Economic-energy-industrial-environmental optimization (EEIEO) model for identification of optimal strategies - a case study of Beijing-Tianjin-Hebei region, China

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Abstract. An economic-energy-industrial-environmental optimization (EEIEO) model is proposed for identification of optimal economic, industry, energy and environment strategies. The EEIEE model is applied to a real case of Beijing-Tianjin-Hebei (BTH) region, which is the important economic growth pole of northern China. The EEIEO model could fully consider the interaction between industrial, energy, urbanization and environment sector, and generate the optimized economic development, industrial restructuring, energy consumption and environment management schemes. This is first attempt to introduce economic, energy, industrial, urbanization and environmental sectors into an optimization framework, while sustainable energy and environment development pathways are explored through EEIEO model. The results suggest that: (i) the GDP of BTH region would increase about 73.80% over the planning horizon; (ii) the contribution of tertiary industry for BTH region’s economic development would gradually increase from 54.00% in 2015 to 65.00% in 2030; (iii) the consumption of coal would decrease by 36%, and the natural gas would obviously increase by 97.70% over the planning horizon; and (iv) the SO2, smoke and dust emissions and CO2 would reduce by 30.20%, 35.30% and 4.50% from 2015 to 2030, respectively.

1. Introduction

Energy resources are highly relevant to the economic, industrial structure, environment and urbanization, which importance for national prosperity development, people’s living standards and social stability [1]. Beijing-Tianjin-Hebei (BTH) region, as one of the important poles of economic growth in China, is the economy, political and culture center of northern China. In the recent years, it
has achieved great economic development. According to China Statistical Bureau, the gross domestic product (GDP) reached up to $6.27 \times 10^{13}$ RMB¥ in 2013, which occupied 11% of China’s GDP. The rapid economic development results in the celerity growth of energy demands. Until 2013, the total terminal energy consumption amount was 346.26 million ton of coal equivalent (tce) until 2013, with a growth rate of 19.30% in the past 3 years. 

Rapidly increasing of energy consumption demands caused serious environmental pollution problems. Currently, Beijing-Tianjin-Hebei region becomes one of the most polluted places of China. By 2012, the \( \text{SO}_2 \), \( \text{NO}_x \) and \( \text{CO}_2 \) emissions have reached up to 1.59 million, 1.43 million and 1.46 million tons, respectively [2]. About 90% of \( \text{SO}_2 \) emissions, 66.00% of \( \text{NO}_x \) emissions and 90.00% of \( \text{CO}_2 \) emissions are from burning coal. On December 20th, 2014, Chinese government implemented “Action plan for energy development strategy, 2014-2020”, which set a target to mitigate about 80.00 million tons of coal consumption amounts comparing to that of 2005 in BTH region. However, in view of the stage of current economic development and economic operation pattern, the conflict between coal mitigation, pollutant emission and economic growth is inevitable, which will affect economic growth rate of BTH region [3]. Therefore, it is both important and necessary for the government to coordinate economic development and mainly pollutants (i.e., \( \text{SO}_2 \), \( \text{NO}_x \), smoke and dust), \( \text{CO}_2 \) emissions [3].

