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Dynamic simulation of China's carbon emission reduction potential by 2020

Research Memorandum 2013-23

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Dynamic Simulation of China's Carbon Emission Reduction Potential by 2020

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Abstract Along with the rapid economic development of China, carbon dioxide (CO₂) emissions will inevitably rise in the future. This will happen even though the Chinese government has made a series of attempts to constrain the CO₂-emissions, and is committed to reduce its CO₂-emissions per unit of gross domestic product (GDP) by 40-45 percent (1,045 to 1,140 tons/million dollars) by 2020 from 2005 levels. However, according to estimates, the total amount of CO₂-emissions will grow to more than 13 billion tons, and the carbon intensity will be twice of the world average. In order to improve this situation, this research study will construct a comprehensive dynamic simulation model to forecast China's CO₂-emissions and GDP development under different carbon intensity constraints from 2008 to 2020, in order to find out the potential for Chinese carbon intensity reduction in view of the economic development and the total amount of controlled CO₂-emissions. The comprehensive model we constructed includes a CO₂-emission model, an energy balance model, and a socio-economic model. Through a dynamic simulation analysis established by LINGO programming, this study provides the minimum carbon intensity that China can achieve under the current situation, i.e., 1,040 tons/million dollars in 2020 (a 45 percent reduction compared with the situation in 2005), while the CO₂-emissions will be 12.51 billion tons, the proportion of non-fossil energy 15 percent, and the average annual increase in GDP 9 percent. This research offers an effective method to estimate the interaction between economic growth and CO₂-emissions reduction, with alternative energy utilization in the future.

Keywords: *Dynamic simulation, CO₂-emissions, Carbon intensity, China*

JEL Classification: C61, O21, Q54

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1. Introduction

As economic growth has increased, environmental pollution problems have become serious in places where social and political stability are at risk. Global carbon dioxide (CO₂) emissions have increased from 22.5 billion tons in 1990 to 31.5 billion tons in 2008 (PBL, 2009). Global warming as an increasingly obvious problem has attracted considerable attention from people all over the world; in particular, China's large amount of CO₂-emissions is becoming a serious problem. There is a trade-off between economic development and environmental protection. The high speed of economic development will inevitably mean sacrificing certain benefits of environmental quality. Between 1979 and 2007, the Chinese economy grew at an average annual rate of 9.8 percent (Morrison, 2008). China has overtaken the United States and became the number one CO₂-emitter since 2006 (Gregg et al., 2008), as a result of its phenomenal economic growth, coal-dominated energy structure, and increasing exports (Weber and Matthews et al., 2008). Some studies point out that the rising consumption levels of energy-intensive goods have led to an increase in greenhouse gas emissions all over the world (Machado et al., 2001; Wiedmann et al., 2007). With a large population, a rapidly expanding economy, and a heavy reliance on coal, China's CO₂-emissions are expected to continue to grow in the years ahead.

The Chinese government has realized the importance of environmental protection, and has given a high priority to environmental protection, particularly to reducing the CO₂-emissions, in order to alleviate the environmental risks for China and the rest of the world. China has pledged it would do its best to reduce its CO₂-emissions per unit of GDP by 40-45 percent from the 2005 levels by 2020, and increase the share of non-fossil fuels in primary energy consumption to approximately 15 percent (Wei, 2010). In 2005, the carbon intensity was 1,900 tons/million dollars (as 6.5 CNY to dollar) (World Bank, 2011), while the world average is 780 tons/million dollars. The Chinese target is to reduce carbon intensity to between 1,045 and 1,140 tons/million dollars in 2020. However, there is still a large gap between China's targets in 2020 and the world average level in 2005 (Lin and Sun, 2010). Previous research has proved that it is possible to accomplish Chinese CO₂-emission targets if the energy and the industry structure are adjusted in China, according to current policies and situations (Xu et al., 2012). Therefore, this gives rise to a fascinating research topic: to explore the potential of further reducing China's carbon intensity based on the world average level with strong approaches, such as higher renewable energy development and associated policy enforcement. In order to trace the optimal development plan for the Chinese government, it is necessary to use a simulation method to estimate the impacts of economic development on the environment, and on CO₂-emissions, in particular.

The aims of this paper are:

- Constructing a dynamic comprehensive simulation model to forecast the CO₂-emissions and GDP development under different scenarios in China from 2008 to 2020.

