Equilibrium strategy of economic cost and carbon emission reduction of green electric-coal supply chain

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\textbf{Abstract:} As the government pays more attention to energy conservation and emission reduction in the energy industry, the contradiction between economic cost and carbon emission reduction in the electric-coal supply chain becomes more and more serious, which needs to be solved urgently. Therefore, based on the theory of green supply chain, this research constructs a dynamic multi-objective model under the uncertain decision-making environment with the realization of the equilibrium of the total economic cost and carbon emission of electric-coal supply chain as the decision goal, and taking the coal supply capacity and other practical requirements as the constraints. The following equilibrium model is applied to an electric-coal supply chain in the southwestern region of Y Province. With full consideration of different carbon emission reduction scenarios, the total economic cost and carbon emission balance plan of electric-coal supply chain under five different emission reduction scenarios were obtained, which verified the practicability and effectiveness of the equilibrium model. The results show that the equilibrium model can effectively alleviate the conflict between the economic cost and carbon emission reduction. Finally, based on data analysis, we put forward management suggestions from macro, meso and micro levels to better realize the greenization of electric-coal supply chain.

1. Introduction

As the main mode of power generation in China, coal generation has accounted for two-thirds of the total power generation [1]. Although coal generation has begun to decline amid the government's push for greener energy, there is still a long way to go. So it is still necessary to optimize the management of coal power generation, especially the coordination of the coal and power industry chain, which is particularly important for China to achieve a resource-saving and environment-friendly society [2]. Therefore, in the context of the increasingly tense relationship between the upstream and downstream of the industrial chain, the construction of a “green electric-coal supply chain” has become an important way to ease the contradiction between the two and promote energy conservation and emission reduction in the energy industry [3].

One of the problems in the research of green electric-coal supply chain is how to reduce carbon emission. The carbon emissions from China's coal-fired power plants are huge, and are expected to reach 1.8 billion tonnes by 2030 [4]. In recent years, the carbon emission reduction effect of electric-coal supply chain has been minimal. This is mainly due to the difficulty in achieving efficient synergy between China's coal industry and the power market. Therefore, it is not feasible to study the carbon emission reduction strategy of electric-coal supply chain from the perspective of a single industry, and...
it is more necessary to explore a systematic carbon emission reduction plan from the perspective of green supply chain [3]. Meanwhile, the main driving force of green electric-coal supply chain is to reduce costs and achieve profitability, and minimizing the total economic cost is also the focus of research, such as production costs, power generation costs and other cost minimization issues [5]. In addition, some scholars have discussed the balanced development of economic cost and carbon emission reduction under green electric-coal supply chain based on the perspective of “hard path” such as technological improvement, and proposed effective technical solutions [6]. However, these “hard path” technical solutions are costly, and are not suitable for developing countries. Therefore, studying the balance and optimization of carbon emission reduction and economic cost in China's green electric-coal supply chain based on the “soft path” perspective is of rich practical significance and important research value.

The existing research on the economic cost of green electric-coal supply chain is not systematic. For example, Wu et al. (2016) simply sorted out the economic costs of electric-coal supply chain, mainly including direct costs related to coal input, and indirect costs embodied in different links of coal production, transportation, and storage [7]; Gupta et al. (2018) used the analytic hierarchy process to study the transportation optimization problem in the coal industry [8]. The above studies either only considered the costs of different links but did not carry out system optimization, or only focused on the cost optimization of a certain link. These studies are difficult to achieve the optimization of the total economic cost on the overall level of electric-coal supply chain. At the same time, research on carbon emissions in the green electric-coal supply chain has similar flaws. For example, some scholars considered the carbon emissions of electric-coal supply chain, but ignored the differences in specific subsystems [9]; and other scholars have found that the specific proportions of carbon emissions in different links of coal production, transportation, and storage are different, but they have ignored the overall control of the entire supply chain [10]. It can be said that most existing studies have not organically integrated the subsystem with the entire electric-coal supply chain.

Therefore, based on the theory of green supply chain, this research analyzes the equilibrium optimization problem of the total economic cost and carbon emission of the green electric-coal supply chain, and constructs a dynamic multi-objective equilibrium model in an uncertain decision-making environment. Different from previous studies, the model proposed in this research comprehensively considers the four subsystems in the production cycle of electric-coal supply chain, namely, production, transportation, storage and consumption subsystems [11]. In addition, the decision-making process of this research can be divided into three stages: (1) selecting coal suppliers; (2) confirming the specific coal purchase quantity of the selected suppliers; (3) determining the quantity of coal burned by the power plants. In summary, the model constructed in this research involves multi-objective planning and multi-stage decision-making, which can effectively solve the problem of balanced optimization of economic costs and carbon emissions.

