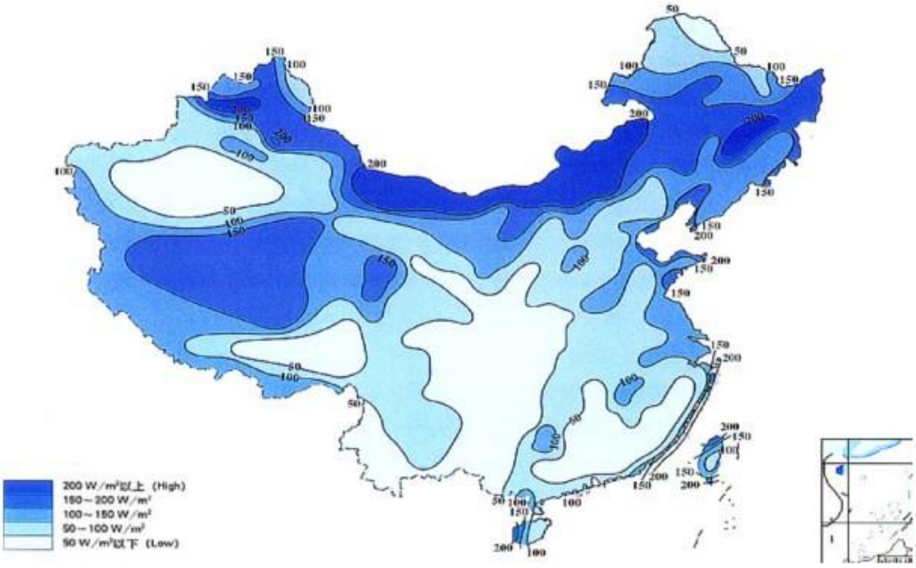


Figure 2-9 Distribution of effective wind power density in 2008 (CWERA, 2009)

According to the medium- and long-term renewable energy development plan, the target of wind power capacity is 5 GW for 2010, and 30 GW for 2020. However, the installed capacity of grid-connected wind power reached 6 GW in 2007, and as such had already exceeded the target for 2010. Moreover, China is planning to construct seven wind farm bases in six provinces, including Xinjiang, Gansu, Jiangsu, Inner Mongolia, Hebei, and Jilin (Xinhua, 2010). Despite of the rapid development, China’s wind power still faces the barrier of technical bottle neck for integration, because at present wind power impacts frequency control of power grid, voltage regulation, power supply quality, fault level and stability of power grid (Wang and Chen, 2004).

(7) Solar power

Solar energy resources are very abundant in China because more than two-thirds of the country receives an annual radiation of more than 5,000 MJ/m^2 and more than 2,000 h of sunshine (CWERA, 2009). As indicated in Figure 2-10, the areas with great solar energy include Tibet, Qinghai, Xinjiang, southern Inner Mongolia, Shanxi, northern Shannxi, Hebei, Shandong, Liaoning, western Jilin, Yunnan, Guangdong, Fujian, Hainan, and southwest Taiwan. In particularly, the Qinghai-Tibet Plateau receives the most radiation.

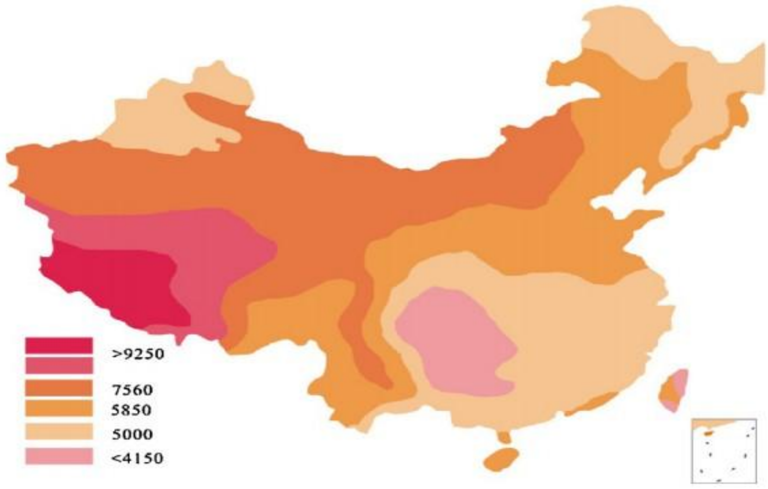


Figure 2-10 **S**tatistics of solar energy density in China (MJ/m^2 per year) (CWERA, 2009)

In China, solar photovoltaic (SPV) technologies are more mature than solar thermal power generation technologies. And solar thermal power generation technologies are still under research and have few applications in China. So the solar power discussed in this paper mainly refers to SPV power generation. At the end of 2007, the cumulative installed capacity of solar power was about 105 MW, with a new capacity 25 MW. According to medium- and long-term renewable energy plan, the target of solar power capacity is 0.3 GW for 2010, and 1.8 GW for 2020. However, this target is too conservative. And an updated plan is in discussion that the new target for solar power in 2020 would be 20 GW (Wang et al., 2011).

The biggest barrier in China’s solar power development is high cost. In 2007, the average on-grid electricity price of solar power plants is 4 Yuan/kWh (Liu et al., 2011), compared to the average on-grid electricity price of coal-fired power generation 0.346 Yuan/kWh (CEC, 2008). It is difficult to enable solar power generation to advance on a large scale before the technological advancement substantially reduces the cost of solar power generation.

(8) Biomass power

As the largest agriculture country, China has various kinds of biomass resources, namely crop straw, forestry waste, municipal solid waste, and organic wastewater which associated with the industrial production, agricultural activities and human daily lives. Limited by the data available, the biomass energy hereby is referred to crop straw. Crop straw is the residues after agriculture crop harvest, which is the main byproduct of agriculture production. In 2007, the total output of crops including food crops, oil crops, cottons, bastfiber crops can reach 0.658 billion ton, and 0.533 billion ton of crop straw could be produced.

However, more than 50 percent of straw crops were burned in an uncontrolled manner, rather than for biomass energy generation, resulting in incomplete combustion (NDRC, 2011). The open burning of straw crops is a serious issue in China, and the government has established special regulations to prohibit burning straw crops in fields (NDRC, 2011). But due to the flagging development of straw crop utilization industries, open burning is still very common during the harvest season and has many negative impacts on society, such as the increased frequency of fire disasters during the harvest season and the increased concentration of atmospheric particles that are harmful to human health (Bi, 2010). Moreover, the open burning of straw crops is an important greenhouse gas (GHG) emissions source in China, because the incomplete combustion of straw crops would emit copious amounts of methane and nitrous oxide, which have considerably higher GWP, 21 and 310, respectively, than carbon dioxide. In 2007, the GHG emissions from the open burning of straw crops were 17.63 $MtCO_2e$. Therefore, the promotion of the development of the biomass power industry by using crop straw is significant.

By the end of 2007, the installed capacity of biomass power in China reached 2.2 GW. According to the medium- and long-term renewable energy plan, the target for biomass power installed capacity is 30 GW for 2020, and among them the installed capacity of straw power generation would reach 24 GW.

At present, the raw material of crop straw is the main barrier in the development of biomass power in China. In the rural areas, the price of crop straw has increased from 200 Yuan/ton in 2007 to 310 Yuan/ton in 2008. Moreover, the quality of crop straw has decreased as farmer added water and even sand into the crop straw to increase its weight so as to make more money (Liu and Jiang, 2009).

(9) Other renewable energy resources

Other renewable energies, such as geothermal power, tidal power, wave power, and ocean energy, are currently being studied but rarely used for commercial power generation. Therefore, these renewable energies are not discussed in this thesis.

In sum, we grasp the exploitable reserves, consumption patterns, and development potential of various energy resources in China. Coal is dominant in China’s energy supply, and nearly half of them are used for power generation every year. As to renewable energy, China has abundant resources of wind power, solar power, and biomass power. However, the main technological, financial, and institutional risks associated with China’s renewable energy development still remain, especially the high cost. It spurs us to propose the comprehensive policy proposals of carbon tax and subsidy to stimulate the development of renewable energy in China.

2.2.2 China’s Electricity System

As the world’s single largest source of GHG emissions (IEA, 2012), China’s electricity system plays an important role in mitigating the global warming. This section describes the operation and generation characteristics of China’s current electricity system.

(1) Operation and administration

China’s current electricity operation and administration system have been formed since 2002. As illustrated in Figure 2-11, there are five independent electricity generating companies (Huaneng, Huadian, Guodian, Datang, China Power Investment) responsible for the power generation, and two transmission companies (State Grid Corporation, and Southern Power Grid) are set to manage the power grid. And all the electricity generating and transmitting companies are under the lead of NDRC, SERC, and NEB.

Besides, China has two state-owned power grid companies, the State Grid Corporation of China (SGCC) and China Southern Power Grid Company Limited (CSG). SGCC is the largest state-owned electric power transmission and distribution company in China as well as in the world. SGCC’s power network operation covers 26 provinces, autonomous regions and municipalities with subsidiaries of North China, East China, Central China, Northeast China and Northwest China. CSG covers five southern provinces including Guangdong, Guangxi, Yunnan, Guizhou and Hainan.

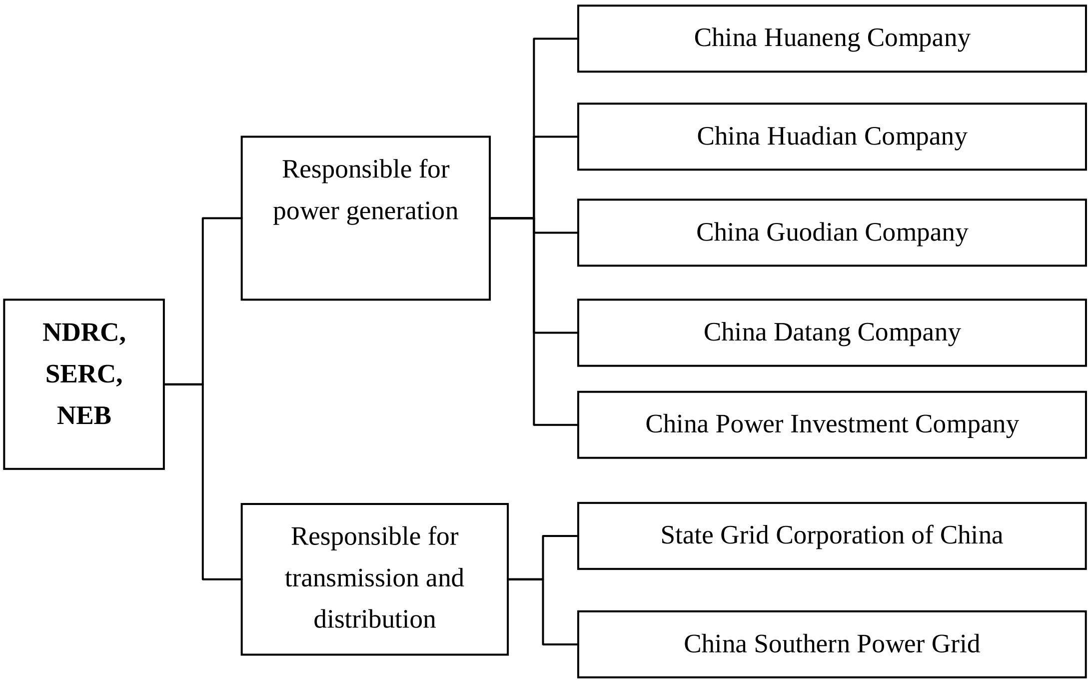


Figure 2-11 the structure of electricity operations and administrations in China

Note: NDRC represents National Development and Reform Commission; SERC represents the State Electricity Regulatory Commission; NEB represents the National Energy Bureau

Still governed by planned economy institutions, China's current electricity system lacks the flexibility in transmission, distribution, and pricing necessary to integrate renewable energy and reduce GHG emissions on a large scale at an acceptable level of cost and reliability. Recognizing these problems, China launched the smart grid plan in 2009, which will improve the reliability and efficiency of the power grid.

(2) Generation structure

With the rapid economic development, China's electricity demand is increasing greatly. As indicated in Figure 2-12, the total electricity generation was 4,228.1 TWh in 2010, three times more than that of 2000. As to the generation structure, the share of coal-fired power generation has been over 80% in the total electricity generation for the recent years (Figure 2-13), implying that China's electricity system is predominantly based on coal.

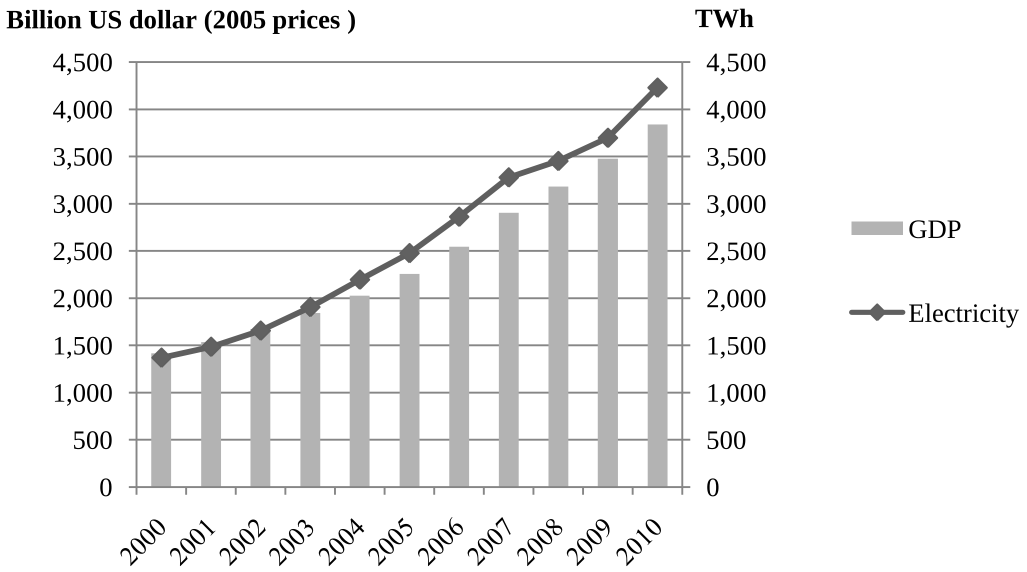


Figure 2-12 China’s GDP and electricity generation

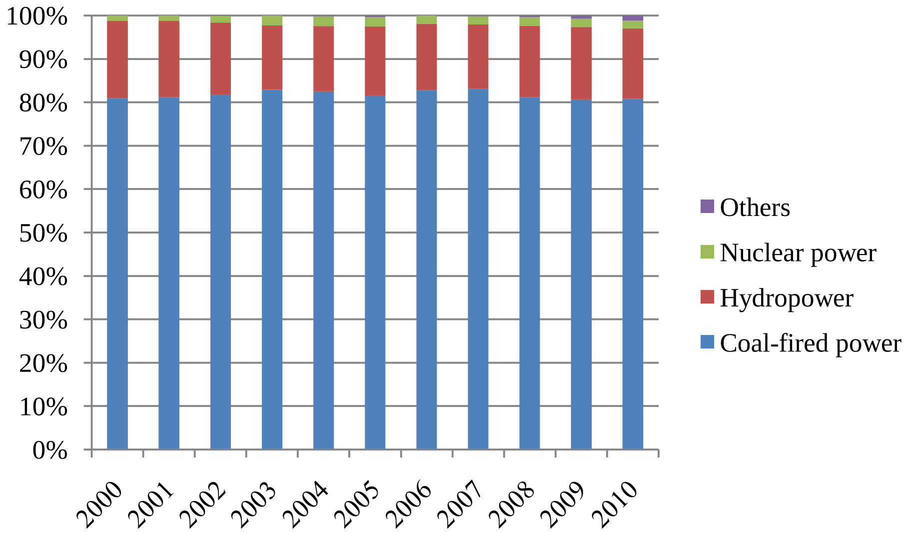
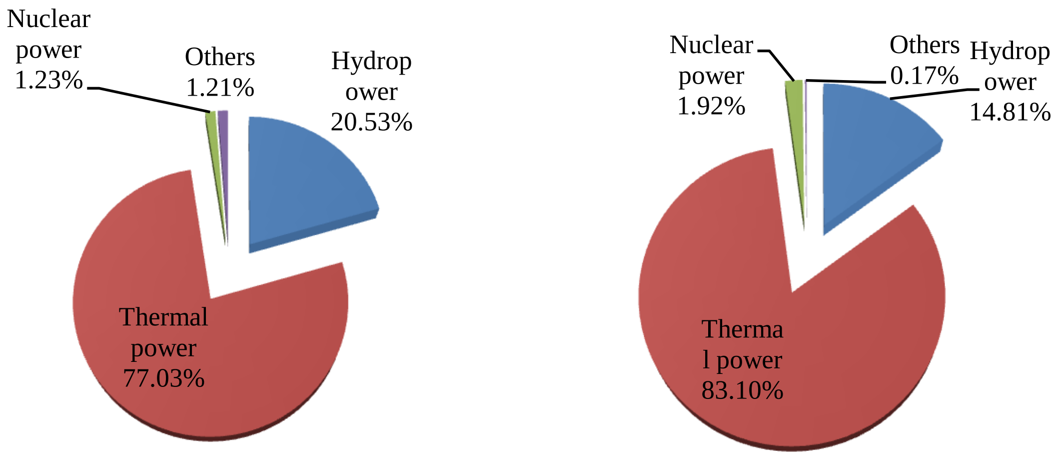


Figure 2-13 China’s electricity generation structure

In order to specify China’s generation mix, we choose the year 2007 to analyze its installed capacity and electricity generation. As illustrated in Figure 2-14, the total installed capacity was 718.22 GW in 2007, in which the share of thermal power (mainly referred to coal-fired plants) reached 77.03%. In terms of electricity generation, China's power output reached 3,256 TWh in 2007, and coal-fired plants accounted for 83.10% of all power generated. In Figure 2-14, the item of "others" refers to new energy power generation, including wind power, solar power and biomass power. The development of new energy power generation in China is still in the initial stage. Although the government has emphasized on the promotion of new energy development, its share is only 0.17% in the total electricity generation in 2007. Due to the technological and institutional barriers, the development of new energy power generation is not so stable in China. As indicated in Figure 2-15, although the installed capacity of new energy power generation is increasing year by year, the annual increase rate of wind power and biomass power is not steady in the recent years.



Total installed capacity in 2007: 718 GW

Total generation in 2007: 3,256 TWh

Figure 2-14 China's fuel mix for power generation in 2007

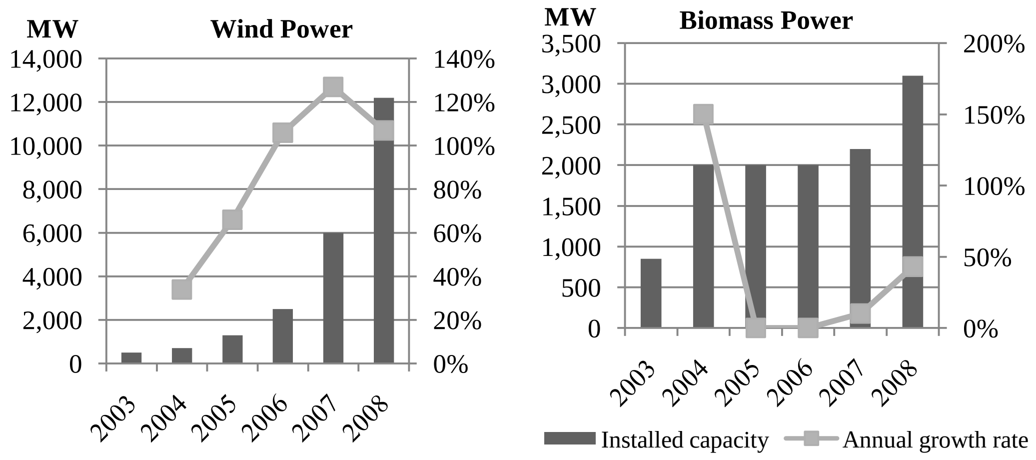


Figure 2-15 Installed capacity and annual growth rate of new energy power

In sum, the great characteristic of China's electricity generation structure is coal-dominant, resulting in the increasing GHG emission in China. Despite of abundant resources, the development of wind power, solar power, and biomass power still faces a lot of barriers. Therefore, the key to mitigation in China is to transform the coal-dominant electricity system into a low carbon one. In this study, we will propose the comprehensive policy proposals of carbon tax and subsidy to stimulate the development of new energy power generation.

2.3 China's GHG Emissions

2.3.1 Characteristics of China's GHG Emissions

As the world's largest GHG emitting country, China is facing great pressure in the international climate negotiations to combat global climate change. In order to understand the responsibilities China should take, we conclude its characteristics of GHG emission as follows.

Firstly, although China has overtaken the United States to become the world's largest GHG emitter since 2007, China's cumulative GHG emissions are still very low compared to the United States. As indicated in Figure 2-16, China's GHG emission kept less than 3,000 $MtCO_2e$ before the year 2000, and it began to increase greatly since the year 2001 when China's economy has been flourished. During the period of 10th Five-Year Program (2001-2005), China has gone out of the Asia Financial Crisis, and the annual growth rate of GDP was 8.8% (Xinhua, 2005). In contrast, the GHG emissions in the United States are almost stable around 5,000 $MtCO_2e$ for the past two decades. Because of the undissociated property, GHG emitted in the time of the industrial revolution still remains in the atmosphere now. The current high concentration of GHG emission in the atmosphere is mainly produced by the developed countries having more than 150 years of industrial activities. Therefore, the principle of "common but differentiated responsibilities" should be insisted in the international climate negotiations.

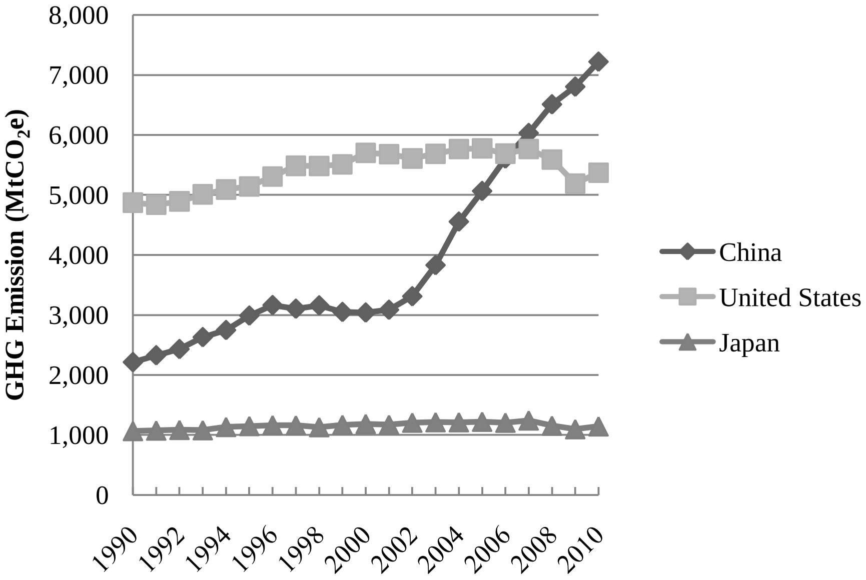


Figure 2-16 Trend of GHG emission in main countries

Secondly, China's current per capita GHG emission is very low compared with the other countries. As indicated in Figure 2-17, China's per capita GHG emission is about 5 ton CO_2 per capita, less than United States' 20 ton CO_2 per capita and Japan's 10 ton CO_2 per capita.

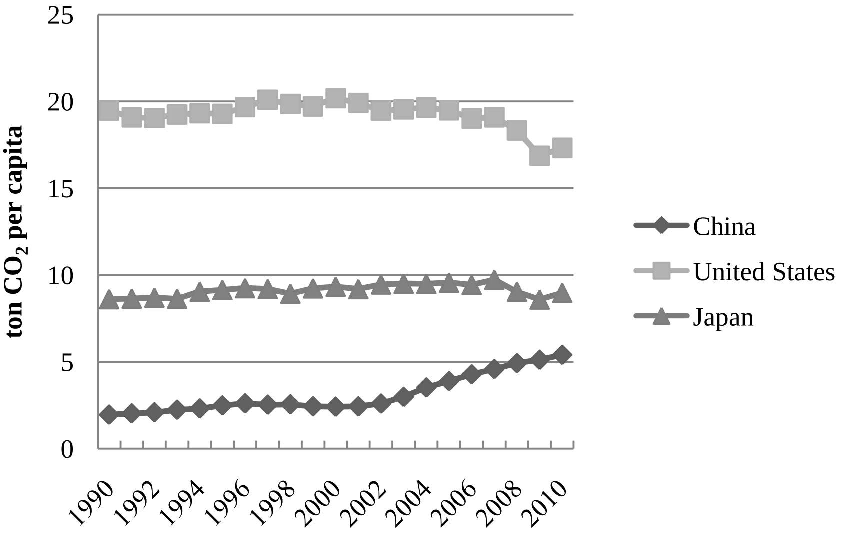


Figure 2-17 Trend of Per capita GHG emission in main countries

Thirdly, although China's GHG intensity has been declining in the recent two decades, it is still very high in the world wide. As indicated in Figure 2-18, China's GHG intensity in 2010 was 1.88 kgCO_2/US dollar, higher than that of United States and Japan. Recognizing the urgency of mitigation, China has promised to reduce its GHG intensity by 40-45% by 2020 comparing with 2005 level. However, if this target is realized, China's GHG intensity is still higher than that of United States. But we cannot conclude that China's reduction target is too conservative. That is because GHG intensity is a relative indicator, related with GHG emission and GDP. As indicated in Figure 2-19, China's GDP was much less than United States in 2010, while China's GHG emission was almost the same with United States. Therefore, the key to reduce China's GHG intensity is to transform the coal-dominant energy system into a low carbon one.