This model will include all the major factors that impact on CO₂-emissions;

- Simulating the CO₂-emissions to find out the potential for China to reduce CO₂ by 2020, and identifying the possibility to realize the world average carbon intensity level for China by 2020;
- Finding the suitable energy structure adjustments for an optimal development plan, especially the proportion of non-fossil energy under different scenarios to guarantee the energy demand for economic development, and proposing corresponding policies to improve CO₂-mitigation for China in the long term.

The introduction to the paper has described the current situation of CO₂-emissions in China and the related research backgrounds, while Section 2 below will explain the methodology. Then, Section 3 is devoted to the simulation framework and modeling formulation, and to the preparation of the data. Section 4 then presents the simulation results, and analyses the effectiveness of the policies we have proposed for pursuing the potential of CO₂-emission reduction with consideration of economic development and energy supply. The final section concludes.

A comprehensive policy evaluation is necessary to imitate reality and to pre-assess the policies' impacts on environmental protection and economic development, in order to provide optimal policy proposals for governmental decision-making, and to avoid inappropriate policies or the failure of policy implementation.

2. The Methodology

There are various studies that estimate China's CO₂-emissions and economic development trends in the next 10-40 years. Trend extrapolation can indicate whether a country is on course to meet its carbon intensity targets. Various simulation methods have been used to predict the economic and energy resource demand trend for China. These methods include CGE model analysis (Zhang, 1998), bottom-up analysis (Holf et al., 2009), and the LEAP (Wang et al., 2011). It is important to forecast CO₂-emissions to establish the optimal development policies necessary to achieve a low-carbon economy. By comparison, the published scenario literature – though technology- and policy-rich – lacks transparency regarding the many assumptions and model construction foundations. However, up till now only a few studies and approaches have provided insight into the comprehensive socio-economic systems in the simulations concerned. Our comprehensive simulation and optimization model forms an integrated system which considers all factors that will impact on CO₂-emissions, energy consumption, and industrial development. Our study aims to construct an original comprehensive simulation model to predict the energy and industrial structure, and CO₂-emissions trends, based on the latest data and the appreciation of the comprehensive simulation system. This simulation model considers many key drivers, such as population growth, GDP growth, energy consumption, and the existing distinct sub-sectorial policy targets.

The comprehensive simulation model contains many variables and constraints. We will adopt here a dynamic linear programming procedure for solving the optimization model, as this is often the most efficient way to provide a basis for policy-making. In this respect, LINGO (developed by the LINDO company) is a comprehensive tool designed to make building and solving linear, nonlinear, quadratic, and integer optimization models faster, easier, and more efficient (see Li and Higano, 2007). We will employ here the LINGO programming language to carry out the dynamic simulation in our investigation.

3. The Model Simulation

Our study first builds a comprehensive simulation model system to forecast the CO₂-emissions based on an input-output table and balances, that simulate social, economic and environmental developments (Higano et al., 2002).

3.1 Simulation Model Framework

As depicted in Figure 1, the comprehensive simulation model developed in our study has one objective function: to maximize GDP from 2008 to 2020 with constraints on carbon intensity. There are three balances in this simulation model: the value flow balance in socio-economic development; the energy flow balance; and the material flow balance which reflects the CO₂-emissions.

Figure 1. Simulation model architecture

Concerning the sector classification, our study adopts the traditional three-industry division (primary, secondary, tertiary) to compare the changes in the national industrial structure. The energy sector will be specifically introduced as a new integrated sector to specify the energy balance; in addition, six types of energy resources (fossil energy: coal, natural gas, oil; non-

fossil energy: hydro power, nuclear power, and other new energies) are considered in this simulation to classify the energy supply trends.

3.2 Case Setting

We set up our cases (Case 1 and Case 2) on the basis of China's carbon intensity constraints in the year 2020, where the carbon intensity is supposed to be reduced from 2008 to 2020. In each scenario, the energy structure and industry structure are combined to achieve the carbon intensity targets. Meanwhile, the proportion of non-fossil energy in total energy supply can be identified through simulation, while guaranteeing the goals of the economic development and the carbon emission reduction. The simulation aims to trace the impacts on the CO₂-emissions, energy consumption, and economic development brought about by carbon intensity and energy-supply structure changes.

Table 1. Case setting

	Carbon intensity in 2020 (tons/million dollars)	Non-fossil energy proportion
Case 1	$\leq 1,140$	15%
Case 2	≤ 780	No-limit

3.3 Simulation Modeling Formulation

In the simulation model, the decision variables can be classified into two types: endogenous (en) and exogenous (ex). The exogenous parameters are calculated based on current data; the endogenous variables will be determined by simulation. The time span (t) is 13 years, from 2008 to 2020.

