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Projections and Recommendations for Energy Structure and Industrial Structure Development in China through 2030: A System Dynamics Model

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Received: 26 June 2019; Accepted: 22 August 2019; Published: 7 September 2019

Abstract: In this research, we established a System Dynamics Model named "E&I-SD" to study the development of the energy structure and industrial structure in China from 2000 to 2030 using Vensim Simulation Software based on energy economy theory, system science theory and coordinated development theory. We used Direct Structure Test, Structure-oriented Behavior Test, and Behavior Pattern Test to ensure the optimal operation of the system. The model's results showed that the indicators of total energy consumption, total added value of GDP after regulation, energy consumption per capita, and GDP per capita were on the rise in China, but emissions per unit of energy showed a downward trend. Separately, the model predicted average annual growth rates in China through 2030. Based on these findings, we proposed important policies for China's sustainable development. Firstly, short- and long-term policy measures should be implemented to replace fossil fuels with clean energy. Secondly, the utilization efficiency of raw coal should be appraised future. The planning should provide for steady development and improvement of the primary, secondary, and tertiary sectors. Thirdly, the mid- and long-term plans for development and management of various industrial sectors and the corresponding energy consumption should be based on technological trends. Finally, a market-oriented pricing mechanism for energy should be established in China as soon as possible.

Keywords: energy structure; industrial structure; coordinated development; system dynamics

1. Introduction

Economic growth in China faces a conflict between the needs of the expanding industrial structure and the importance of a clean, modern energy system. The intensification of these competing demands has aroused widespread concern among researchers, and brought about increased national efforts to strengthen regulations and control macroeconomic policy. The 13th Five Year Plan [1] and the 19th National Congress of the Communist Party of China [2] provided important guidance with respect to the coordinated development of energy structure and industrial structure. Their published positions reflected a wide consensus that the long-term fundamentals of China's economic development will not change over the next few years. To promote modernization, China must embrace the energy revolution actively, while vigorously developing its economy and optimizing its industrial structure. To augment its energy supply structure, China must enhance the efficiency of energy utilization, and build a clean (low-carbon), safe, and efficient energy system. However, the issues of imbalance and lack of coordination between economic growth and energy consumption are critical. The energy structure and industrial structure not only have their own characteristics to develop and change independently, but also have mutual influence and promotion to each other. Since both of these subsystems are an important part of the overall economic system, it is imperative that they confront the increasingly serious waste of resources, environmental pollution, and ecological destruction. Therefore, the future and systematic research on coordinated development of the energy structure and industrial structure has great significance for China's sustainable economic development.

2. Literature Review

Energy shortage has been the bottleneck of economic and social sustainable development in China. The new task to improve energy efficiency has been put on the agenda of the "13th Five-Year" Plan. Therefore, numerous research papers have analyzed the relationship between economy and energy, with valuable results [3]. Most of the existing literature focused on two variables: energy consumption and economic growth [4–8]. Some of the studies focused on energy consumption and industrial structure change [9], while others looked at economic growth and the energy structure [10]. In response to rapid development of the world economy and the increasingly severe issues of energy supply and demand, population growth, and environmental pollution [11,12], an increased number of studies have applied econometrics analysis methods to analyze the development of China's energy structure and industrial structure [13,14]. Many researchers analyzed the impact of energy structure, technological progress, and industrial structure on energy intensity with the logarithmic mean Divisia index technique, the results show that energy structure and industrial structure have different effects on energy intensity [15–17]. Cross-correlations between energy structure and industrial structure based on the well-known detrended cross-correlation analysis are shown to be significant and strong [18,19]. Some authors described the historical evolution of various end uses in the different energy sectors through mapping Sankey diagrams. They use the information from the energy flow analysis to project future scenarios [20,21]. Furthermore, the Granger causality test, input–output analysis, Grey correlation analysis, impulse response function and variance decomposition methods are also applied to analyze the influence relationship between the energy structure and industrial structure [22–25]. These studies on the interaction between energy structure and industrial structure provide massive meaning findings, but most of this work has come in the form of static studies [26].

In recent years, some authors attend to build energy–economy–environment models have increased gradually as well [27–30]. However, there are few studies on the dynamic coordinated development of the energy structure and industrial structure. In our research, we proposed a system dynamics approach referred to as the Coordinated Development of Energy Structure and Industrial Structure in China (E&I-SD) model. This study has both theoretical and practical value for analyzing the development of clean energy and industry in China, and lays the foundation for planning future coordinated development as well. The contributions mainly include two aspects: (1) The dynamic simulation model of the coordinated development of energy structure and industrial structure based on system dynamics theory, energy economy theory and coordinated development theory is established. This E&I-SD model may serve as a guidance to policymakers towards their efforts to plan the coordinated development of energy structure and industrial structure strategies by using the information of simulation and prioritizing uncertainties through driving the E&I-SD mode from the economic, energy and environmental perspectives. (2) This study simulates, analyzes, and predicts the coordinated development of China's energy structure and industrial structure in 2030 by using the E&I-SD mode. According to the results, the paper provides reasonable suggestions for the policy makers.

The remainder of this paper is structured as follows. Section 3 presents our methods and the data used in this study, along with a brief introduction to the system dynamics model. In Section 4, we describe the details of the E&I-SD model and the tests used to validate the model. Section 5 provides the E&I-SD model's predictions of China's development trends through 2030. Finally, Section 6 presents our conclusions and recommendations based on the model's the results, and provides some concluding remarks.

3. Methods and Data

3.1. Objectives and Requirements of Modeling

The objective of this research was to explore the mechanism of the dynamic changes in the energy structure and industrial structure of China. For this purpose, we established the E&I-SD system dynamics model, which enabled us to run simulations. From the perspective of system dynamics, this paper analyzed China's opportunities and challenges with respect to the coordinated development of its energy and industrial subsystems, with particular attention to problems of the environment and population growth. We explored the feedback relationship between the two subsystems, clarified the relationships among the internal variables, and described the operation mode and track of the subsystems. Having established the current status of China's energy structure and industrial structure, and we studied the internal relations between energy consumption, the employed population, environmental pollution, and economic development. Finally, we specified the direction of China's coordinated energy and economic development by creating a projection of the growth trends in these areas under the constraints of the anticipated environment in 2030.

3.2. Brief Introductin to the System Dynamics

System dynamics as a methodology was created by Professor Jay Forrester of the Massachusetts Institute of Technology in the late 1950s [31–33]. System dynamics is a branch of system science, and is a related discipline of communications in the fields of natural and social sciences. The value of system dynamics is that it provides an effective modeling technique for understanding and exploring complex systems and their inherent feedback mechanisms. System dynamics provides a method for developing computational simulations of large-scale systems that has been applied widely to the study of various industries, the economy, ecology, and the environment, among other areas. System dynamics has been used extensively in research focused on the relationships between energy supply, prediction of energy demand, and industrial development, particularly with respect to problems of periodicity, protracted nature, and insufficient data [34]. Essentially, the energy structure and industry structure together form a complex nonlinear system that is influenced mainly by economic growth, social development, and energy supply and demand. The system dynamics approach is popular for analyzing energy policies because it can link the observable patterns of a system to micro-level structures and the decision-making process [35].

