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RESEARCH ARTICLE

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Carbon performance evaluation model from the perspective of circular economy—The case of Chinese thermal power enterprise

Abstract Carbon emission reduction is the only way to alleviate environmental problems, such as global warming. Effective evaluation of carbon performance can help enterprises to carry out energy saving and emission reduction activities to a certain extent and promote sustainable development. This paper constructs a carbon performance evaluation index system that includes the four dimensions of carbon resource (energy) input, cycle, output, and carbon management by incorporating the principles of circular economy and the theory of resource value circulation from the perspective of the flow trajectory of carbon-containing resources in the circulation of enterprises combined with the production characteristics of thermoelectric enterprises. Subsequently, combined with the case study, this paper discusses the scientific and practical nature of the system and provides another way of thinking for carbon performance evaluation of micro-enterprises in other industries. This paper expands the application boundary of matter–element model and supplements the literature of carbon performance, which has certain theoretical and practical significance.

Keywords circular economy, carbon performance, comprehensive evaluation, thermal power enterprise

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1 Introduction

With the global climate change, greenhouse effect, smog, and other environmental issues are affecting people's lives and have become a bottleneck that restricts sustainable economic development (Goldstein and Greenberg, 2018; van Zyl et al., 2018). The report of the 19th National Congress clearly stated that we should accelerate green development, establish and improve the economic system of green and low-carbon cycle development, and build a clean and low-carbon energy system. The energy and relative CO_2 emission intensities have significantly declined through the government's and society's commitment toward energy conservation and emission reduction. In recent years, the increasing amount of consumed oil and coal resources — which are finite — has become an important problem of resource utilization. Thus, maintaining the balance between our environment and the existing economy has become a challenge that demanding prompt solution (Sun et al., 2019b). To address this challenge, domestic and foreign governments have issued relevant climate policies. For example, the European Union has set a "20–20" goal of cutting emissions by 20% by 2020 and a 60%–80% commitment by 2050. China formally confirmed to the Secretariat of the United Nations Framework Convention on Climate Change in 2016 that its carbon emissions would peak around 2030 and that it would strive to reach the peak as soon as possible. The carbon emission intensity per unit of GDP was set as a target for voluntary action to be 60% to 65% lower than that in 2005 (Wang et al., 2017). Under the increasingly tense situation of international emission reduction, the carbon performance of enterprises has become the focus of scholars (Ang and Goh, 2016; Kim and Kim, 2016; Moussa et al., 2020).

Enterprise is the main source of carbon-based fuel inputs and greenhouse gas emissions, especially in industry, such as an electricity-generating one, which consumes substantial resources (Kim and Kim, 2016). Significant corporate carbon consumption and emissions will affect the society greatly. Therefore, micro-enterprises' development of a low-carbon economy is an important force to achieve comprehensive carbon emission reduction. Such low-carbon economy requires the means and tools for evaluation. Consequently, evaluating its carbon performance is necessary for a micro-enterprise. Therefore, based on the perspective of circular economy, this paper applies matter–element extension model to the carbon performance evaluation system of thermoelectric enterprises, constructs the carbon performance evaluation index system, and conducts case analysis by applying the carbon performance evaluation model to micro-enterprise. The possible innovations and contributions of this paper are detailed as follows. (1) Combined with the 3R principle of circular economy, a carbon performance evaluation index system with four index dimensions of carbon resource (energy) input, cycle, output, and carbon management was constructed to supplement the literature on carbon performance. (2) A greater focus on international climate governance issues, additional research of carbon performance evaluation of thermoelectric enterprises, and a broadened application boundary of matter–element model are provided by applying the matter–element extension model to the carbon performance evaluation system of the thermoelectric enterprises. (3) Conducting carbon performance research from the micro-enterprise level provides new ideas and directions for carbon performance evaluation research.

2 Current research on corporate carbon performance

To develop a low carbon economy, we should innovate at the technical level and reform the system. In terms of technological innovation, the development and use of new technologies have the potential to increase the recycling rate of resources, reduce carbon gas emissions, and lower the level of damage to the environment. At present, Chinese and foreign researches on corporate carbon performance evaluation are still in the early stage and have not yet formed a systematic theory and evaluation system.

2.1 Connotation of the corporate carbon performance

Foreign concern about the corporate carbon performance evaluation led to the European Union Emission Trading System. Foreign businesses among the Fortune 500, especially those in high emission and high energy consumption manufacturing and energy industries, have begun to study the effects of greenhouse gases (Ang and Goh, 2016). The United States' company and Japan's Canon have established a special group to research on the sustainable development of enterprises. However, the current research on carbon performance is complex and involves various aspects; thus, standard and authoritative definitions are lacking (Ashraf et al., 2014; Zhang et al., 2018a).

At the level of enterprise application, carbon performance, which is specifically used to measure their efficiency and effect, refers to the contribution of enterprises in carbon emission reduction and carbon management (Haque, 2017; Qian and Schaltegger, 2017). Based on the specific connotation of environmental performance, carbon performance refers to the incorporation of low-carbon elements into the financial evaluation system of enterprises and the ratio of carbon emission to the income of enterprises, which is used to evaluate the carbon performance of enterprises while obtaining economic benefits (Dahlmann et al., 2017; Velte et al., 2020). With the deepening of global climate governance, more scholars include carbon dioxide emissions or "carbon footprint" in environmental performance indicators to measure the carbon performance of products or production activities (Liesen et al., 2017; Padilla-Rivera et al., 2018).