A great number of research efforts were undertaken for above problems [4-11]. Wang and Yang [3] quantitatively analyzed the delinking indicators on industry growth and environmental pressures in Beijing-Tianjin-Hebei economic band from 1996-2010, which based on the tow-level logarithmic mean divisia index method. Tian et al. [6] conducted both the regional analysis throughout the China and case studies focused on nine typical regions to identify regional patterns of industrial structure change and \( \text{CO}_2 \) emissions, the results indicate that structural change in industry structure was highly correlated with the stage of economic development. Chen et al. [7] proposed a tri-objective linear programming program for generation expansion planning by maximizing the total power generation, minimizing the total system cost and the ratio of the total power generation to the total \( \text{CO}_2 \) emission. Chen et al. [8] employed a multi-regional input-output model at the provincial level to evaluate the environmental costs of coal burning in China in 2007, in terms of its damages from climate change externality. Zhang et al. [10] developed an integrated assessment model including provincial energy conservation supply curves, the greenhouse gas and air pollution interactions and synergies model (which can be used to calculate air pollutant emissions) to assess the potential of energy saving in terms of emission mitigation of \( \text{CO}_2 \) and air pollutants an multiple benefits of energy efficiency measures at the provincial level during the period 2011-2030. In terms of the contents of research, the studies focused on the relationship between economics and \( \text{CO}_2 \) emissions, but often failed overall considering the economic development industrial structure restructuring, urbanization, energy consumption, energy structure adjustment and environment into a framework, as well as the impacts of economic development industrial structure restructuring, urbanization, energy consumption on the atmosphere pollutants are not fully considered. In real world, the relationships between industrial structure, urbanization, energy consumption, and environment are often complicated by the interactions of themselves; any changes in one sector could lead to a series of consequences. For example, the changes of industrial structure or urbanization could result in variations in economic, energy consumption and environmental. In planning such energy systems, independent consideration of one or several sectors would be unable to completely reflect the overall system characteristics.
Therefore, this study aims to develop an economic-energy-industrial-environmental optimization (EEIEO) model with taking a fully consideration of the interaction between industrial, energy, urbanization and environment sectors. The EEIEO model could effectively coordinate of the conflict among economic development, energy resources consumption, industrial restructuring and pollutant mitigation. In detail, the development of EEIEO model could: (i) reflect the relationship between economic, industrial and urbanization’s impact on the energy and environment systems; (ii) generate the optimized economic development, industrial restructuring and energy consumption schemes; and (iii) evaluate the pollutants emissions under the optimized economic development, industrial restructuring and energy consumption schemes.

2. Overview of the study system

Beijing-Tianjin-Hebei (BTH) contains two municipalities (Beijing, Tianjin) and one province (Hebei). BTH, as one of the most economically vibrant regions in China, covers 2.28% of the Chinese territory, while generated 11.00% of the total national GDP in 2012. The population of BTH region was 110.50 million in 2013, accounting for 8.12% of the Chinese population. The urbanization rate amounted to 61.00%, which was higher than the average of Chinese (53.40%). The industry structure (primary industry, second industry and tertiary industry) proportion of BTH region was 6.00: 43.00 : 51.00 in 2013. Figure 1 shows the GDP and industry structure of BTH region from 2001-2013 [12-14].

![Figure 1. The GDP and industry structure of BTH region from 2001 to 2013.](image)

With the increasing development of economy and society, the total amount of terminal energy demand has a rapidly growth. Figure 2 shows that the total terminal energy consumption amount was 346.26 million tons of coal equivalent until 2013, with a growth rate of 19.30% compared with 2010. The terminal consumption of coal was 82.77 million tons of coal equivalent until 2013, which accounted for 23.90% of the total energy consumption. The proportion of terminal coal consumption had decreased from 26.15% in 2010 to 23.90% in 2013. The terminal consumption amount of natural gas had shown an increase trend, which increase from 11.49 million tons of coal equivalent in 2010 to 15.72 million tons of coal equivalent in 2013. The terminal consumption amount of electricity had increased from 128.79 million tons of coal equivalent in 2010 to 160.05 million tons of coal equivalent in 2013, which proportion had increased from 44.37% in 2010 to 46.22% in 2013 [12-14]. Summarily, the city’s terminal energy consumption structure has been improved in recent years.
A large number of fossil fuels (such as coal, crude oil, and natural gas) lead to serious atmospheric environment issues of BTH region [15]. Currently, Beijing-Tianjin-Hebei region becomes one of the most polluted places of China. Until 2013, the SO$_2$ emissions reached to $1.59 \times 10^6$ tons; the NO$_x$ emissions reached to $1.43 \times 10^6$ tons; the smoke and dust emissions reached to $1.46 \times 10^6$ tons. The mainly pollutants average concentration are obviously higher that the standard regulated, which have negative effects on the human health and hinder the sustainable development of BTH region [16]. Therefore, it is necessary to propose some low-carbon and environment friendly plans of economic, industrial as well as energy consumption to support the sustainable development and reduce pollutant emissions of BTH region.

3. EEIEO modelling formulation

The interactive relationship among economic, energy consumption, industry, urbanization and environmental is complex. Any change in one subsystem will cause the variations of others, and finally vary the economic, environmental, and social costs. For example, the economic and industry development policy can change a series of activities, such as the types of energy resources, energy consumption and pollutants emissions. To maximize the GDP with considering the requirements of air pollutants mitigation, an effective economic, energy and environment planning model is required to identify the optimal social development pattern.