3.3. Logical Framework of the E&I-SD Model

Establishing system boundaries is central for attaining a focused and accurate system model for research because the core issues of the system become more centralized and accurate. Clear boundaries are a prerequisite for developing the E&I-SD model and producing accurate analyses. The E&I-SD system includes three subsystems: the economy, energy, and society. China's energy structure and industrial structure has been changing dynamically in response to the constant exchange of information, materials, and energy, along with the interrelationships and interactions between the variables of the three subsystems. Among them, the economic and energy subsystems are the basic components of the system model, and they are the core parts of the research on the coordinated development of China's energy structure and industrial structure. The social subsystem is considered an external influence that includes external factors such as population, environment, employment, and similar considerations. The details are as follows:

(1) Sub-module reflecting of the impact of industrial structure on energy structure

The sub-module of the impact of industrial structure on energy structure explores the impact of three industries structure changes on primary energy consumption structure. It is mainly composed of 32 variables in energy structure and industrial structure—among which, the industrial structure is represented by the proportion of added value of primary industry, secondary industry and tertiary industry to GDP; energy structure only refers to the energy consumption structure, and it is represented by the proportion of raw coal, crude oil, natural gas and other energy consumption to the total energy consumption.

(2) Sub-module reflecting the impact of energy structure on industrial structure

The sub-module of the impact of energy structure on industrial structure consists of 59 variables in energy structure and industrial structure. In addition, it explores the impact of energy structure changes on three industries structure. Energy structure includes energy consumption structure, production structure, import structure and export structure, in which energy production structure is represented by the proportion of raw coal, crude oil, natural gas and other energy production to the total energy production; energy import structure is represented by the proportion of raw coal, crude oil, natural gas and other energy imports to the total energy imports; and energy export structure is represented by the proportion of raw coal, crude oil and natural gas and other energy exports to the total energy exports.

(3) Sub-module reflecting of social factors

The E&I-SD model introduces the necessary social factors as important indicators to restrict the coordinated development of energy structure and industrial structure in China. Solving the problem of employment is the fundamental task for the development of people's livelihood. The employment structure has an important impact on the development of three industries and energy consumption. Therefore, the effective correlation between employment structure and industrial structure can make the analysis of the coordinated development of energy structure and industrial structure more complete. In addition, this social sub-module is mainly composed of 18 variables.

3.4. Data Source

The data for this study covered from 2000 to 2016 in China. First, the energy and industrial sectors were defined according to the *China Statistical Yearbook 2016* [36] and *China Energy Statistical Yearbook 2016* [37]. Primary energy was divided into raw coal, crude oil, natural gas, and other forms of energy. The category of "other energy" consisted mainly of hydro power, nuclear power, wind power, solar power, and biomass energy, among others. We considered the Chinese economy as divided into three sectors: primary, secondary, and tertiary industries. Among them, the primary sector comprises agriculture, forestry, animal husbandry, fisheries, and other industries directly involved with natural resources. The secondary sector comprises industry and construction. The tertiary sector comprises service industries: wholesale and retail trades; transport, storage, and postal services; hotels and catering services; and financial intermediation including real estate among others.

4. The E&I-SD Model Description and Validation Test

Using the E&I-SD model, we simulated the coordinated development of China's energy structure and industrial structure from 2000 to 2030. We set the running time of the simulation at thirty years, with a time step of one year, beginning with the year 2000. For this work, VENSIM (VENSIM is an industrial strength simulation tool for improving the performance of real systems. Its rich feature set emphasizes model quality, connections to data, flexible distribution, and advanced algorithms.) was employed to write the simulation programs, and EVIEWS software was used to regress parts of the equations. There were 115 system dynamics equations and parameters established through repeated modification and improvement on the model, parts of typical variables and equations are shown in Appendix A Table A1.

4.1. Causal Loop Framework

The E&I-SD model links the important variables in the three subsystems of energy, economy, and society by defining the relationships between the variables. The causal framework of the model system is shown in Figure 1. The three subsystems are combined organically by the important variables of

GDP, added value of different industries, total energy consumption, major pollutant emissions, total population, and so on. The arrows represent the relationships between variables, and the "+" or "-" sign at the end of the influence lines indicates the direction of the effect. The "+" indicates that the variables change in the same direction, and the "-" indicates the opposite.

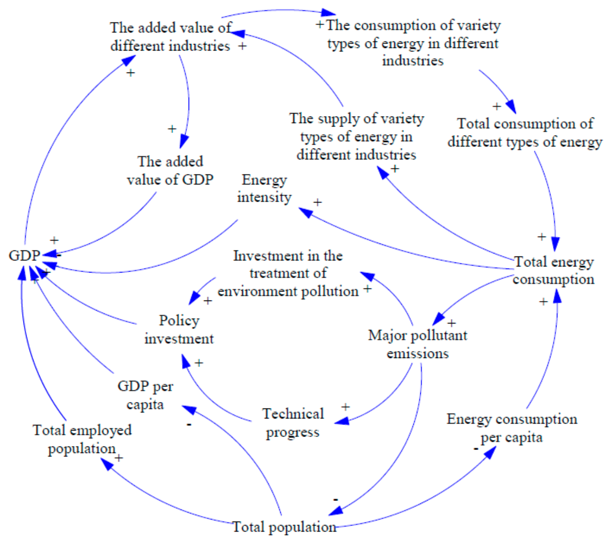

Figure 1. The causal loop framework of E&I-SD model.

The structure of a system in system dynamic methodology is captured by causal loop diagrams. A causal loop diagram represents the major feedback mechanisms. These mechanisms are either negative feedback or positive feedback loops. Table 1 shows typical feedback loops in the E&I-SD model.

Table 1. The typical feedback loops in the E&I-SD model.

Type	Typical Feedback Loops
Positive	GDP—(+) the added value of different industries—(+) the consumption of variety types of energy in different industries—(+) total consumption of different types of energy—(+)total energy consumption—(+) major pollutant emissions—(+) Investment in the treatment of environment pollution—(+) policy investment—(+) GDP
	GDP—(+) the added value of different industries—(+)the consumption of variety types of energy in different industries—(+) total consumption of different types of energy—(+) total energy consumption—(+) major pollutant emissions—(+) technical progress—(+) policy investment—(+) GDP
Negative	GDP—(+) the added value of different industries—(+) the consumption of variety types of energy in different industries—(+) total consumption of different types of energy—(+) total energy consumption—(+) major pollutant emissions—(-)total population—(-) total employed population—(-) GDP
	The added value of different industries—(+) the consumption of variety types of energy in different industries—(+) total consumption of different types of energy—(+) total energy consumption—(-) energy security—(+) the supply of variety types of energy in different industries—(+) the added value of different industries

4.2. *Stock Flow Diagram*

The stock flow diagram is the core of a system dynamics model, and represents the process of quantization and materialization of the causal loop framework. For this research, the stock flow diagram was constructed according to the causal loop framework of the E&I-SD model, which was composed of two level variables, three rate variables, and 107 auxiliary variables, as shown in Figure 2.