The core of carbon performance lies in "energy saving and emission reduction". Energy saving refers to the actual actions and results of consuming less energy during production and consumption (Hamilton and Kelly, 2017; Zhang et al., 2018b). Emission reduction refers to the actual specific measures and implementation effects for the control and reduction of carbon and pollutant emissions in the production and consumption of enterprises (Sun et al., 2018). Carbon performance plays an important role in encouraging enterprises to reduce carbon emission (Córdova et al., 2018), which is conducive to promoting the coordinated development of enterprises' economic interests and environmental protection (Lewandowski, 2017; Trumpp and Guenther, 2017).

2.2 Subject and method of carbon performance evaluation

The research subjects of carbon performance evaluation can be divided into three levels, namely, macro, medium, and micro. At the macro level, the carbon performance evaluation mainly focuses on the region (Allan et al., 2017; Liu et al., 2017; Sun et al., 2019a). In this context, a regional carbon performance evaluation system is established to analyze the status of carbon performance in various regions, and the main factors that affect carbon performance are identified to support the optimization of the economic development model of the region (Simoes et al., 2017; Yue and Cheng, 2017). However, carbon performance evaluation systems in different regions also vary because of the different economic and political variations (Guler et al., 2018). At the medium level, carbon performance evaluation is mainly focused on a specific industry, and the research objects are mainly concentrated in industries and enterprises with high energy consumption, such as coal, construction, and electricity (Modak et al., 2017; Rietbergen et al., 2017; Song et al., 2018), or in special industries that are closely related to environmental protection, such as tourism (Sun et al., 2020). Such medium-level research examines and analyzes specific data or cases and investigates specific situations of carbon emission reduction through the carbon performance evaluation of industries. At the micro level, research mainly focuses on the carbon performance evaluation of micro-enterprises, specifically analyzing the resource flow and comprehensive utilization efficiency of enterprises (Yan et al., 2018).

Evaluation method that can be applied to all carbon performance evaluation does not exist. According to the experiment, the best combination of quantitative and qualitative methods to evaluate carbon performance varies. In addition, economic, environmental, and many other factors affect performance evaluation greatly, thereby a comprehensive evaluation method is required, various factors should be selected, and the applicability of each method should be considered (Tarnoczi, 2017). Currently, the main methods involved in carbon performance evaluation include the input–output analysis method and the integrated system model method (Cheng et al., 2019; Sejian et al., 2018).

2.3 Evaluation index of corporate carbon performance

Domestic and foreign scholars' research on enterprise carbon performance evaluation mainly focuses on the comprehensive evaluation of enterprise carbon performance. The selection of evaluation indicators is diversified, that is, it addresses traditional financial and non-financial indicators (Newton, 2014; Chiang et al., 2020; Haque, 2017). From the perspective of input and output, monetary and physical indicators can be selected. In addition, the "carbon management" dimension and entropy theory can be introduced into the evaluation system. For example, low-carbon deviation index and other indicators can be designed from the carbon emission accounting principle to evaluate the carbon performance level of enterprises (Rietbergen et al., 2017; Padilla-Rivera et al., 2018).

Moreover, a multi-index carbon performance evaluation index system can be constructed from different perspectives. Considerations, such as carbon resource transfer, carbon cost efficiency, carbon economic efficiency, carbon emission reduction efficiency, and other aspects, should be combined to establish a carbon performance evaluation index system (Zhou et al., 2018). In combination with ecological economics, non-financial factors, such as energy saving and consumption reduction, emission reduction and pollution control benefits, and social benefits, should also be considered (Dahlmann et al., 2017). In addition, considering that carbon performance indicators include quantitative and qualitative ones, conducting carbon performance evaluation based on low-carbon awareness and behavior while considering carbon source consumption, carbon emissions, and other indicators is necessary (Büchs et al., 2018).

Combining the above analysis, we can find that the domestic and foreign scholars' study is inadequate for the performance evaluation of micro-enterprise carbon focus. To construct a performance evaluation index system combined with enterprise's internal production processes, research theory and analysis are needed. Therefore, this article, from the micro-enterprise level, introduces the concept of circular economy, to build a thermal power industry carbon performance evaluation model and discuss case application.

3 Construction of carbon performance evaluation model for thermal power enterprise

Most research on corporate carbon performance evaluation index selection remains in the traditional financial and non-financial indicators without considering specific enterprises' production processes and resource recycling.

Therefore, this article combines the 3R principle — reduce, reuse, recycle — of circular economy, draws lessons from resource value stream calculations, and introduces the enterprise internal resource flow cost into the evaluation of carbon performance. This approach incorporates perspectives, such as product life cycle, building carbon resource (energy) input, carbon resource (energy) cycle, and carbon resource (energy) output into the four dimensions of carbon management performance evaluation index system, using the improved matter–element extension model of the thermal power enterprise carbon performance evaluation.

The carbon performance evaluation process is shown in Fig. 1. First, we need to determine and analyze the evaluation pair. Second, according to the production process of thermoelectric enterprises, we construct a specific evaluation index system through index analysis and screening. Third, we select the evaluation method for comprehensive evaluation. Finally, some suggestions are put forward on the basis of the evaluation results.

3.1 Construction of carbon performance evaluation index system

The literature review shows that the existing study on evaluation index mainly includes financial and non-financial indicators. The enterprise production