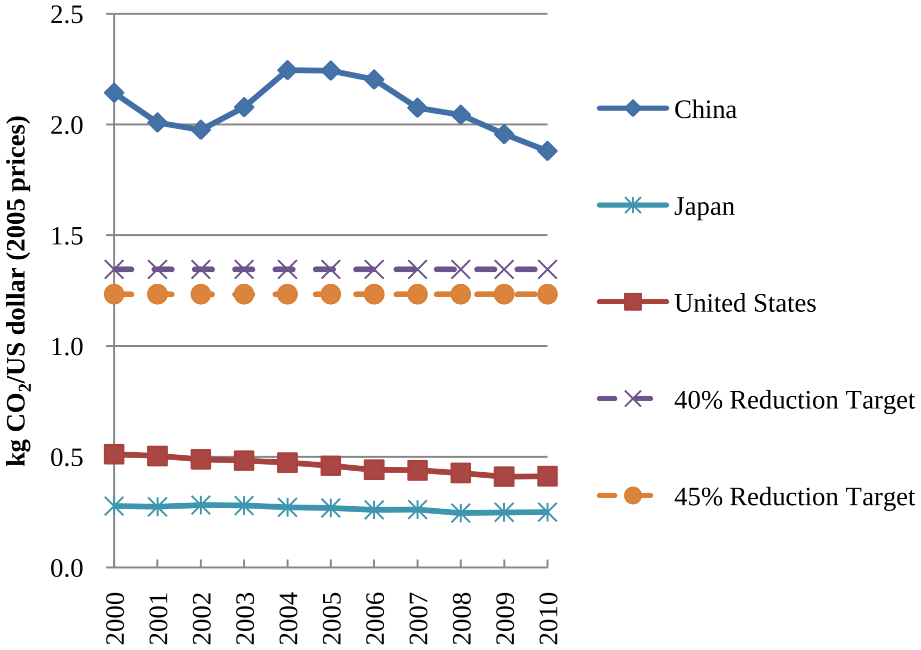


Figure 2-18 Trend of GHG intensity of main countries

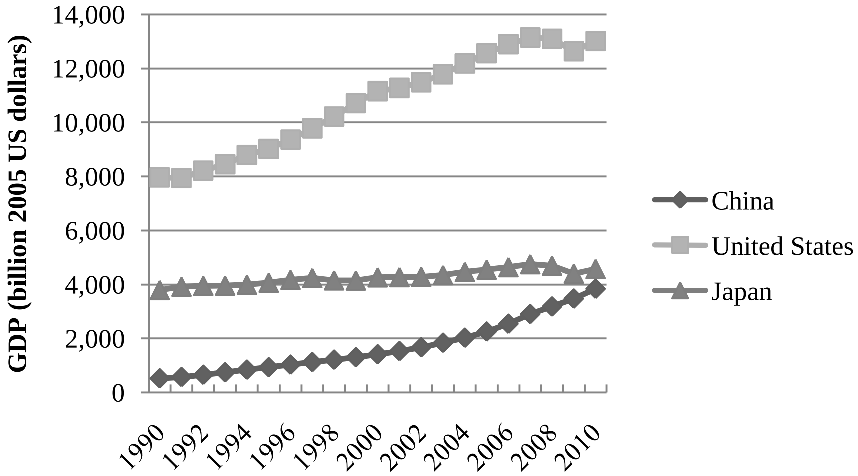


Figure 2-19 Main countries' GDP from 1990 to 2010

Fourthly, in terms of GHG emission by sector, the electricity and heat production sector is the single largest GHG emitting source in China. As indicated in Figure 2-20, the GHG emission in the electricity and heat production sector was almost half of the total GHG emission in 2010. On the other hand, in terms of fuel type, combustion of coal is the largest GHG emitting source in China. As indicated in Figure 2-21, China's GHG emission in the last decade is mainly from the combustion of coal. It is consistent in the largest emitting sector and fuel type, because almost half of raw coal consumption is used for power generation in China.

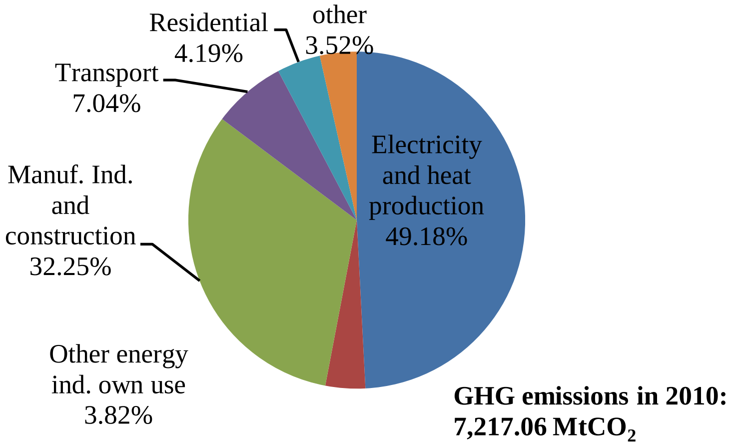


Figure 2-20 GHG emission by sector in 2010

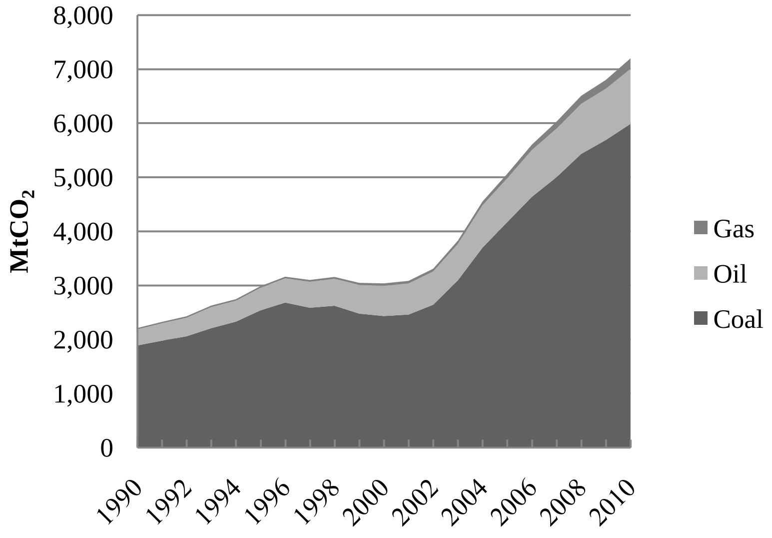


Figure 2-21 Trend of GHG emissions by fuel in China

2.3.2 Implications for Future GHG Emissions

With the recent growing focus on the climate change, a range of outlook models are developed across different institutions to forecast the future GHG emissions in China. The economic modeling approaches have already been presented in Section 1.2.5. Therefore, only some important observations particularly related to China are mentioned here. Prior to this, we describe IPCC's findings on the world emission trajectories for stabilization.

According to "IPCC Climate Change 2007 Synthesis Report" (AR4), in order to stabilize the concentration of GHG in the atmosphere, the global emissions would need to peak and decline thereafter. Besides, IPCC also found that the lower the stabilization level, the more quickly this peak would occur. To limit the global average temperature increase in excess of 2 degree, the concentration of GHG in the atmosphere would need to be stabilized at a level around 450 ppm CO_2e, an objective that is gaining widespread support around the world. The findings of IPCC have far-reaching implications on the global GHG emission trajectory, as well as on China's outlook.

Now let us turn to the outlook of China's GHG emission. The China Energy Group of LBNL has compared five institutions' studies in the modeling methodologies, scenarios, drivers, aggregate energy and CO_2 emission outlook (Zheng et al., 2010), and given us a lot of insights in understanding the previous studies. In this part, we choose two typical studies, including China's Energy Research Institute's 2050 China Energy and CO_2 emissions report (CERI, 2009), and the China Energy Group at LBNL China's outlook to 2050 (Zhou et al., 2011a).

Prior to comparing the results of GHG emission, we will introduce the scenario settings in each study. First is the CERI's study in which three scenarios are set. Baseline scenario is the business as usual case where economic growth continues at rapid pace. In the low carbon scenario (LC), greater policies focus on energy security, environmental protection and low carbon pathways are adopted. And there are more aggressive policy actions under global concerted efforts to reduce GHG in the accelerated low carbon scenario (ALC). Second is the LBNL's study in which continued improvement scenario (CIS) and accelerated improvement scenario (AIS) are set. In CIS, the continuing current and planned portfolio of programs, policies and technology are deployed. In AIS, accelerated efficiency improvements and technologies are employed across all sectors, and the non-fossil fuel generation is accelerated.

By comparing the results of GHG emission in the studies above, we get China's GHG emission trajectory from 2005 to 2050. Due to different assumptions about mitigation potential and abatement technologies employment, there is a much greater rage in results among the scenarios. As indicated in Figure 2-22, most studies forecast China's GHG emissions peaking around 12,000 $MtCO_2e$ in the 2030s. In CERI's study, the emission peak in baseline scenario is 12,925 $MtCO_2e$ in 2040, and the peak in ALC scenario is 8,169 $MtCO_2e$ in 2030. Both scenarios of LBNL's study have the emission peak in 2030, 11,931 $MtCO_2e$ in CIS and 9,680 $MtCO_2e$ in AIS. In sum, the trajectory of China's GHG emission can be concluded as follows: It will keep increasing from 2005 to 2030, and peak in 2030s. Thereafter, China's GHG emission will be declining.

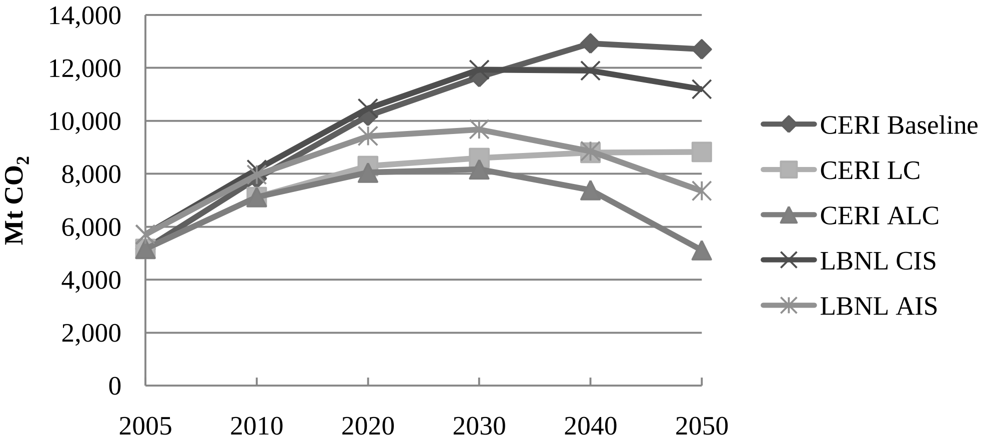


Figure 2-22 Comparison of total CO_2 emissions in different studies

2.4 Concluding Remarks

In this chapter I have analyzed the current situation of energy system and GHG emission in China. The following findings can be concluded:

On the one hand, the coal-dominant energy system is the main reason of high GHG emission in China. At present, the electricity and heat production sector is the single largest GHG emitting source in China, accounting for almost half of the total GHG emission in 2010. In China's energy system, coal-fired plants are accounted for over 80% of all power generated for the recent years. Therefore, the key to mitigation in China is to develop the renewable energy to transform the coal-dominant energy system.

On the other hand, although China has abundant renewable energy resources, the main technological, financial, and institutional risks associated with China's renewable energy development still remain. Especially the high cost of renewable energy should not be neglected.

Therefore, we propose the mitigation policies of carbon tax and subsidy to promote the renewable energy development in China, in order to transform the coal-dominant energy system and coordinate the economic development, energy consumption and GHG mitigation. In the next chapter, we will construct a comprehensive model to evaluate the impacts of proposed policies on China's economy, energy, and environment.

CHAPTER 3 COMPREHENSIVE EVALUATION MODEL CONTRUCTION OF SOCIO-ECONOMIC AND ENVIRONMENTAL POLICIES

3.1 Introduction

In this chapter, we will construct a comprehensive evaluation model for energy and environmental policy analysis of the Chinese economy. The comprehensive evaluation model of Chinese economy is nonlinear, with equations specifying supply and demand behavior across all markets. This model allows endogenous substitution among different types of energy as well as endogenous determination of relocation in production and foreign trade in the Chinese economy in order to cope with the GHG emission constraint, at both sectoral and macroeconomic levels. And the simulation of the model can produce a lot of detailed information for a given year, including GDP, GHG emission, capital stock, capital formation, household income, house consumption, and energy consumption patterns.

The remainder of this chapter proceeds as follows. Section 3.2 presents the sectoral classification for this study, and an extended input-output table is constructed. In Section 3.3, the model framework is discussed in an integrated view of social-economic development. Section 3.4 describes the specific formulations of this model for the following blocks: objective function, commodity flow balance, energy flow balance, value flow balance, GHG emission, household income and expenditure, government revenue and expenditure, carbon tax and subsidy, investment and saving balance, production function, dynamic equations of capital stock, and GHG emission constraint. We use scenario analysis method in this research, so the case setting is described in Section 3.5. Data preparation is finished in Section 3.6. In Section 3.7, some concluding remarks are drawn.

3.2 Sectoral Classification

Construction of an extended input-output table is the foundation of this comprehensive evaluation model. In China, large scale input-output surveys across the country are conducted every five years. So far, five detailed input-output tables are available for 1987, 1992, 1997, 2002 and 2007. We use the 2007 input-output table in this model (NBS, 2009).

Before turning to the construction of an extended input-output table, the sectoral classification for this study is presented in Table 3-1, together with the corresponding sector codes of the original 42-sector input-output table from which 16-sector is aggregated, and the other 5 sectors are newly introduced. Therefore there are 21 sectors in this model, including 7 energy sectors. All the sectors are further divided into four groups, namely usual, thermal power, hydropower, and new energy power industries.

In this model, we propose to introduce new energy industry, including wind power, solar power, and biomass power. As to biomass power, there are three types of technologies, such as direct combustion of crop straw for power generation (Domestic technology), direct combustion of crop straw for power generation (Denmark technology), and straw gasification power generation. Because the public statistics for constructing the new energy industries are not available at present, the economic and technological parameters of these new energy industries are collected from the Clean Development Mechanism (CDM) projects registered by United Nations Framework Convention on Climate Change (UNFCCC), as shown in Table 3-2.

As indicated in Table 3-3, an extended I-O table can be constructed, which is the basis of our comprehensive evaluation model. In the row, the total output of usual industry is composed of intermediate demand by all the industries and final demand including household consumption, government purchase, capital formation and net export. In the column, the total input of each industry is comprised of intermediate input and added value including depreciation, indirect tax, and income.

Table 3-1 Classification of sectors in the comprehensive model

Industry	15-Sector	42-Sector
Usual industry	1. Agriculture	01
	2. Mining industry	02-05
	3. Light industry	06-10
	4. Petroleum and coking	11
	5. Chemical industry	12
	6. Nonmetal mineral products	13
	7. Smelting of metals	14
	8. Metal products	15
	9. Other manufacture industry	16-22
	10. Production of gas	24
	11. Production of Water	25
	12. Construction	26
	13. Transport and postal services	27-29
	14. Other services	30-42
Thermal power industry	15. Thermal power	23
Hydropower industry	16. Hydropower	23
New energy industry	17. Wind power	
	18. Solar power	
	19. Biomass power-I	
	20. Biomass power-II	
	21. Biomass power-III	

Note: In the 42-sector input-output table, No. 23 sector is electricity and heat production sector. We divide this sector into thermal power sector and hydropower sector based on the electricity statistical table (NBS, 2008a).

Table 3-2 Parameters of new energy industry

New energy industry	Technology	CDM Project	Installed capacity
1. Wind power industry	Wind power technology	Jiangxi Duchang Jishanhu Wind Farm Project	1,500 kW
2. Solar power industry	Solar power technology	Huadian Ningxia Ningdong 10MWp Solar Power station Project	10,000 kW
3. Biomass power industry	I: Direct combustion of crop straw for power generation (Domestic)	Beiliu kaidi biomass power project	30,000 kW
	II: Direct combustion of crop straw for power generation (Denmark)	Straw generation project in Wei county Hebei province, P.R. China	30,000 kW
	III: Straw gasification power generation	Gaoyou 4MW Biomass Power Generation Project	4,000 kW

Table 3-3 Extended I-O table in this model

		Intermediate demand				**Final demand**				**Total output**
		Usual	Thermal power	Hydropower	New energy	C	G	Capital formation	Net export	
Intermediate input	Usual									
	Electricity									
Added value	Depreciation									
	Indirect tax									
	Income									
Total input										

Note: C is household consumption; G is government purchase.

3.3 Model Framework

We construct the comprehensive socio-economic model in three view points of value flow balance, energy flow balance, and commodity flow balance, which are necessary in the comprehensive environmental evaluation. The objective function of this model is to maximize the sum of discounted GDP from 2007 to 2020, subject to all the constraints.

In this part, the comparison of model framework between the cases without and with comprehensive policy proposals is conducted, as shown in Figure 3-1 and Figure 3-2. All the economy entities can be divided into two groups of industry and final demand, and GHG will be emitted by all the economy entities. The commodity flow balance and value flow balance take place in all the economic entities, which will be illustrated specifically in Section 3.4.

As to energy flow balance, the energy demand side consists of industry and final demand, while the energy is supplied by different kinds of power generation technologies. The energy supply must meet the energy demand in each year. The biggest difference between the two cases is energy supply. In the case of without comprehensive policy proposals, the energy is supplied by thermal power and hydropower. Due to the controversy on river ecosystems damage and human displacement problem in the development of hydropower, we assume that China will not build large hydropower facilities by 2020. So the increasing of energy demand in the case without comprehensive policy proposals is almost dependent on thermal power which is generated in the combustion process of coal and emits a lot of GHG. In contrast, in the case of introducing comprehensive policy proposals, the energy is supplied by thermal power, hydropower, and new energy power generation. New energy power generation can substitute the equivalent thermal power in the market, resulting in the reduction of GHG emission in the national wide.

Besides, we consider the market behaviors among four economy entities, namely industry, government, household and the oversea. The market behaviors include the activities in two markets, capital market and commodity market. As shown in Figure 3-3, the revenue of government is composed of indirect tax from industries and direct tax from households. The carbon tax is a special tax, and not included in the government revenue. It is levied on thermal power industry, and all the revenue of carbon tax is used as subsidy to give incentives to develop new energy industry. The expenditure of government includes government purchase and government saving. The household income is spent in three aspects, household consumption, direct tax and household saving. In the capital market, the government saving, household saving and net export will be used as investment for industries. On the other hand, the commodities produced by industries are sold to government, households, and the oversea through the commodity market.

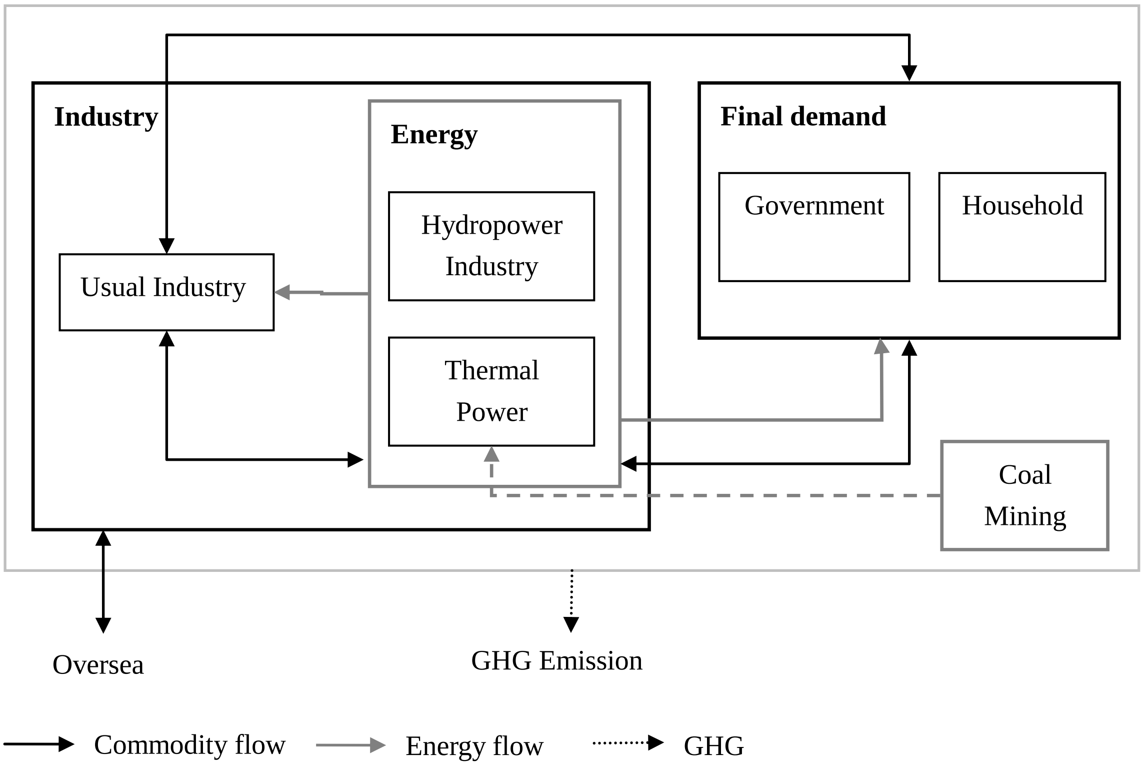


Figure 3-1 Model framework of the case without policy proposals

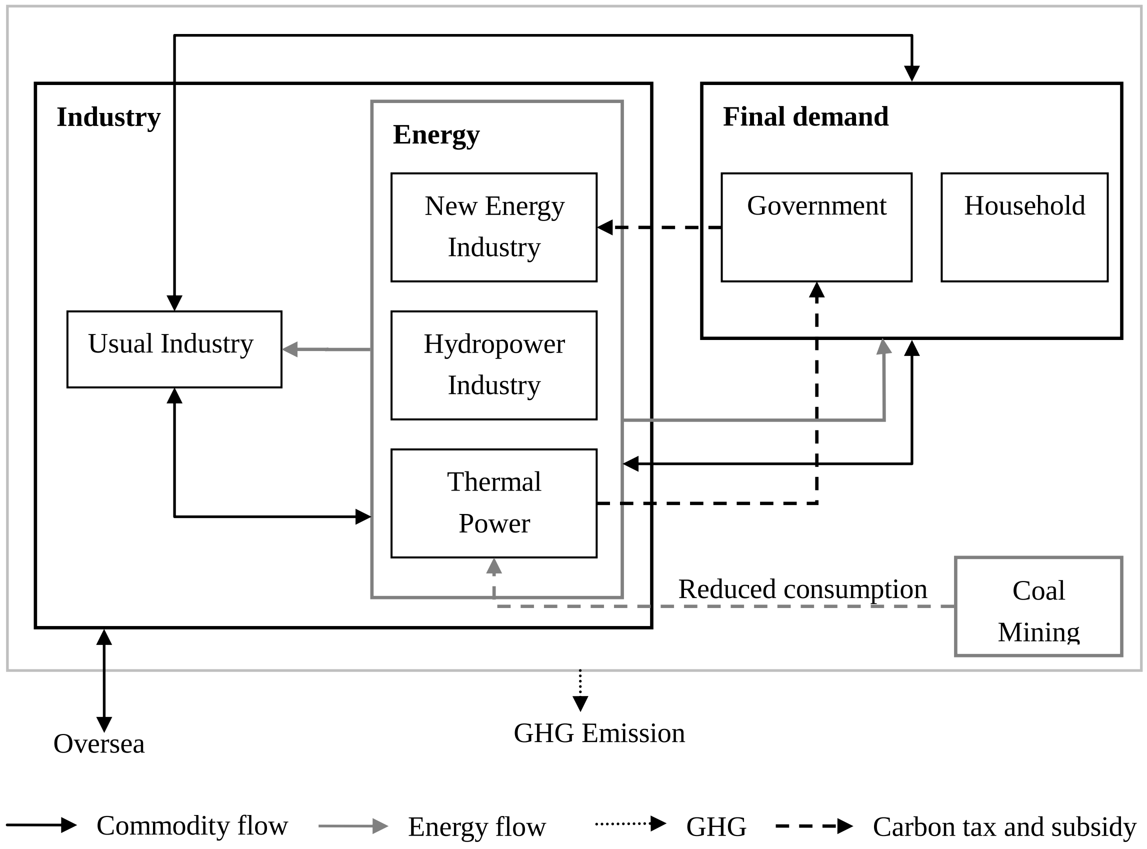


Figure 3-2 Model framework of the case with policy proposals

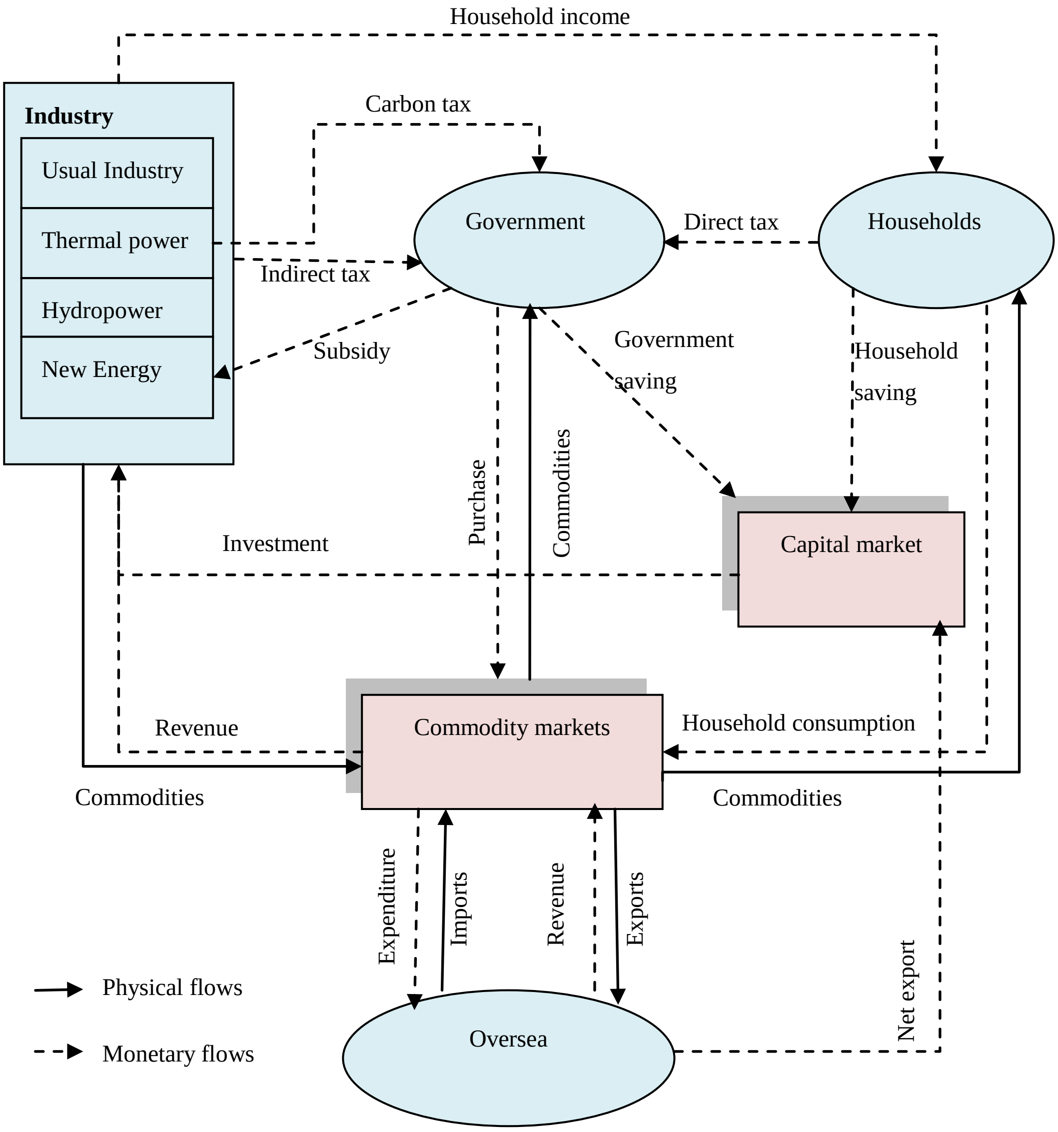


Figure 3-3 Interrelationship among the economy entities

3.4 Specific Formulations of the Model

In describing the equations, there are two types of variables in this model, exogenous (ex) and endogenous (en). The exogenous variables are given on the base year data, and the endogenous variables are produced by the simulation.