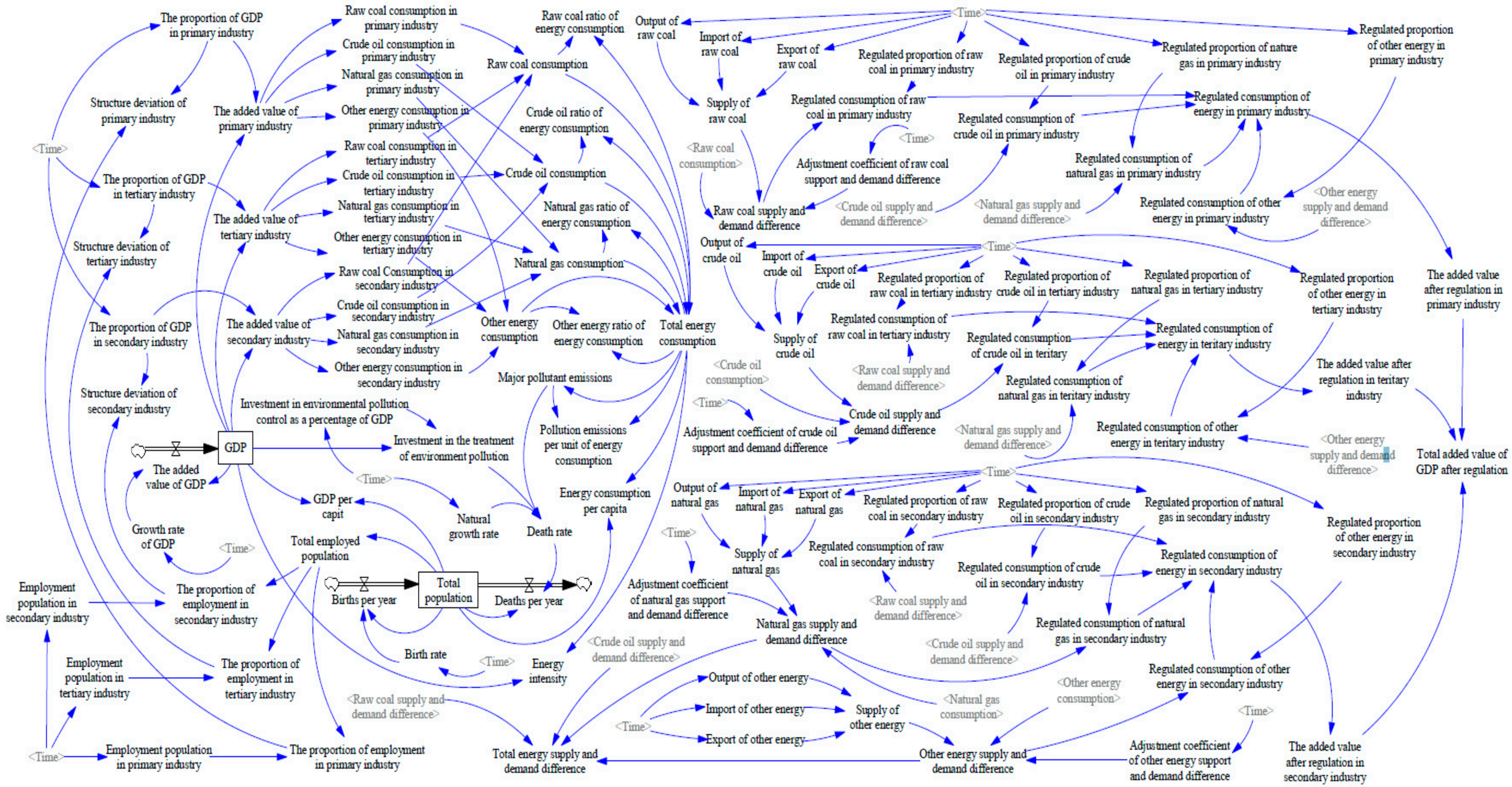

Figure 2. The stock flow diagram of E&I-SD model.

4.3. Hypotheses and Boundaries of the E&I-SD Model

The consensus in the literature holds that building a model entails understanding the essential features of a system through abstraction and induction. An excellent model should be as simple as possible based on a true reflection of the research questions. Accordingly, this study simplified the system while ensuring the integrity of the model. We made the following hypotheses and set the boundaries of the E&I-SD model as described:

(1) Since the data of each variable and parameter were known only through 2016, we chose to project the 2016 standard values as constant from 2016 to 2030. The variables for the three economic sectors (primary, secondary, and tertiary) included variables such as the following:

- The proportion of GDP;
- Output of different forms of primary energy, Import of different forms of primary energy, Export of different forms of primary energy;
- Regulated proportion of different forms of primary energy;
- Natural growth rate, employment population;
- Investment in the treatment of environment pollution.

(2) The data concerning environmental pollution were too extensive to include in its entirety. The data included pollution of wastewater, waste gas, and solid waste as well as noise, light, and radiation pollution. Since the units of measurement of each type of pollutant were not uniform, and the degree of correlation was very small, for this model, we chose to represent pollution by the total amount of wastewater.

4.4. Validation Test of the E&I-SD Model

The E&I-SD model can be used to research China's future coordinated development policy for its energy structure and industrial structure. To ensure the correctness and validity of the model, and establish the feasibility of forecasting future development [38], we applied three test methods: a direct structure test, structure-oriented behavior test, and a behavior pattern test.

4.4.1. Direct Structure Test

The direct structure test was designed to verify the rationality of the empirical and theoretical structure, causal relationships, stock-flow diagram, definition of variables, and parameter confirmation of our model. The research summarized the advantages and disadvantages of the model structure, and tried to perfect the model to match the actual situation, making the model scientifically logical and reasonable based on extensive data and reading a large amount of literature. It is necessary to judge the rationality of the model's results after testing the dimension consistency to realize formal inspections of the model [39].

4.4.2. Structure-Oriented Behavior Test

The structure-oriented behavior test provides an advantage because it is more suitable for formalization and quantification than the direct structure test. A behavior sensitivity test can verify and track the correctness of the simulation model through its automatic identification function. The E&I-SD model is sensitive to parameter changes and inertial resistance to policy changes. Such changes are reflected in the lag of one factor over the other. Because of the large number of factors affecting a real-world system, and the complex relationship between the variables, realistic systems generally exhibit relative stability. It is vital to investigate the stability of the system model in the simulation test. If the values of the system indexes change greatly during different time intervals, it is probable that the system model is unstable. In that case, the model would not be able to complete the simulation correctly, and any predictions about the real-world system would demonstrate strong variability [40]. Therefore, the time steps for simulation analysis were set to one year, six months, and three months.