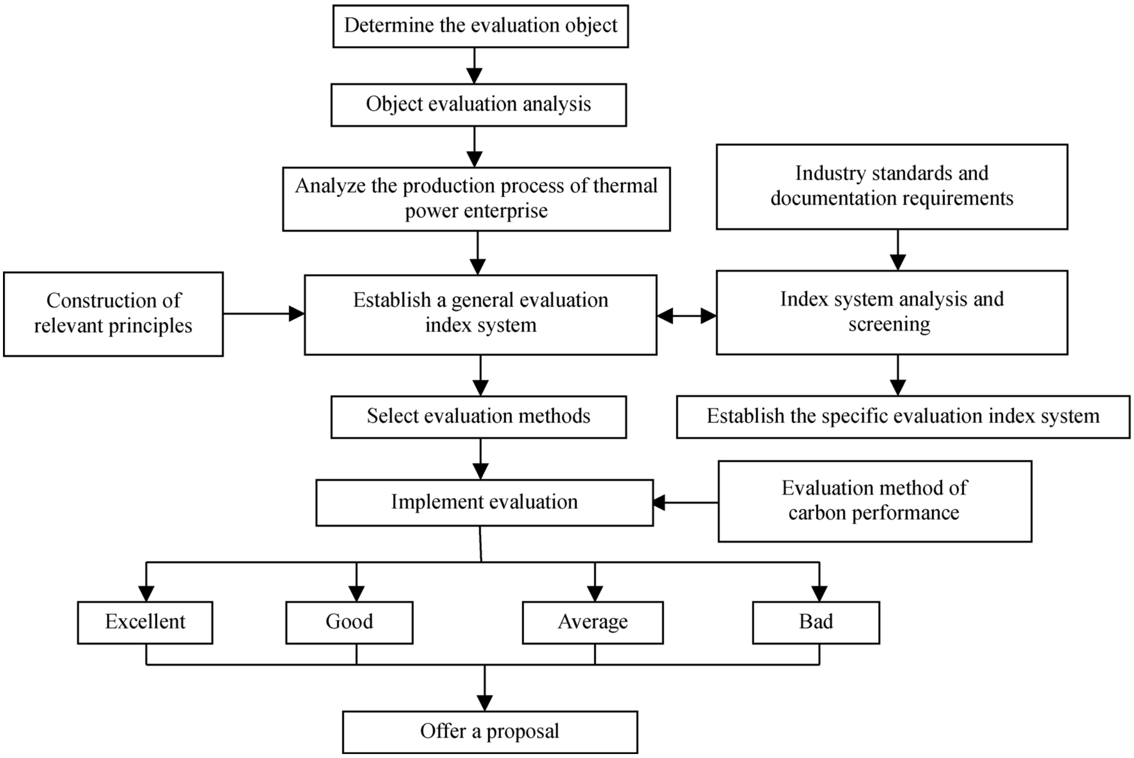

Fig. 1 Comprehensive evaluation process of carbon performance in thermal power enterprise.

characteristics and processes indexed to evaluate the carbon performance are not available. Thus, the evaluation index of carbon performance should be considered from the perspective of internal resource value flow. According to the production and the material resources involved in general thermal power enterprises, we draw the material resource flow process diagram (Fig. 2).

The organization structure of thermoelectric enterprises generally includes raw coal storage and transportation center, boiler combustion center, and turbo generator set center. According to these organizational structures, we draw the internal resource balance flow of the thermal power enterprises (Fig. 3).

This paper, through the index form, improves the primary indexes and index system by determining the index hierarchy: Target layer, rule layer, and index layer; by consulting and collecting information on thermoelectric enterprises, such as China Coal Power Enterprises Clean Production Evaluation Guidelines; and by combining internal production processes of thermoelectric enterprise with the use of theoretical analysis and expert consultations (Zhang and Choi, 2013; Song et al., 2018; Wu and Ma, 2019). This paper analyzes the index of principal component and ultimately provides 17 evaluation indicators that cover the four dimensions of carbon resources (energy) input, cycle, output and carbon management.

Among these indicators, the carbon resource (energy) input part of production, which mainly includes carbon-containing raw materials, energy, and other materials' input quantity cost index, reflects the "reduction" principle. Carbon resource (energy) cycle, as part of an enterprise's carbon resource circulation and re-circulation stage, reflects the "reuse" principle. Meanwhile, the carbon resource (energy) output and carbon management dimensions, including CO_2 emissions and disposal costs, apply the "recycle" principle. The comprehensive performance evaluation index system of thermoelectric enterprises is finally determined in Table 1.

3.2 Selection of carbon performance evaluation method

The literature review shows that evaluation methods of enterprise carbon performance in the micro-enterprise level include analytic hierarchy process (AHP) method, balanced scorecard, and fuzzy comprehensive evaluation method. The comprehensive evaluation of thermal power enterprises' carbon performance involves many aspects, including qualitative and quantitative double indexes. Comprehensive evaluation problem is a multi-objective matter–element extension method. The types of objects a model evaluates can be fuzzy, dissimilar, or incompatible. The quantitative numerical representation associated with each level sets the size of evaluation results by establishing a multi-level evaluation model with multi-index. To determine the level of matter–element, comprehensive evaluation can reflect the object's level better.

Therefore, this paper opts to use the matter–element model based on the AHP weight of subjective and