(1) Objective Function

The objective of this simulation is to maximize China's GDP; accordingly, the objective function can be formulated as follows:

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

$$GDP(t) = \sum_{n=1}^3 v^n \cdot X_n(t) + \sum_{e=1}^6 v^e \cdot X_e(t),$$

where $GDP(t)$ (en) is determined by: the sector production $X_n(t)$ (en) (n=1, primary sector; n=2, secondary sector; n=3, tertiary sector); the production of six types of energy sector ($X_e(t)$, en) (e=1, coal; e=2, oil; e=3, natural gas; e=4, hydro power; e=5, nuclear power; and e=6, other new energy); and their respective value-added ratio v_n (ex); ρ is the social discount rate, set at 0.05 (ex).

(2) CO₂-emissions

The CO₂-emission model incorporated the various ways of CO₂ generation, including industrial activity, energy supply, and household consumption.

$$CO_2(t) = \sum_{n=1}^3 Acn \cdot X_n(t) + \sum_{e=1}^6 Ace \cdot X_e(t) + Acr \cdot Z(t),$$

where $CO_2(t)$ is the amount of CO₂-emissions in China at time t (en), while the total CO₂-emissions are determined by the industrial production, six types of energy utilization ($X_e(t)$, en), and household consumption at time t ($Z(t)$, en). Acn , Ace , and Acr are the CO₂-emission coefficients of industrial production, energy utilization, and population, respectively (ex).

(3) Energy Flow Balance Model

The energy flow balance model demonstrates the energy supply and demand flow. Energy supply ($EST(t)$, en) can be supported by six types of energies, while the energy supply structure will have a significant impact on the CO₂-emission. Energy demand ($EDT(t)$, en) is determined by normal industrial production ($X_n(t)$) and household activities. Generally, the energy supply must meet the energy demand in each year. This can be written as:

$$EST(t) = \sum_{e=1}^6 Ecm \cdot X_e(t)$$

$$EDT(t) = \sum_{n=1}^4 Ecn \cdot X_n(t) + Ecr \cdot Z(t)$$

$$X_4(t) = \sum_{e=1}^6 X_e(t),$$

where Ecn and Ecr are the energy demand coefficients of the sectors $X_n(t)$ and population $Z(t)$, respectively (ex); Ecm is the respective coefficient of the six types of energy supply resources in relation to their production (en). In particular, $X_n(t)$ ($n=4$, energy sector) is the total production of the energy industry which combines the six energy sectors.

(4) Input-Output Constraint

The calculation of China's GDP is based on a standard Input-Output model (Leontief, 1970).

$$X_n(t) \geq A_{nn}X_n(t) + C_n(t) + G_n(t) + I_n(t) + E_n(t) - M_n(t) \quad (n=1, \dots, 4),$$

where $X_n(t)$ should obey the output balance between the industries, household consumption ($C_n(t)$, en), government consumption ($G_n(t)$, en), investment ($I_n(t)$, en), exports ($E_n(t)$, en), and imports ($M_n(t)$, en). The simulation will be proceed based on the initial data provided below.

The initial values of the endogenous indexes are shown in Table 2, and the values of the relevant exogenous parameters are shown in Table 3. In 2007, the population of China was

1,321 million. Population $Z(t)$ is calculated based on the previous year's population and the annual population rate of increase (0.57 percent in 2007).

Table 2. Simulation indicators and their initial data in 2007 (billion CNY)

	X_1 (Primary)	X_2 (Secondary)	X_3 (Tertiary)	X_4 (Energy)
Xn	4889.30	54498.66	19238.51	3259.43
Cn	1115.60	3687.42	4584.74	267.50
Gn	34.16	0.00	3484.93	0.00
In	471.33	9320.53	903.48	118.41
En	66.60	8154.29	1326.70	6.51
Mn	-232.80	-6584.64	-582.82	-1.80

Table 3. Values of parameters in simulation in 2007

A	X_1	X_2	X_3	X_4
A ₁	0.14066	0.04572	0.01325	0.00002
A ₂	0.20043	0.60148	0.27195	0.28515
A ₃	0.06334	0.09269	0.20133	0.08815
A ₄	0.00941	0.02990	0.01505	0.27725
v	0.5862	0.2302	0.4984	0.3494
Ecn	200.8728	282.4293	165.2479	2954.0959
Acn	0.5270	0.4136	0.3819	9.561

Based on the comprehensive evaluation model, this model aims to include most of the important factors that will impact on the construction of a low-carbon society. LINGO programming language is utilized to accomplish this simulation model.