The variables of total energy consumption and death rate were selected as the test variables in the system. The graphs of the simulations are shown in Figure 3. The results show that the model system was stable, without violent shocks and fluctuations. The system's performance was in line with the actual system, so that the model was operating in accordance with the actual system.

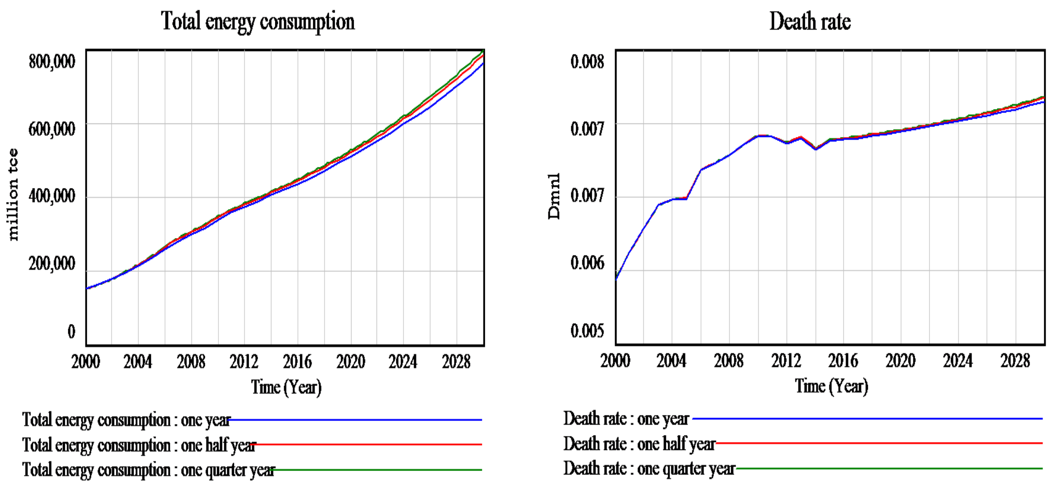

Figure 3. Results of the structure-oriented behavior test of the E&I-SD model.

4.4.3. Behavior Pattern Test

The behavior pattern test aimed at justifying the reliability of the model and providing confidence for model application [41]. We used the E&I-SD model to simulate the results from 2000 to 2030. Then, we compared the model's results for the test variables with actual historical data. We selected the following test variables for examination and comparison: GDP, added value of various industries, investment in the treatment of environmental pollution, total energy consumption, raw coal consumption in secondary industries, crude oil consumption in secondary industries, total consumption of different types of energy, death rate, total population, total employed population, major pollutant emissions, and differences in supply and demand for various types of energy.

Some important variables results of the behavior pattern test are shown in Appendix A Table A2. As can be seen, the deviation of test variables was within ±10% for the most part, demonstrating that the model met simulation requirements. Note that the error rate of the simulation value and the real value for individual years were slightly greater for a few variables. This finding can be explained by the many uncertainties in the coordinated development of China's energy structure and industrial structure. For example, changes in national policies, natural disasters, or other external factors caused statistical data to fluctuate at certain points. In such cases, when using the linear regression model to determine the relationship between variables, there are larger individual errors in the variables. This conclusion was consistent with the findings of Zhu et al. [42]. Because of the rapid development of China's economy, the demand for energy rose rapidly across the three economic sectors. The degree of fitting of the simulation data for the individual variables in the model from 2000 to 2002 years was low. Therefore, the model can be used to predict and analyze the coordinated development of energy and industry.

5. The Model Applications and the Result Analysis

Based on the E&I-SD model, the preliminary prediction results of the coordinated development of China's energy structure and industrial structure in 2030 are shown in Table 2.

Table 2. The results of E&I-SD model in 2030.

Indicator	Total Added Value of GDP after Regulation	Energy Consumption per Capita	GDP per Capita	Pollution Emissions per Unit of Energy Consumption
unit	100 million yuan	10,000 tce/million capita	100 million yuan/million capita	10,000 tons/million tce
2020	287.536	3.59944	3.93371	16.7992
2025	639.574	4.27966	5.35941	16.2288
2030	1,106.050	5.13482	7.30722	15.7428

The model's projection shows that the total added value of GDP after regulation, Energy consumption per capita, GDP per capita and other indicators have a different degree of upward trend and the pollution emissions per unit of energy consumption have a degree of downward trend compared with 2015. We also used the innovative O-S method (The orthogonal scenario analysis method combines orthogonal experimental design with scenario analysis methods. This approach selects the representative factors and levels in the comprehensive scenario planning group based on the orthogonal principle, and finally identifies the best scenario group of the corresponding indicators) to analyze the evolution trend and causes of the key factors in the current stage of China's energy structure and industrial structure development, and summarized the important opportunities and challenges facing China's future energy structure and industrial structure coordinated development depend on the predicted results as follows:

(1) The slowdown of the world and China's economic growth forces the optimization and upgrading of energy structure and industrial structure in China.

Facing the increasingly severe situation of resource shortage, environmental deterioration, ecological destruction, population reduction and technological progress hindered, the traditional low-cost competitive advantages are gradually losing. Especially under the impact of the international financial crisis and the slowdown of economic growth in the world and China, resulting in a significant reduction in the total energy demand, which in turn forced the energy structure and industrial structure to be continuously upgraded and optimized.

(2) Optimizing the national energy structure strategy is an urgent requirement for expanding international cooperation.

Firstly, in order to reduce the rising price of crude oil caused by geopolitics and the security of energy supply, which have a significant impact on China's economic development, the Chinese government has put forward new requirements for controlling the dependence of crude oil on foreign countries in the 12th Five Year Plan and the 13th Five Year Plan. Secondly, the government has put forward a new strategic thinking of energy reform. The ideas of energy development are from extensive to intensive and from fossil energy to renewable energy. The continuous expansion of international energy cooperation by the Chinese government and the diversification of natural gas and other energy import channels helps the economy resist political risks that may jeopardize supply stability. Thirdly, under the pressure of environmental pollution, the development of renewable energy such as wind power, hydropower, solar energy, biomass energy, nuclear power and other energy sources has become a new direction of energy market:

(3) New requirements of environmental protection on the development technology and consumption of raw coal.

The greenhouse gases produced by the combustion of raw coal are the main cause of climate warming. The promulgation and implementation of environmental protection laws and regulations were the main reasons for the increased cost of raw coal development. As the actual investment in the raw coal industry in resources, environment, safety, technology and other aspects, it will cause the energy cost to rise and the energy profit to decrease continuously. When the output of raw coal reaches a certain limit, the contribution of the increase in raw coal output to the China's economy growth will gradually decrease:

(4) The improvement of energy efficiency has promoted the transformation and upgrading of China's energy structure and industrial structure.