3.4.1 Objective Function

As the largest developing country, China puts the economic development as the top priority. In the 12th Year-Plan, the target of annual GDP growth rate from 2011 to 2015 is set as 7%, subject to some constraints on CO_2 emission per unit GDP (17% reduction by 2015), energy consumption per unit GDP (16% reduction by 2015), and share of non-fossil energy in primary energy consumption (increase to 11.4% in 2015) and so on. Therefore, in our model, the objective function is constructed to maximize the discounted GDP from 2007 to 2020, subject to a series of constraints.

$$MAX \ \sum_t \left(\frac{1}{1+\rho}\right)^{t-1} GDP(t) \tag{3-1}$$

$$GDP(t) = V_u X_u(t) + V_m X_m(t) + V_r X_r(t) + V_n X_n(t) \tag{3-2}$$

in which

ρ: social discount rate (ex) (Table A3-39);

GDP(t): China's gross domestic production in term t (en);

V_u: added value rate of usual industry (ex) (see Table A3-43);

V_m: added value rate of thermal power industry (ex) (see Table A3-40);

V_r: added value rate of hydropower industry (ex) (see Table A3-41);

V_n: added value rate of new energy industry (ex) (see Table A3-42);

$X_u(t)$: production of usual industry in term t (en);

$X_m(t)$: production of thermal power industry in term t (en);

$X_r(t)$: production of hydropower industry in term t (en); and

$X_n(t)$: production of new energy industry in term t (en).

3.4.2 Commodity Flow Balance

Each industry must produce enough goods/service to meet the demand by the entire economy. This balance between supply and demand for the commodity is called commodity flow balance.

$$\begin{aligned} X_u(t) \geq\ & A_{uu}X_u(t) + A_{um}X_m(t) + A_{ur}X_r(t) + A_{un}X_n(t) + C_u(t) + G_{u\_d} \\ & + Q_{uu}\Delta K_u(t) + Q_{um}\Delta K_m(t) + Q_{ur}\Delta K_r(t) + Q_{un}\Delta K_n(t) + E_{u\_d} - M_u(t) \end{aligned} \tag{3-3}$$

in which

A_{uu}: input coefficient to usual industry i by usual industry (ex) (Table A3-1);

A_{um}: input coefficient to thermal power industry by usual industry (ex) (see Table A3-2);

A_{ur}: input coefficient to hydropower industry by usual industry (ex) (see Table A3-2);

A_{un}: input coefficient to new energy industry by usual industry (ex) (see Table A3-3);

$C_u(t)$: household consumption of usual industry in term t (en);

G_{u_d}: government consumption of usual industry in base year (ex) (see Table A3-10);

Q_{uu}: investment demand to usual industry induced by one unit capital formation in usual industry (ex) (see Table A3-7);

Q_{um}: investment demand to usual industry induced by one unit capital formation in thermal power industry (ex) (see Table A3-8);

Q_{ur}: investment demand to usual industry induced by one unit capital formation in hydropower industry (ex) (see Table A3-8);

Q_{un}: investment demand to usual industry induced by one unit capital formation in new energy industry (ex) (see Table A3-9);

$\Delta K_u(t)$: capital stock formation of usual industry in term t (en);

$\Delta K_m(t)$: capital stock formation of thermal power industry in term t (en);

$\Delta K_r(t)$: capital stock formation of hydropower industry in term t (en);

$\Delta K_n(t)$: capital stock formation of new energy industry in term t (en);

E_{u_d}: export of usual industry in base year (ex) (see Table A3-10); and

$M_u(t)$: import of usual industry in term t (en).

In this equation, left side represents the supply of commodity while right side is the total demand by the entire economy. The production of commodity in each industry must meet the demand in all years. As to the total demand on the right side, it can be divided into two parts of intermediate demand (from the first item to the fourth), and final demand (from the fifth item to the twelfth). The intermediate demand is Leontief input-output coefficient matrix, and the final demand includes consumption (the fifth and sixth items), investment (the items from the seventh to tenth), and foreign trade (the eleventh and twelfth items). The constraint of the foreign trade will be illustrated in Section 3.4.11.

3.4.3 Energy Flow Balance

The energy balance describes the relationship between supply and demand of electricity in China. The electricity supply must meet the total demand by the entire economy.

$$bX_e(t) = A'_{eu}X_u(t) + A'_{em}X_m(t) + A'_{er}X_r(t) + A'_{en}X_n(t) + C'_e(t) + E'_{e\_d} - M'_e(t) \qquad (3\text{-}4)$$

in which

b: rate of electricity generation to production (ex);

$X_e(t)$: production of electricity industry (en);

A'_{e_u}: electricity consuming factor of usual industry (ex);

A'_{e_m}: electricity consuming factor of thermal power industry (ex);

A'_{e_r}: electricity consuming factor of hydropower industry (ex);

A'_{e_n}: electricity consuming factor of new energy industry (ex);

$C'_e(t)$: electricity consumption by households (en);

E'_{e_d}: export of electricity in base year (ex); and

$M'_e(t)$: import of electricity (en).

In this model, by introducing carbon tax to internalize the externality of thermal power, it reaches an equilibrium state in which all the kinds of electricity can compete with each other at the same price in the market. So the rate of electricity generation to production (b) is the same in all the supply sides. We can get the following equation if the rate b is divided in two sides of the equation above.

$$X_e(t) = A_{eu} X_u(t) + A_{em} X_m(t) + A_{er} X_r(t) + A_{en} X_n(t) + C_e(t) + E_{e\_d} - M_e(t) \qquad (3\text{-}5)$$

in which

A_{eu}: input coefficient to usual industry by electricity industry (ex) (see Table A3-4);

A_{em}: input coefficient to thermal power industry by electricity industry (ex) (see Table A3-5);

A_{er}: input coefficient to hydropower industry by electricity industry (ex) (see Table A3-5);

A_{en}: input coefficient to new energy industry by electricity industry (ex) (see Table A3-6);

$C_e(t)$: household consumption of electricity industry (en);

E_{e_d}: export of electricity in value in base year (ex) (see Table A3-11); and

$M_e(t)$: import of electricity in value (en).

Left side represents the total electricity supply, including thermal power, hydropower, wind power, solar power, and biomass power. And the total electricity demand is on the right side, including electricity demand by industries (from the first item to the fourth), household (the fifth), and foreign trade (the sixth and seventh).

3.4.4 Value Flow Balance

In the market, each industry must produce enough revenues to surpass the costs used to develop this industry. Otherwise, it will go into bankruptcy. The balance between revenue and cost for industries is called value flow balance. Because the price fluctuation is common in the market, the concept of price rate is adopted to describe the market behaviors of each industry in this model. Price rate of each industry in market equilibrium is expressed as relative price. In the model, the price of agriculture in all years is set to be the numeraire of the integrated system ($P_u(1,t)=1$). And price rates of the other industries can be changed in a certain extent. We will introduce the value flow balance for industries one by one.

(1) Value flow balance of usual industry

$$P_u(t)X_u(t) \le P_u(t)A_{uu}X_u(t) + P_e(t)A_{eu}X_u(t) + Y_{hu}(t) + \delta_u K_u(t) + \zeta_u X_u(t) \qquad (3\text{-}6)$$

in which

$P_u(t)$: price rate of usual industry in term t (en);

$P_e(t)$: price rate of electricity in term t (en);

$Y_{hu}(t)$: household income of usual industry (en);

δ_u: depreciate rate of usual industry (ex) (see Table A3-15);

$K_u(t)$: capital stock of usual industry (en); and

ζ_u: indirect tax rate of usual industry (ex) (see Table A3-12).

Left side represents the revenue produced by usual industry in the market. And the right side specifies the total cost of usual industry, including intermediate input (the first item and the second), wages paid to workers (the third item), depreciation of fixed capital stock (the forth item), and indirect tax paid to the government (the fifth item). The revenue produced by usual industry must cover the total cost used to develop the industry.

(2) Value flow balance of thermal power industry

$$\begin{aligned} P_e(t)X_m(t) \le {} & P_u(t)A_{um}X_m(t) + P_e(t)A_{em}X_m(t) + \\ & Y_{hm}(t) + \delta_m K_m(t) + \tau_m X_m(t) + \zeta_c ef_m X_m(t) \end{aligned} \qquad (3\text{-}7)$$

in which

$Y_{hm}(t)$: household income of thermal power industry (en);

δ_m: depreciate rate of thermal power industry (ex) (see Table A3-16);

$K_m(t)$: capital stock of thermal power industry (en);

ζ_m: indirect tax rate of thermal power industry (ex) (see Table A3-13);

ζ_c: carbon tax rate (ex); and

ef_m: GHG emission factor of thermal power industry (ex) (see Table A3-20).

Thermal power industry is the largest GHG emission source in China. The excessive emission leads to the global warming and climate change. So the thermal power industry produces negative externality on the public goods. Carbon tax is levied to internalize the negative external cost of thermal power industry, and it is a kind of Pigouvian tax.

(3) Value flow balance of hydropower industry

$$P_e(t)X_r(t) \le P_u(t)A_{ur}X_r(t) + P_e(t)A_{er}X_r(t) + Y_{hr}(t) + \delta_r K_r(t) + \zeta_r X_r(t) \qquad (3\text{-}8)$$

in which

$Y_{hr}(t)$: household income of hydropower industry (en);

δ_r: depreciate rate of hydropower industry (ex) (see Table A3-17);

$K_r(t)$: capital stock of hydropower industry (en); and

ζ_r: indirect tax rate of hydropower industry (ex) (see Table A3-14).

(4) Value flow balance of new energy industry

$$P_e(t)X_n(t) + \sigma_n X_n(t) \le P_u(t)A_{un}X_n(t) + P_e(t)A_{en}X_n(t) + Y_{hn}(t) + \delta_n K_n(t) \qquad (3\text{-}9)$$

in which

σ_n: subsidy rate of new energy industry in term t (en);

$Y_{hn}(t)$: household income of new energy industry (en);

δ_n: depreciate rate of new energy industry (ex) (see Table A3-18); and

$K_n(t)$: capital stock of new energy industry (en).

The new energy industry has positive externality on the public goods because of low-carbon electricity generation. We introduce a subsidy to internalize the positive externality of new energy industry, and it is called a kind of Pigouvian subsidy. After the introduction of carbon tax and subsidy, the socio-economic system will reach an equilibrium stage and the outcomes shall be optimal.

3.4.5 GHG Emission

The following greenhouse gases are covered in the 2006 IPCC Guidance (IPCC, 2006): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3), trifluoromethyl sulphur pentafluoride (SF_5CF_3), halogenated ethers ($C_4F_9OC_2H_5$), and other halocarbons not covered by the Montreal Protocol including CF_3I etc. In this model, we only consider the emissions of CO_2 and CH_4. Because plants have absorbed CO_2 emissions in the photosynthesis process, GHG emitted in the open-burning process of crop straw only include CH_4, not include CO_2. In sum, the GHG emission sources in this model include industries, household consumption and open-burning of crop straw.

$$GHG(t) = ef_u X_u(t) + ef_m X_m(t) + ef_n X_n(t) + ef_c C_u(t) + ef_w W(t) \qquad (3\text{-}10)$$

in which

GHG(t): GHG emission in term t (en);

ef_u: GHG emission factor of usual industry (ex) (see Table A3-19);

ef_n: GHG emission factor of new energy industry (ex) (see Table A3-21);

ef_c: GHG emission factor of household consumption (ex) (see Table A3-22);

ef_w: GHG emission factor of crop straw in the open-burning process (ex) (see Table A3-23); and

W(t): the quantity of crop straw treated by open-burning (en).

3.4.6 Amount of Crop Straw

As the world’s largest agricultural country, China has ample straw crop resources (Yang et al., 2010; Liu and Shen, 2007; Liu et al., 2008; Zhou et al., 2011b). In 2007, the total potential crop output, including food crops, oil crops and cottons, among others, was 658 million tons, and the theoretical production of straw crops was 533 million tons (Yang et al., 2010). However, greater than 50 percent of straw crops were burned in an uncontrolled manner, rather than for biomass energy generation, resulting in incomplete combustion (NDRC, 2011). The open burning of straw crops is a serious issue in China, and the government has established special regulations to prohibit burning straw crops in fields (NDRC, 2011). However, due to the flagging development of straw crop utilization industries, open burning is still very common during the harvest season and has many negative impacts on society, such as the increased frequency of fire disasters during the harvest season, the increased GHG emission, and the increased concentration of atmospheric particles that are harmful to human health (Bi, 2010). So we propose to adopt the advanced biomass power technologies to utilize the crop straw in the new energy industry. The amount of crop straw is described as following.

$$W(t) = A_{wu} X_u(t) - A_{wn} X_n(t) \tag{3-11}$$

in which

A_{wu}: disposed coefficient of crop straw by usual industry (ex) (see Table A3-24); and

A_{wn}: treated coefficient of crop straw by new energy industry (ex) (see Table A3-25).

3.4.7 Household Income and Expenditure

In the macroeconomics, household and government are two important economic entities, whose behaviors will effect the investment on industries. First we discuss the household income and expenditure.

(1) Household income

The household provides labor for the industry development. And in return, the wages will be paid to the household, which is the source of household income.

$$Y_{hu}(t) = y_u X_u(t) \tag{3-12}$$

$$Y_{hm}(t) = y_m X_m(t) \tag{3-13}$$

$$Y_{hr}(t) = y_r X_r(t) \tag{3-14}$$

$$Y_{hn}(t) = y_n X_n(t) \tag{3-15}$$

in which

$y_u(t)$: income rate of usual industry (ex) (see Table A3-26);

$y_m(t)$: income rate of thermal power industry (ex) (see Table A3-27);

$y_r(t)$: income rate of hydropower industry (ex) (see Table A3-28); and

$y_n(t)$: income rate of new energy industry (ex) (see Table A3-29).

(2) Household disposable income

The household should pay direct tax to the government, and the remaining part is the disposable income.

$$Y_d(t) = (1-\zeta^d)\{Y_{hu}(t) + Y_{hm}(t) + Y_{hr}(t) + Y_{hn}(t)\} \tag{3-16}$$

in which

$Y_d(t)$: disposable income of households (en); and

ζ_d: direct tax rate (ex) (see Table A3-30).

(3) Household consumption

The household disposable income can be divided into two parts of household consumption and household saving. And the household consumption is composed of usual industry's consumption and electricity's consumption. The household consumption can thus be written as

$$P_u(t) * C_u(t) = (1-\beta)Y_d(t)\alpha_u \tag{3-17}$$

$$P_e(t) * C_e(t) = (1-\beta)Y_d(t)\alpha_e \tag{3-18}$$

$$\alpha_u + \alpha_e = 1 \tag{3-19}$$

in which

β: household saving rate (ex) (see Table A3-31);

α_u: share of usual industry's consumption in the total household consumption (ex) (see Table A3-32); and

α_e: share of electricity's consumption in the total household consumption (ex) (see Table A3-33).

(4) Household saving

$$Sh(t) = \beta Y_d(t) \tag{3-20}$$

in which

$Sh(t)$: household saving in term t (en).

3.4.8 Government Revenue and Expenditure

Total government revenue is generated from two sources: 1) indirect taxes; 2) direct taxes. The government expenditure includes two parts: 1) government purchase; 2) government saving. As usual, the government purchase is set exogenously, same as the base year. Thus, the government revenue and expenditure can be expressed as follows:

$$\begin{aligned}&\tau_u X_u(t) + \tau_m X_m(t) + \tau_r X_r(t) + \zeta^d \{Y_{hu}(t) + Y_{hm}(t) + Y_{hr}(t) + Y_{hn}(t)\} \\ &= G_{u\_d} + Sg(t)\end{aligned} \tag{3-21}$$

in which

Sg(t): government saving in term t (en).

3.4.9 Carbon Tax and Subsidy

In this model, carbon tax is a special tax, all of which is used as subsidy to promote the development of new energy industry.

$$\tau_c ef_m X_m(t) = \sigma_{\mathrm{n}} \mathrm{X}_{\mathrm{n}}(\mathrm{t}) \tag{3-22}$$

3.4.10 Investment and Saving Balance

In the model, investment and saving balance describes the macroeconomic balance in different economy entities. Since there are four economy entities in this model, including household, government, industry, and foreign trade, it satisfies the macroeconomic law of four-sector economy: Investment on industries + net export = household saving + government saving.

$$\begin{aligned}&\{\Delta K_u(t) - \delta_u K_u(t)\} + \{\Delta K_m(t) - \delta_m K_m(t)\} + \\ &\{\Delta K_r(t) - \delta_r K_r(t)\} + \{\Delta K_n(t) - \delta_n K_n(t)\} \\ &+ \{E_{u\_d} - M_u(t)\} + \{E_{e\_d} - M_e(t)\} \\ &= Sh(t) + Sg(t)\end{aligned} \tag{3-23}$$

3.4.11 Restriction of Net Export

The net export is restricted as follows:

$$\varphi_{\min}\{Sh(t)+Sg(t)\}\le\{E_d-M(t)\}\le\varphi_{\max}\{Sh(t)+Sg(t)\} \tag{3-24}$$

in which

φ_{min}: minimum share of net export in total saving (ex) (see Table A3-35); and

φ_{max}: maximum share of net export in total saving (ex) (see Table A3-35).

3.4.12 Production Function

In the model, the technologies adopted in each industry are assumed to be unchanged during the period from 2007 to 2020, so the output of each sector follows a linear production function related to capital stock through a fixed coefficient. The production function is expressed as follows:

$$h_u X_u(t)=K_u(t) \tag{3-25}$$

$$h_m X_m(t)=K_m(t) \tag{3-26}$$

$$h_r X_r(t)=K_r(t) \tag{3-27}$$

$$h_n X_n(t)=K_n(t) \tag{3-28}$$

in which

h_u: capital input coefficient (capital input amount per unit production) in usual industry (ex) (see Table A3-34);

h_m: capital input coefficient in thermal power industry (ex) (see Table A3-36);

h_r: capital input coefficient in hydropower industry (ex) (see Table A3-37); and

h_n: capital input coefficient in new energy industry (ex) (see Table A3-38).

3.4.13 Dynamic Equation of Capital Stock

The capital stock in term (t+1) is related to the capital stock in the last term and the investment in this term. So the capital stock of each industry in term (t+1) is specified as follows:

$$K_u(t+1) = (1-\delta_u)K_u(t) + \Delta K_u(t+1) \quad (3\text{-}29)$$

$$K_m(t+1) = (1-\delta_m)K_m(t) + \Delta K_m(t+1) \quad (3\text{-}30)$$

$$K_r(t+1) = (1-\delta_r)K_r(t) + \Delta K_r(t+1) \quad (3\text{-}31)$$

$$K_n(t+1) = (1-\delta_n)K_n(t) + \Delta K_n(t+1) \quad (3\text{-}32)$$

3.4.14 GHG Emission Constraint

There is one restriction on the GHG emission for each year, and the specific illustration of GHG emission constraint is in Section 3.5.

$$GHG(t) \le \overline{GHG(t)} \quad (3\text{-}33)$$

in which

$\overline{GHG(t)}$: restriction of GHG emission at time t (ex).

This completes the description of our comprehensive evaluation model. In the next sections, we will discuss the case setting and data preparations for the simulation.

3.5 Case Setting

We set up three cases. Case 0 is the business as usual case, which is a simulation of the present development trajectory. And then we do a kind of without- and with-comparison analysis by simulating Case 1, which is the case without comprehensive policy proposals, and Case 2, with comprehensive policy proposals, under various GHG emission constraints.

The comprehensive policy proposals are referred to introduce carbon tax and subsidy to promote the development of new energy industry. Hereby carbon tax is a special tax. It is levied on the thermal power industry, and all the revenue will be used as subsidy to the new energy industry. Considering that the government is expected to levy a carbon tax at a low level starting in 2012 (NDRC, 2010), we assume the carbon tax is changing from 10 to 50 Yuan/ton CO_2e.

As to GHG emission constraint, China has promised to reduce its GHG intensity by 40-45% comparing with 2005 level by 2020, which is a relative reduction target rather than an absolute one. Given that China's GHG emission in 2010 was 2.37 times more than that of 2000, it is a challenge for China to control its GHG emission by 2020 in the range of 1.4~2.0 times more than the base year. In this model, GHG emission constraint is set as: GHG emission in term t is less than n times more than that of base year (n=1.4~2.0). The upper bound of annual GHG emission is set as 12,512 (n=2), 11,886 (n=1.9), 11,260 (n=1.8), 10,635 (n=1.7), 10,009 (n=1.6), 9,384 (n=1.5), and 8,758 MtCO_2e (n=1.4).

Table 3-4 Case setting

	GHG Emission Constraint	Comprehensive policy proposals
Case0	No	No
Case1	Yes	No
Case2	Yes	Yes

3.6 Data Preparations

Data preparations play an important role in achieving accurate results. We have listed all the exogenous parameters in the Appendix, which should be determined before the simulation takes place.

3.6.1 Input Coefficient

The input coefficients Aij reflect the input to industry j by industry i per unit production of industry j. And they are calculated based on the input-output table, using the following equation:

$$A_{ij} = \frac{X_{ij}}{X_j} \qquad (3\text{-}34)$$

in which

A_{ij}: input coefficient to industry j by industry i;

X_{ij}: input to industry j by industry i in 2007 input-output table; and

X_j: production of industry j in 2007 input-output table.

3.6.2 GHG Emission Factor

In terms of GHG emission factors, we first calculated the GHG emission by each industry in 2007, and then the emission factors can be calculated in the following equations.

$$ef_i = \frac{GHG_i}{X_i} \tag{3-35}$$

in which

ef_i: GHG emission factor of industry i;

GHG_i: GHG emitted by industry i; and

X_i: production of industry i.

According to 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), there are three Tiers to estimate emissions from fossil fuel combustion. Tier 1 and Tier2 methods are fuel-based, since emissions from all sources of combustion can be estimated on the basis of the quantities of fuel combusted and average emission factors. The difference is in Tier 2 the country-specific emission factors are used, while the defaults are used in Tier 1. We use the Tier 2 method to estimate the GHG emissions from fossil fuel combustion in China for 2007. Based on the quantities of fuel combusted and emission factors in China Statistics Yearbook 2008, we calculated the total GHG emission in 2007 as 6,285.98 million ton CO_2e. And the GHG emission by each sector is shown in Table 3-5.