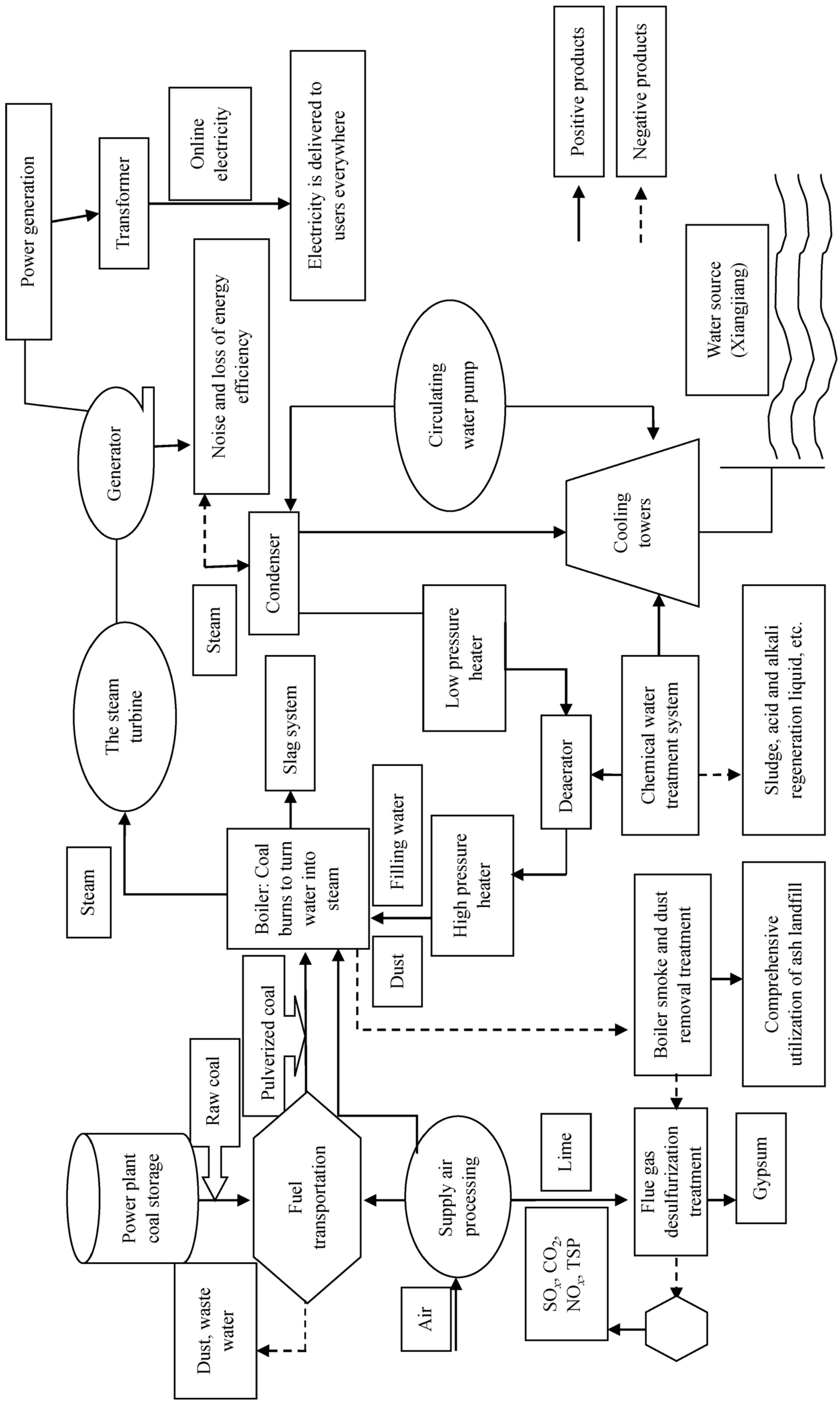

Fig. 2 Resource material flow chart of thermal power enterprise.

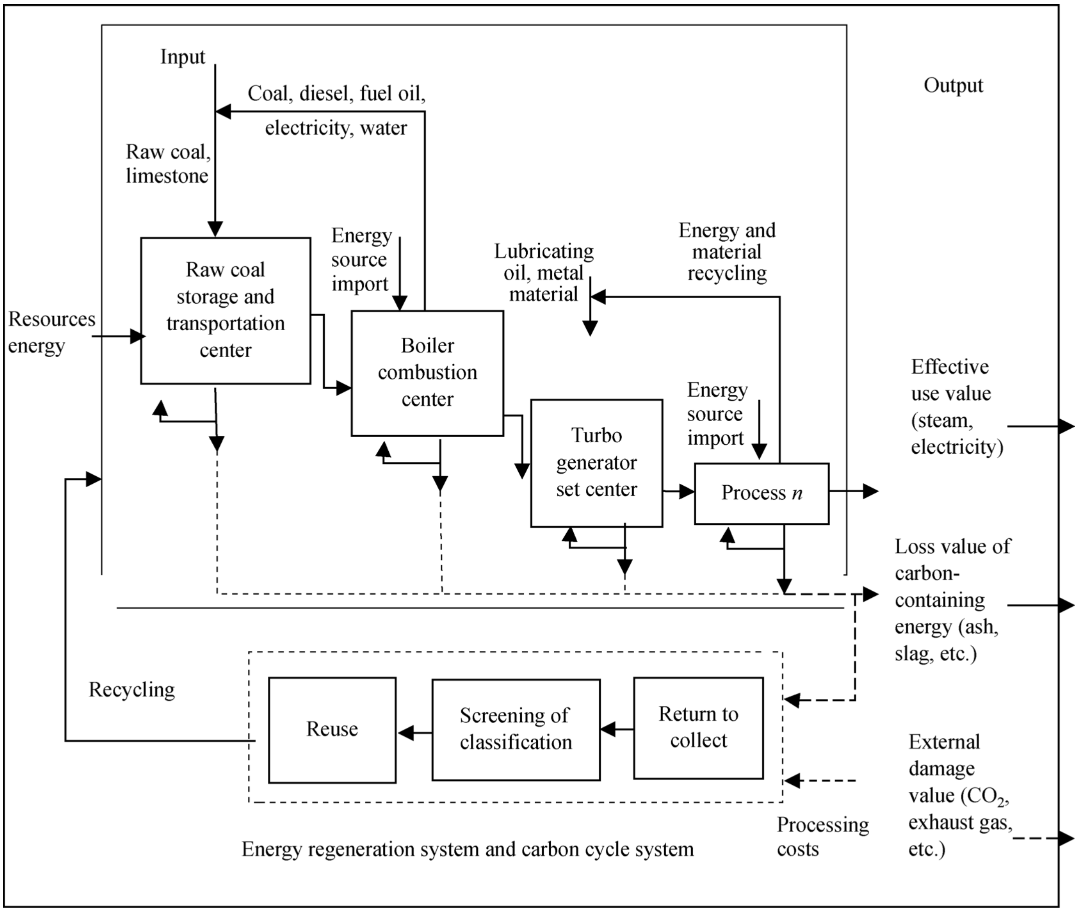

Fig. 3 Internal resource balance flow of thermal power enterprise.

objective assignment methods divided by the index calculation on the use of the improved matter–element extension model. Based on the classical domain, the computational domain and the correlation degree determine the grade that belongs to the enterprise's carbon performance.