The proposed EEIEO model could not only effectively coordinate of the conflict interactions among economic development, energy resources consumption, industrial restructuring and pollutant mitigation, but also generate optimized economic development, energy structure adjustment and industrial restructuring, urbanization, as well as environment management schemes. In the study systems, five terminal energy consumption resources (such as coal, oil, natural gas, electricity and heat) are considered to satisfy the energy demand for end-users. End users of energy resources can be categorized into agriculture, industry, construction, transportation, wholesale and retail trade and other industries. The objective of proposed EEIEO model is to maximize the GDP of BTH region, with considering the constraints of the energy, industry, population and environment aspects. In detail, the EEIEO model can be formulated as follows:
objective function:

\[ \text{Max} \quad \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{GDP}_{ij}}{\text{XY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \]

constraints:

(1) Constraints for mass balance for energy resources:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{XY}_{ij}}{\text{EDY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \leq \text{ET}_{ij} \]

(2) Constraints for industry structure:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{XY}_{ij}}{\text{EDY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \leq \text{YCL}_{ij} \]

(3) Constraints for population:

\[ \text{XR}_{ij} + \text{XU}_{ij} \leq \text{RL}_{ij} \]

(4) Constraints for urbanization:

\[ \text{XR}_{ij} + \text{XU}_{ij} \geq \text{RLX}_{ij} \]

(5) Constrain for environment

(a) Constraints for SO₂ emission amount:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{XY}_{ij}}{\text{EDY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \leq \text{SPT}_{ij} \]

(b) Constraints for NOₓ emission amount:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{XY}_{ij}}{\text{EDY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \leq \text{NPT}_{ij} \]

(c) Constraints for smoke and dust emission amount:

\[ \sum_{i=1}^{n} \sum_{j=1}^{m} \left( \frac{\text{XY}_{ij}}{\text{EDY}_{ij}} + \frac{\text{XE}_{ij}}{\text{EDE}_{ij}} + \frac{\text{XS}_{ij}}{\text{SDPS}_{ij}} \right) \leq \text{SDPT}_{ij} \]

The study time considered four periods, t = 1 for 2015, t = 2 for 2020, t = 3 for 2025, t = 4 for 2030, which focused on the periods of China’s 13th Five Year Plan (2016-2020), 14th Five Year Plan...
(2021-2025) and 15th Five Year Plan (2026-2030). Table 1 shows the energy consumption intensity of terminal department (i.e., agriculture, industry, construction industry, transportation department, wholesale and retail trade and other industries) in planning periods. Table 2 shows the environment emission coefficient of terminal departments. Table 3 presents the upper bound of terminal energy consumption amount during planning periods, which obtained through Logistic prediction method based on data in past 18 years (1995-2013).

Table 1. Energy consumption intensity of terminal departments in 2015, 2020, 2025 and 2030.

| Energy intensity consumption | Terminal department | 2015   | 2020   | 2025   | 2030   |
|------------------------------|---------------------|--------|--------|--------|--------|
| Coal (ton/10^6 RMB¥)         | Agriculture         | 5.14   | 4.05   | 3.73   | 3.62   |
|                              | Industry            | 30.00  | 28.00  | 22.00  | 14.00  |
|                              | Construction industry | 1.96  | 1.54   | 1.42   | 1.42   |
|                              | Transportation department | 1.38  | 1.08   | 1.00   | 1.00   |
|                              | Wholesale and retail trade | 2.22  | 1.74   | 1.60   | 1.60   |
|                              | Other industries    | 3.00   | 2.50   | 2.10   | 2.10   |
| Oil (ton/10^6 RMB¥)          | Agriculture         | 5.87   | 4.78   | 4.31   | 4.31   |
|                              | Industry            | 6.08   | 6.20   | 6.20   | 6.20   |
|                              | Construction industry | 10.82 | 8.80   | 7.95   | 7.55   |
|                              | Transportation department | 22.96 | 18.67  | 16.85  | 16.85  |
|                              | Wholesale and retail trade | 1.32  | 1.08   | 0.97   | 0.92   |
|                              | Other industries    | 1.25   | 1.01   | 0.92   | 0.87   |
| Natural gas (cubic meter/10^6 RMB¥) | Agriculture | 1.73   | 1.79   | 1.96   | 1.96   |
|                              | Industry            | 3299.89| 4000.00| 4000.00| 4000.00|
|                              | Construction industry | 215.40| 223.12 | 244.52 | 246.12 |
|                              | Transportation department | 1370.13| 1419.27| 1555.37| 1756.40|
|                              | Wholesale and retail trade | 1459.24| 1511.57| 1656.53| 1870.63|
|                              | Other industries    | 1525.39| 1580.10| 1731.63| 1955.43|
| Electricity (kWh/10^6 RMB¥)  | Agriculture         | 3.02   | 2.76   | 2.52   | 2.52   |
|                              | Industry            | 15.95  | 18.00  | 18.00  | 18.00  |
|                              | Construction industry | 2.10  | 1.92   | 1.75   | 1.67   |
|                              | Transportation department | 2.46  | 2.25   | 2.05   | 2.20   |
|                              | Wholesale and retail trade | 1.95  | 1.78   | 1.63   | 1.70   |
|                              | Other industries    | 2.22   | 2.03   | 1.86   | 1.77   |
| Heat (Million kJ/10^6 RMB¥)  | Agriculture         | 0.00   | 0.00   | 0.00   | 0.00   |
|                              | Industry            | 169.26 | 168.33 | 168.33 | 158.00 |
|                              | Construction industry | 9.43  | 9.38   | 10.15  | 9.00   |
|                              | Transportation department | 16.34 | 16.25  | 17.60  | 16.00  |
|                              | Wholesale and retail trade | 27.53 | 27.38  | 29.65  | 29.00  |
|                              | Other industries    | 59.76  | 59.43  | 64.37  | 63.40  |