As there is no accurate information about the CH_4 emission factor in the open-burning process of crop straw, the default value of 0.0027 t CH_4 per ton of dry biomass as in ACM0018 is adopted. Considering the conservativeness factor 0.73, GWP of CH_4 21, and the proportion of dry biomass in total crop straw 0.79, so the GHG emission factor of crop straw is 0.03307 t CO_2 per ton straw.

Table 3-5 GHG emission by each sector in China for 2007

	GHG emission ($MtCO_2e$)
Agriculture	115.11
Mining industry	408.04
Light industry	203.42
Petroleum and coking	17.72
Chemical industry	444.30
Nonmetal mineral products	374.48
Smelting of metals	1,217.91
Metal products	10.74
Other manufacture industry	82.83
Production of gas	1.42
Production of Water	0.79
Construction	31.85
Transport and postal services	395.84
Other services	123.73
Thermal power	2,639.91
Household	185.24
Open-burning of crop straw	32.67
Total	6,285.98

3.6.3 Disposed Coefficient of Crop Straw

In respect of crop straw, it is the residues after agricultural crop harvest, which is the main byproduct of agriculture production. We estimated the amount of crop straw by the agricultural crop production which could be found in statistical databases, and ratio of residue to grain. In 2007, the total output of crops including food crops, oil crops, cottons, bastfiber crops etc can reach 658 million ton, and 533 million ton crop straw could be produced, as shown in Table 3-6.

Since crop straw is the main byproduct of agriculture production, we only need to calculate the disposed coefficient of crop straw by usual industry.

$$A_{wu} = \frac{W(1)}{X_u(1)} \tag{3-36}$$

in which

A_{wu}: disposed coefficient of crop straw by usual industry;

W(1): amount of crop straw disposed by usual industry in base year; and

$X_u(1)$: production of usual industry in base year.

Table 3-6 Amount of crop straw resources in China for 2007

Types of crops		Crop output/10^4t[a]	Ratio of residue to grain	Theoretical crop output/10^4t
Food crops	Rice	18,603.4	0.68	12,650.31
	Wheat	10,929.8	0.73	7978.75
	Corn	15,230.0	1.25	19,037.50
	Legume crop	1720.1	1.5	2580.15
	Tuber crop	2807.8	1.0	2807.80
	Others	869.1	1.5	1303.65
Oil crops	Peanut	1302.8	1.01	1315.83
	Rapeseed	1057.3	1.01	1067.87
	Sesame	55.7	1.01	56.26
	Others	153	1.01	154.53
	Cotton	762.4	5.51	4200.82
	Bastfiber crop	72.8	2	145.60
	Total	65,752.4		53,299.08

[a] It is derived from China Statistical Yearbook of 2008 (NBS, 2008b).

3.7 Concluding Remarks

In this chapter, we construct a comprehensive evaluation model for Chinese economy based on the value flow balance, energy balance, material balance, and macroeconomic balance. The above-described equations in our comprehensive model make it possible to analyze the interactions among Chinese economy development, energy consumption, and GHG emission simultaneously. We have discussed the model framework and some practical problems that arise when running the comprehensive model of Chinese economy. These are related to sectoral classification, specific formulations, case setting, and data requirements, which are crucial to the quality of the comprehensive model as well as the simulation results. Some concluding remarks are given as follows.

First, of all the issues considered, the work on constructing an extended input-output table for China is the most difficult because of the shortage of data, particularly in the part of new energy industries. The industries are divided into 21 sectors, including 16 existing sectors and 5 newly introduced industries. We should estimate the interrelationship between all the existing industries and 5 newly introduced industries, in terms of input coefficients to new energy industries by usual industry. Moreover, even to the existing industries, some important parameters are not available publicly, such as depreciation rate, fixed capital stock, capital and production factor. Therefore, constructing an extended input-output table and collecting the relevant data is the foundation of our research.

Second, we construct a comprehensive evaluation model for China's energy and environmental policy analysis. The objective function is to maximize the sum of discounted GDP from 2007 to 2020, subject to a serious of constraints. These constraints are set in three view points of value balance, energy balance, and material balance, which are necessary in the comprehensive environmental evaluation. Besides, we also consider the macroeconomic balance among different economy entities.

Third, we set up three cases to simulate how to coordinate the economic development with GHG mitigation. The three cases can be divided into two groups of without and with new energy industry. In the group of without new energy industry, Case 0 is the simulation of the present development trajectory, and the GHG emission constraint is considered in Case 1. On the other hand, Case 2 belongs to the group of with new energy industry, in which the incentive mechanism of carbon tax is introduced to promote the development of new energy industries. Our model can be used to assess the business as usual case, and also evaluate the impacts of carbon tax on China's economy-energy-environment system since the incentive mechanism of carbon tax is included.

Undoubtedly, our comprehensive model provides a suitable approach for analyzing the economic and energy impacts of compliance with GHG emission constraints. Nevertheless, there are some areas where there is a need for further work to enrich the current model. First is considering the technological innovation in each industry. In the current model, the input coefficients are fixed and the production function is linear, which assume to omit the influences brought by technology innovation. Second is incorporating the multi-regional balance. The study area in the current model is the entire China, and it gives an overview of renewable energy development in the national wide. However, since the distribution of resources in China is uneven, it needs to divide China into multi regions and analyze the characteristics of each zone in the future.

CHAPTER 4 COMPREHENSIVE SIMULATION RESULTS ANALYSIS

4.1 Introduction

In this chapter, the dynamic comprehensive model of the Chinese economy, which has been described in Chapter 3, is used to evaluate the economy-wide impacts of the policy proposal introducing carbon tax and new energy industries in China. Before turning to the comprehensive analysis of policy proposals, we first analyze the cases without introducing the policy proposals in Section 4.2, including Case 0 and Case 1. Case 0 is the business as usual case, assuming no policy intervention to limit GHG emission in China. In Case 1, the annual GHG emissions are restricted to specific constraints. In Section 4.3, the cases with new energy industry are developed to evaluate the impacts of the policy proposals, and the optimal case is identified for China. This chapter ends with some concluding remarks.

4.2 Cases without Introducing the Proposed Policies

4.2.1 Analysis of Case 0

In this model, Case 0 is developed for China’s economic development, energy consumption, and GHG emissions outlook to 2020, because any assessment of economic impacts of limiting GHG emissions starts with establishing a plausible baseline scenario. Case 0 is the baseline scenario of our research.

Running the simulation returns the following results: the GDP for the base year is 26,604 billion Yuan, and the GHG emissions for the base year are 6,256 Million ton CO_2e, with errors of 0.01 percent and 0.05 percent, respectively, compared with the public statistics in 2007. The simulation results are well within the usual margins of error; therefore, the model reflects actual social, economic and environmental development with high reliability. As indicated in Figure 4-1, China’s GDP will reach

73,793 billion Yuan in 2020, with 8.24% annual growth rate of GDP. And China's GHG emission would climb to 14,198 Million ton CO_2e in 2020.

GHG intensity is defined as the GHG emission per unit of GDP, and it is an important indicator for China since China promised to reduce its GHG intensity by 40-45% compared with the 2005 level by 2020. By the simulation, GHG intensity in Case 0 is 1.92 tCO_2/10,000 Yuan in 2020, reduced by 31.77% compared with the 2005 level, which reflects the urgency of GHG emission mitigation in China (Figure 4-2).

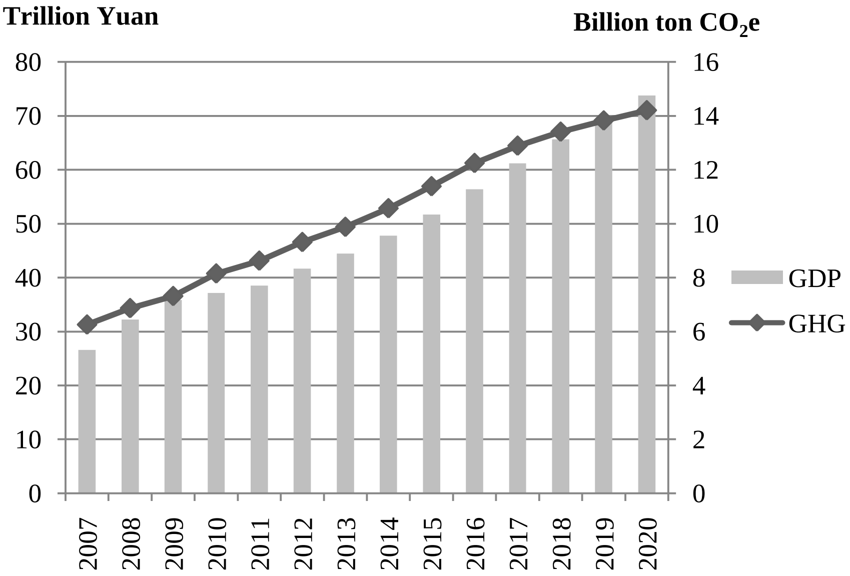


Figure 4-1 Trend of economic growth and GHG emission in Case 0

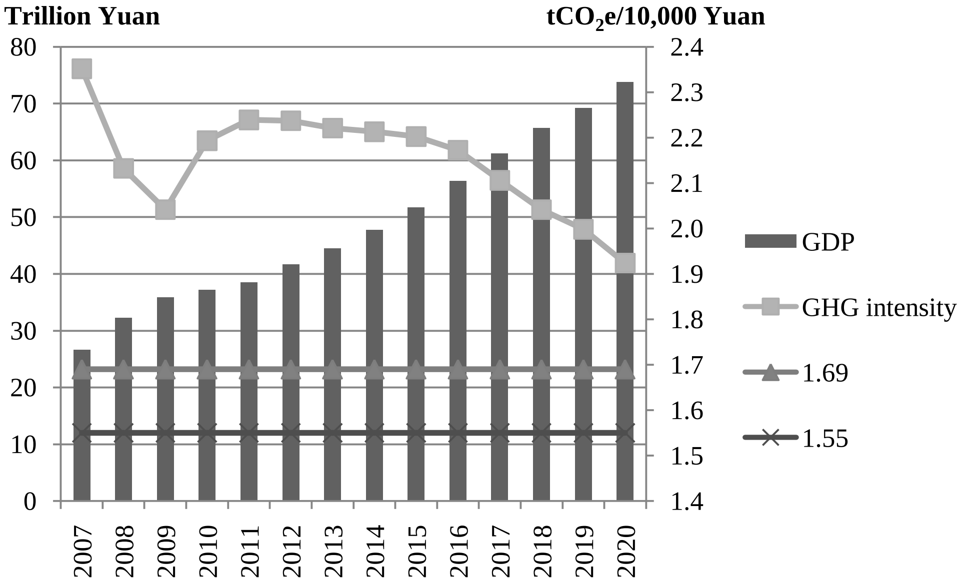


Figure 4-2 Trend of GHG emission intensity in Case 0

Note: 1.55-1.69 tCO_2e/10,000 Yuan is the target of China's climate commitment. China promised to reduce its GHG emission intensity by 40% (1.69 tCO_2e/10,000 Yuan) - 45% (1.55 tCO_2e/10,000 Yuan) comparing with 2005 level by 2020.

4.2.2 Analysis of Case 1

Given the fact that China is already the world's largest GHG emitter and its GHG emissions continue to rise rapidly with its industrialization and urbanization, there is no disagreement that China eventually needs to take on binding the GHG caps. But at present, China only has a relative target in terms of GHG intensity.

In this model, we set GHG emission constraint in Case 1 as following: GHG emission in term t is less than n times more than that of base year (n=1.4~2.0). The upper bound of annual GHG emission is set as 12,512 (n=2), 11,886 (n=1.9), 11,260 (n=1.8), 10,635 (n=1.7), 10,009 (n=1.6), 9,384 (n=1.5), and 8,758 $MtCO_2e$ (n=1.4).

Running the simulation, we get the trends of total GDP and GHG emission from 2007 to 2020 in different GHG emission constraints, shown in Figure 4-3. It implies that the economic development will be restricted more and more tightly with the stricter GHG emission constraint.

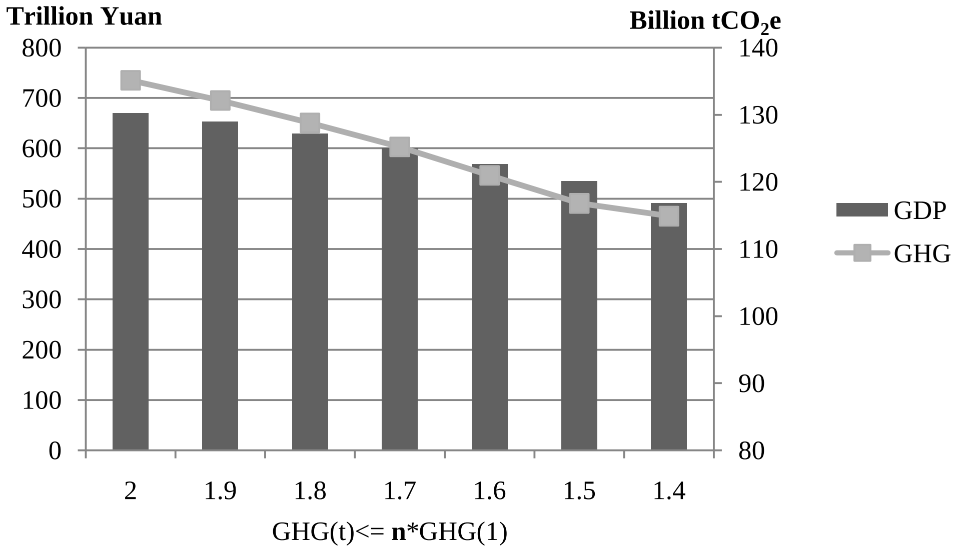


Figure 4-3 Analysis of total GDP and GHG emission from 2007 to 2020

As to the economic growth trend, it always keeps rising in each case from 2007 to 2020 (Figure 4-4). Under GHG emission constraints from 12,512 $MtCO_2e$ (n=2) to 8,758 $MtCO_2e$ (n=1.4), the annual growth rate of GDP is 7.88% (n=2), 7.51% (n=1.9), 6.89% (n=1.8), 6.21% (n=1.7), 5.32% (n=1.6), 4.44% (n=1.5), and 3.93% (n=1.4) separately. As indicated in Figure 4-5, GHG emission is also keeps increasing from 2007 to 2020 in each case. And China’s climate commitment cannot be realized without introducing the proposed policies (Figure 4-6).

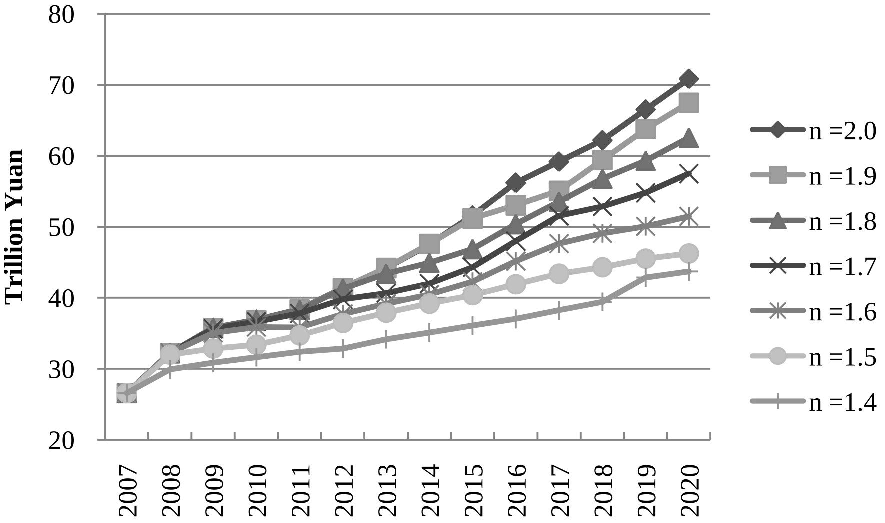


Figure 4-4 Analysis of economic growth trend in Case 1

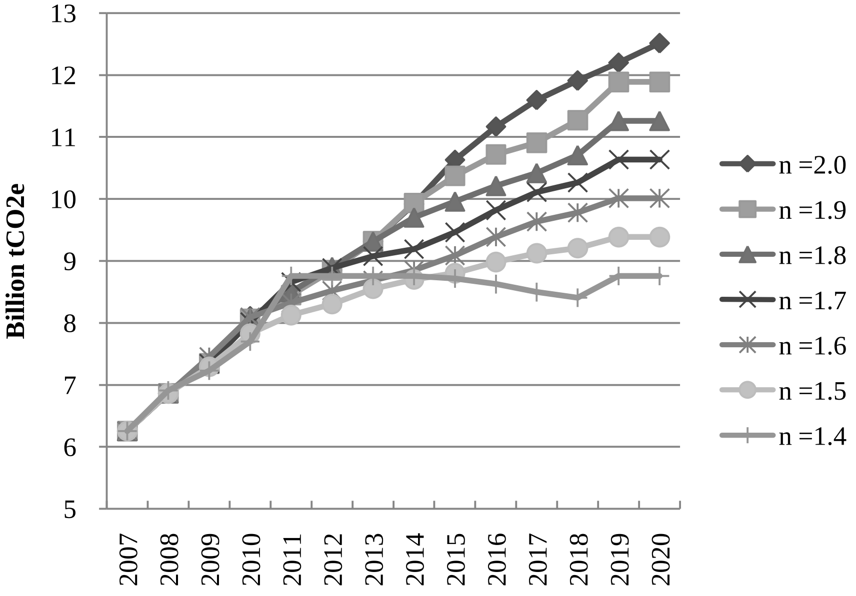


Figure 4-5 Analysis of GHG emission trend in Case 1

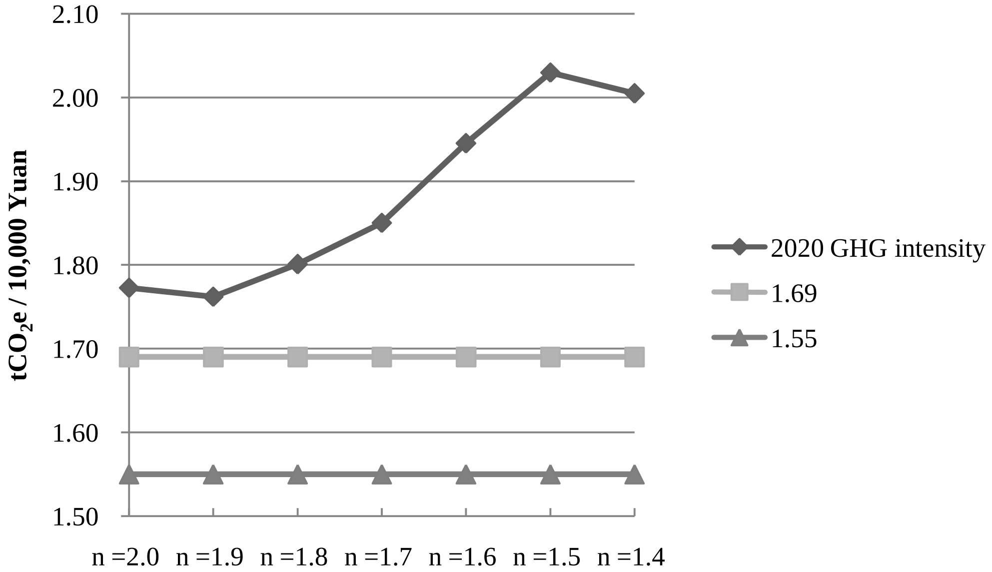


Figure 4-6 GHG intensity in 2020 under different GHG emission constraints

4.3 Cases with Introducing the Proposed Policies

4.3.1 Analysis of Case 2

Because there is no absolute target of GHG emission reduction in China, it is necessary to assess the impacts of proposed policies in different GHG emission constraints, in order to find the optimal case for China. Similar to Case 1, Case 2 has seven types of GHG emission constraints (n=1.4~2.0).

In Case 2, we introduce carbon tax and subsidy policy to promote the development of new energy industries. Carbon tax is levied on the thermal power industry, and all the revenue is used as subsidy to give incentives to develop new energy industries. In this model, carbon tax is exogenous, changing in the range of 10~50 Yuan/tCO_2e. So there are five cases in each GHG emission constraint. In this part, our main work is to select the best carbon tax in each GHG emission constraint.

The objective function of this model is to maximize the sum of discounted GDP from 2007 to 2020, which reflects the impacts on economy development. Running the simulation, we get the objective function in each case. As indicated in Figure 4-7, when the GHG emission constraint is set as two times more than base year, the case of 20 Yuan/tCO_2e has the largest objective function. Therefore the best carbon tax for two times GHG emission constraint (n=2) is 20 Yuan/tCO_2e. In the same way, we choose the best carbon tax as 40 Yuan/tCO_2e for 1.9 times GHG emission constraint (n=1.9), 30 Yuan/tCO_2e for 1.8 times GHG emission constraint (n=1.8), 20 Yuan/tCO_2e for 1.7 times GHG emission constraint (n=1.7), 10 Yuan/tCO_2e for 1.6 times GHG emission constraint (n=1.6), 40 Yuan/tCO_2e for 1.5 times GHG emission constraint (n=1.5), 10 Yuan/tCO_2e for 1.4 times GHG emission constraint (n=1.4), separately (Figure 4-8, 4-9, 4-10, 4-11, 4-12, 4-13).

In sum, the best carbon tax in different GHG emission constraints can be identified, as shown in Table 4-1.

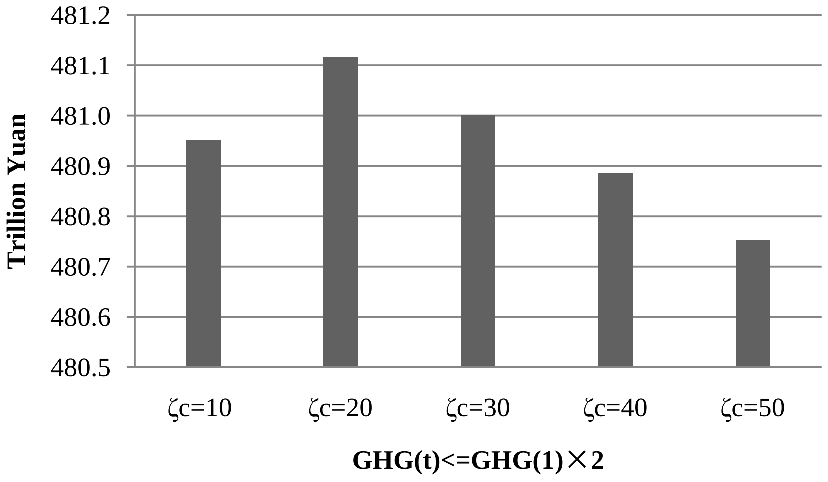


Figure 4-7 Comparison of objective function in cases (n=2)

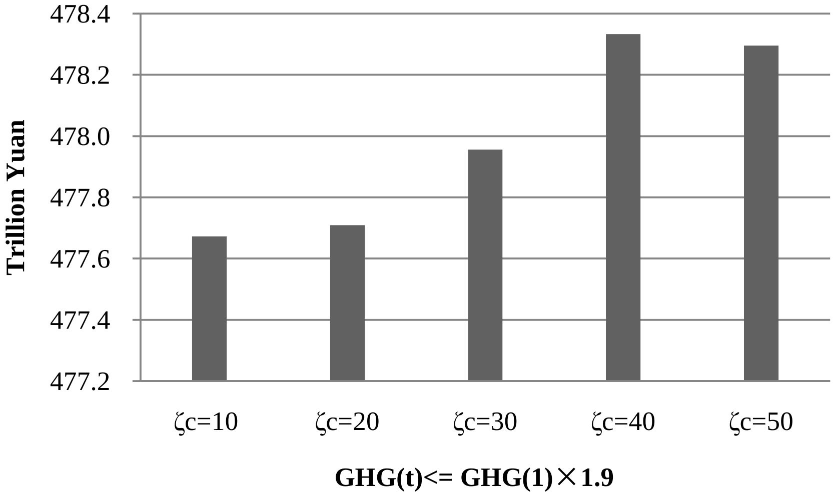


Figure 4-8 Comparison of objective function in cases (n=1.9)

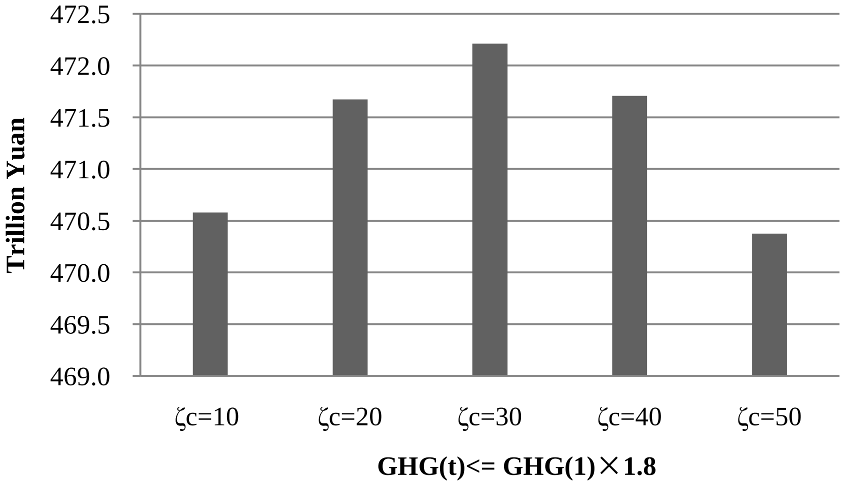


Figure 4-9 Comparison of objective function in cases (n=1.8)