Matter–element extension synthetic evaluation model

The joint domain is established through the classical domain using the matter–element model with matter–element theory and extension set theory as the theoretical foundation. The degree of evaluation is calculated to evaluate the correlation value of matter–element based on the measured data and determine the evaluation object level. Using the improved comprehensive matter–element extension evaluation model, the evaluation object is first divided into j grades, where the scope of each level is determined by the industry standard, expert opinion, or existing research. Second, the comprehensive correlation degree is measured, and the improvement is calculated by using the AHP of the subjective and objective weighting methods to determine the weights of evaluation indexes and the values of the grade set evaluation index. When the comprehensive correlation degree is larger, the degree of compliance with this class set is higher.

Matter–element refers to the logical unit of matter–element extension model, which is the basic element used to describe things by the ordered triples $R = (P, C, V)$. P is the thing name, C is the characteristic of the thing, and V is the quantity value. The basic steps of the improved matter–element extension model are as follows:

(1) Determine the classical domain, the joint domain, and the object to be evaluated.

First:

$$R_j = (P_j,\ C_i,\ V_{ij}) = \begin{bmatrix} P_j & c_1 & v_{1j} \\ & c_2 & v_{2j} \\ & \vdots & \vdots \\ & c_n & v_{nj} \end{bmatrix} = \begin{bmatrix} P_j & c_1 & (a_{1j},\ b_{1j}) \\ & c_2 & (a_{2j},\ b_{2j}) \\ & \vdots & \vdots \\ & c_n & (a_{nj},\ b_{nj}) \end{bmatrix}, \tag{1}$$

where P_j is the j evaluation rating; c_1, c_2,..., c_n are the n different features of P_j; v_{1j}, v_{2j},..., v_{nj} are the span of P_j

Table 1 Carbon performance evaluation index

First-level index	Second-level index	Third-level index	Calculating formula
Thermoelectric enterprise carbon performance evaluation index system A	Carbon resource (energy) input index B_1	C_1: Material cost rate	Material cost/Product sales revenue
		C_2: Energy cost rate	Energy cost/Product sales revenue
		C_3: Standard coal consumption rate of power supply	Consumption of standard coal/Electricity
		C_4: Standard coal consumption per unit heating	Consumption of standard coal/Amount of heating
		C_5: Whole plant thermal efficiency	(Heating capacity + Generated energy × 3600)/(Power generation and heat supply using standard coal × 29271)
		C_6: Heat-to-electric ratio	Heating capacity/(Generated energy × 3600)
	Carbon resource (energy) cycle index B_2	C_7: Material cost loss rate	Material cost/Total energy cost
		C_8: Energy cost loss rate	Energy cost/Total energy cost
		C_9: Internal resource value and external damage value ratio	Internal resource value/External damage value
		C_{10}: Comprehensive utilization of fly ash	Ash utilization/Ash production
		C_{11}: Comprehensive utilization of gypsum	Gypsum utilization/Gypsum production
	Carbon resource (energy) output index B_3	C_{12}: External damage value per unit of output	External damage/Gross output value of waste
		C_{13}: Carbon emission reduction rate	Carbon reduction cost/Carbon emission treatment year cost
		C_{14}: Low carbon economy increase	Purchase of equipment for carbon emission reduction/Economic value added
	Enterprise carbon management index B_4	C_{15}: Carbon emission reduction per unit energy saving investment	Reduced amount of coal consumption/Investment amount of energy saving project
		C_{16}: Staff's post skill training	Technical training expenditure
		C_{17}: Carbon emission reduction results recognition	Recognition of achievements

correspond to c_1, c_2,..., c_n as classical domain; and a_{ij} and b_{ij} are the boundary values of v_{ij}.

$$R_P = (P,\ C_i,\ V_{pi}) = \begin{bmatrix} P & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix} = \begin{bmatrix} P & c_1 & (a_{p1},\ b_{p1}) \\ & c_2 & (a_{p2},\ b_{p2}) \\ & \vdots & \vdots \\ & c_n & (a_{pn},\ b_{pn}) \end{bmatrix}, \tag{2}$$

where P represents all of the objects to be evaluated; and v_{p1}, v_{p2},..., v_{pn} are the span of P that correspond to c_1, c_2,..., c_n as the joint domain.

Order:

$$R_0 = (P_0,\ C_i,\ V_i) = \begin{bmatrix} P_0 & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix}, \tag{3}$$

where R_0 is the object to be evaluated; and v_1, v_2,..., v_n are the measured data of P_0 about c_1, c_2,..., c_n, which are the actual data of the object to be evaluated.

Then, weights are determined.

The reliability evaluation index weight affects the correctness of the evaluation results. Therefore, in determining the weights of evaluation indexes, one should avoid uncontrollable factors. We use the subjective and objective comprehensive evaluation method combined with AHP to determine the weight of each index.

(2) Calculation and evaluation of the comprehensive correlation function.

The correlation function value of each index on each evaluation grade is indicated as the distance between R_0 of the object to be evaluated and normalized classic domain D_j.

$$D_j(v_i) = \left| v_i \frac{a_{ij} + b_{ij}}{2} \right| - \frac{1}{2}\left(b_{ij} - a_{ij}\right). \tag{4}$$

In this paper, we consider the closeness degree and the maximum membership degree of each criterion to determine the level of the object to be evaluated.

$$N_j(P_0) = \frac{1}{2} \times \left[\left(1 - \frac{1}{n} \sum_{i=1}^{n} Dw_i \right) + \left(1 - \sum_{i=1}^{n} Dw_i \right) \right], \tag{5}$$

where w_i is the weight of the evaluation index and n is the number of evaluation indicators.