With the rapid progress of technology, the efficiency of energy processing and conversion, energy use efficiency and recycling level have been steadily improved, resulting in a decrease of total energy demand, and upgrading of China's energy structure and industrial structure to a new mode of modern energy and economic development with clean, low-carbon, quality and efficiency.

(5) As domestic energy production continues to increase and new requirements for international renewable energy diversification, China's industrial structure needs to be continuously optimized.

Since China's reform and opening up, economic growth has been positively correlated with the overall trend of raw coal production. This is due to the natural resource endowment of China's rich coal, which has formed an energy consumption structure led by raw coal consumption at this stage.

The development of the secondary industry encountered new bottlenecks. With the improvement of the specialization of the secondary industry and the level of product processing continuing to deepen, the product cost has been gradually increased. The share of China's secondary industry in the international market is basically stable. In the future, the development direction of this industry is to eliminate backward production capacity, increase product added value, reduce environmental pollution and focus on the development of domestic strategic emerging industries. It will gradually transition from extensive and high speed development mode to a new development mode of high efficiency, high quality and stable secondary industry.

The potential and space for the development of tertiary industry are enormous. According to the Kuznets Theorem [43] and the existing research literature [44,45], the proportion of the tertiary industry surpassing the secondary industry is an important symbol of the industrial structure upgrading. With the increase of national income and urbanization level, the trend of the added value of the three industries is: the proportion of the primary industry decrease, the proportion of the secondary industry changed from rapid rise to decline, and the proportion of the tertiary industry showed a clear upward trend and eventually became the largest industry in the national economy.

From the experience of industrial structure development of various developed countries, the United States, Germany, Japan, South Korea and other countries have followed this development law. This further shows that the trend of China's three industries conforms to the general law of industrial structure evolution. The contribution rate of the tertiary industry to economic growth will continue to increase and the development potential of service industry is huge in the future. China has entered a new stage of rapid development of the service industry.

The development of the tertiary industry and the secondary industry is mutually supportive and reinforcing. That is to say, the solid foundation of China's primary and secondary industries has driven the rapid development of the tertiary sector headed by producer services. In recent years, with the promulgation of the national policy for the development of tertiary industry, the injection of foreign capital and the increase of national income, the tertiary industry has developed rapidly. Compared with the secondary industry, China's tertiary industry is mainly oriented to the domestic market and its service level is relatively low. In the short term, it should focus on developing the domestic market, mastering its core technologies and creating and maintaining its tertiary industry with an international competitive advantage. This argument further clarifies the necessity of adhering to the national optimization policy of "steadily developing the primary industry, improving and upgrading the secondary industry and increasing the proportion of the tertiary industry".

6. Recommendations and Conclusions

In this research, we utilized the E&I-SD model to simulate, analyze, and predict China's coordinated energy and industrial growth from 2016 through 2030. According to the results, we propose the following conclusions and policy suggestions:

(1) The E&I-SD model's forecast showed that China's primary energy consumption of raw coal and crude oil is on a sharp uptrend. Effective short- and long-term policy measures to replace fossil fuels with clean energy should be proposed and implemented across economic sectors. First, efforts to optimize China's energy structure should start by reducing the percentage of raw coal in energy consumption, simultaneously increasing the proportion of natural gas and other primary energy sources. However, it is unrealistic to expect China to substitute low carbon energy sources for fossil fuels quickly. Second, the utilization efficiency of raw coal should be appraised further. In the short term, policies should aim to accelerate the popularity and application of technologies such as pithead power, clean coal, and coal-based polygeneration. In addition, it is necessary to increase investment in the innovation and utilization of new energy technologies, improve the utilization rate of terminal energy, and achieve the effective replacement of fossil fuels with clean energy over the medium and long term.

(2) Mid- and long-term plans for managing the development of various economic sectors should be based on technological progress in China. The research groundwork can be accomplished through further adjustment and improvement of the E&I-SD model. Based on the simulation results, policies could be proposed for the healthy development of China's energy structure and industrial structure, along with energy management planning suitable for China's development.

(3) A market-oriented pricing mechanism for energy should be established in China as soon as possible. The Chinese government's intervention in energy prices, along with the oil companies' monopoly of the energy market, have led to the non-marketization of energy prices. Currently, energy prices fail to reflect energy scarcity, and also seriously hinder the coordinated development of energy structure and the economic structure. Therefore, one of the most effective ways to promote the coordinated development of the energy structure and industrial structure would be by strengthening the regulation and control of the energy pricing system. A sound pricing system can inhibit the increase of total energy consumption. This conclusion is consistent with the work of Wang [46].

(4) The optimization of China's industrial structure relies mainly on the steady development of the primary industries, improvement and upgrading of the secondary industries, and promotion of the tertiary industries. Currently, the secondary industries participate in international industrial specialization, while the tertiary sector remains oriented toward the domestic market in China. Most of the production that requires high energy consumption comes from the secondary industries. The increasing amount of activity in secondary industries will become the main reason for a rise in energy intensity in China. For China's secondary industries to maintain their share of the international markets, they should accelerate the rate at which they upgrade their output from low value-added to high value-added products. In addition, China should encourage elimination of the backward production capacity associated with high energy consumption and serious pollution, and promote the development of advanced manufacturing industries and emerging sectors of strategic importance.

In contrast with the secondary economic sector, the tertiary industries primarily face the domestic market, and the quality of service remains lower. In the short term, China should focus on the growth of the domestic market, along with greater innovation in core technologies. This approach would allow China to grasp the key core technologies, and create and maintain the competitive advantage of the tertiary sector. In the medium and long term, China needs to establish the national core-tech brand of China's service industry, and gradually participate in international service industrial specialization. Only by realizing coordination and steady development of all three economic sectors can China reduce its energy intensity effectively, and coordinate the development of China's energy structure and industrial structure harmoniously.

This study did encounter certain limitations. Due to the length of the article, the concept of the self-innovated O-S method and its application principle are not described in detail. Using the self-innovated O-S method and E&I-SD model, we were able to simulate multiple scenarios, and put forward important and feasible policy proposals. The proposal portion of our work has been completed another paper titled, "Scenario Analysis of the Coordinated Development of China's Energy Structure and Industry Structure in 2030 based on the System Dynamics Model and Orthogonal Experimental Design Method," that will be published at a future date.

Author Contributions: Conceptualization, Methodology and Writing—original draft, S.H.; Supervision, B.Z.; Project administration, C.L.; Validation, A.F.

Funding: This research was funded by National Key R&D Program of China, grant number 2018YFC0704400. And the APC was funded by Research Institute of Standards and Norms, Ministry of Housing and Urban-Rural Development of the People's Republic of China.