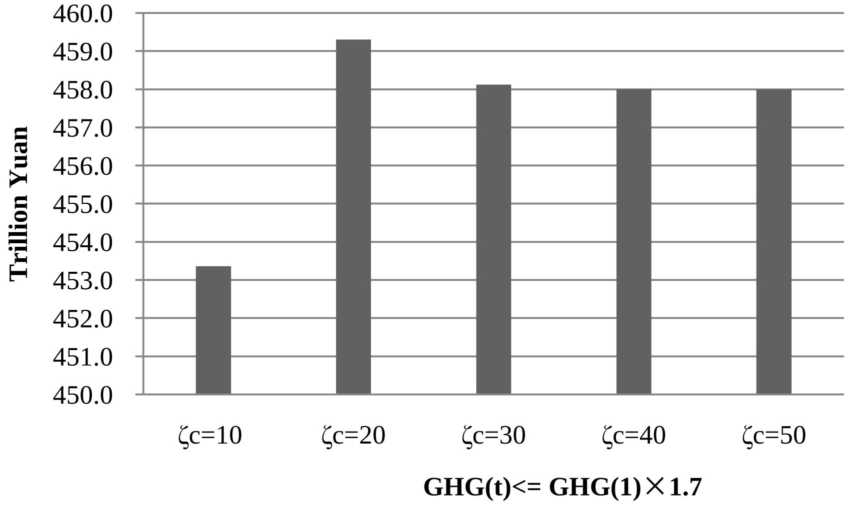


Figure 4-10 Comparison of objective function in cases (n=1.7)

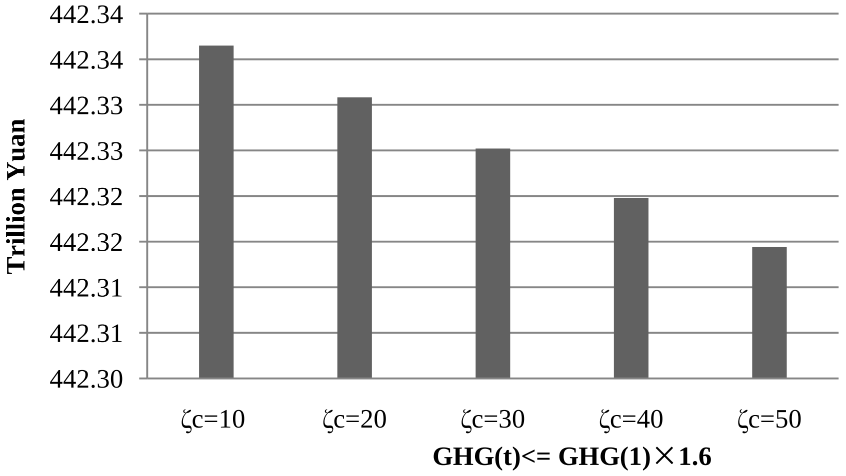


Figure 4-11 Comparison of objective function in cases (n=1.6)

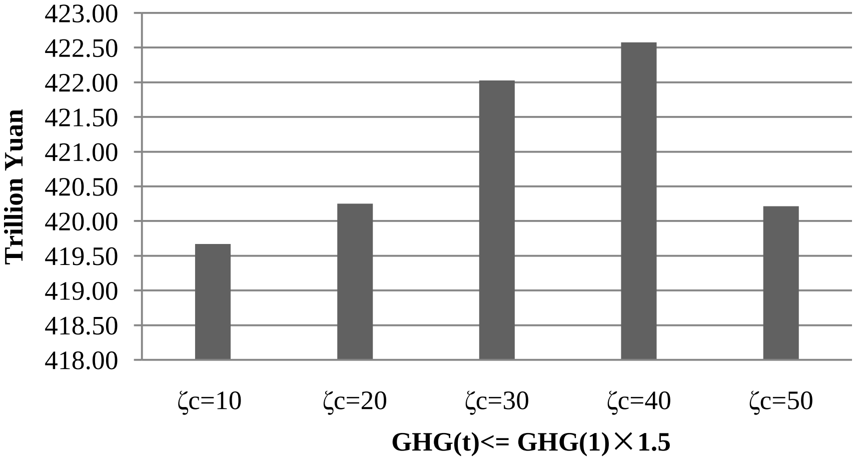


Figure 4-12 Comparison of objective function in cases (n=1.5)

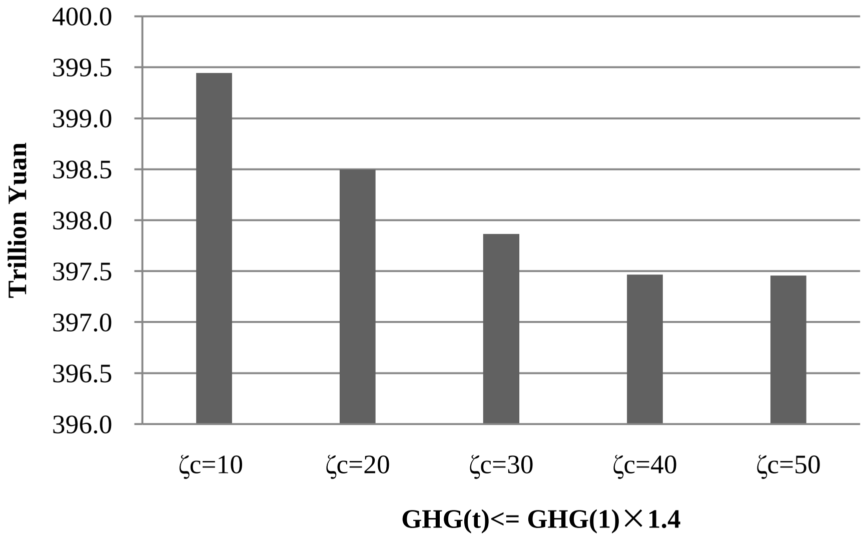


Figure 4-13 Comparison of objective function in cases (n=1.4)

Table 4-1 the best carbon tax in different GHG emission constraints

GHG emission constraint	Best carbon tax (Yuan/tCO_2e)
n =2.0	20
n =1.9	40
n =1.8	30
n =1.7	20
n =1.6	10
n =1.5	40
n =1.4	10

4.3.2 Optimal Case Choice

As analyzed above, we have selected the best carbon tax in seven types of GHG emission constraints. When the GHG emission constraint is set as two times more than the base year, the best carbon tax is 20 Yuan/tCO$_2$e (n=2). And it is 40 Yuan/tCO$_2$e (n=1.9), 30 Yuan/tCO$_2$e (n=1.8), 20 Yuan/tCO$_2$e (n=1.7), 10 Yuan/tCO$_2$e (n=1.6), 40 Yuan/tCO$_2$e (n=1.5), and 10 Yuan/tCO$_2$e (n=1.4). In this part, we will identify the optimal case from the cases above. To be simple, we use Case 2 (n=1.4~2) to represent the case with best carbon tax in different GHG emission constraints.

Firstly, we evaluate the impacts of proposed policies by comparing the objective function between Case 1 and Case 2 in different GHG emission constraints. As indicated in Figure 4-14, the objective function in Case 2 is higher than Case 1 in each GHG emission constraint, which implies that it is effective to promote the economic development by introducing the comprehensive policy proposals.

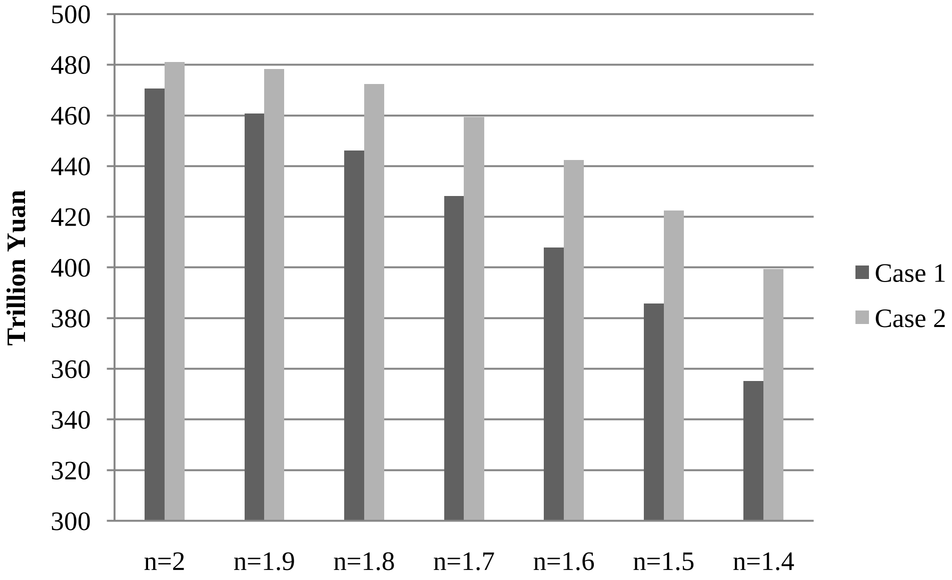


Figure 4-14 Comparison of objective function in cases

And then we will identify the optimal case in Case 2 from five aspects, such as economic development, GHG intensity, renewable energy development, energy intensity, and investment effect.

(1) Economic indicator

As the largest developing country, China put the economic development at the top-priority position and set the mandatory target of economic growth rate in the Five-Year Plan. During the 11th Five-Year period (2006-2010), the target of annual economic growth rate is set as 7.5%. In fact, China overfilled this target and the annual growth rate of GDP has reached 11.2% from 2006 to 2010. Besides, in the latest establishment of 12th Five-Year Plan (2011-2015), the target of annual economic growth rate is set as 7%. Furthermore, President Hu Jintao proclaimed China would double its 2010 GDP by 2020 in the 18th National Congress of Chinese Communist Party. Therefore, China's annual growth rate of GDP should be at least 7% from 2007 to 2020.

Running the simulation, we can get the trend of economic development in the cases with best carbon tax under different GHG emission constraints. As indicated in Figure 4-15, the annual growth rate of GDP is 8.19% in GHG emission constraint of two times more than base year (n=2), 8.11% in GHG emission constraint of 1.9 times more than base year (n=1.9), 7.91% in GHG emission constraint of 1.8 times more than base year (n=1.8), 7.37% in GHG emission constraint of 1.7 times more than base year (n=1.7), 6.72% in GHG emission constraint of 1.6 times more than base year (n=1.6), 6.06% in GHG emission constraint of 1.5 times more than base year (n=1.5), 5.14% in GHG emission constraint of 1.4 times more than base year (n=1.4).

Combined with China's target of economic growth rate, we choose the cases in which the annual growth rate of GDP is above 7% as the most likely scenarios for China. They are the cases of 20 Yuan/tCO_2e in the GHG emission constraint of two times more than the base year (n=2), 40 Yuan/tCO_2e in the GHG emission constraint of 1.9 times more than the base year (n=1.9), 30 Yuan/tCO_2e in the GHG emission constraint of 1.8 times more than the base year (n=1.8), and 20 Yuan/tCO_2e in the GHG emission constraint of 1.7 times more than the base year (n=1.7). In the following part, we will identify the optimal case among the four cases.

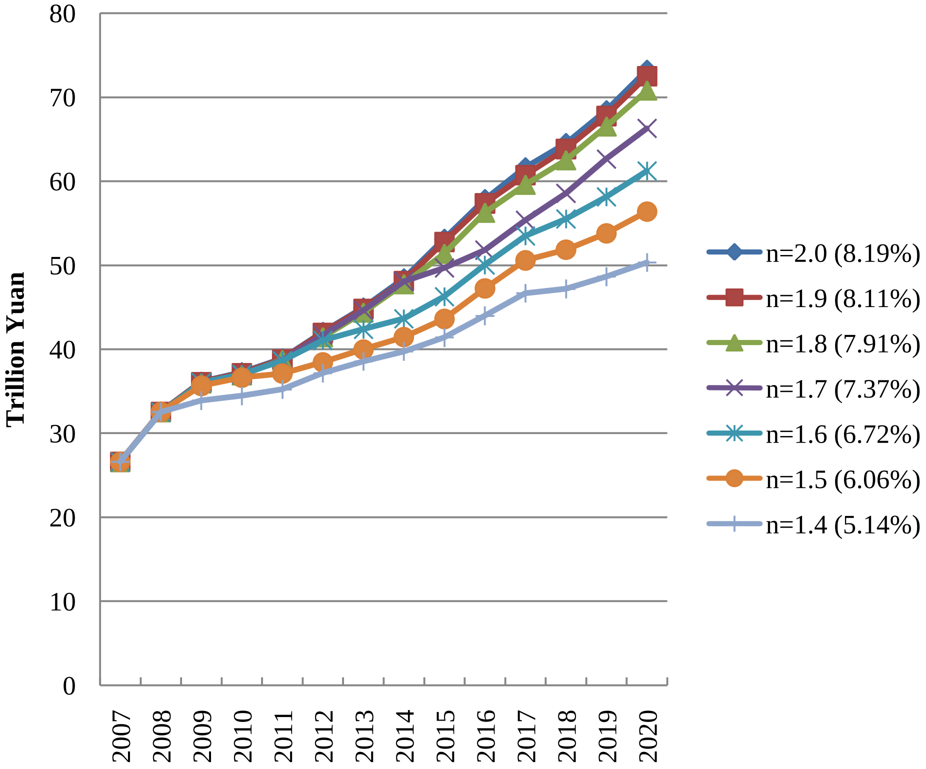


Figure 4-15 Trend of GDP in different GHG emission constraints

(2) Indicator of GHG intensity

GHG intensity is an important indicator describing the amount of GHG emission by increasing one unit of GDP. Average GHG intensity reflects the average amount of GHG emission by increasing one unit of GDP from 2007 to 2020. And 2020 GHG intensity is GHG intensity in 2020, indicating the implementation progress of China’s climate commitment.

As indicated in Figure 4-16, the case with 30 Yuan/ tCO_2 in the GHG emission constraint of 1.8 times more than the base year (n=1.8) has the lowest value in both average GHG intensity and 2020 GHG intensity in all cases. In this case, China needs to emit at least 1.89 tCO_2 to increase 10,000 Yuan GDP from 2007 to 2020. The corresponding GHG intensity in 2020 is 1.60 tCO_2/10,000 Yuan, reduced by 43.13% compared with the 2005 level, which indicates that China’s climate commitment can be realized successfully.

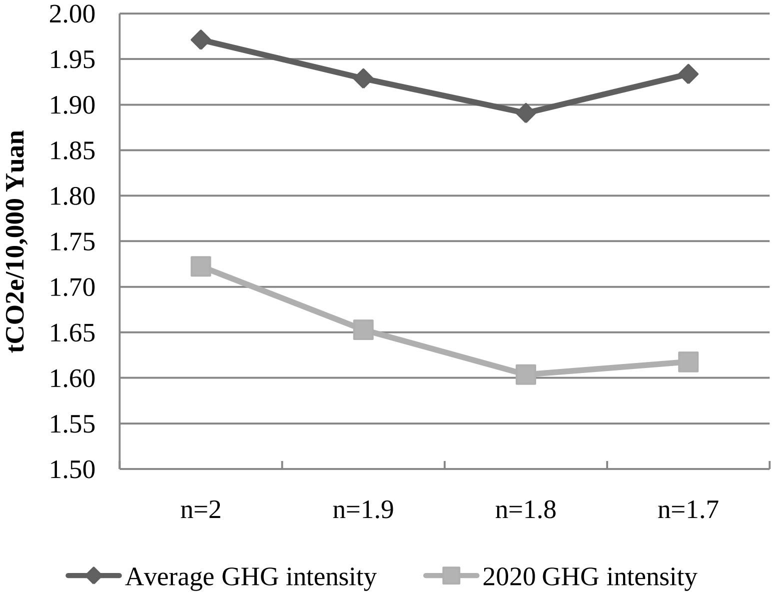


Figure 4-16 Comparison of GHG intensity in cases

(3) Indicator of renewable energy development

In our research, renewable energy includes hydropower, wind power, solar power, and biomass power. Due to the high cost, the development of wind power, solar power and biomass power is delayed in the base year. So we propose the comprehensive policies of introducing carbon tax to promote the development of new energy industries, including wind power, solar power, and biomass power. As indicated in Figure 4-17, the case of 30 Yuan/tCO$_2$e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8) has the highest share of renewable energy power generation, accounting for 19.24% in the total electricity generation from 2007 to 2020. Therefore, the case of 30 Yuan/tCO$_2$e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8) can promote the renewable energy development rapidest.

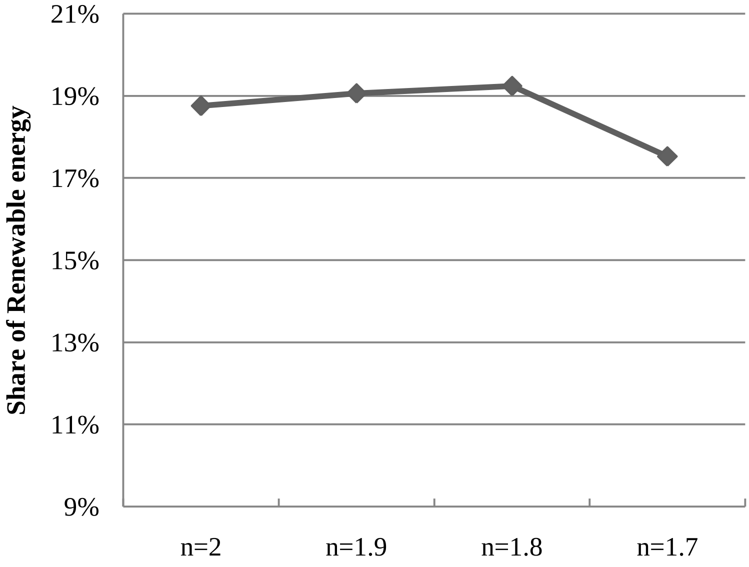


Figure 4-17 Comparison of renewable energy development in cases

(4) Indicator of energy intensity

Energy intensity is defined as energy consumption by increasing one unit of GDP, which reflects the utilization efficiency of energy in the economic development. As indicated in Figure 4-18, the case of 30 Yuan/tCO$_2$e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8) has the lowest energy intensity, implying that it is the most efficient in energy consumption to trade off GHG mitigation and economic development.

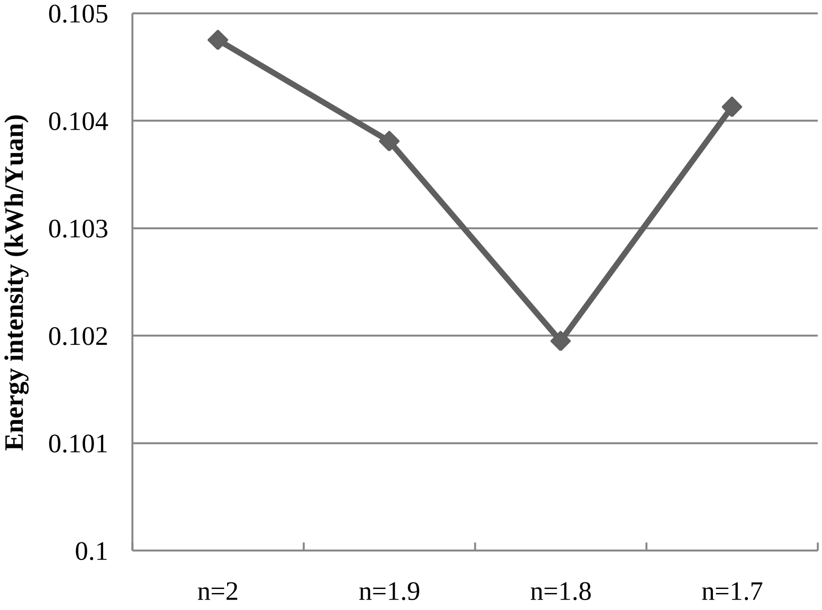


Figure 4-18 Comparison of energy intensity in cases

(5) Indicator of investment effect on GDP

Investment effect on GDP (α) is an important indictor for policymaking, which reflects the economic feasibility of implementing the proposed policies. We adopt the cost-benefit ratio to evaluate the investment effect on GDP. It is defined as follows:

$$\alpha = \Delta GDP / \Delta S \tag{4-1}$$

in which

ΔS: total investment to new energy industries from 2007 to 2020; and

ΔGDP: increasing of GDP brought by new energy industries from 2007 to 2020.

As indicated in Figure 4-19, the case of 30 Yuan/tCO_2e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8) has the best investment effect on GDP, and it is the most feasible economically in promoting China’s sustainable development.

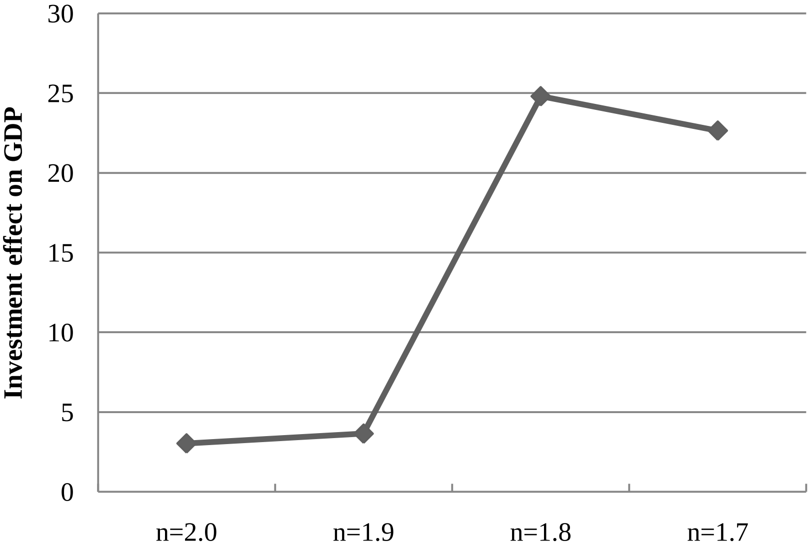


Figure 4-19 Comparison of investment effect on GDP in cases

In sum, the optimal case is identified as the case of 30 Yuan/tCO_2e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8), because it can stimulate the renewable energy development, GHG mitigation, and economic development most effectively.

4.3.3 Optimal Case Analysis

As described above, the optimal case for China is identified as the case of 30 Yuan/tCO_2e carbon tax in the GHG emission constraint of 1.8 times more than the base year (n=1.8). We will analyze the optimal case from the following three aspects.

(1) Economic development and GHG emission

Running the simulation, we get the trend of GDP and GHG emission in the optimal case. As indicated in Figure 4-20, China's economic development and GHG emission keep rising from 2007 to 2020. With 7.91% annual growth rate of GDP, China's GDP has reached 36.91 Trillion Yuan in 2010, and 70.79 Trillion Yuan in 2020. In the 18th National Congress of Chinese Communist Party, the Chinese government has established its economic development target in 2020 of doubling its 2010 GDP. Our simulation results indicate that the government target can be realized by introducing the comprehensive policies of carbon tax and new energy industry.

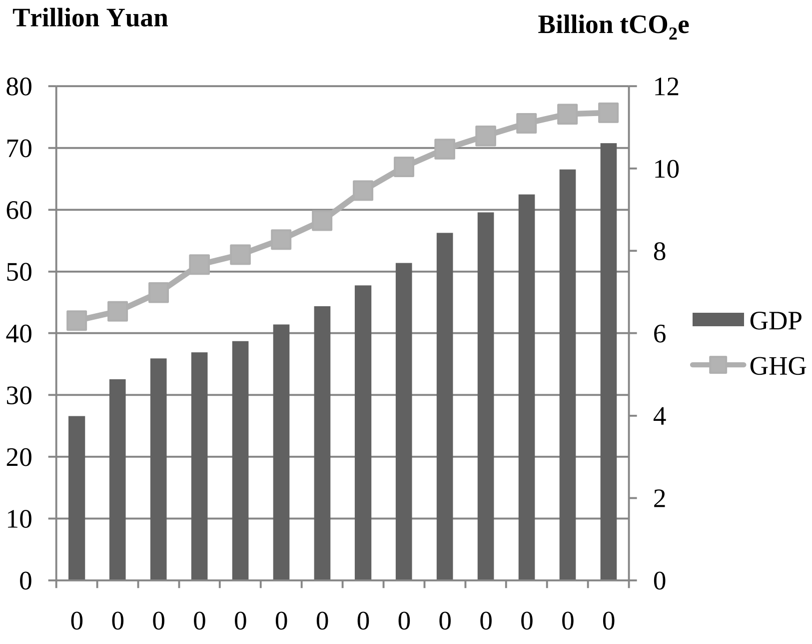


Figure 4-20 Trend of GDP and GHG emission in optimal case

Besides, tax rate is an indictor to describe the burden ratio at which an economic entity is taxed. It is the rate of total carbon tax paid by an industry in the production of this industry. By the simulation, thermal power industry has the largest average tax rate among all the industries, which is 2.52% annually in the optimal case. It implies that 30 Yuan/tCO_2e carbon tax is endurable for all the industries in China.

In the optimal case, China’s GHG emission in 2020 has climbed to 11.35 Billion tCO_2e. By comparing the total GHG emission from 2007 to 2020 between Case 0 and optimal case, the mitigation potential of optimal case is 17.98 Billion tCO_2e. As indicated in Figure 4-21, the top two sectors in reducing GHG emission in optimal case are thermal power industry and usual industry.