4. Simulation Results and Discussion

Simulation provides an effective approach to estimate the social, economic, and CO₂-emission trends throughout a comprehensive system. It may also estimate the carbon intensity change potential under different scenarios. The simulation results prove that this model can reflect the actual social and economic development with high validity and reliability.

4.1 Carbon Intensity

As the case setting, we run the simulation to find the minimum carbon intensity that can be achieved under these two cases.

Figure 2. Carbon intensity trends from 2008 to 2020 in Case1 and Case2

Figure 2 demonstrates that the minimum carbon intensity that can be obtained is 1,040 tons/million dollars, which is a 45.26 percent reduction compared with the scenario in 2005. The Chinese government plan (1,045-1,140 tons/million dollars) can be achieved when the non-fossil energy contributes 15 percent of the total energy supply. And, even if we adjust the energy supply structure without any limitation, we can also reach the world average standard of 780 tons/million dollars in 2020.

4.2 Economic Development Trend

It appears in the simulation experiment, under carbon intensity constraints, that China's GDP can also develop steadily. In both cases, its GDP can reach more than 65,000 billion CNY by 2020.

Figure 3. GDP trends from 2008 to 2020 in Case1 and Case2

The average GDP increase rate is 9 percent and 8 percent in Case 1 and Case 2, respectively. The results show that high carbon intensity constraints will limit economic development; and the economic growth rate will slow down in the later years after 2016 in Case 2 with strict carbon intensity limits.

4.3 CO₂ Emission Trend

Along with economic development, China's CO₂-emissions will inevitably increase. As shown in Figure 4, in Case 1 the total amount of CO₂-emissions will reach 12.51 billion tons by 2020, which is double the amount of 2007, while in Case 2 the emissions will be 8.05 billion tons by 2020.

Figure 4.CO₂-emission trends from 2008 to 2020 in Case 1 and Case2

4.4 Energy-Supply Structure Trend

In order to improve economic development, as well as to respect the carbon intensity constraint, an adjustment in the energy supply structure will be the key method to achieve these dual targets. As set in Case 1, the proportion of non-fossil energy in the total energy supply is 15 percent. The minimum carbon intensity we can get from the simulation is 1,040 tons/million dollars under this constraint.

Figure 5. Energy supply trends from 2008 to 2020 in Case1

The specific energy supply structure is shown in Figure 6 by comparing Case 1 and Case 2. In Case 1, the total energy supply will be 5,039 million TCE in 2020, compared with 2,469 million TCE in 2007 (IEA, 2007). The higher energy supply comes from relatively low CO₂-emission resources, oil, natural gas, and non-fossil energy, while the ratio of coal will decrease from 77.7 percent in 2007 to 51 percent in 2020.

Figure 6. Energy supply structure comparison in 2020 in Case1 and Case2

However, in Case 2, in order to get the 780 tons/million dollars carbon intensity in 2020, the proportion of non-fossil energy needs to increase to 60 percent, as tested through our simulation experiment. It is however, unlikely that such a high energy structure change can be achieved by 2020; therefore, the simulation results prove that it is unfeasible for China to pursue the world average CO₂-emission standard in the short term.

5. Conclusion

The present study has utilized a comprehensive simulation model to identify a minimum carbon intensity under the current situation of energy supply and economic development. The simulation model constructed included all important factors that impact on carbon intensity, and was based on an integrated system which incorporated a CO₂-emission model, an energy balance model, and a socio-economic model. A dynamic optimization simulation was accomplished by using linear LINGO programming.

Our simulations forecast the interaction between economic growth and CO₂-emission reduction with alternative forms of energy utilization in the future until the year 2020. This study finds that the minimum carbon intensity that China can achieve under the current scenario conditions is 1,040 tons/ million dollars in 2020, while the CO₂-emissions will be 12.51 billion tons, if the proportion of non-fossil energy is 15 percent. Even under this carbon intensity limitation, China's GDP can also achieve a 9 percent average annual increase from 2008 to 2020.

However, the simulation results also show that it is unfeasible to pursue the world average CO₂-emission standard of 780 tons/million dollars by 2020, unless there is a breakthrough in the structure of energy supply (65 percent non-fossil energy would then be required).

Our simulation results also provide specific future trends for the economy, CO₂-emissions, and energy supply structure. This study can thus offer a more effective and reliable method to mitigate global warming in China using a simulation approach. The simulation method can also be easily applied to analyse other issues relevant to a low carbon society.

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