Table 2. The environment emission coefficients of terminal departments (kilogram/ton).

| Terminal department | Energy type | CO₂   | SO₂   | NOₓ   | Smoke and dust |
|---------------------|-------------|-------|-------|-------|----------------|
| Agriculture         | Coal        | 2715.18| 27.97 | 2.93  | 112.05         |
Oil  2126.27  5.83  2.93  2.00  
Natural gas  1634.81  0.00  1.47  0.00  

| Industry | Coal  | 2715.18 | 27.97 | 8.79 | 112.05 |
|          | Oil   | 2126.27 | 5.83  | 5.86 | 2.00   |
|          | Natural gas | 1634.81 | 0.00  | 4.40 | 0.00   |

| Wholesale and retail trade | Coal  | 2715.18 | 27.97 | 2.93 | 112.05 |
|                           | Oil   | 2126.27 | 5.83  | 2.93 | 2.00   |
|                           | Natural gas | 1634.81 | 0.00  | 1.47 | 0.00   |

| Transportation department | Coal  | 2147.53 | 5.41  | 23.45 | 2.00 |
|                          | Oil   | 2009.32 | 0.58  | 17.58 | 2.00 |
|                          | Natural gas | 1634.81 | 0.00  | 17.58 | 0.00 |

| Life | Coal  | 2715.18 | 27.97 | 2.93 | 2.00 |
|      | Oil   | 2126.27 | 5.83  | 2.93 | 2.00 |
|      | Natural gas | 1634.81 | 0.00  | 1.47 | 0.00 |

**Table 3.** The upper bound of terminal energy consumption amount from 2015 to 2030.

|                  | 2015      | 2020      | 2025      | 2030      |
|------------------|-----------|-----------|-----------|-----------|
| Coal (million tons) | 10968.22  | 9824.22   | 8600.00   | 7500.00   |
| Oil (million tons)  | 9000.00   | 10000.00  | 10000.00  | 8000.00   |
| Natural gas (billion m³) | 180.00   | 250.00    | 300.00    | 380.00    |
| Electricity (billion kWh) | 6000.00   | 6500.00   | 7000.00   | 9000.00   |
| Heat (million kJ)   | 83000.00  | 120000.00 | 140000.00 | 170000.00 |

4. **Results analysis**

The proposed EEIEO model could generate the optimized results for economic development, industry adjustment, energy consumption and air pollutants emissions in 2015, 2020, 2025 and 2030. In detail, it is as follows:

4.1. **Economic development**

Figure 3 shows the gross economic product (GDP) and economic structure of BTH region from 2015 to 2030. As results, the GDP of BTH region would obviously increase over the planning horizon, being 7080.00 billion RMB¥ in 2015, 8474.00 billion RMB¥ in 2020, 10505.00 billion RMB¥ in 2025, and 12307.00 billion RMB¥ in 2030. However, the economic growth rate would gradually slow down over the planning horizon, which would decrease from 20.00% (2015 to 2020) to 14.00% (2025 to 2030). From Figure 3, there would be a shift in BTH region’s economy structure towards the tertiary industry. The proportion of tertiary industry would increase from 54.00% in 2015 to 65.00% in 2030. The proportion of secondary industry would decrease from 40.00% in 2015 to 31.00% in 2030.
4.2. Population and urbanization