2. Methodology and data

2.1. Objective function of electric-coal supply chain

According to the characteristics of electric-coal supply chain, the model aims to achieve the lowest system cost, including coal production cost, transportation cost, storage cost and power generation cost [11]. The objective function is as follows:

$$
\text{Min } TEC = \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{t=1}^{T} Q_{ij} T E C_{ij} \left( \tilde{P}_{ij} \right) + \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{t=1}^{T} Q_{ij} D_{ij} T E C_{ij} \left( L C_{ij} \right) + \sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{t=1}^{T} S_{ij} + \frac{S_{ij}^{t+1}}{2} T E C_{ij} \left( SC_{ij} \right) + \sum_{i=1}^{l} \sum_{j=1}^{l} q_{ij} T E C_{ij} \left( \overrightarrow{OC}_{ij} \right)
$$

Where $TEC$ is the total economic cost of electric-coal supply chain (RMB); $Q_{ij}^{t}$ is the amount of coal supplied by coal supplier $i$ to power plant $j$ at production stage $t$ (tonne); $\tilde{P}_{ij}$ is the production
cost of unit coal \(i\) at production stage \(t\) (RMB/tonne); \(D_{ij}\) is the transportation distance from the coal supplier \(i\) to the power plant \(j\) (km); \(\overline{LC}_{ij}\) is the unit cost of railway transport used from coal supplier \(i\) to power plant \(j\) (RMB/tonne•km); \(S'_{ij}\) is inventory quantity of coal \(i\) in power plant \(j\) at production stage \(t\) (tonne); \(SC'_j\) is unit coal inventory cost of power plant \(j\) at production stage \(t\) (RMB/tonne); \(t_{ijq}\) is quantity of coal \(i\) burned by power plant \(j\) at production stage \(t\) (tonne); \(t_{ijG}\) is the amount of electricity produced by burning a unit of coal \(i\) in power plant \(j\) at production stage \(t\) (kWh/tonne); \(t_{jOC}\) is unit operating cost required for unit power generation of power plant \(j\) at production stage \(t\) (RMB/kWh).

Similarly, the objective function of the total carbon emissions of electric-coal supply chain is as follows:

\[
\text{Min } TCE = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left[Q_{ij}^t \cdot EF_i \cdot CF \cdot CC + \left(\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} \left[Q_{ij}^t \cdot D_{ij} \cdot \overline{LC}_{ij}\right] \cdot \left[\tilde{a} \cdot V\right]\right)\right]
\]

Where \(TCE\) is the total carbon emission of electric-coal supply chain (kg); \(EF_i\) is CH\(_4\) emission coefficient of unit coal produced by coal supplier \(i\) (m\(^3\)/tonne); \(EF_j\) is CH\(_4\) emission coefficient of unit coal storage in power plant \(j\) (m\(^3\)/tonne); \(CC\) is conversion factor from CH\(_4\) to CO\(_2\) (44/12); \(CF\) is density of CH\(_4\) that can be expressed at 20\(^\circ\)C and a standard atmospheric pressure (0.67kg/m\(^3\)); \(SF\) is unit fuel consumption by railway transportation (kg/tonne•km); \(\tilde{a}\) is carbon emission factor by railway transportation (kg/kj); \(V\) is average burning value of diesel oil (42652kj/kg); \(\tilde{\beta}_{ij}\) is carbon emission coefficient of unit coal \(i\) burned by power plant \(j\) (kg/tonne).

2.2. Constraints

\[
\sum_{j=1}^{J} Q_{ij}^t \leq E\left[\overline{SQ}_{i}^t\right] X_i \quad (3)
\]

\[
S'_{ij} \geq S_{ij\min} \quad (4)
\]

\[
S'_{ij} = S_{ij}^{t+1} + Q'_{ij} - q'_{ij} \quad (5)
\]

\[
\sum_{j=1}^{J} \sum_{t=1}^{T} q'_{ij} \cdot \overline{G}_{ij} \geq E\left[\overline{TD}^t\right] \quad (6)
\]

\[
E\left[\overline{LQR}_{jk}^t\right] \leq \sum_{j=1}^{J} E\left[Q\overline{R}_{ik}^t\right] q'_{ij} \leq E\left[U\overline{QR}_{jk}\right] \quad (7)
\]

\[
Q'_{ij}, q'_{ij} \leq X_i M; Q'_{ij}, q'_{ij} \geq 0; X_i \in (0,1) \quad (8)
\]