The comprehensive correlation coefficient for each grade of the object to be evaluated is:

$$N_j(P_0) = \frac{1}{2} \times \left[\left(1 - \frac{1}{n} \sum_{i=1}^{n} D_j(v_i) w_i(X) \right) + \left(1 - \sum_{i=1}^{n} D_j(v_i) w_i(X) \right) \right]. \tag{6}$$

Calculate the characteristic value of the class variable. Order:

$$\overline{N}_j(P_0) = \frac{N_j(P_0) - \min N_j(P_0)}{\min_j N_j(P_0) - \min_j N_j(P_0)}. \tag{7}$$

Finally,

$$j^* = \frac{\sum_{j=1}^{m} j \overline{N}_j(P_0)}{\sum_{j=1}^{m} \overline{N}_j(P_0)}. \tag{8}$$

4 Case analysis

This paper takes a Changsha thermoelectric enterprise as example to further verify the application of extension matter–element model in enterprise carbon performance evaluation. The production process system of the thermoelectric enterprise is shown in Table 2. The enterprise currently has 3 75 t/h circulating fluidized bed (CFB) boilers. Through the internal flow status of coal and limestone powder combustion cycles, the boiler can ensure high combustion efficiency. The combustion system performs low-temperature staged combustion for limestone and coal to reduce emissions of harmful substances from flue gas. The combustion system contains a large amount of fly ash within the boiler, with the cyclone body separating about 40% of the coarsest ash and not fully burning fuel returned to the furnace. The remaining ash mixes with flue gas after dust removal by high chimney. The fuel after full combustion is collected by a pneumatic slag. Finally, ash is sent to the fishpond and is eventually rushed to downstream enterprises to be used as raw materials.

4.1 Data sources

The authors collected data from a project research. Some of the data were calculated through expert scoring. According to the resource value flow accounting, the cost of qualified products and external damage part of the enterprise and the amount are shown in Table 3. The 2015 carbon performance evaluation index of the plant value is shown in Table 4.

Table 2 Thermal power plant production process system

System name	Main process	Main equipment and facilities	Output	Main pollutants
Fuel and accessory system	Procurement of raw coal and limestone	Coal quality inspection equipment	Raw coal	Transport noise
Storage and transportation system	Storage and transport of raw coal and limestone	Coal yard, coal silo, coal bunker, coal belt, bin, etc.	Coal, limestone	Dust, flushing water, transport noise
Combustion system	Heat the water from burning coal and limestone powder into steam	Coal feeder, limestone daily warehouse, limestone fan, boiler drum, etc.	Steam	Flue gas, slag, coal ash, noise
Thermodynamic system	Thermal function conversion in the process of thermodynamic cycle	Boiler steam water system, steam turbine thermal system, heating steam supply system	Steam, water	Waste water of thermal system
Ash and slag handling system	Slag and fly ash were collected and cleaned	Equipment for collecting and cleaning slag and fly ash	Slag, fly ash	Transport dust
Water system	Reclaimed water is treated as the supplementary water of the boiler and the circulating cooling water; the waste water in the production process is treated and reused	Ultra filtration, reverse osmosis water purification equipment	Salt water, reuse water	Sewage
Power generation operating system	Heat energy in the steam turbine will be converted into mechanical energy, and then the mechanical energy can be converted into electrical energy in the generator	Steam turbine, generator, transformer	Electricity	Noise

Table 3 Thermal power enterprise carbon resource cost accounting summary

Matter center	Rejected materials	Internal resource flow cost (10000 yuan/year)	External damage cost (10000 yuan/year)
Coal reserves	Coal gangue	90.95	11.13
Boiler combustion	Ash	491.52	1472.46
Steam turbine generator	Waste gas	305.73	95.15
Total		888.20	1578.74

4.2 Classical domain, establishment of the section and the object to be evaluated, and the normalization of the treatment

(1) Establishment of the classical domain. The classical domain carbon performance evaluation index of thermal power enterprises is determined on the basis of the industry standard, expert experience, and existing academic knowledge. The evaluation index of the classical field matter–element R_j is divided into four levels: P_1, P_2, P_3, and P_4. The carbon performance of thermal power enterprises can be regarded as "excellent", "good", "fair", and "poor". The classical domain is normalized as:

$$R_j = \begin{bmatrix} P_j & P_1 & P_2 & P_3 & P_4 \\ c_1 & (0,\ 0.3) & (0.3,\ 0.5) & (0.5,\ 0.55) & (0.55,\ 1) \\ c_2 & (0,\ 0.2) & (0.2,\ 0.5) & (0.5,\ 0.7) & (0.7,\ 1) \\ c_3 & (0.5,\ 0.625) & (0.625,\ 0.8) & (0.8,\ 0.917) & (0.917,\ 1) \\ c_4 & (0.666,\ 0.748) & (0.748,\ 0.83) & (0.83,\ 0.91) & (0.91,\ 1) \\ c_5 & (0.8,\ 1) & (0.6,\ 0.8) & (0.4,\ 0.6) & (0,\ 0.4) \\ c_6 & (0.799,\ 1) & (0.597,\ 0.799) & (0.4,\ 0.597) & (0.194,\ 0.4) \\ c_7 & (0,\ 0.2) & (0.2,\ 0.5) & (0.5,\ 0.7) & (0.7,\ 1) \\ c_8 & (0,\ 0.2) & (0.2,\ 0.5) & (0.5,\ 0.7) & (0.7,\ 1) \\ c_9 & (0,\ 0.2) & (0.2,\ 0.5) & (0.5,\ 0.7) & (0.7,\ 1) \\ c_{10} & (0.97,\ 1) & (0.9,\ 0.97) & (0.8,\ 0.9) & (0,\ 0.8) \\ c_{11} & (0.97,\ 1) & (0.9,\ 0.97) & (0.8,\ 0.9) & (0,\ 0.8) \\ c_{12} & (0,\ 0.1) & (0.1,\ 0.3) & (0.3,\ 0.6) & (0.6,\ 1) \\ c_{13} & (0.7,\ 1) & (0.5,\ 0.7) & (0.2,\ 0.5) & (0,\ 0.2) \\ c_{14} & (0,\ 0.385) & (0.385,\ 0.585) & (0.585,\ 0.769) & (0.769,\ 1) \\ c_{15} & (0.8,\ 1) & (0.6,\ 0.8) & (0.4,\ 0.6) & (0,\ 0.4) \\ c_{16} & (0.8,\ 1) & (0.6,\ 0.8) & (0.4,\ 0.6) & (0,\ 0.4) \\ c_{17} & (0.8,\ 1) & (0.6,\ 0.8) & (0.4,\ 0.6) & (0,\ 0.4) \end{bmatrix}.$$

(2) Establishment of the region. The thermal power enterprise carbon performance of various indicators of R_P domain corresponds to the classical domain.

(3) Establishment of matter–element. According to the measured data, each index of the thermal power enterprises can establish carbon performance evaluations to evaluate the measured data of R_0. This thermoelectric enterprise element was achieved in 2015 from an actual investigation of thermal power enterprises. The qualitative index is based on expert scoring, industry standards, and existing research to determine R_P and R_0.

Table 4 Thermal power enterprise carbon performance evaluation index value

First-level index	Second-level index	Third-level index	Measured value
Thermoelectric enterprise carbon performance evaluation index system A	Carbon resource (energy) input index B_1	C_1: Material cost rate	0.3647
		C_2: Energy cost rate	0.0222
		C_3: Standard coal consumption rate of power supply	543.7
		C_4: Standard coal consumption per unit heating	39.44
		C_5: Plant thermal efficiency	0.6812
		C_6: Thermoelectric ratio	5.568
	Carbon resource (energy) cycle index B_2	C_7: Material cost loss rate	0.1372
		C_8: Energy cost loss rate	0.1326
		C_9: Internal resource value and external damage value ratio	0.5626
		C_{10}: Comprehensive utilization of fly ash	1
		C_{11}: Comprehensive utilization of gypsum	1
	Carbon resource (energy) output index B_3	C_{12}: External damage value per unit of output	0.0915
		C_{13}: Carbon emission reduction rate	0.236
		C_{14}: Low carbon economy increase	27.3
	Enterprise carbon management index B_4	C_{15}: Carbon emission reduction per unit energy saving investment	7.053
		C_{16}: Staff's post skill training	5
		C_{17}: Carbon emission reduction results recognition	5

$$R_0 = \begin{bmatrix} P_1 & c_1 & 0.3467 \\ & c_2 & 0.0222 \\ & c_3 & 543.7 \\ & c_4 & 39.44 \\ & c_5 & 0.6812 \\ & c_6 & 5.568 \\ & c_7 & 0.1372 \\ & c_8 & 0.1326 \\ & c_9 & 0.5626 \\ & c_{10} & 1 \\ & c_{11} & 1 \\ & c_{12} & 0.0915 \\ & c_{13} & 0.236 \\ & c_{14} & 27.3 \\ & c_{15} & 7.053 \\ & c_{16} & 5 \\ & c_{17} & 5 \end{bmatrix}, R_P = \begin{bmatrix} P_1 & c_1 & (0,\ 1) \\ & c_2 & (0,\ 1) \\ & c_3 & (300,\ 600) \\ & c_4 & (34.1,\ 51.2) \\ & c_5 & (0,\ 1) \\ & c_6 & (1.3,\ 6.7) \\ & c_7 & (0,\ 1) \\ & c_8 & (0,\ 1) \\ & c_9 & (0,\ 1) \\ & c_{10} & (0,\ 1) \\ & c_{11} & (0,\ 1) \\ & c_{12} & (0,\ 1) \\ & c_{13} & (0,\ 1) \\ & c_{14} & (0,\ 10) \\ & c_{15} & (0,\ 10) \\ & c_{16} & (0,\ 10) \\ & c_{17} & 5 \end{bmatrix}.$$

4.3 Determination of weight coefficient

Analytic hierarchy process (AHP), which has been proposed by Saaty in the early 1970s, is a multi-objective decision-making analysis method that combines quantitative analysis with qualitative analysis. In the application of

AHP to calculate the index weight coefficient, a judgment matrix must be constructed to compare and analyze the importance of the two indexes, calculate the weight coefficient of each index, and then check the consistency of the judgment matrix to determine the combined weight.

In this paper, AHP-subjective and objective evaluation methods are used to construct the target layer. The behavior layer of five judgment matrices, the weight of each index, and the consistency of the test are shown in Tables 5 to 9.

Table 5 Calculation results of carbon performance index A of thermoelectric enterprises (Consistency of judgment matrix: 0.0103)

A	B_1	B_2	B_3	B_4	w_i
B_1	1.000	2.000	3.000	4.000	0.467
B_2	0.500	1.000	2.000	3.000	0.277
B_3	0.333	0.500	1.000	2.000	0.160
B_4	0.250	0.333	0.500	1.000	0.095

Based on the aforementioned results, we can obtain the weight of each index in the enterprise's carbon performance index system with respect to the upper layer (Table 10).