Figure 4 shows the population change of BTH region from 2015 to 2030. The population of BTH region would gradually increase from 111.00 million in 2015 to 125.00 million in 2030. The urban population would show an obviously increase trend. The urban population would increase from 69.60 million in 2015 to 88.15 million in 2030, with a growth rate of 32.00%. While, the rural population would appear a negative growth trend, being 44.40, 39.80, 38.40 and 36.80 million in 2015, 2020, 2025 and 2030, respectively. In the next few years, BTH region experienced rapidly urbanization process. According to results, the urbanization of BTH region would reach to 60.00% in 2015, 66.00% in 2020, 68.00% in 2025, and 71.00% in 2030.

Figure 3. Solutions of the gross economic product (GDP) of BTH region from 2015 to 2030.

Figure 4. Solutions of the population of BTH region from 2015 to 2030.
4.3. Terminal energy consumption

The totally terminal energy consumption amount and terminal energy consumption structure are presented in Figure 5. Figure 5 shows that the terminal energy consumption amount would show an increased trend, being 368.87 million tons of coal equivalent (tce) in 2015, 409.55 million tce in 2020, 437.73 million tce in 2025, 447.19 million tce in 2030. The growth rate of energy consumption amount would show a sharply decrease trend, being 11.00% from 2015 to 2020, 7.00% from 2020 to 2025, 2.00% from 2025 to 2030, respectively. As results, the terminal energy consumption structure would obviously improve in planning periods. The terminal coal consumption amount would experience negative growth in planning periods, which would decrease from 74.88 million tce in 2015 to 47.60 million tce in 2030. And the proportion of terminal coal consumption amount would gradually decrease from 20.30% in 2015 to 10.60% in 2030. While, some relatively clean energy resources would be vigorously encouraged over the planning horizon. For example, the terminal consumption amount of natural gas would increase from 20.91 million tce to 41.35 million tce, which a growth rate of 97.69%. The proportion of terminal natural gas consumption amount would increase from 5.67% in 2015 to 9.25% in 2030. The terminal electricity consumption amount would show an increased trend, being 183.52 million tce in 2015, 212.32 million tce in 2020, 227.16 million tce in 2025, 242.62 million tce in 2030, respectively. In conclusion, the terminal energy consumption structure would obviously improve because of the shift in BTH region’s economy structure towards the tertiary industry.

Figure 5. Solutions of the terminal energy consumption amount from 2015 to 2030.

4.4. Pollutant and carbon dioxide emissions

Figure 6 presents the results of pollutants (i.e., SO$_2$, NO$_x$, smoke and dust) and carbon dioxide (CO$_2$) emissions from terminal energy consumption. In Figure 6, the SO$_2$ emissions from terminal energy consumption would show a decrease trend during the planning horizon, being $840.12 \times 10^3$, $801.53 \times 10^3$, $724.82 \times 10^3$, and $586.19 \times 10^3$ tons in 2015, 2020, 2025 and 2030, with a decrease rate of 20.01% during the planning periods. The results indicate the coal would be the major contributor for SO$_2$ emissions. For example, coal consumption would generate 87.00% of total SO$_2$ emissions in
2015. While, the NO\textsubscript{X} emission from terminal energy consumption would obviously increase from $458.20 \times 10^3$ tons in 2015 to $510.63 \times 10^3$ tons in 2030, which mainly because of the sharply increase of the terminal oil and natural gas consumption amount. The oil’s contribution rate for NOx emissions would increase from 48.80% in 2015 to 67.70% in 2030. The smoke and dust emissions would decrease during planning periods, with a decrease rate of 35.30%. The results indicated that CO\textsubscript{2} emission would increase from 350.79 million tons in 2015 to 371.18 million tons in 2025. While, it would decrease about 9% from 2025 to 2030, which because the negative growth of oil consumption from 2025 to 2030. In the further 15 years, oil would become the major contributor for CO\textsubscript{2} emissions, which accounts for about 50% of total CO\textsubscript{2} emissions till 2030.
Figure 6. Solutions of the pollutants (i.e., SO$_2$, NO$_X$, smoke and dust) and carbon dioxide (CO$_2$) emissions from terminal energy consumption from 2015 to 2030.