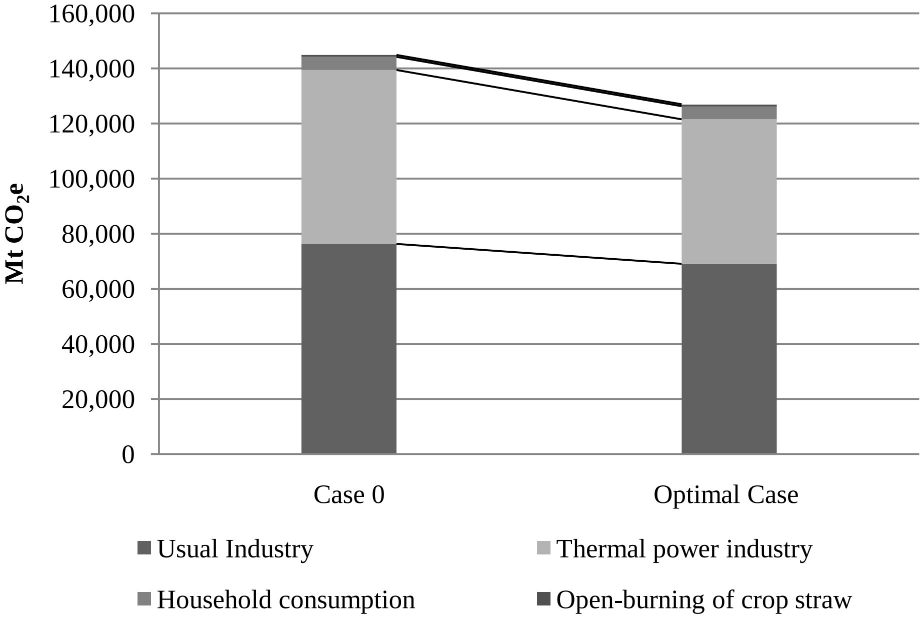


Figure 4-21 Comparison of total GHG emission from 2007 to 2020

Besides, GHG intensity is an important indicator for China, and the trend of GHG intensity can reflect the relationship between the growth rate of GHG emission and economic growth rate. As indicated in Figure 4-22, the declining trend of GHG intensity from 2007 to 2020 reflects the annual growth rate of GHG emission is less than the growth rate of GDP. GHG intensity in 2020 is 1.60 tCO_2e/10,000 Yuan, reduced by 43.13% compared with 2005 level. It implies that China’s climate commitment of reducing the GHG intensity by 40-45% in 2020 comparing with 2005 is appropriate for China, which can be realized by introducing the comprehensive policies of carbon tax and new energy industry.

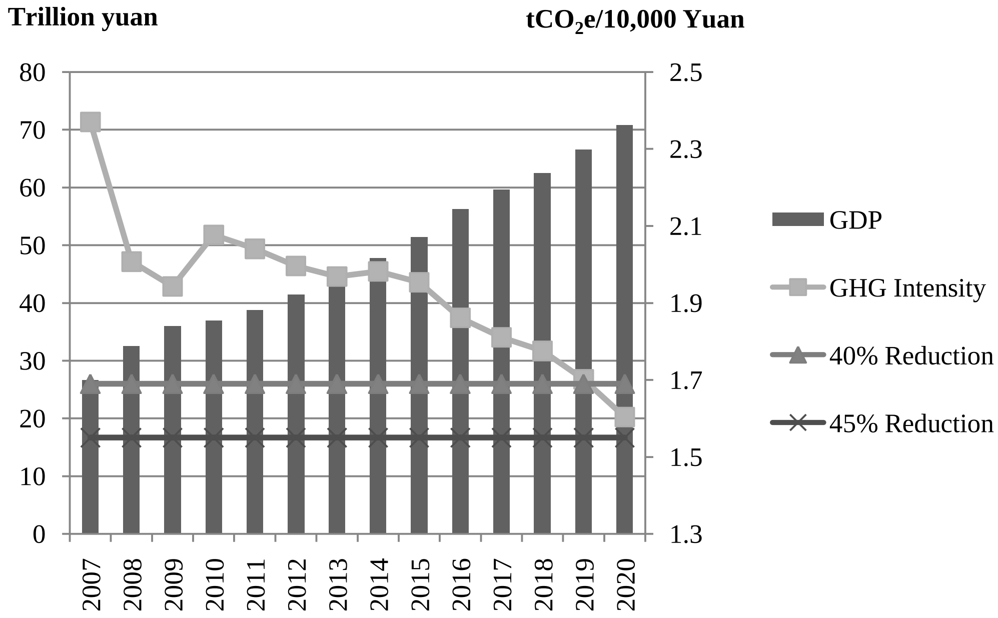


Figure 4-22 Trend of GHG intensity in optimal case

(2) Impact analysis of the proposed policies

In this part, we will assess the impacts of the proposed policies on China's economic development and GHG mitigation. To be comparable to the optimal case, Case 1 in this part is referred to the case in which GHG emission constraint is the same as that of optimal case, 1.8 times more than the base year.

Comparison between Case 1 and optimal case in Figure 4-23 shows that the comprehensive proposed policies will increase the discounted sum of GDP over 2007 to 2020 by 42.60 Trillion Yuan and on the other hand, decrease the sum of GHG emission by 1.84 Billion t CO_2e. It proves that the proposed policies are effective to promote both economic development and GHG mitigation in China. Besides, it is interesting to find the unequal change of GDP and GHG emission between Case 1 and optimal case. If the contribution by the new energy industry to GDP is huge, in that case the GHG emission in optimal case will become far below the upper constraint of GHG emission. However, the results show GHG emission is not reduced so much in optimal case. Therefore, we will analyze the difference of GHG emission and GDP between Case 1 and optimal case, in order to check the contributions by each industry to the unequal changes.

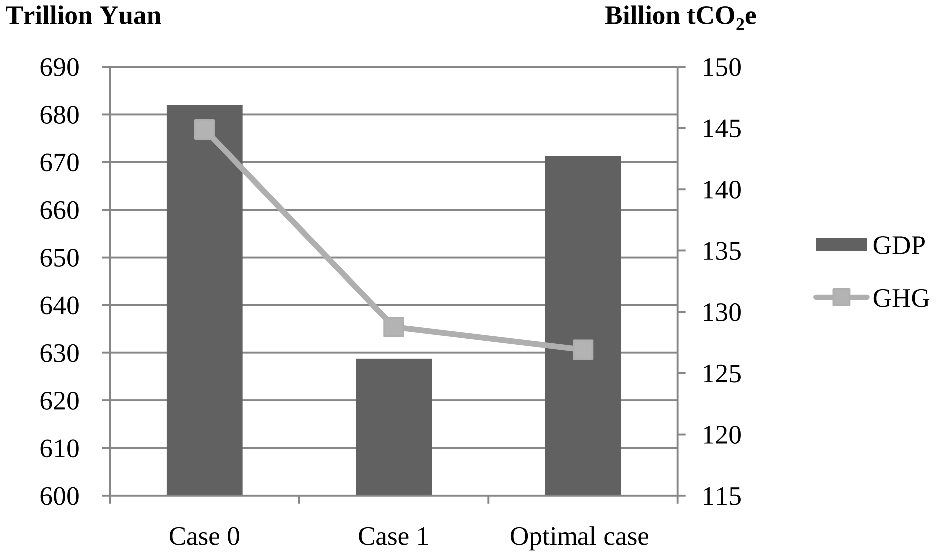


Figure 4-23 Comparison of GDP and GHG emission in cases

As indicated in Figure 4-24, the decrease of GHG emission in optimal case is mainly from thermal power industry, which has the largest GHG emission factor in all sectors (Figure 4-25). It implies that electricity substitution is an important mitigation measure in optimal case. In Case 1, the electricity is supplied by thermal power and hydropower. In optimal case, the electricity is supplied by thermal power, hydropower, wind power, solar power and biomass power. Because the development of hydropower remains controversial on river ecosystems damage and human displacement problem, we assume that China will not build large hydropower facilities by 2020. As shown in Figure 4-26, the total electricity demand in Case 1 and optimal case is nearly the same, but the thermal power generation in optimal case is declining compared with Case 1. That is because the electricity generated by new energy industry in optimal case can substitute the equivalent thermal power.

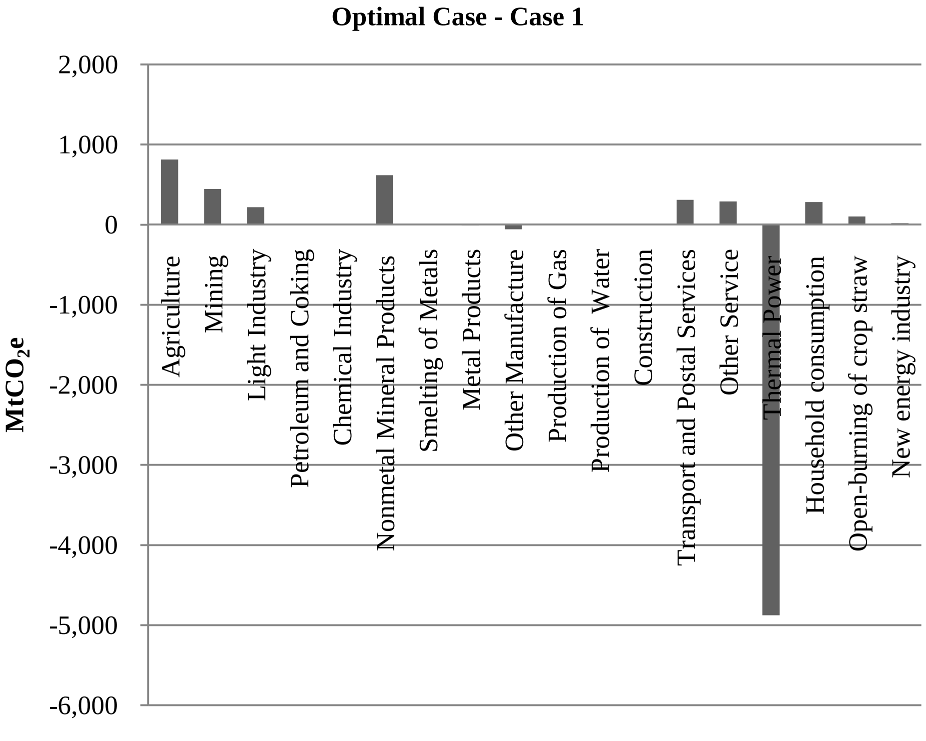


Figure 4-24 Difference of GHG emission in each industry

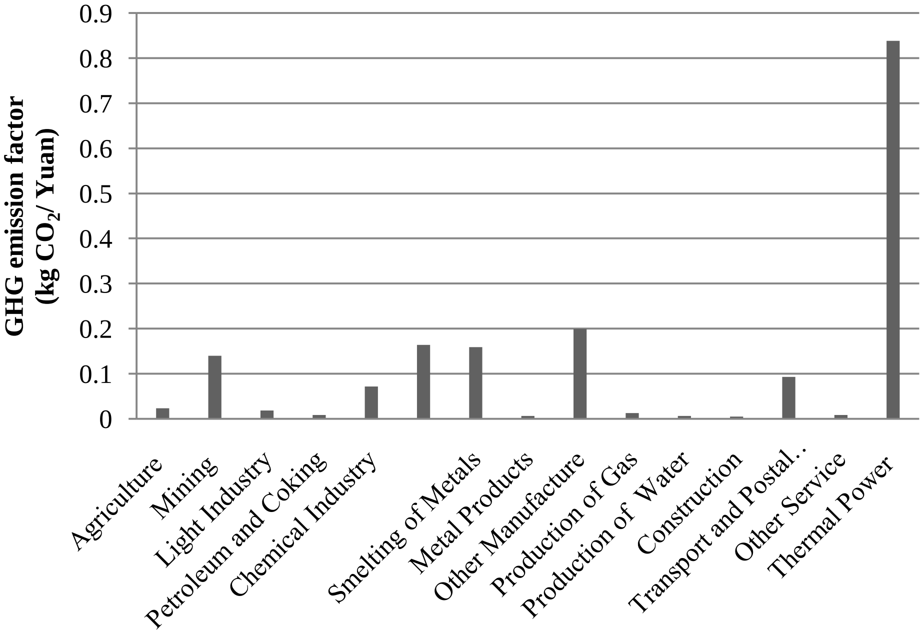


Figure 4-25 GHG emission factors of industries

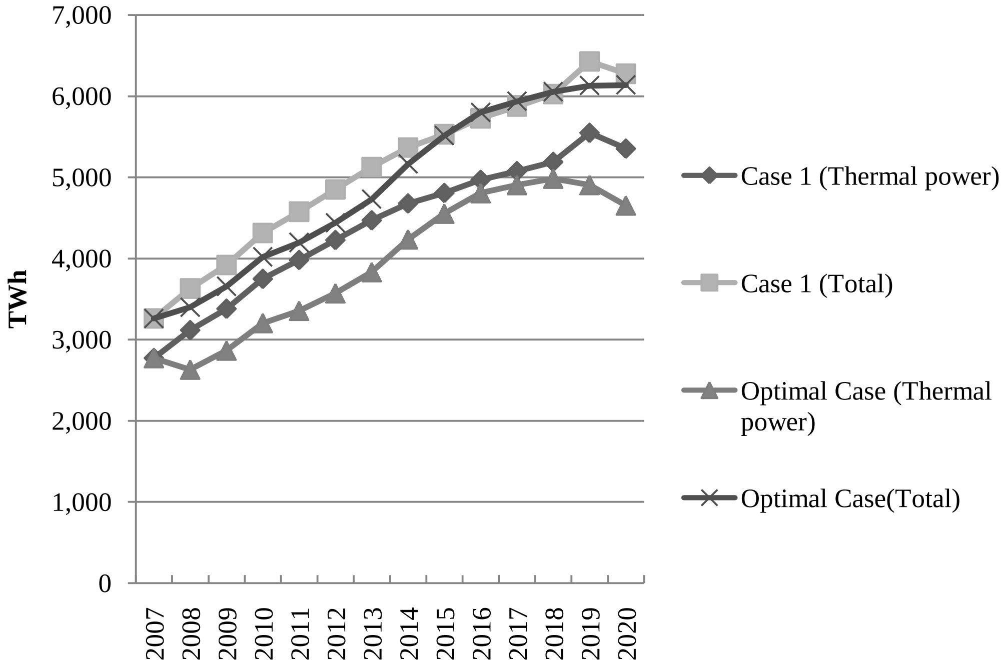


Figure 4-26 Electricity supply trend between optimal case and Case 1

And then we will check the contribution to GDP by each industry between optimal case and Case 1. As indicated in Figure 4-27, the increase of GDP in optimal case is mainly benefit from the industrial structure adjustment. In the optimal case, the added-value of agriculture (GDP_u(1)), other service (GDP_u(14)), light industry (GDP_u(3)) is increasing, while the added-value of other manufacture industry (GDP_u(9)) is declining. Therefore, industrial structure adjustment is another key method to promote the economic development and satisfy the GHG emission constraint.

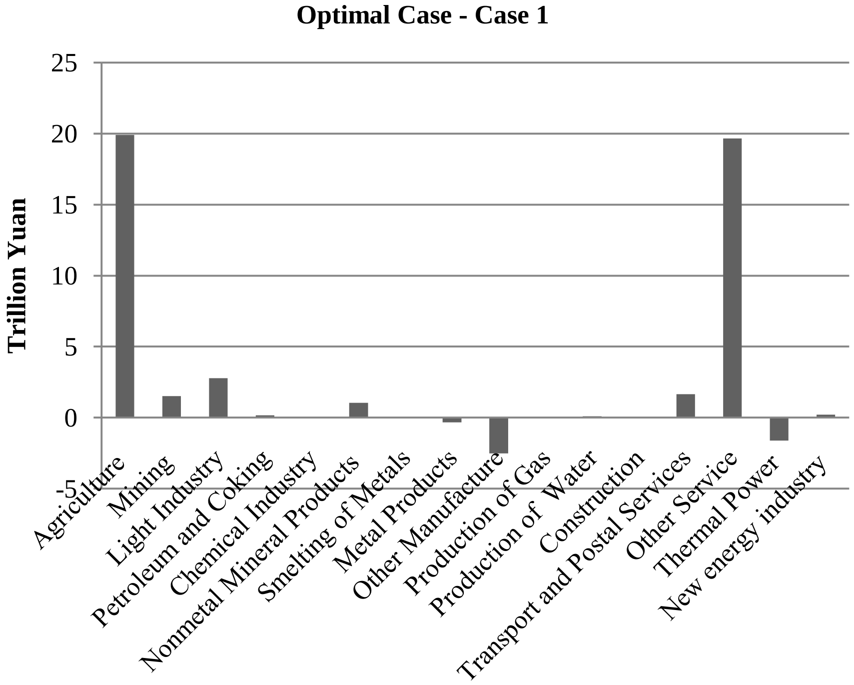


Figure 4-27 Difference of Added-value in each industry

In order to analyze the characteristics of industrial structure adjustment, we choose two typical sectors for discussion, other service industry and other manufacture industry. As indicated in Figure 4-28, the production of other service industry is increasing with introduction of the proposed policies. This increase implies that to trade off the economic development and GHG mitigation, the model will promote the development of sectors with higher added-value rate and less GHG emission factor (Figure 4-25, 4-30). Otherwise, the development of sectors with less added-value rate and higher GHG emission factor will be constrained, such as other manufacture industry (Figure 4-29).

Besides, the price rate of all the industries is 1.00 in Case 0 and Case 1, because carbon tax policy is not introduced in these two cases. In contrast, with the introduction of carbon tax policy, the price rate of all the industries has changed, and the effect on power industries is more obvious. In this mechanism, carbon tax will increase the cost of thermal power industry, while subsidy will decrease the cost of renewable energy industries. At last, it reaches an equilibrium state in which the cost of thermal power industry is the same with renewable energy industries.

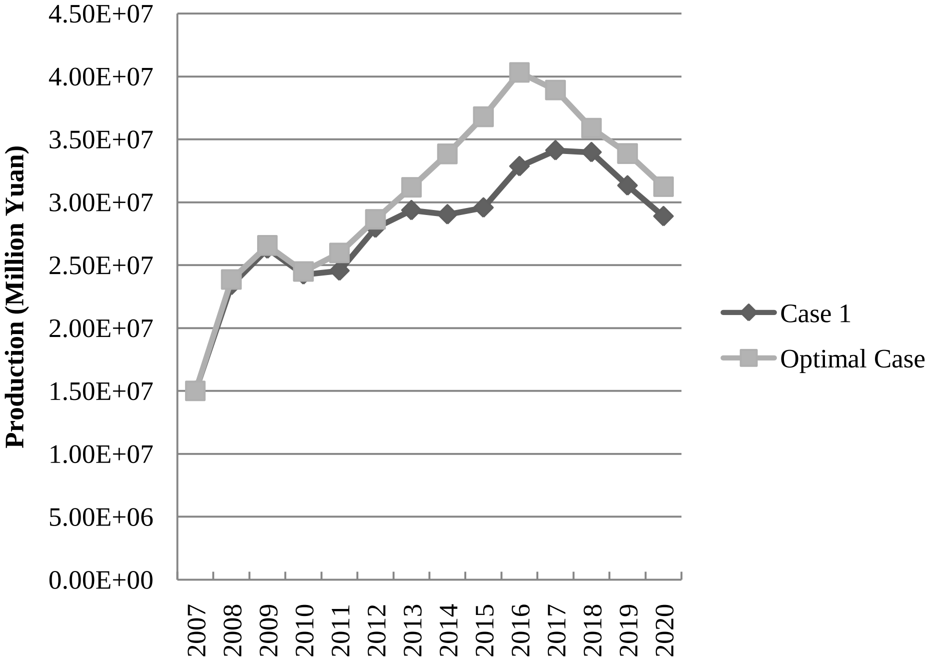


Figure 4-28 Production of other service industry in cases

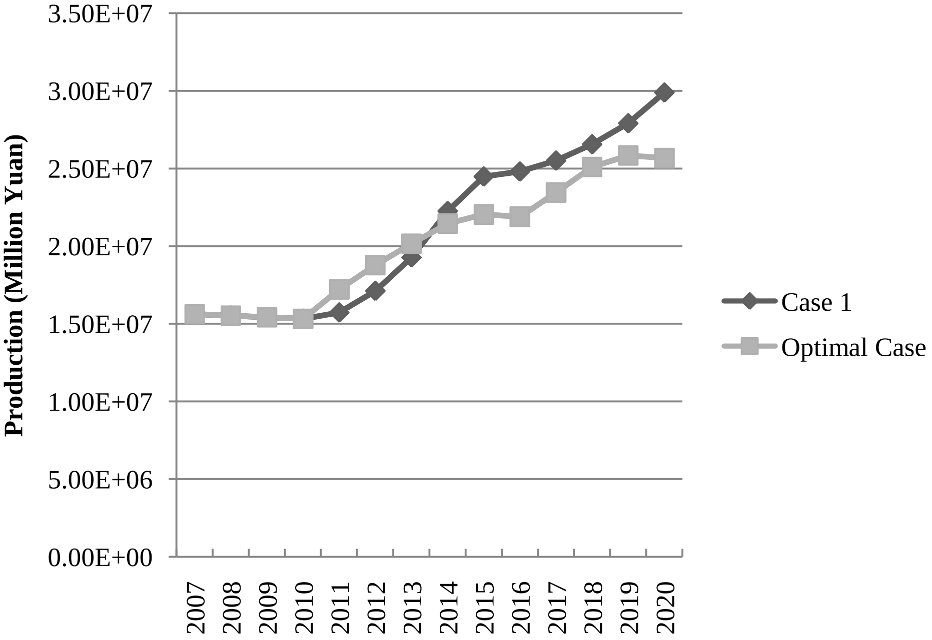


Figure 4-29 Production of other manufacture industry in cases

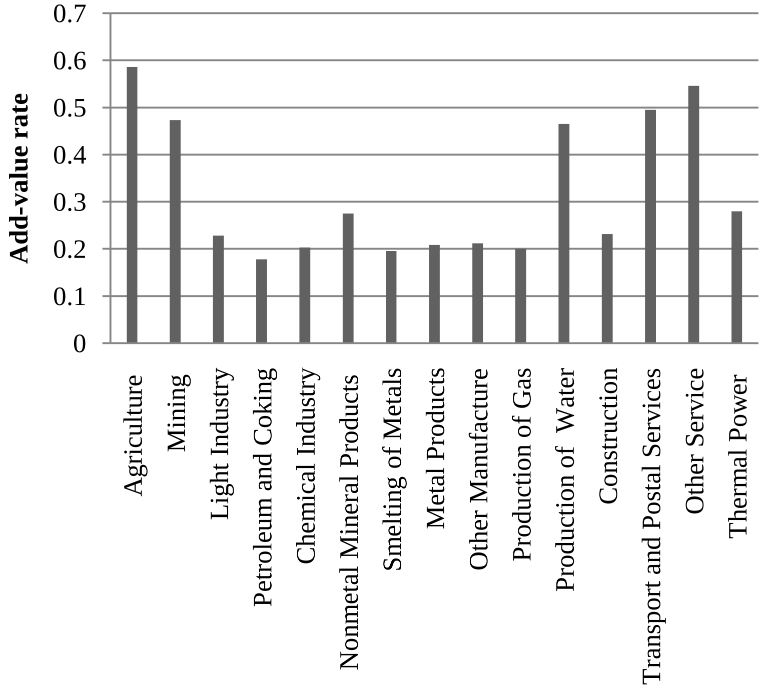


Figure 4-30 Added-value rate of industries

(3) Energy system transformation

At last, let us analyze the energy system transformation in optimal case. As indicated in Figure 4-31, total electricity demand keeps rising from 2007 to 2020, and the growing trend becomes stable since 2017. The reason is that China's GHG emission has almost reached the upper limit in 2017, and GHG emission constraint will restrict the development of all the industries, resulting in the total electricity demand nearly stable since 2017. Besides, due to the own advantages, wind power, biomass power and solar power can be developed in the optimal case. The cost of wind power is less than that of biomass power and solar power, while biomass power can reuse the biomass waste. And there is no GHG emitted in the process of solar power generation.

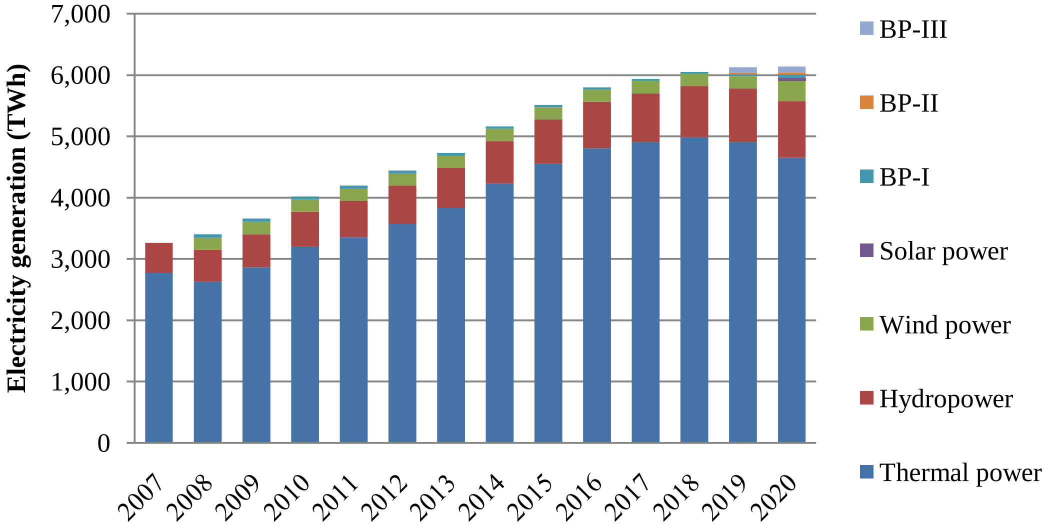


Figure 4-31 Electricity supply structure in optimal case

With the subsidy from 30 Yuan/tCO$_2$e carbon tax, the new energy power generation is increasing greatly. As indicated in Figure 4-32, total electricity generation of wind power is 2,726.05 TWh, biomass power 803.98 TWh, solar power 44.00 TWh. The developing priority of new energy is determined by the subsidy distribution. The total subsidy from 2007 to 2020 is 1,494.56 Billion Yuan, 80% used in wind power industry (Figure 4-33). That is why the wind power developed rapidest in this simulation.