Acknowledgments: The authors are also grateful to professors from the IFP School for helpful suggestions that improve this paper. The authors gratefully acknowledge the editors for kind help and the anonymous reviewers for their beneficial comments and encouragement.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The variables and equations in VENSIM software.

No.	System	Equation	Unit
1	Parameter	INITIAL TIME = 2000	Year
2	Parameter	FINAL TIME = 2030	Year
3	Parameter	Time step = 1	Year
4	Economy	GDP = INTEGER (The added value of GDP, 100280.1)	100 million yuan
5	Economy	The added value of GDP = GDP × Growth rate of GDP	100 million yuan
6	Economy	The proportion of GDP in tertiary industry = WITH LOOKUP ((Time, [(2000,0)(2030,1)],(2000,0.398),(2001,0.412),(2002,0.422),(2003,0.42),(2004,0.412),(2005,0.413),(2006,0.418),(2007,0.429),(2008,0.428),(2009,0.443),(2010,0.441),(2011,0.442),(2012,0.453),(2013,0.467),(2014,0.478),(2015,0.502),(2016,0.502),(2017,0.502),(2018,0.502),(2019,0.502),(2020,0.502),(2021,0.502),(2022,0.502),(2023,0.502),(2024,0.502),(2025,0.502),(2026,0.502),(2027,0.502),(2028,0.502),(2029,0.502),(2030,0.502))	Dmnl
7	Economy	The added value of secondary industry = GDP × The proportion of GDP in secondary industry	100 million yuan
8	Economy	GDP per capita=GDP/Total population	100 million yuan/10000 persons
9	Energy	Raw coal consumption in primary industry = 0.372699 × The added value of primary industry − 2920.026	10,000 tce
10	Energy	Crude oil consumption in secondary industry = 0.082784 × The added value of secondary industry + 12785.54	10,000 tce
11	Energy	Natural gas consumption in secondary industry = 0.064632 × The added value of secondary industry − 600.3673	10,000 tce
12	Energy	Other energy consumption in secondary industry = 0.091 × The added value of secondary industry	10,000 tce
13	Energy	Raw coal consumption in tertiary industry = 0.165659 × The added value of tertiary industry + 20593.55	10,000 tce
14	Energy	Crude oil consumption in tertiary industry = 0.229194 × The added value of tertiary industry + 7904.51	10,000 tce

Table A1. *Cont.*

No.	System	Equation	Unit
15	Energy	Natural gas consumption = Natural gas consumption in primary industry + Natural gas consumption in secondary industry + Natural gas consumption in tertiary industry	10,000 tce
16	Energy	Total energy consumption = Raw coal consumption + Crude oil consumption + Natural gas consumption + Other energy consumption	10,000 tce
17	Energy	Natural gas ratio of energy consumption = Natural gas consumption/Total energy consumption	10,000 tce
18	Energy	Other energy ratio of energy consumption = Other energy consumption/Total energy consumption	10,000 tce
19	Energy	Energy consumption per capita = Total energy consumption/Total population	10,000 tce /10,000 persons
20	Energy	Energy intensity = Total energy consumption/GDP	10,000 tce /100 million yuan
21	Energy	Supply of raw coal = Output of raw coal + Import of raw coal − Export of raw coal	10,000 tce
22	Energy	Supply of other energy = Output of other energy + Import of other energy − Export of other energy	10,000 tce
23	Energy	Total energy supply and demand difference = Raw coal supply and demand difference + Crude oil supply and demand difference + Natural gas supply and demand difference + Other energy supply and demand difference	10,000 tce
24	Energy	Natural gas supply and demand difference = Supply of natural gas − Natural gas consumption	10,000 tce
25	Energy	Other energy supply and demand difference = Supply of other energy − Other energy consumption	10,000 tce
26	Energy	Regulated consumption of energy in teritary industry = Regulated consumption of raw coal in tertiary industry + Regulated consumption of crude oil in teritary industry + Regulated consumption of natural gas in teritary industry + Regulated consumption of other energy in teritary industry	10,000 tce
27	Energy	Regulated consumption of crude oil in primary industry = Crude oil supply and demand difference × Regulated proportion of crude oil in primary industry	10,000 tce
28	Energy	Regulated consumption of natural gas in primary industry = Natural gas supply and demand difference × Regulated proportion of nature gas in primary industry	10,000 tce
29	Energy	Regulated consumption of crude oil in secondary industry = Crude oil supply and demand difference × Regulated proportion of crude oil in secondary industry	10,000 tce
30	Energy	Regulated consumption of natural gas in teritary industry = Natural gas supply and demand difference × Regulated proportion of natural gas in tertiary industry	10,000 tce
31	Economy	The added value after regulation in primary industry = 2.81367 × Regulated consumption of energy in primary industry	100 million yuan
32	Economy	The added value after regulation in secondary industry = 0.559261 × Regulated consumption of energy in secondary industry	100 million yuan
33	Economy	The added value after regulation in teritary industry = 1.331794 × Regulated consumption of energy in teritary industry	100 million yuan
34	Economy	Total added value of GDP after regulation = The added value after regulation in primary industry + The added value after regulation in secondary industry + The added value after regulation in teritary industry	100 million yuan