Where \(X_i\) is binary variable, 1 denotes that coal supplier \(i\) is selected, otherwise 0; \(\overline{SQ}_{i}^t\) is coal supply capacity of coal supplier \(i\) at production stage \(t\) (tonne); \(S_{ij\min}\) is minimum inventory of coal \(i\) required to ensure the normal operation of power plant \(j\) at production stage \(t\) (tonne); \(\overline{TD}^t\) is
total electricity demand of the entire system at production stage \( t \) (kWh); \( 
abla \overline{Q}_{ik} \) is the \( k \)th coal quality properties of coal \( i \), where \( k=1 \) represents volatile matter content (%), \( k=2 \) represents heat rate (Gj), \( k=3 \) represents ash content (%), \( k=4 \) represents moisture content (%), \( k=5 \) represents sulfur content (%); \( LQR_{jk} \) is lower bound of coal quality \( k \) that meets the requirements of power plant \( j \); \( UQR_{jk} \) is upper bound of coal quality \( k \) that meets the requirements of power plant \( j \); \( M \) is a very large real number, like 100 million.

Finally, the decision variables of this research is \( X_i \), \( \tilde{Q}^i \) and \( \tilde{q}^i \).

2.3. Multi-objective processing

China attaches great importance to the balanced development of economy and environment, and economic development should not be carried out at the cost of destroying environment. So regional governments need to limit \( \text{CO}_2 \) emissions to an acceptable level. In the previous production cycle, the carbon emission of the whole system are set as \( TCE \) (3.9116×10⁹ kg); simultaneously, it is assumed that the attitude of the regional government towards \( \text{CO}_2 \) emission reduction of the whole system is \( \lambda \). Therefore, the objective function of the total carbon emissions of electric-coal supply chain can be transformed into the constraint conditions, as shown below:

\[
TCE \leq \lambda TCE_0 \quad (9)
\]

2.4. Data collection

Taking electric-coal supply chain in the southwest of Y province as the background of the case study, two power plants (I, II) and the corresponding four coal suppliers (A, B, C, D) were selected. Meanwhile, based on the seasonal variation characteristics of power demand, the research time was set as four production stages (i.e., \( T=4 \)). The input data and parameters of the model can be roughly divided into two categories: certain data and fuzzy random data. The collection of certain data is mainly based on annual reports or publicly available data from power plants and their coal suppliers, such as the data for variable \( \tilde{D}_{ij} \), as shown in Table 1. The collection of fuzzy random data should be carried out in the form of fuzzy random theory, that is, it should be determined by interviewing experts or engineers and combining historical data, such as the data for variable \( \tilde{\beta}_j \), as shown in Table 2. Due to confidentiality requirements and space limitations, not all data are listed in the article.

| Power Plant I | Coal Supplier A | Coal Supplier B | Coal Supplier C | Coal Supplier D |
|---------------|----------------|----------------|----------------|----------------|
| 30            | 212            | 172            | 332            |
| 51            | 256            | 117            | 319            |

Table 1. Transport distance between coal supplier and power plant: \( D_{ij} \) (km).

| Power Plant I | Power Plant II |
|---------------|----------------|
| (1892.42, \( \phi(\omega),1927.12 \)) | (1879.99, \( \phi(\omega),1925.22 \)) |
| \( \phi(\omega) \sim \text{N}(1909.96,21) \) | \( \phi(\omega) \sim \text{N}(1895.62,18) \) |
| (1930.86, \( \phi(\omega),1985.25 \)) | (1921.49, \( \phi(\omega),1956.95 \)) |
| \( \phi(\omega) \sim \text{N}(1952.46,14) \) | \( \phi(\omega) \sim \text{N}(1939.92,15) \) |
| (1920.73, \( \phi(\omega),1963.31 \)) | (1900.86, \( \phi(\omega),1947.73 \)) |
| \( \phi(\omega) \sim \text{N}(1942.04,25) \) | \( \phi(\omega) \sim \text{N}(1921.53,12) \) |
| (2169.87, \( \phi(\omega),2211.97 \)) | (2143.80, \( \phi(\omega),2177.45 \)) |
| \( \phi(\omega) \sim \text{N}(2185.67,9) \) | \( \phi(\omega) \sim \text{N}(2160.77,16) \) |