5. Discussion

5.1. Verify the results with truth value

In this paper, in order to verify whether the results of proposed EIEEO model are reliable or not, the optimized schemes about economic (GDP, the added value of first industrial, the added value of secondary industry, the added value of tertiary industry), society (population, urban populations, rural population, urbanization) and energy (the energy consumption amount, coal consumption amount, oil consumption amount, natural gas consumption amount, electricity consumption amount, heat consumption amount) aspects would be compared with truth value in 2014 and 2015. Table 4 shows the optimized value from EIEEO model, truth value and error value. As table 4 shows, the error value is lower than 20.00%, except the natural gas consumption amount. This is mainly because EIEEO model would encourage faster speed for energy structure adjustment. The verification results show the
The proposed model is efficient for generating the optimized plans for economic development. In detail, it is as follows:

### Table 4. The optimized value from EIEEO model, truth value and error value.

| Aspect                        | Truth value | Optimized value | Error value |
|-------------------------------|-------------|-----------------|-------------|
| **Society aspect**            |             |                 |             |
| Population (2015)             | 11142.37    | 11500.00        | 3.21%       |
| Urban population (2014)       | 6748.00     | 7245.00         | 7.37%       |
| Rural population (2014)       | 4304.00     | 4255.00         | -1.14%      |
| Urbanization (2014)           | 60.56%      | 63.00%          | 4.03%       |
| **Economic aspect**           |             |                 |             |
| GDP (in 2015, 10^9 RMB¥)      | 69312.89    | 70806.10        | 2.15%       |
| The added value of first industry (10^9 RMB¥) | 3790.11    | 3802.07         | 0.32%       |
| The proportion of first industry added value | 5.47%   | 5.37%           | -1.80%      |
| The added value of secondary industry (10^9 RMB¥) | 26638.00   | 28768.73        | 8.00%       |
| Industry (10^9 RMB¥)          | 23270.37    | 25766.66        | 10.73%      |
| Construction (10^9 RMB¥)      | 3490.23     | 3002.07         | -13.99%     |
| The proportion of secondary industry added value | 38.43%    | 40.63%          | 5.72%       |
| The added value of tertiary industry (10^9 RMB¥) | 38884.78   | 38235.29        | -1.67%      |
| The proportion of tertiary industry added value | 56.10%  | 54.00%          | -3.74%      |
| **Energy aspect (2014)**      |             |                 |             |
| Energy consumption amount (10^6 tons of coal equivalent) | 34067.00   | 37093.04        | 8.88%       |
| Coal consumption amount (10^6 tons of coal equivalent) | 8090.80    | 7496.66         | -7.34%      |
| Oil consumption amount (10^6 tons of coal equivalent) | 6321.44    | 6265.00         | -0.89%      |
| Natural gas consumption amount (10^6 tons of coal equivalent) | 1698.93    | 2122.90         | 24.96%      |
| Electricity consumption amount (10^6 tons of coal equivalent) | 15560.69   | 18402.37        | 18.26%      |
| Heat consumption amount (10^6 tons of coal equivalent) | 2395.14    | 2806.11         | 17.16%      |

Note: the truth value for economic and society are acquired from [17-20]. The Energy Statistical Yearbook in 2016 is not publicly available, so the truth value for energy consumption in 2015 could not be obtained.

5.2. Compared the results with correlation research

In this paper, in order to further verify whether the results of proposed EIEEO model, some related study results were discussed in this paper. Several researchers have made efforts to predict the GDP, industry structure and population of BTH region with growth rate, regression analysis and grey predict methods. However, these studies could not fully consider the interaction between economic, industry, energy consumption and environment. For example, Li [21] used the growth rate and regression methods to forecast the proportion of firstly industry, secondary industry and tertiary industry. According to results, the proportion of firstly industry, secondary industry and tertiary industry would be reached to 3.45:55.70:40.80 in 2015; 3.00:54.30:42.70 in 2020, which has a deviation with the actual value (5.47%: 38.43%: 56.10% in 2015). Lin [22] predicted the urbanization rate of BTJ region with the scenario analysis method, which results indicated the urbanization rate would reach to 66.00-68.00% in 2015, 76.00-79.00% in 2020, 83.00-84.00% in 2025, and 86.00-90.00% in 2030, respectively. Yang [23] predicted the urbanization rate and proportion of tertiary industry would reach to 60.00% and 70.00% with fully consideration the “new normal” for Chinese
economic. In conclusion, the results from EIEEO model are reasonable and reliable, which could propose the decision supports for local managers.