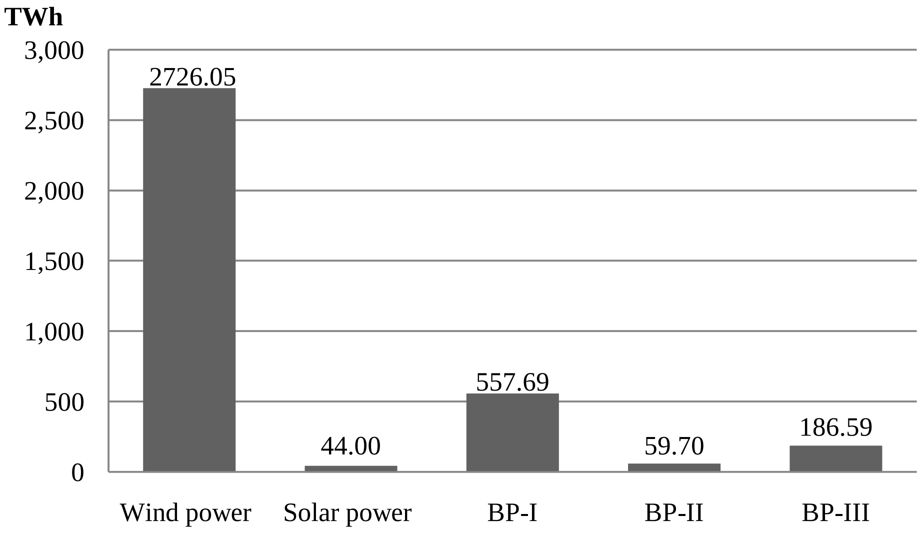
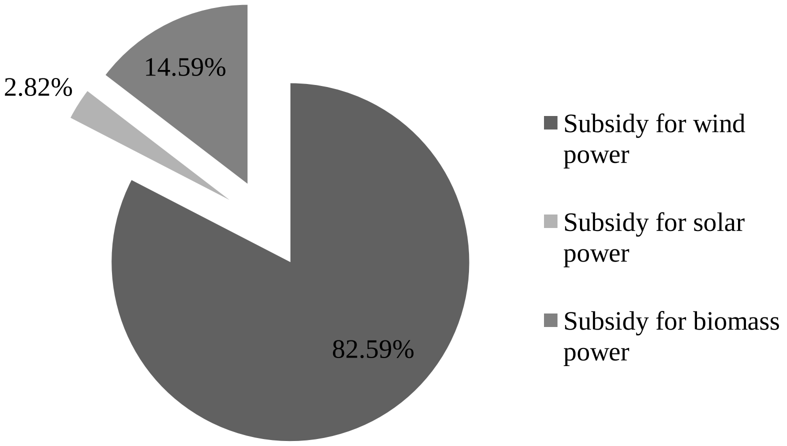


Figure 4-32 New energy power generation from 2007 to 2020



Total subsidy: 1,494.56 Billion Yuan

Figure 4-33 Subsidy distribution in optimal case from 2007 to 2020

Running the simulation, we can get the electricity supply structure in the base year and target year. In the base year of 2007, the share of thermal power is 85% in the total electricity supply. In contrast, the share of thermal power is reduced to 75.83% in the target year of 2020, and the share of new energy power generation in the total electricity supply is increased to 9.14%, as shown in Figure 4-34.

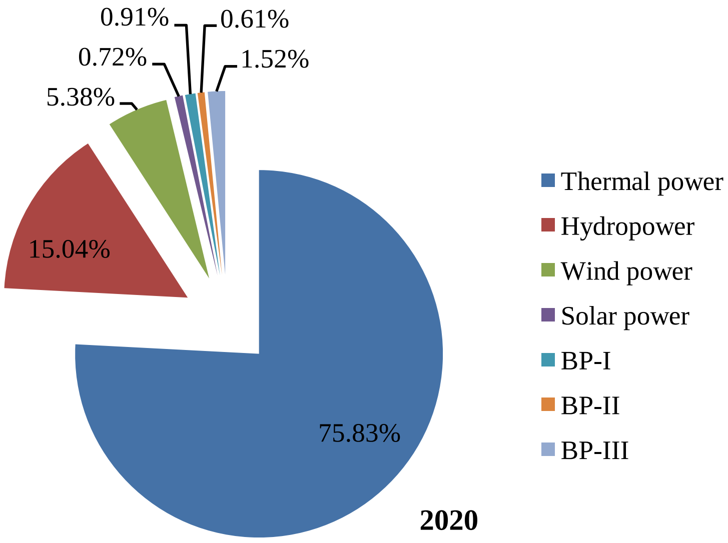


Figure 4-34 Electricity supply structure in 2020

Comparing with China’s target of renewable energy development, it indicates that the government target of new energy power generation can be realized with introducing the comprehensive proposed policies (Table 4-2). Besides, the exploited percentage of wind power reaches 15.47% in 2020, solar power 0.0026%, which indicates the reasonable development of wind power and solar power in China. Therefore, the gap between simulation results and government target indicates that China’s target of wind power and solar power need to upgrade.

Table 4-2 Comparison of simulation results with China’s development target

	Simulation results (TWh)	Average capacity factor	Installed capacity (GW)	2020 Target (GW)
Hydropower	922.87	0.38	277.24	300
Wind power	330.01	0.25	154.68	30
Solar power	44.23	0.25	25.09	1.8
Biomass power	186.59	0.71	33.27	30

Note: 2020 target refers to the renewable energy development targets in the “Medium and long-term development plan for renewable energy in China” (NDRC, 2007b). Hydropower capacity factor is a 1980-2006 historical average, from CEG (2008); wind and solar capacity factors are estimates; biomass power capacity factor is 2009 average level.

4.4 Analysis of IPCC Cases

4.4.1 IPCC Case Setting

In the above, we have analyzed the optimal case for China’s economic development and GHG mitigation. However, the effects on the other countries are not evaluated. In the view of combating the global climate change, IPCC has recommended the GHG emission for China in the future. Therefore, in this part we will analyze the IPCC recommended cases.

According to the Fourth Assessment Report of the United Nations

Intergovernmental Panel on Climate Change (IPCC, 2007), global GHG emission will continue to grow over the next few decades. In order to stabilize the concentration of GHG in the atmosphere, emissions would need to peak and decline thereafter. To prevent dangerous anthropogenic interference with the climate system, an objective of limiting the global temperature increase to 2 degrees Celsius is established in the Copenhagen Accord. Combined with the IPCC projections, the concentration of GHG in the atmosphere would need to stabilized at a level around 450 per million of CO_2e (ppm CO_2e), in order to limit to 50% the probability of a global average temperature increase in excess of 2 degrees Celsius. In this case, IPCC recommended value of China's GHG emission in 2020 is 8,500 MtCO_2e (IEA, 2009). We use the IPCC recommended value as the GHG emission constraint in the IPCC cases.

As indicated in Table 4-3, we will do the comparison analysis between IPCC Case 1 without the proposed policies, and IPCC Case 2 with introduction of 30 Yuan/t CO_2e carbon tax.

Table 4-3 Case setting in IPCC Case

	GHG emission constraint	Comprehensive policy proposals
IPCC Case 1	Yes	No
IPCC Case 2	Yes	Yes (30 Yuan/tCO_2e)

4.4.2 Analysis of IPCC Cases

Running the simulation, we get the information on China's economic development and GHG emission in the IPCC cases. Comparing with the optimal case, China's economic growth is much slower in the IPCC Cases (Figure 4-35). The annual growth rate of GDP is only 4.59% in IPCC Case 2, indicating that China's target of 7% annual growth rate of GDP cannot be realized in IPCC Cases. However, by comparing the total GDP and GHG emission from 2007 to 2020 in cases, we find the total GDP in IPCC Case 2 is still larger than that of IPCC Case 1 (Figure 4-36), which proves that it is effective to promote the economic development by introducing the comprehensive policy proposals.

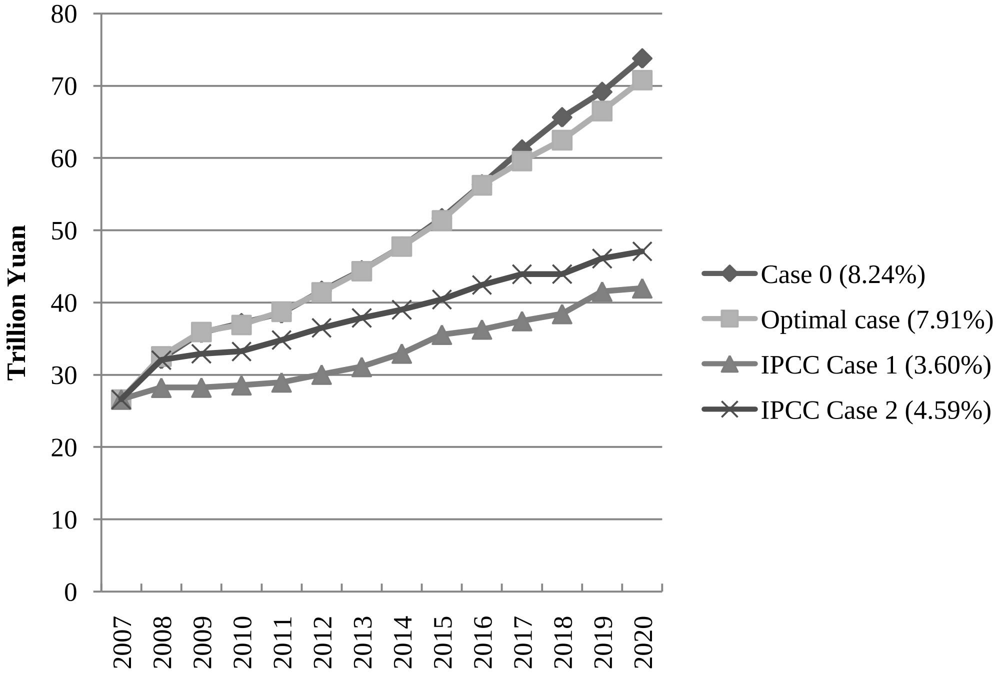


Figure 4-35 Trend of GDP from 2007 to 2020

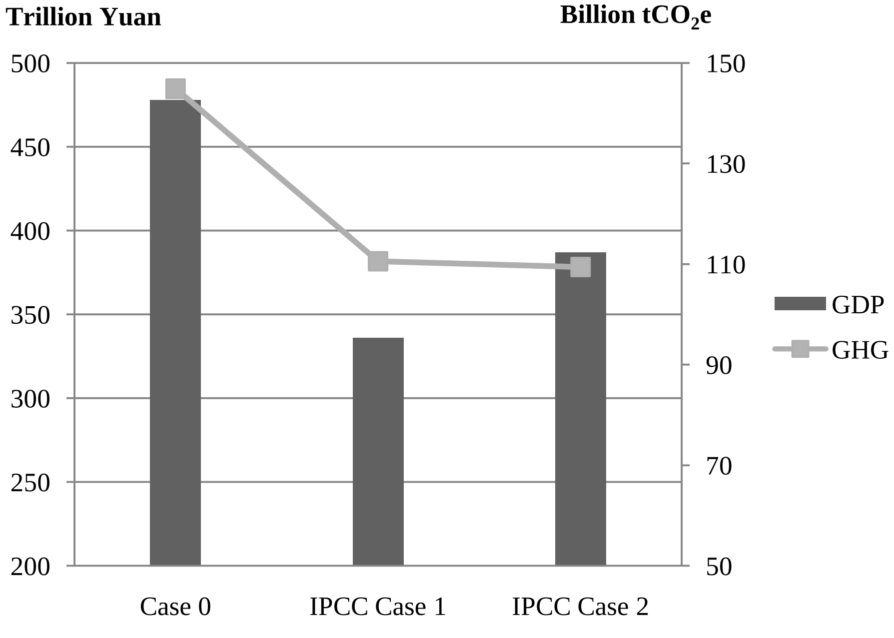


Figure 4-36 Comparison of total GDP and GHG emission from 2007 to 2020

As indicated in Figure 4-37, China’s GDP in 2020 is 47.09 Trillion Yuan in IPCC Case 2, only 1.42 times more than that of 2010. China’s target of doubling its 2010

GDP by 2020 cannot be realized in the GHG emission constraint recommended by IPCC. Besides, China’s GHG intensity will be reduced by 36% comparing with 2005 level in IPCC Case 2.

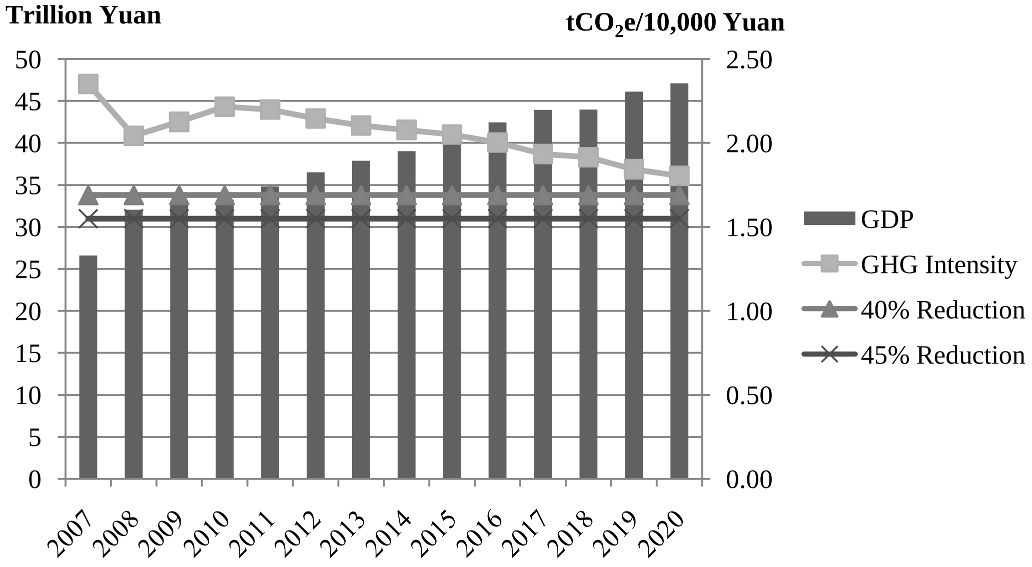


Figure 4-37 Trend of GHG intensity in IPCC Case 2

At last, we will compare the GHG emission between optimal case and IPCC recommended case. As indicated in Figure 4-38, China’s 2020 GHG emission in the optimal case is 2.85 Billion tCO_2e more than that of IPCC Case 2. And the total GHG emission from 2007 to 2020 in the optimal case is 17.5 Billion tCO_2e more than IPCC Case 2 (Figure 4-39). China’s GHG emission in the optimal case is further more than the IPCC recommended value. That means if China’s GHG is emitted in the future as optimal case, it will lead to the increase of global temperature more than 2 degrees Celsius, and bring great damage to the whole world on the ecosystem, food, water, and health of human being. Besides, it reflects the urgency of taking more other mitigation measures other than wind power, solar power, and biomass power, such as nuclear power, energy efficiency improvement, carbon capture and storage (CCS) technology etc.

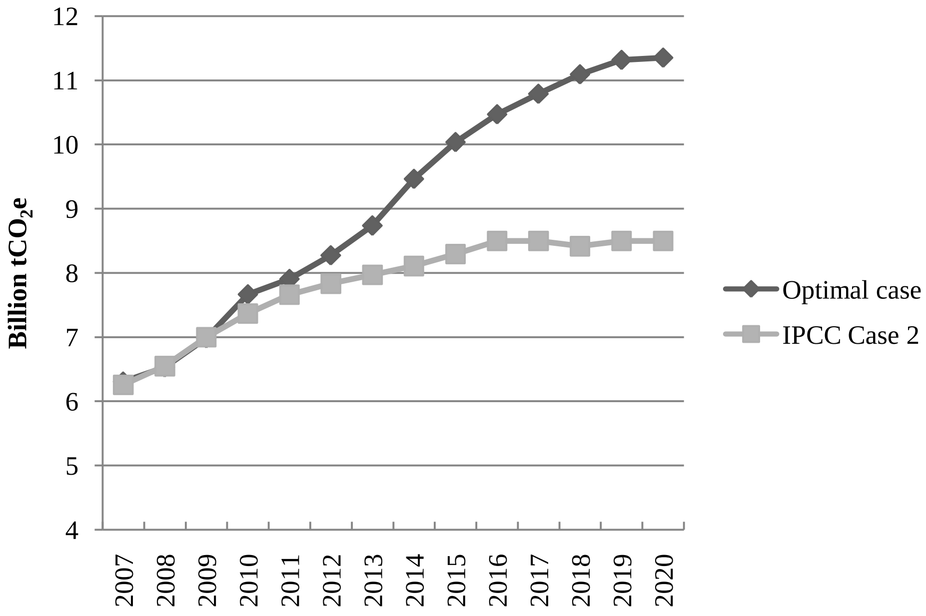


Figure 4-38 Trend of GHG emission in cases

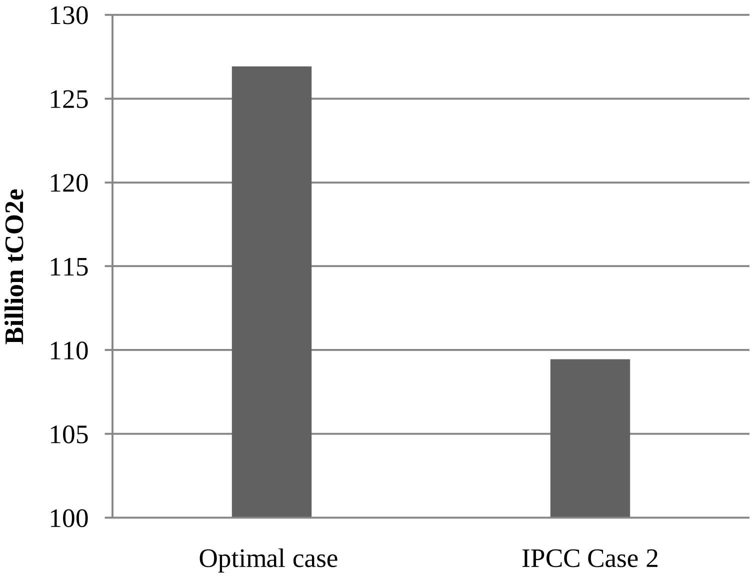


Figure 4-39 Comparison of total GHG emission in cases

4.5 Discussion and Conclusion

As a starting point of impact analysis of the comprehensive policy proposals, cases without the proposed policies have first been developed, including Case 0 and Case 1. The simulation results show that a rapid growth of the Chinese economy will take place until the year 2020 in Case 0. Consequently, this will lead to increased GHG emission. Besides, we introduce different GHG emission constraints in Case 1, and find the economic development will be restricted more with the stricter GHG emission constraint. Moreover, China’s climate commitment of reducing its GHG intensity by 40-45% comparing with 2005 level by 2020 cannot be realized in the cases without introducing the proposed policies.

Then, using a time-recursive comprehensive model and assuming that carbon tax revenues are used as subsidies to the new energy industries, Section 4.2 analyzes the implications of proposed policies in different constraints, and identifies the optimal case for China. Our main findings can be summarized as follows.

First, the optimal case for China is identified as the case of levying 30 Yuan/tCO_2e carbon tax in the GHG emission constraint of 1.8 times more than the base year. Not only because it has the lowest GHG intensity and best investment effect on GDP, but it is most efficient in energy consumption among all the cases. Currently, only few countries have implemented carbon tax, such as Finland, Denmark, Netherlands, Sweden and Norway as well as followers like Italy, New Zealand, Switzerland and Canada. In the year 2005, the carbon tax was 20, 26, 21 and 58 US$/t$CO_2$ in Denmark, Finland, Netherlands and Sweden respectively (Zhou, 2008). In our research, the optimal carbon tax for China is identified as 30 Yuan/tCO_2e, equivalent to 5 US$/t$CO_2$, further lower than that of the other countries. However, we should notice that the initial carbon tax in Finland was only 1.62 US$/t$CO_2$ in 1990. In an initial stage, it is reasonable to levy carbon tax at a lower level, in order to make it acceptable by the public.

Second, the proposed policies of introducing carbon tax to give incentives to the new energy industry are proven to be effective to promote the economic development and GHG mitigation in China. In the optimal case, China’s GDP will reach 70.79 Trillion Yuan in 2020, and the annual growth rate of GDP is 7.91%. GHG intensity in 2020 will be reduced by 43.13% relative to 2005 by 2020, and China’s climate commitment can be realized with introduction of the proposed policies.

Third, electricity substitution and industrial structure adjustment are two main approaches to achieve the optimization of economic growth and GHG mitigation in this model. The electricity substitution of renewable energy power generation with thermal power would contribute a lot to China’s GHG mitigation. As to the industrial structure adjustment, the sectors with higher added-value rate, less GHG emission factor, and less energy coefficient will be developed rapidly. Otherwise, the production of sectors with less added-value, higher GHG emission factor, and higher energy coefficient will be restricted to trade-off the economic development and GHG mitigation.

Fourth, the comprehensive proposed policies are effective to promote the development of new energy power generation in China. With the subsidy from 30 Yuan/tCO_2e carbon tax, the total electricity of wind power, solar power, and biomass power is 3,574.03 TWh from 2007 to 2020. The share of renewable energy power generation in the total electricity generation has increased to 24.17% in 2020, and China’s target of renewable energy development will be realized.

In Section 4.4, IPCC recommended cases are developed to evaluate the damage of China’s GHG emission to the whole world. In order to keep the rapid economic growth, China should take more mitigation measures other than the proposed policies, such as nuclear power, CCS technology, energy efficiency improvement etc.

CHAPTER 5 CONCLUSIONS

This study makes a systematic and comprehensive attempt to promote the development of renewable energy with carbon tax in China. This chapter summarizes the main conclusions. Given the purpose of the study, the summary of findings focus on the following topics:

- Analysis of Current Situation;
- Integrated Modeling Approach;
- Comprehensive evaluation of socio-economic and environmental policies for energy system transformation in China.

In addition, relevance and potential use of this study for science and policy-making are discussed briefly. Finally, some suggestions for further methodological and empirical work are provided in order to enrich the policy relevance of the study.

5.1 Summary of Findings

5.1.1 Analysis of Current Situation

As a result of soaring energy demand from the rapid economic growth, China overtook the United States to become the world's largest GHG emitter in 2007. Facing the mounting mitigation pressure, China promised to reduce its GHG intensity by 40-45% by 2020 comparing to 2005 level. China's GHG emission was 7,217.06 $MtCO_2$ e in 2010, in which 49.18% was emitted by the sector of electricity and heat production. That is, the sector of electricity and heat production is the single largest GHG emitting source in China. It is concluded that electricity demand is the largest driver of the rise in China's GHG emission.

On the other hand, China's demand of electricity is increasing greatly with the rapid economic development. During the period of 11th Five-Year Program (2006-2010), the annual growth rate of GDP in China has reached 11.2%, leading to

10.3% annual increasing rate of electricity demand. Moreover, coal-fired power generation is dominant in China’s energy system, representing over 80% of the total electricity generation for the recent years. Therefore, it is concluded that China’s coal-dominant energy system is the main reason of its high GHG emission.

In sum, the key to mitigation in China is to develop renewable energy to transform the existing coal-dominant energy system. However, although China has abundant renewable energy resources, the main technological, financial, and institutional risks associated with China’s renewable energy development still remain. Especially the high cost of renewable energy should not be neglected. Therefore, we propose the mitigation policies of carbon tax and subsidy to promote the renewable energy development in China, in order to transform the coal-dominant energy system and coordinate the economic development, energy consumption and GHG mitigation.

5.1.2 Integrated Modeling Approach

In this study, we construct an integrated model for China’s energy and environmental policy analysis, into which the principles of commodity flow balance, energy flow balance, and value flow balance are embedded in order to comprehensively evaluate and identify the optimal environmental policies for mitigating the global warming in China.

The objective function is to maximize the sum of discounted GDP from 2007 to 2020, subject to a series of specific formulations. These constraints are set in three view points of value flow balance, energy flow balance, and commodity flow balance, which are necessary in the comprehensive environmental evaluation. Besides, we also consider the macroeconomic balance among different economy entities. All the equations in the model make it possible to analyze the interactions among Chinese economy development, energy consumption, and GHG emission simultaneously.

Running the simulation, we can get the specific information on economic development, GHG emission, and energy supply trends in the future. It is found that our model can reflect the social, economic, and environment development trends with high reliability. Therefore, the integrated modeling approach is a useful and effective method in policy evaluation, which can be easily applied to analyze the similar issues.

5.1.3 Comprehensive Evaluation of Socio-Economic and Environmental Policies for Energy System Transformation

From comprehensive simulation towards environmental policies evaluation with an emphasis on energy infrastructure transformation, we find that the proposed environmental policies of introducing carbon tax and new energy industry are effective to coordinate the relationship among China’s economy, energy and GHG mitigation.