Table A1. *Cont.*

No.	System	Equation	Unit
35	Energy	Output of raw coal = WITH LOOKUP (Time, [(2000,0) − (2030,300000)], (2000,101009),(2001,107045),(2002,114307),(2003,135052), (2004,158116),(2005,177304),(2006,189881),(2007,205446), (2008,213024),(2009,219564),(2010,237839),(2011,264574), (2012,267464),(2013,270507),(2014,266230),(2015,260801), (2016,260800),(2017,260800),(2018,260800),(2019,260800), (2020,260800),(2021,260800),(2022,260800),(2023,260800), (2024,260800),(2025,260800),(2026,260800),(2027,260800), (2028,260800),(2029,260800),(2030,260800))	10,000 tce
36	Energy	Output of crude oil = WITH LOOKUP (Time, (2000,0) − (2030,40000)], (2000,23299.6),(2001,23368),(2002,23900.4),(2003,24183.3), (2004,25141.5),(2005,25984.3),(2006,26359.4),(2007,26687.8), (2008,27088.2),(2009,27106.7),(2010,28891.1),(2011,29074.1), (2012,29718.3),(2013,29944.2),(2014,30253.4),(2015,30682.5), (2016,30680),(2017,30680),(2018,30680),(2019,30680),(2020,30680), (2021,30680),(2022,30680),(2023,30680),(2024,30680),(2025,30680), (2026,30680),(2027,30680),(2028,30680),(2029,30680),(2030,30680))	10,000 tce
37	Energy	Import of crude oil = WITH LOOKUP (Time, [(2000,0) − (2030,60000)], (2000,13603.8),(2001,12653),(2002,14248.8),(2003,18516.3), (2004,24320.2),(2005,24043.4),(2006,27175.1),(2007,29401.3), (2008,32151.3),(2009,35918.3),(2010,40908.6),(2011,43943.7), (2012,46124.8),(2013,47754.3),(2014,50693.3),(2015,55573.3), (2016,55570),(2017,55570),(2018,55570),(2019,55570),(2020,55570), (2021,55570),(2022,55570),(2023,55570),(2024,55570),(2025,55570), (2026,55570),(2027,55570),(2028,55570),(2029,55570),(2030,55570))	10,000 tce
38	Energy	Export of crude oil = WITH LOOKUP (Time, [(2000,0) − (2030,8000)], (2000,2933.64),(2001,2719.57),(2002,2849.2),(2003,3350.98), (2004,2712.32),(2005,3539.46),(2006,3094.74),(2007,3139.38), (2008,3496.08),(2009,4757.34),(2010,4804.85),(2011,4707.05), (2012,4400.77),(2013,4924.6),(2014,4993.02),(2015,6288.28), (2016,6288),(2017,6288),(2018,6288),(2019,6288),(2020,6288), (2021,6288),(2022,6288),(2023,6288),(2024,6288),(2025,6288), (2026,6288),(2027,6288),(2028,6288),(2029,6288),(2030,6288))	10,000 tce
39	Population	Natural growth rate = WITH LOOKUP ((Time, [(2000,0) − (2030,0.01)], (2000,0.0076),(2001,0.007),(2002,0.0065),(2003,0.006),(2004,0.0059), (2005,0.0059),(2006,0.0053),(2007,0.0052),(2008,0.0051),(2009,0.0049), (2010,0.0048),(2011,0.0048),(2012,0.005),(2013,0.0049),(2014,0.0052), (2015,0.005),(2016,0.005),(2017,0.005),(2018,0.005),(2019,0.005), (2020,0.005),(2021,0.005),(2022,0.005),(2023,0.005),(2024,0.005), (2025,0.005),(2025,0.005),(2026,0.005),(2027,0.005),(2028,0.005), (2029,0.005),(2030,0.005))	Dmnl
40	Population	Death rate = −0.45369 × Natural growth rate + 0.0000000303 × Investment in the treatment of environment pollution + 0.000000000031 × Major pollutant emissions + 0.008951	Dmnl
41	Population	Deaths per year = Total population × Death rate	10,000 persons

Table A1. *Cont.*

No.	System	Equation	Unit
42	Population	Birth rate=WITH LOOKUP ((Time,[(2000,0) − (2030,0.1)],(2000,0.014), (2001,0.0134),(2002,0.0129),(2003,0.0124),(2004,0.0123), (2005,0.0124),(2006,0.0121),(2007,0.0121),(2008,0.0121), (2009,0.012),(2010,0.0119),(2011,0.0119),(2012,0.0121), (2013,0.0121),(2014,0.0124),(2015,0.0121),(2016,0.0121), (2017,0.0121),(2018,0.0121),(2019,0.0121),(2020,0.0121), (2021,0.0121),(2022,0.0121),(2023,0.0121),(2024,0.0121), (2025,0.0121),(2026,0.0121),(2027,0.0121),(2028,0.0121), (2029,0.0121),(2030,0.0121))	Dmnl
43	Population	Births per year = Total population × Birth rate	10,000 persons
44	Population	Total population = INTEGER (Births per year − Deaths per year,126743)	10,000 persons
45	Employment	Total employed population = 0.487541 × Total population + 10700.22	10,000 persons
46	Employment	The proportion of employment in tertiary industry = Employment population in tertiary industry/Total employed population	Dmnl
47	Employment	Employment population in secondary industry = WITH LOOKUP (Time, ([(2000,0) − (2030,30000)], (2000,16219),(2001,16234),(2002,15682),(2003,15927), (2004,16709),(2005,17766),(2006,18894),(2007,20186), (2008,20553),(2009,21080),(2010,21842),(2011,22544), (2012,23241),(2012,23241),(2013,23170),(2013,23170), (2014,23099),(2014,23099),(2015,22693),(2016,22690), (2017,22690),(2018,22690),(2019,22690),(2020,22690), (2021,22690),(2022,22690),(2023,22690),(2024,22690), (2025,22690),(2026,22690),(2027,22690),(2028,22690), (2029,22690),(2030,22690))	10,000 persons
48	Employment	Structure deviation of tertiary industry = The proportion of GDP in tertiary industry/The proportion of employment in tertiary industry − 1	Dmnl
49	Environment	Investment in environmental pollution control as a percentage of GDP = WITH LOOKUP (Time,(2000,0) − (2030,0.1)],(2000,0.0101),(2001,0.01), (2002,0.0112),(2003,0.0118),(2004,0.0118),(2005,0.0127), (2006,0.0117),(2007,0.0125),(2008,0.0155),(2009,0.0151), (2010,0.0184),(2011,0.0145),(2012,0.0153),(2013,0.0152), (2014,0.0149),(2015,0.0128),(2016,0.0128),(2017,0.0128), (2018,0.0128),(2019,0.0128),(2020,0.0128),(2021,0.0128), (2022,0.0128),(2023,0.0128),(2024,0.0128),(2025,0.0128), (2026,0.0128),(2027,0.0128),(2028,0.0128),(2029,0.0128), (2030,0.0128))	Dmnl
50	Environment	Investment in the treatment of environment pollution = GDP × Investment in Environmental Pollution Control as a Percentage of GDP	100 million yuan
51	Environment	Major pollutant emissions = 13.61567 × Total energy consumption + 1622315	10,000 tons
52	Environment	Pollution emissions per unit of energy consumption = Major pollutant emissions/Total energy consumption	10,000 tons /10,000 tce

Table A2. Results of a behavior pattern test.