**Table 5.** The comparison between optimized value and research results from other researchers.

| Author         | Institution                                                      | Index                      | Model             | Scenario      | 2015          | 2020          | 2025          | 2030          |
|----------------|------------------------------------------------------------------|----------------------------|-------------------|---------------|---------------|---------------|---------------|---------------|
| This paper     | Institute of Geographical sciences and natural resources research | GDP                        | —                 | 7080.61       | 8474.58       | 10505.58      | 12307.70      |
|                |                                                                  | Industry structure         | —                 | 5.37:40:63:54.00 | 4.72:36.2:8:59.00 | 4.57:31.08:64.35 | 4.11:30.8:65.00 |
|                |                                                                  | Urbanization               | EIEEO model       | —             | 60.00%        | 66.00%        | 68.00%        | 70.52%        |
|                |                                                                  | Population (10^6 persons)  | —                 | 111.00        | 117.16        | 120.00        | 125.00        |
| Li M           | Tianjin University                                               | Population (10^6 persons)  | Gray model        | —             | 108.36        | 116.07        | —             | —             |
|                |                                                                  | Industry structure         | Formulate growth rate; regression analysis | —             | 3.45:55.7:4.08 | 3.0:54.3:42.7 | —             | —             |
| Lin W          | China University of Geosciences                                  | Urbanization               | Scenario analysis | Low scenario  | 66.00%        | 76.00%        | 83.20%        | 86.00%        |
|                |                                                                  |                            |                   | Medium scenario | 67.00%        | 77.50%        | 83.40%        | 87.00%        |
|                |                                                                  |                            |                   | Medium-low scenario | 67.00%      | 78.00%        | 83.80%        | 88.00%        |
|                |                                                                  |                            |                   | High scenario   | 68.00%        | 78.50%        | 84.00%        | 90.00%        |
| Yang KZ        | Peking University                                               | Tertiary industry         | Formulate growth rate | —             | —             | 60.00%        | —             | —             |
|                |                                                                  | Urbanization               |                    | —             | —             | 70.00%        | —             | —             |
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A. 1 Nomenclatures for parameters and variables
$GDP_t$ Gross National Product in period $t$ ($10^9$ RMB¥);
$i$ Type of the secondary industry, $i = 1, 2$; $i = 1$ for industry, $i = 2$ for construction industry;
$j$ Type of tertiary industry, $j = 1, 2, 3$; $j = 1$ for transportation department, $j = 2$ for wholesale and retail trade, $j = 3$ for other industries;
$m$ Type of energy resource for terminal sector, $m = 1, 2, 3, 4, 5$; $m = 1$ for coal, $m = 2$ for oil, $m = 3$ for natural gas, $m = 4$ for electricity, $m = 5$ for heat;
$t$ Time period, $t = 1, 2, 3, 4$; $t = 1$ for 2015, $t = 2$ for 2020; $t = 3$ for 2025; $t = 4$ for 2030;

A. 2 Model parameters
$ET_{mt}$ The upper bound of energy resource $m$ in period $t$ ($10^6$ tons of coal equivalent);
$ETX_{mt}$ The lower bound of energy resource $m$ in period $t$ ($10^6$ tons of coal equivalent);
$EDY_{mt}$ Energy consumption intensity of energy type $m$ for agriculture in period $t$ (ton/10$^6$ RMB¥);
$EDE_{imt}$ Energy consumption intensity of energy type $m$ for second industry $i$ in period $t$ (ton/10$^6$ RMB¥);
$EDS_{jmt}$ Energy consumption intensity of energy type $m$ for tertiary industry $j$ in period $t$ (ton/10$^6$ RMB¥);
$EDU_{mt}$ Energy consumption intensity of energy type $m$ for urban residents in period $t$ (ton/person);
$EDR_{mt}$ Energy consumption intensity of energy type $m$ for rural residents in period $t$ (ton/person);
$YCL_t$ The lower bound proportion of agriculture in period $t$ (%);
$YCS_t$ The upper bound proportion of agriculture in period $t$ (%);
$ECL_t$ The lower bound proportion of second industry in period $t$ (%);
$ECS_t$ The upper bound proportion of second industry in period $t$ (%);
$SCL_t$ The lower bound proportion of tertiary industry in period $t$ (%);
$SCS_t$ The upper bound proportion of tertiary industry in period $t$ (%);
$RL_t$ The upper bound of population in period $t$;
$RLX_t$ The lower bound of population in period $t$;
$CZHL_t$ The lower bound of urbanization in period $t$;
$CZHS_t$ The upper bound of urbanization in period $t$;
$SPY_{mt}$ The SO$_2$ generation efficiency for energy type $i$ of agriculture in period $t$ (kilogram/ton);
$SPE_{imt}$ The SO$_2$ generation efficiency for energy type $i$ of second industry in period $t$ (kilogram/ton);
$SPS_{jmt}$ The SO$_2$ generation efficiency for energy type $i$ of tertiary industry in period $t$ (kilogram/ton);
$SPU_{mt}$ The SO$_2$ generation efficiency for energy type $i$ of urban residents in period $t$ (kilogram/ton);
The SO₂ generation efficiency for energy type \( i \) of rural residents in period \( t \) (kilogram/ton);