Table 2. Carbon emission coefficient of unit coal burned by power plant: \( \tilde{\beta}_j \) (kg/tonne).
3. Results and discussion

3.1. Emission reduction scenario solutions

This research discussed the changes of total economic cost and emission reduction effect under different emission reduction scenarios (i.e., different attitudes of regional governments to carbon emission reduction). By inputting the collected data into the proposed equilibrium model and running the model on the Lingo software, the satisfactory solutions for the equilibrium optimization of the total economic cost and carbon emission of electric-coal supply chain under five different emission reduction scenarios are calculated. When $\lambda = 1$, the coal supplier selection results are supplier A, C and D; and detailed solutions of the remaining four emission reduction scenarios are shown in Table 3:

### Table 3. Solutions of the model under different emission reduction scenarios ($10^8$ tonne).

| CS | PP | $q_j^u / q_j^l$ |
|----|----|-----------------|
| A  | I  | 13.9/26.7       |
|    | II | 0.0/0.0         |
| C  | I  | 11.4/14.7       |
|    | II | 26.2/30.3       |
| D  | I  | 24.9/25.6       |
|    | II | 0.0/0.5         |

### Scenario 2: $\lambda = 98\%$

| CS | PP | $q_j^u / q_j^l$ |
|----|----|-----------------|
| A  | I  | 13.9/14.5       |
|    | II | 0.0/0.4         |
| C  | I  | 11.4/12.0       |
|    | II | 18.9/14.7       |
| D  | I  | 24.9/25.6       |
|    | II | 0.0/0.0         |

### Scenario 3: $\lambda = 96\%$

| CS | PP | $q_j^u / q_j^l$ |
|----|----|-----------------|
| A  | I  | 13.9/14.5       |
|    | II | 0.0/0.4         |
| C  | I  | 11.4/12.0       |
|    | II | 18.9/14.7       |
| D  | I  | 24.9/25.6       |
|    | II | 0.0/0.0         |

### Scenario 4: $\lambda = 94\%$

| CS | PP | $q_j^u / q_j^l$ |
|----|----|-----------------|
| A  | I  | 13.9/14.5       |
|    | II | 0.0/0.4         |
| C  | I  | 11.4/12.0       |
|    | II | 18.9/14.7       |
| D  | I  | 24.9/25.6       |
|    | II | 0.0/0.0         |

### Scenario 5: $\lambda = 92\%$

| CS | PP | $q_j^u / q_j^l$ |
|----|----|-----------------|
| A  | I  | 13.9/14.5       |
|    | II | 0.0/0.4         |
| C  | I  | 11.4/12.0       |
|    | II | 18.9/14.7       |
| D  | I  | 24.9/25.6       |
|    | II | 0.0/0.0         |

3.2. Analysis of emission reduction scenarios

Before analysis, this research collates the specific economic costs and carbon emissions of electric-coal supply chain and its different subsystems under different emission reduction scenarios, as shown in Table 4; and data of economic costs and carbon emissions related to power plants under different emission reduction scenarios are collated, as shown in Table 5. On this basis, this research analyzes the equilibrium problem of electric-coal supply chain and its production, transportation, storage and consumption subsystems from the macro, meso and micro levels.

3.2.1. Macro-level analysis.

It can be concluded from Table 4 that under the emission reduction equilibrium method, with the increase of carbon emission reduction intensity in the electric-coal supply chain, the economic cost would increase gradually and the increase amplitude would be larger and larger. For example, under Scenario 1, the total economic cost of electric-coal supply chain is $13.13 \times 10^8$ RMB; under Scenario 3, when the carbon emission reduction target is set at 4%, the total economic cost is $13.46 \times 10^8$ RMB, which is 2.51% higher than Scenario 1; under Scenario 5, when the carbon emission reduction target is set at 8%, the total economic cost is $14.16 \times 10^8$ RMB, which is 5.20% higher than Scenario 3. Therefore, the government should not blindly increase emission reduction efforts, but should adjust and control the growth range of total economic costs while choosing appropriate carbon emission reduction policies, so as to achieve the balanced optimization of the two.
3.2.2. Meso-level analysis.