Variable	Total Energy Consumption			Raw Coal Consumption in the Secondary Industry			Crude oil Consumption in the Secondary Industry			Investment in the Treatment of Environment Pollution		
Unit	10000 tce			10000 tce			10000 tce			100 million yuan		
Year	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation
2000	150948	140993	6.59%	78530.6	74466.31	5.18%	16562.7	15312.67	7.55%	1012.83	1014.9	−0.20%
2001	161846	148264	8.39%	85915.5	79039.68	8.00%	16813.3	15472.36	7.98%	1086.03	1084.541	0.14%
2002	175353	161935	7.65%	95391.8	86439.30	9.38%	17150.4	16708.70	2.58%	1327.03	1331.77	−0.36%
2003	194054	189269	2.47%	109844	104821.98	4.57%	17705.5	17982.76	−1.57%	1537.93	1545.259	−0.48%
2004	211681	220738	−4.28%	122412	126164.23	−3.07%	18238	19979.27	−9.55%	1693.25	1695.182	−0.11%
2005	233654	250835	−7.35%	138495	150119.20	−8.39%	19005.2	19299.72	−1.55%	2030.15	2040.028	−0.49%
2006	257287	275134	−6.94%	154396	166705.73	−7.97%	19884.5	20549.21	−3.34%	2107.81	2109.241	−0.07%
2007	281530	299271	−6.30%	168184	184709.24	−9.83%	20773.4	21491.25	−3.46%	2571.71	2582.762	−0.43%
2008	299656	306455	−2.27%	178656	189942.49	−6.32%	21548.2	21110.99	2.03%	3498.24	3491.141	0.20%
2009	316187	321336	−1.63%	186153	201183.74	−8.07%	22167.5	22692.05	−2.37%	3728.31	3723.37	0.13%
2010	337881	343601	−1.69%	197944	204946.71	−3.54%	23275	27064.43	−16.28%	5024.67	5040.05	−0.31%
2011	357172	370163	−3.64%	207083	223614.55	−7.98%	24271.5	26498.75	−9.18%	4335.82	4355.176	−0.45%
2012	372495	381515	−2.42%	212133	224590.46	−5.87%	24885	26132.19	−5.01%	4936.45	4934.669	0.04%
2013	388097	394794	−1.73%	216477	228222.25	−5.43%	25454.5	26381.25	−3.64%	5286.71	5285.642	0.02%
2014	403797	400299	0.87%	221054	226571.00	−2.50%	26101.2	27454.14	−5.18%	5560.68	5554.47	0.11%
2015	418015	402164	3.79%	222346	220300.92	0.92%	26293.4	28609.74	−8.81%	5106.56	5104.19	0.05%

Table A2. *Cont.*

Variable	Raw Coal Consumption			Crude Oil Consumption			Natural Gas Consumption			Other Energy Consumption		
Unit	10000 tce			10000 tce			10000 tce			10000 tce		
Year	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation
2000	108310	100810	6.92%	35074.1	32287.4	7.95%	2107.36	3242.8	−53.88%	5315.34	4652.8	12.47%
2001	116668	106009	9.14%	36478.3	32914.6	9.77%	2771.66	3706.6	−33.73%	5790.77	5634.0	2.71%
2002	127222	116269	8.61%	38074.9	35625.7	6.43%	3544.64	3886.4	−9.64%	6379.74	6153.5	3.55%
2003	142561	138545	2.82%	39743.2	39557.2	0.47%	4437.31	4542.5	−2.37%	7182.67	6624.4	7.77%
2004	156778	161580	−3.06%	41525.2	45913.5	−10.57%	5281.74	5297.7	−0.30%	7988.14	7946.6	0.52%
2005	174017	189130	−8.68%	43876.8	46655.3	−6.33%	6548.55	6270.9	4.24%	9105.06	8779.2	3.58%
2006	191662	207726	−8.38%	46939.1	50074.4	−6.68%	8134.89	7703.8	5.30%	10449.6	9629.7	7.85%
2007	208376	226249	−8.58%	51004.8	52671.7	−3.27%	10086.9	9277.4	8.03%	11978.8	11073.0	7.56%
2008	220996	229841	−4.00%	53893.5	53323.2	1.06%	11502.5	10725.9	6.75%	13199.1	12564.7	4.81%
2009	230965	240681	−4.21%	57536.9	55269.8	3.94%	13225.2	11889.4	10.10%	14403.7	13496.1	6.30%
2010	245236	249798	−1.86%	61349.4	62879.0	−2.49%	15162.5	14431.2	4.82%	16091.2	16492.8	−2.50%
2011	257127	271700	−5.67%	65250.8	65148.7	0.16%	17080.9	17767.8	−4.02%	17692	15546.8	12.12%
2012	265322	275454	−3.82%	69290.7	68291.2	1.44%	18918.2	19457.3	−2.85%	18961.9	18312.7	3.42%
2013	273113	281488	−3.07%	73788.8	71062.9	3.69%	20941.4	22108.5	−5.57%	20269.8	20134.5	0.67%
2014	280937	279409	0.54%	78253.9	74055.3	5.37%	22994.5	24017.9	−4.45%	21642.8	22817.0	−5.43%
2015	286430	273874	4.38%	83614.6	78824.1	5.73%	25265.6	24934.2	1.31%	22749.2	24532.0	−7.84%

Table A2. *Cont.*

Variable	Death Rate			Total Population			Total Employed Population			Major Pollutant Emissions		
Unit	Dmnl			10000 persons			10000 persons			10000 tons		
Year	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation	Simulation Value	Statistical Data	Deviation
2000	0.0056	0.0065	−14.21%	126743	126743	0.00%	72492.6	72085	0.56%	3.67×10^6	–	–
2001	0.0059	0.0064	−8.49%	127801	127627	0.14%	73008.4	72797	0.29%	3.82×10^6	–	–
2002	0.0062	0.0064	−3.95%	128756	128453	0.24%	73474	73280	0.26%	4.01×10^6	–	–
2003	0.0064	0.0064	0.12%	129622	129227	0.30%	73896.2	73736	0.22%	4.26×10^6	–	–
2004	0.0065	0.0064	0.70%	130398	129988	0.31%	74274.6	74264	0.01%	4.50×10^6	4824094	−7.14%
2005	0.0065	0.0065	−0.39%	131158	130756	0.31%	74645.1	74647	0.00%	4.80×10^6	5245089	−9.23%
2006	0.0068	0.0068	−0.60%	131933	131448	0.37%	75022.9	74978	0.06%	5.12×10^6	5144802	−0.40%
2007	0.0068	0.0069	−1.33%	132636	132129	0.38%	75365.7	75321	0.06%	5.45×10^6	5568494	−2.08%
2008	0.0069	0.0071	−2.02%	133333	132802	0.40%	75705.5	75564	0.19%	5.70×10^6	5716801	−0.26%
2009	0.0070	0.0071	−0.79%	134023	133450	0.43%	76041.9	75828	0.28%	5.93×10^6	5890877	0.62%
2010	0.0071	0.0071	0.12%	134689	134091	0.44%	76366.6	76105	0.34%	6.22×10^6	6172562	0.82%
2011	0.0071	0.0071	−0.48%	135333	134735	0.44%	76680.6	76420	0.34%	6.49×10^6	6591922	−1.62%
2012	0.0070	0.0072	−1.57%	135981	135404	0.42%	76996.5	76704	0.38%	6.70×10^6	6847612	−2.27%
2013	0.0071	0.0072	−0.81%	136669	136072	0.44%	77331.9	76977	0.46%	6.91×10^6	6954433	−0.67%
2014	0.0070	0.0072	−2.56%	137352	136782	0.41%	77664.9	77253	0.53%	7.12×10^6	7161751	−0.55%
2015	0.0071	0.0071	−0.65%	138096	137462	0.46%	78027.7	77451	0.74%	7.32×10^6	7353227	−0.51%

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