\[ SPR_{mt} \]

Allowable emission level for SO₂ in period \( t \) (10³ tons);

\[ SPT_t \]

The NOX generation efficiency for energy type \( i \) of agriculture in period \( t \) (kilogram/ton);

\[ NPY_{mt} \]

The NOX generation efficiency for energy type \( i \) of second industry in period \( t \) (ton/10³ tons);

\[ NPE_{mt} \]

The NOX generation efficiency for energy type \( i \) of tertiary industry in period \( t \) (ton/10³ tons);

\[ NPS_{mt} \]

The NOX generation efficiency for energy type \( i \) of urban residents in period \( t \) (ton/person);

\[ NPU_{mt} \]

The NOX generation efficiency for energy type \( i \) of rural residents in period \( t \) (ton/person);

\[ NPR_{mt} \]

Allowable emission level for NOX in period \( t \) (10³ tons);

\[ NPT_t \]

The smoke and dust generation efficiency for energy type \( i \) of agriculture in period \( t \) (kilogram/ton);

\[ SDPY_{mt} \]

The smoke and dust generation efficiency for energy type \( i \) of second industry in period \( t \) (kilogram/ton);

\[ SDPE_{mt} \]

The smoke and dust generation efficiency for energy type \( i \) of second industry in period \( t \) (kilogram/ton);

\[ SDPS_{mt} \]

The smoke and dust generation efficiency for energy type \( i \) of urban residents in period \( t \) (ton/person);

\[ SDPU_{mt} \]

The smoke and dust generation efficiency for energy type \( i \) of urban residents in period \( t \) (ton/person);

\[ SDPR_{mt} \]

Allowable emission level for smoke and dust in period \( t \) (10³ tons);

\[ SDPT_t \]

The CO₂ generation efficiency for energy type \( i \) of agriculture in period \( t \) (kilogram/ton);

\[ CPY_{mt} \]

The CO₂ generation efficiency for energy type \( i \) of second industry in period \( t \) (kilogram/ton);

\[ CPE_{mt} \]

The CO₂ generation efficiency for energy type \( i \) of second industry in period \( t \) (kilogram/ton);

\[ CPS_{mt} \]

The CO₂ generation efficiency for energy type \( i \) of urban residents in period \( t \) (kilogram/ton);

\[ CPU_{mt} \]

The CO₂ generation efficiency for energy type \( i \) of urban residents in period \( t \) (kilogram/ton);

\[ CPR_{mt} \]

The CO₂ generation efficiency for energy type \( i \) of rural residents in period \( t \) (kilogram/ton);

\[ CPY_{mt} \]

A. 3 Decision variables

\( XY_t \) Total output value of the agriculture in period \( t \) (10⁹ RMB¥);

\( XE_t \) Total output value of the second industry in period \( t \) (10⁹ RMB¥);

\( XS_t \) Total output value of the tertiary industry in period \( t \) (10⁹ RMB¥);

\( XU_t \) The population of urban residents in period \( t \) (person);

\( XR_t \) The population of rural residents in period \( t \) (person);

\( CZHR_t \) The urbanization rate in period \( t \) (%);

\( SEM_t \) The SO₂ emission amount in period \( t \) (10³ tons);

\( NEM_t \) The NOX emission amount in period \( t \) (10³ tons);

\( SDEM_t \) The smoke and dust emission amount in period \( t \) (10³ tons);
The CO₂ emission amount in period \( t \) (10³ tons);

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