It can be concluded from Table 4 that, as for economic costs, the economic costs of the production and the consumption subsystem take up a large proportion, and their combined average proportion is 97.50%; and the economic costs of the transportation and storage subsystems are negligible. As for carbon emissions, the consumption subsystem accounts for the largest proportion, with an average of up to 97.42%, while the remaining three subsystems account for only a small proportion. Therefore, the decision-makers of electric-coal supply chain need to establish a good emission reduction management mechanism for the production and consumption subsystems, so as to form a good interactive communication with the upstream and downstream subsystems while realizing the balance of “economy-emission reduction” benefits, and finally realize the coordinated energy conservation and emission reduction of electric-coal supply chain.

Table 4. Economic cost and carbon emissions distribution of subsystems in electric-coal supply chain under different emission reduction scenarios (10^8 RMB/10^9 kg).

| Subsystems       | TEC/TCE | Production subsystem ECc/CEd | Transportation subsystem ECc/CEd | Storage subsystem ECc/CEd | Consumption subsystem ECc/CEd |
|------------------|---------|----------------------------|-------------------------------|---------------------------|------------------------------|
| Scenario 1       | 13.13/3.911 | 7.37/0.071                 | 0.36/0.003                   | 0.02/0.008                | 5.38/3.829                   |
| Scenario 2       | 13.33/3.831 | 7.36/0.074                 | 0.30/0.002                   | 0.02/0.007                | 5.65/3.748                   |
| Scenario 3       | 13.46/3.743 | 7.63/0.074                 | 0.28/0.002                   | 0.01/0.005                | 5.54/3.662                   |
| Scenario 4       | 13.54/3.677 | 7.44/0.070                 | 0.33/0.003                   | 0.02/0.007                | 5.74/3.597                   |
| Scenario 5       | 14.16/3.599 | 7.54/0.070                 | 0.33/0.003                   | 0.02/0.007                | 6.28/3.519                   |

* Economic cost  
* Carbon emission

3.2.3. Micro-level analysis.

It can be seen from Table 3, suppliers with good coal quality are more likely to be selected. For example, coal suppliers A and C are selected in all five emission reduction scenarios, while coal supplier D is only selected once. Therefore, coal suppliers should expand their own high-quality coal production to obtain more coal supply opportunities. In addition, as show in Table 5, the proportion of economic costs and carbon emissions related to power plant I gradually decreases, while that of power plant II is opposite. This indicates that power plant I undertakes the main power generation task at the initial stage, but with the gradual increase of carbon emission reduction, power plant II begins to acquire more power generation tasks. The main reason is that the carbon emission factor in the power generation process of power plant II is small. Therefore, power plants need to optimize the combustion process and equipment, and purchase as much low-carbon, clean and high-quality coal as possible to reduce the carbon emission level, so as to obtain more power generation tasks.

Table 5. Economic cost and carbon emissions distribution of different power plants in electric-coal supply chain under different emission reduction scenarios (10^8 RMB/10^9 kg).

| Subsystems       | TEC/TCE | Power plant I ECc/CEd | Power plant II ECc/CEd |
|------------------|---------|-----------------------|------------------------|
| Scenario 1       | 13.13/3.911 | 11.57/3.495           | 1.56/0.416             |
| Scenario 2       | 13.33/3.831 | 9.54/2.835            | 3.79/0.996             |
| Scenario 3       | 13.46/3.743 | 10.57/3.012           | 2.89/0.732             |
| Scenario 4       | 13.54/3.677 | 8.09/2.327            | 5.44/1.350             |
| Scenario 5       | 14.16/3.599 | 5.26/1.443            | 8.90/2.156             |

* Economic cost  
* Carbon emission

4. Conclusions

Based on the concept of green supply chain, this research studies how to realize the balanced optimization of total economic cost and carbon emission in the electric-coal supply chain. Aiming at solving this optimization problem, based on the analysis of the relationship between the electric-coal
supply chain and different subsystems, a dynamic multi-objective equilibrium model under fuzzy random environment is established. Then, in order to verify the validity and feasibility of the model, the equilibrium model was applied to an electric-coal supply chain in the southwest of Y province, and the equilibrium optimization scheme of the total economic cost and carbon emission under five different emission reduction scenarios was obtained. The results show that the balanced optimization strategy based on the total economic cost and carbon emission of green electric-coal supply chain plays a good role in carbon emission reduction, and does not cause significant increase in economic cost. Furthermore, this research analyzes and discusses the electric-coal supply chain, subsystems and enterprises under five different emission reduction scenarios from three levels: micro, meso and macro. Finally, some suggestions are put forward for enterprises, electric-coal supply chain and government management departments.

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