First, the optimal case for China is identified as the case of levying 30 Yuan/tCO_2e carbon tax in the GHG emission constraint of 1.8 times more than the base year. Not only because it has the lowest GHG intensity and best investment effect on GDP, but it is the most efficient in energy consumption among all the cases.

Second, the comprehensive proposed policies are proven to be effective to promote the economic development, GHG mitigation, and energy system transformation in China. In the aspect of economic development, China’s GDP will reach 70.79 Trillion Yuan in 2020, and the annual growth rate of GDP is 7.91%. As to GHG mitigation, China’s GHG intensity will be reduced by 43.13% relative to 2005 by 2020, and China’s climate commitment can be realized with introduction of the proposed policies. Moreover, with the subsidy from 30 Yuan/tCO_2e carbon tax, the total electricity of wind power, solar power, and biomass power is 3,574.03 TWh from 2007 to 2020. The share of renewable energy power generation in the total electricity generation has increased to 24.17% in 2020, and China’s target of renewable energy development will be realized.

Finally, electricity substitution and industrial structure adjustment are two main approaches to achieve the optimization of economic growth and GHG mitigation in this model.

5.2 Relevance and Potential Use of This Study for Science and Policy-making

Prior to the Copenhagen conference, China promised to reduce its GHG intensity by 40-45% by 2020 comparing with 2005 level. Meanwhile, China has made great efforts to develop an appropriate response strategy for climate change. The government has taken serious actions to account the national GHG inventory and submitted Chinese Second National Communication to the UNFCCC in 2012. Besides, China has established its annual report of countermeasures for climate change, in order to focus on the capacity improvement of mitigating and adapting climate change. And several projects have been initiated that forecast China’s GHG emission in the future.

Nevertheless, in China systematic and comprehensive research on the economic implications of energy system transformation for Chinese GHG mitigation is still in its infancy. In this regard, the simulation results of this study, although still preliminary at this stage, should be of interest to the policymakers in China and to those who seek to advise them. Moreover, it offers a useful method to evaluate the mitigation issues in an integrated view of socio-economic development by constructing a comprehensive model, which can be applied in the mitigation policy evaluation.

5.3 Suggestion for Further Work

The current integrated model provides a suitable and flexible basis for evaluating the impacts of environmental policies on energy system transformation and GHG mitigation. Nevertheless, there are some areas where there is a need for further methodological and empirical work in order to enrich the policy relevance of this study.

First, it would be desirable to incorporate a multi-regional balance into the current model, making it a zone model. The study area in the current model is the entire China, and the simulation results give an overview of renewable energy development in the national wide. However, since the distribution of resources in China is uneven, it needs to divide China into multi regions and analyze the characteristics of each zone in the future. Based on the survey of energy resources, China can be divided into seven regions, such as Northeast China (including the provinces of Heilongjiang, Jilin, and Liaoning), North China (including the provinces of Hebei, Beijing, Tianjin, Shanxi, Inner Mongolia, and Shandong), East China (including the provinces of Jiangsu, Anhui, Shanghai, Zhejiang, and Fujian), Central China (including the provinces of Henan, Jiangxi, Hunan, and Hubei), South China (including Guangdong, Guangxi, and Hainan), Northwest China (including Shannxi, Ningxia, Gansu, Qinghai, and Xinjiang), and Southwest China (including the provinces of Tibet, Sichuan, Chongqing, Guizhou, and Yunnan). Hydro resource is abundant in the region of Southwest China, while Northwest China has received great solar radiation. As to biomass energy, it is abundant in Northeast China, North China, and Central China. And the transportation of biomass waste among different regions should be considered in the zone model.

Second, it would be useful to incorporate power quality into the current model. Although the current integrated model is appropriate to balance the electricity supply and demand in China’s economy, it does not consider the different demand of power quality in industries and households. Power quality is the quality of the voltage, determining the fitness of electrical power to consumer devices. Because of mature technologies and sufficient resources, China’s thermal power and hydropower belong to the group of high power quality, assuring the reliability of the power grid. However, due to the uncertainty of resources and inherent intermittency, wind power, solar power and biomass power will influence power supply reliability, classified as poor power quality. In order to keep continuous production, the industry plants need high reliability in power supply. So it is preferred to utilize thermal power and hydropower in the development of industries, while wind power, solar power and biomass power are suitable for the demand of households.

Third, it would be desirable to incorporate more mitigation measures into the current model. Although this study proves it is feasible to realize the government target on GHG intensity reduction and renewable energy promotion, China’s GHG emission in 2020 has climbed to 11.35 Billion tCO_2e, much more than the IPCC recommended value. Therefore, China should take more mitigation measures in the future, such as nuclear power, energy efficiency improvement, carbon capture and storage (CCS) technology etc.

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APPENDIX

Table A3-1 Input coefficients to usual industry by usual industry ($\mathbf{A}_{\mathbf{uu}}$)

	Agriculture	Mining industry	Light industry	Petroleum and coking	Chemical industry	Nonmetal mineral products	Smelting of metals
Agriculture	0.140657	0.002677	0.200305	0.000023	0.026896	0.000381	0.000068
Mining industry	0.000677	0.074990	0.004336	0.617494	0.055910	0.126775	0.168272
Light industry	0.098614	0.013924	0.343635	0.007517	0.038930	0.037423	0.007069
Petroleum and coking	0.008064	0.035224	0.004167	0.057620	0.063492	0.030422	0.046038
Chemical industry	0.076272	0.038296	0.075208	0.018675	0.416432	0.076150	0.013021
Nonmetal mineral products	0.001417	0.013054	0.004547	0.004089	0.006890	0.165930	0.013615
Smelting of metals	0.000241	0.037032	0.004902	0.000812	0.009381	0.024298	0.336673

(Continued)

	Metal products	Other manufacture industry	Production of gas	Production of Water	Construction	Transport and postal services	Other services
Agriculture	0.000176	0.004247	0.000120	0.000000	0.004134	0.008943	0.014476
Mining industry	0.015831	0.003327	0.563168	0.003046	0.014215	0.003570	0.001856
Light industry	0.031305	0.023691	0.016430	0.012814	0.027307	0.021160	0.085260
Petroleum and coking	0.009676	0.005357	0.021629	0.008578	0.020200	0.140092	0.011768
Chemical industry	0.039446	0.058675	0.005533	0.052969	0.039138	0.010822	0.044605
Nonmetal mineral products	0.010336	0.011642	0.001907	0.002965	0.212607	0.001312	0.002577
Smelting of metals	0.355959	0.139749	0.002078	0.001199	0.156502	0.002750	0.000848

(Continued)

	Agriculture	Mining industry	Light industry	Petroleum and coking	Chemical industry	Nonmetal mineral products	Smelting of metals
Metal products	0.002743	0.016407	0.007407	0.004054	0.008280	0.028003	0.010358
Other manufacture industry	0.011983	0.101168	0.027729	0.023750	0.032540	0.060366	0.088848
Production of gas	0.000038	0.002340	0.000451	0.001733	0.002289	0.001097	0.001251
Production of Water	0.000186	0.001375	0.001131	0.000602	0.001584	0.001442	0.001062
Construction	0.000232	0.000926	0.000237	0.000559	0.000334	0.000295	0.000291
Transport and postal services	0.019855	0.043897	0.025867	0.028571	0.028283	0.041462	0.030033
Other services	0.043487	0.065261	0.056766	0.033553	0.058407	0.068294	0.041279

(Continued)

	Metal products	Other manufacture industry	Production of gas	Production of Water	Construction	Transport and postal services	Other services
Metal products	0.002743	0.016407	0.007407	0.004054	0.008280	0.028003	0.010358
Other manufacture industry	0.011983	0.101168	0.027729	0.023750	0.032540	0.060366	0.088848
Production of gas	0.000038	0.002340	0.000451	0.001733	0.002289	0.001097	0.001251
Production of Water	0.000186	0.001375	0.001131	0.000602	0.001584	0.001442	0.001062
Construction	0.000232	0.000926	0.000237	0.000559	0.000334	0.000295	0.000291
Transport and postal services	0.019855	0.043897	0.025867	0.028571	0.028283	0.041462	0.030033
Other services	0.043487	0.065261	0.056766	0.033553	0.058407	0.068294	0.041279

Table A3-2 Input coefficients to thermal power industry and hydropower industry by usual industry ($\mathbf{A}_{\mathbf{um}}$, $\mathbf{A}_{\mathbf{ur}}$)

	$\mathbf{A}_{\mathbf{um}}$	$\mathbf{A}_{\mathbf{ur}}$
Agriculture	0.000016	0.000000
Mining industry	0.137118	0.000000
Light industry	0.010288	0.000000
Petroleum and coking	0.047633	0.000000
Chemical industry	0.003494	0.000000
Nonmetal mineral products	0.002306	0.000000
Smelting of metals	0.001075	0.000000
Metal products	0.005376	0.000000
Other manufacture industry	0.061864	0.273998
Production of gas	0.001237	0.000000
Production of Water	0.001473	0.004341
Construction	0.000006	0.002000
Transport and postal services	0.020290	0.000000
Other services	0.048361	0.200000

Table A3-3 Input coefficients to new energy industry by usual industry ($\mathbf{A}_{\mathbf{un}}$)

	Wind power industry	Solar power industry	Biomass-I	Biomass-II	Biomass-III
Agriculture	0.000000	0.000000	0.276376	0.228571	0.020190
Mining industry	0.000000	0.000000	0.000000	0.000000	0.000000
Light industry	0.000000	0.000000	0.000000	0.000000	0.000000
Petroleum and coking	0.000000	0.000000	0.000000	0.000000	0.000000
Chemical industry	0.000000	0.003843	0.000000	0.000000	0.000000
Nonmetal mineral products	0.000000	0.100527	0.000000	0.000000	0.000000
Smelting of metals	0.000000	0.000000	0.000000	0.000000	0.000000
Metal products	0.000000	0.000212	0.000000	0.000000	0.000000
Other manufacture industry	0.650634	0.567572	0.590437	0.668224	0.682370
Production of gas	0.000000	0.000000	0.000000	0.000000	0.000000
Production of Water	0.000000	0.003871	0.003289	0.001317	0.148456
Construction	0.172498	0.036751	0.000000	0.000000	0.000000
Transport and postal services	0.000000	0.000000	0.000000	0.000000	0.000000
Other services	0.099291	0.236562	0.025650	0.022488	0.029691

Table A3-4 Input coefficients to usual industry by electricity (**A_{eu}**)

	Agriculture	Mining industry	Light industry	Petroleum and coking	Chemical industry	Nonmetal mineral products	Smelting of metals
Electricity	0.009373	0.080525	0.015407	0.022908	0.047238	0.062955	0.046877

(Continued)

	Metal products	Other manufacture industry	Production of gas	Production of Water	Construction	Transport and postal services	Other services
Electricity	0.046033	0.013705	0.016666	0.196120	0.013188	0.013671	0.014544

Table A3-5 Input coefficients to thermal power industry and hydropower industry by electricity (**A_{em}, A_{er}**)

	A_{em}	A_{er}
Electricity	0.387374	0.196149

Table A3- 6 Input coefficients to new energy industry by electricity (**A_{en}**)

	Wind power industry	Solar power industry	Biomass-I	Biomass-II	Biomass-III
Electricity	0.000000	0.003602	0.000000	0.000000	0.000000

Table A3-7 Investment demand to usual industry induced by one unit capital formation in usual industry ($\mathbf{Q_{uu}}$)

	Agriculture	Mining industry	Light industry	Petroleum and coking	Chemical industry	Nonmetal mineral products	Smelting of metals
Agriculture	0.140657	0.002677	0.200305	0.000023	0.026896	0.000381	0.000068
Mining industry	0.000677	0.074990	0.004336	0.617494	0.055910	0.126775	0.168272
Light industry	0.098614	0.013924	0.343635	0.007517	0.038930	0.037423	0.007069
Petroleum and coking	0.008064	0.035224	0.004167	0.057620	0.063492	0.030422	0.046038
Chemical industry	0.076272	0.038296	0.075208	0.018675	0.416432	0.076150	0.013021
Nonmetal mineral products	0.001417	0.013054	0.004547	0.004089	0.006890	0.165930	0.013615
Smelting of metals	0.000241	0.037032	0.004902	0.000812	0.009381	0.024298	0.336673

(Continued)

	Metal products	Other manufacture industry	Production of gas	Production of Water	Construction	Transport and postal services	Other services
Agriculture	0.000176	0.004247	0.000120	0.000000	0.004134	0.008943	0.014476
Mining industry	0.015831	0.003327	0.563168	0.003046	0.014215	0.003570	0.001856
Light industry	0.031305	0.023691	0.016430	0.012814	0.027307	0.021160	0.085260
Petroleum and coking	0.009676	0.005357	0.021629	0.008578	0.020200	0.140092	0.011768
Chemical industry	0.039446	0.058675	0.005533	0.052969	0.039138	0.010822	0.044605
Nonmetal mineral products	0.010336	0.011642	0.001907	0.002965	0.212607	0.001312	0.002577
Smelting of metals	0.355959	0.139749	0.002078	0.001199	0.156502	0.002750	0.000848

(Continued)

	Agriculture	Mining industry	Light industry	Petroleum and coking	Chemical industry	Nonmetal mineral products	Smelting of metals
Metal products	0.002743	0.016407	0.007407	0.004054	0.008280	0.028003	0.010358
Other manufacture industry	0.011983	0.101168	0.027729	0.023750	0.032540	0.060366	0.088848
Production of gas	0.000038	0.002340	0.000451	0.001733	0.002289	0.001097	0.001251
Production of Water	0.000186	0.001375	0.001131	0.000602	0.001584	0.001442	0.001062
Construction	0.000232	0.000926	0.000237	0.000559	0.000334	0.000295	0.000291
Transport and postal services	0.019855	0.043897	0.025867	0.028571	0.028283	0.041462	0.030033
Other services	0.043487	0.065261	0.056766	0.033553	0.058407	0.068294	0.041279

(Continued)

	Metal products	Other manufacture industry	Production of gas	Production of Water	Construction	Transport and postal services	Other services
Metal products	0.125288	0.032070	0.008248	0.028682	0.036230	0.002995	0.004822
Other manufacture industry	0.079477	0.407003	0.035797	0.037219	0.084796	0.109946	0.057664
Production of gas	0.000882	0.000555	0.044322	0.003247	0.000108	0.000876	0.000643
Production of Water	0.001191	0.000576	0.000733	0.034680	0.000371	0.001028	0.001494
Construction	0.000157	0.000224	0.000591	0.001192	0.009535	0.003225	0.007296
Transport and postal services	0.022518	0.022082	0.025221	0.012840	0.090507	0.072763	0.047874
Other services	0.053484	0.065357	0.057208	0.139525	0.059767	0.112190	0.158090

Table A3- 8 Investment demand to usual industry induced by one unit capital formation in thermal power industry and hydropower industry (**Q_{um}, Q_{ur}**)

	Q_{um}	**Q_{ur}**
Agriculture	0.000016	0.000000
Mining industry	0.137118	0.000000
Light industry	0.010288	0.000000
Petroleum and coking	0.047633	0.000000
Chemical industry	0.003494	0.000000
Nonmetal mineral products	0.002306	0.000000
Smelting of metals	0.001075	0.000000
Metal products	0.005376	0.000000
Other manufacture industry	0.061864	0.273998
Production of gas	0.001237	0.000000
Production of Water	0.001473	0.004341
Construction	0.000006	0.002000
Transport and postal services	0.020290	0.000000
Other services	0.048361	0.200000

Table A3- 9 Investment demand to usual industry induced by one unit capital formation in new energy industry (**Q_{un}**)

	Wind power industry	Solar power industry	Biomass-I	Biomass-II	Biomass-III
Agriculture	0.000000	0.000000	0.276376	0.228571	0.020190
Mining industry	0.000000	0.000000	0.000000	0.000000	0.000000
Light industry	0.000000	0.000000	0.000000	0.000000	0.000000
Petroleum and coking	0.000000	0.000000	0.000000	0.000000	0.000000
Chemical industry	0.000000	0.003843	0.000000	0.000000	0.000000
Nonmetal mineral products	0.000000	0.100527	0.000000	0.000000	0.000000
Smelting of metals	0.000000	0.000000	0.000000	0.000000	0.000000
Metal products	0.000000	0.000212	0.000000	0.000000	0.000000
Other manufacture industry	0.650634	0.567572	0.590437	0.668224	0.682370
Production of gas	0.000000	0.000000	0.000000	0.000000	0.000000
Production of Water	0.000000	0.003871	0.003289	0.001317	0.148456
Construction	0.172498	0.036751	0.000000	0.000000	0.000000
Transport and postal services	0.000000	0.000000	0.000000	0.000000	0.000000
Other services	0.099291	0.236562	0.025650	0.022488	0.029691

Table A3- 10 Government consumption of usual industry in base year (**G_{u_d}**) and export of usual industry in base year (**E_{u_d}**)

	G_{u_d} (Million yuan)	E_{u_d} (Million yuan)
Agriculture	34,162	66,598
Mining industry	0	64,005
Light industry	0	2,048,953
Petroleum and coking	0	76,784
Chemical industry	0	723,792
Nonmetal mineral products	0	148,369
Smelting of metals	0	515,549
Metal products	0	355,852
Other manufacture industry	0	4,180,102
Production of gas	0	0
Production of Water	0	0
Construction	0	40,887
Transport and postal services	162,148	447,807
Other services	3,322,781	878,890

Table A3- 11 Export of electricity in base year (**E_{e_d}**)

	E_{e_d} (Million yuan)
Electricity	6,511

Table A3- 12 Indirect tax rate of usual industry (ζ_u)

	ζ_u
Agriculture	0.000978
Mining industry	0.086233
Light industry	0.058406
Petroleum and coking	0.050167
Chemical industry	0.039022
Nonmetal mineral products	0.059285
Smelting of metals	0.051275
Metal products	0.041931
Other manufacture industry	0.040155
Production of gas	0.014142
Production of Water	0.063437
Construction	0.028704
Transport and postal services	0.041615
Other services	0.064657

Table A3- 13 Indirect tax rate of thermal power industry (ζ_m)

	ζ_m
Thermal power industry	0.041892

Table A3- 14 Indirect tax rate of hydropower industry (ζ_r)

	ζ_r
Hydropower industry	0.004702

Table A3- 15 Depreciation rate of usual industry ($\boldsymbol{\delta_u}$)

	$\boldsymbol{\delta_u}$
Agriculture	0.084200
Mining industry	0.098000
Light industry	0.118200
Petroleum and coking	0.125000
Chemical industry	0.106100
Nonmetal mineral products	0.201300
Smelting of metals	0.139200
Metal products	0.139200
Other manufacture industry	0.121000
Production of gas	0.054500
Production of Water	0.054500
Construction	0.139000
Transport and postal services	0.054200
Other services	0.065200

Table A3- 16 Depreciation rate of thermal power industry ($\boldsymbol{\delta_m}$)

	$\boldsymbol{\delta_m}$
Thermal power industry	0.054500

Table A3- 17 Depreciation rate of hydropower industry ($\boldsymbol{\delta_r}$)

	$\boldsymbol{\delta_r}$
Hydropower industry	0.054500

Table A3- 18 Depreciation rate of new energy industry ($\boldsymbol{\delta_n}$)

	$\boldsymbol{\delta_n}$
Wind power industry	0.049100
Solar power industry	0.047500
Biomass-I	0.080000
Biomass-II	0.080000
Biomass-III	0.080000

Table A3- 19 GHG emission factor of usual industry (**ef_u**)

	ef_u (t CO_2/Yuan)
Agriculture	0.000024
Mining industry	0.000140
Light industry	0.000018
Petroleum and coking	0.000008
Chemical industry	0.000072
Nonmetal mineral products	0.000164
Smelting of metals	0.000199
Metal products	0.000006
Other manufacture industry	0.000005
Production of gas	0.000013
Production of Water	0.000007
Construction	0.000005
Transport and postal services	0.000093
Other services	0.000008

Table A3- 20 GHG emission factor of thermal power industry (**ef_m**)

	ef_m (t CO_2/Yuan)
Thermal power industry	0.000986

Table A3- 21 GHG emission factor of new energy industry (**ef$_n$**)

	ef$_n$ (t CO$_2$/Yuan)
Wind power industry	0.000000
Solar power industry	0.000000
Biomass-I	0.00002582
Biomass-II	0.00002085
Biomass-III	0.0000102

Table A3- 22 GHG emission factor of household consumption (**ef$_c$**)

	ef$_c$ (t CO$_2$/Yuan)
Household consumption	0.000020

Table A3- 23 GHG emission factor of crop straw in the open-burning process (**ef$_w$**)

	ef$_w$ (t CO$_2$/ton straw)
Crop straw in the open-burning process	0.033070

Table A3- 24 Disposed coefficient of crop straw by usual industry (**A_{wu}**)

	A_{wu} (ton straw/million Yuan)
Agriculture	109.013560
Mining industry	0.000000
Light industry	0.000000
Petroleum and coking	0.000000
Chemical industry	0.000000
Nonmetal mineral products	0.000000
Smelting of metals	0.000000
Metal products	0.000000
Other manufacture industry	0.000000
Production of gas	0.000000
Production of Water	0.000000
Construction	0.000000
Transport and postal services	0.000000
Other services	0.000000

Table A3- 25 Treated coefficient of crop straw by new energy industry (**A_{wn}**)

	A_{wn} (ton straw/million Yuan)
Wind power industry	0.000000
Solar power industry	0.000000
Biomass-I	837.503014
Biomass-II	1097.255713
Biomass-III	847.238717

Table A3- 26 Income rate of usual industry (**y_u**)

	y_u
Agriculture	0.555941
Mining industry	0.335293
Light industry	0.142510
Petroleum and coking	0.094441
Chemical industry	0.135173
Nonmetal mineral products	0.179501
Smelting of metals	0.116034
Metal products	0.141896
Other manufacture industry	0.150070
Production of gas	0.107279
Production of Water	0.233482
Construction	0.190323
Transport and postal services	0.327033
Other services	0.399392

Table A3- 27 Income rate of thermal power industry ($\mathbf{y_m}$)

	$\mathbf{y_m}$
Thermal power industry	0.091972

Table A3- 28 Income rate of hydropower industry ($\mathbf{y_r}$)

	$\mathbf{y_r}$
Hydropower industry	0.300000

Table A3- 29 Income rate of new energy industry ($\mathbf{y_n}$)

	$\mathbf{y_n}$
Wind power industry	0.003267
Solar power industry	0.003320
Biomass-I	0.021847
Biomass-II	0.014848
Biomass-III	0.059382

Table A3- 30 Direct tax rate ($\boldsymbol{\zeta_d}$)

	$\boldsymbol{\zeta_d}$
Direct tax rate	0.200000

Table A3- 31 Household saving rate (**β**)

	β
Household saving rate	0.370000

Table A3- 32 Share of usual industry’s consumption in the total household consumption (**α_u**)

	α_u
Agriculture	0.115544
Mining industry	0.001531
Light industry	0.245878
Petroleum and coking	0.007726
Chemical industry	0.024350
Nonmetal mineral products	0.002896
Smelting of metals	0.000000
Metal products	0.004255
Other manufacture industry	0.082284
Production of gas	0.003335
Production of Water	0.003336
Construction	0.009651
Transport and postal services	0.055835
Other services	0.419008

Table A3- 33 Share of electricity's consumption in the total household consumption (**α_e**)

	α_e
Electricity	0.024370

Table A3- 34 Capital input coefficient in usual industry (**h_u**)

	h_u
Agriculture	3.544524
Mining industry	2.568985
Light industry	2.699102
Petroleum and coking	3.714640
Chemical industry	3.044294
Nonmetal mineral products	3.592197
Smelting of metals	3.724887
Metal products	3.756024
Other manufacture industry	3.911881
Production of gas	3.157104
Production of Water	3.536912
Construction	4.122378
Transport and postal services	1.680118
Other services	1.263571

Table A3- 35 Constraint on share of net export in total saving (φ_{min}, φ_{max})

	φ_{min}	φ_{max}
φ	0.100000	0.300000

Table A3- 36 Capital input coefficient in thermal power industry (h_m)

	h_m
Thermal power industry	4.607482

Table A3- 37 Capital input coefficient in hydropower industry (h_r)

	h_r
Hydropower industry	3.960000

Table A3- 38 Capital input coefficient in new energy industry (h_n)

	h_n
Wind power industry	1.500000
Solar power industry	2.000000
Biomass-I	1.500000
Biomass-II	1.500000
Biomass-III	1.500000

Table A3- 39 Social discount rate (**ρ**)

	ρ
Social discount rate	0.05

Table A3- 40 Added value rate of thermal power industry (**V_m**)

	V_m
Thermal power industry	0.272089

Table A3- 41 Added value rate of hydropower industry (**V_r**)

	V_r
Hydropower industry	0.323512

Table A3- 42 Added value rate of new energy industry (**V_n**)

	V_n
Wind power industry	0.077577
Solar power industry	0.047060
Biomass-I	0.104248
Biomass-II	0.079399
Biomass-III	0.119292

Table A3- 43 Added value rate of usual industry (**V_u**)

	V_u
Agriculture	0.586161
Mining industry	0.472905
Light industry	0.227907
Petroleum and coking	0.178040
Chemical industry	0.203116
Nonmetal mineral products	0.274707
Smelting of metals	0.195245
Metal products	0.208241
Other manufacture industry	0.211741
Production of gas	0.200348
Production of Water	0.464922
Construction	0.231394
Transport and postal services	0.494657
Other services	0.546181