4.4 Calculation of the distance between the classical domains of the material to be evaluated

Based on Eq. (4), the results are shown in Table 11.

4.5 Calculation of improved comprehensive correlation degree

First, the distance between R_0 and the classical domain of the object $D_j(v_i')$ to be evaluated is calculated. Then, according to Eq. (6), R_0 of the object to be evaluated and the improved comprehensive correlation degree of each grade are calculated.

$$N_1(P_0)=\frac{1}{2}\times\left[\left(1-\frac{1}{18}\sum_{i=1}^{18}D_1(v_i')w_i(X)\right)+\left(1-\sum_{i=1}^{18}D_1(v_i')w_i(X)\right)\right]=0.956003,$$

$$N_2(P_0)=\frac{1}{2}\times\left[\left(1-\frac{1}{18}\sum_{i=1}^{18}D_2(v_i')w_i(X)\right)+\left(1-\sum_{i=1}^{18}D_2(v_i')w_i(X)\right)\right]=0.979113,$$

$$N_3(P_0)=\frac{1}{2}\times\left[\left(1-\frac{1}{18}\sum_{i=1}^{18}D_3(v_i')w_i(X)\right)+\left(1-\sum_{i=1}^{18}D_3(v_i')w_i(X)\right)\right]=0.919279,$$

Table 6 Calculation results of carbon resources (energy) input index B_1 (Consistency of judgment matrix: 0.0605; Total index weight: 0.467)

B_1	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	w_i
C_{11}	1.000	2.000	0.500	0.500	2.000	2.000	0.1808
C_{12}	0.500	1.000	0.500	0.500	1.000	2.000	0.1266
C_{13}	2.000	2.000	1.000	1.000	2.000	2.000	0.2455
C_{14}	2.000	2.000	1.000	1.000	1.000	1.000	0.2074
C_{15}	0.500	1.000	0.500	1.000	1.000	1.000	0.1248
C_{16}	0.500	0.500	0.500	1.000	1.000	1.000	0.1148

Table 7 Calculation results of carbon resources (energy) cycle index B_2 (Consistency of judgment matrix: 0.0025; Total index weight: 0.2772)

B_2	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	w_i
C_{21}	1.000	2.000	3.000	3.000	3.000	0.3945
C_{22}	0.500	1.000	2.000	2.000	2.000	0.2343
C_{23}	0.333	0.500	1.000	1.000	1.000	0.1237
C_{24}	0.333	0.500	1.000	1.000	1.000	0.1237
C_{25}	0.333	0.500	1.000	1.000	1.000	0.1237

Table 8 Calculation results of carbon resources (energy) output index B_3 (Consistency of judgment matrix: 0.0046; Total index weight: 0.1601)

B_3	C_{31}	C_{32}	C_{33}	w_i
C_{31}	1.000	2.000	3.000	0.540
C_{32}	0.500	1.000	2.000	0.297
C_{33}	0.333	0.500	1.000	0.163

Table 9 Calculation results of enterprise carbon management index B_4 (Consistency of judgment matrix: 0.0268; Total index weight: 0.0954)

B_4	C_{41}	C_{42}	C_{43}	w_i
C_{41}	1.000	3.000	3.000	0.594
C_{42}	0.333	1.000	2.000	0.249
C_{43}	0.333	0.500	1.000	0.157

$$N_4(P_0)=\frac{1}{2}\times\left[\left(1-\frac{1}{18}\sum_{i=1}^{18}D_4(v_i')w_i(X)\right)+\left(1-\sum_{i=1}^{18}D_4(v_i')w_i(X)\right)\right]=0.839668.$$

4.6 Evaluation of carbon performance level of thermal power enterprises

$N_2(P_0)=\max\{N_j(P_0)\}$. The object to be evaluated is good, and the calculation of the characteristic value of the class variable is expressed as follows.

Let:

$$\overline{N}_j(P_0)=\frac{N_j(P_0)-\min N_j(P_0)}{\min\limits_j N_j(P_0)-\min\limits_j N_j(P_0)},$$

then,

$$j^*=\frac{\sum_{j=1}^{m}j\overline{N}_j(P_0)}{\sum_{j=1}^{m}\overline{N}_j(P_0)}=1.8905,$$

where j^* is the assessment of the value of the class variable R_0. That is, the matter–element R_0 is in the good level, and the deviation has an excellent rating.

The application of the model shows that the enterprises carbon performance evaluation has good to excellent rating and a certain improvement space. The existing carbon resource utilization ratio in the production process is low because investment in the recycling of resources is not high. Therefore, enterprises can increase their energy saving and environmental protection equipment, which are investments that would improve the utilization rate of carbon resource. In addition, the thermal power enterprises should improve the accounting and supervision of carbon performance. With this analysis, problems in the daily production and business activities are readily identifiable, and opportunities for improvement can be identified.

Table 10 Weight of each index relative to the upper index

Target layer	Criterion layer	Weight	Index layer	Weight
Thermoelectric enterprise carbon performance evaluation index A	Carbon resource (energy) input index B_1	0.4673	C_1: Material cost rate	0.1808
			C_2: Energy cost rate	0.1266
			C_3: Standard coal consumption rate of power supply	0.2455
			C_4: Standard coal consumption per unit heating	0.2074
			C_5: Plant thermal efficiency	0.1248
			C_6: Thermoelectric ratio	0.1148
	Carbon resource (energy) cycle index B_2	0.2772	C_7: Material cost loss rate	0.3945
			C_8: Energy cost loss rate	0.2343
			C_9: Internal resource value and external damage value ratio	0.1237
			C_{10}: Comprehensive utilization of fly ash	0.1237
			C_{11}: Comprehensive utilization of gypsum	0.1237
	Carbon resource (energy) output index B_3	0.1601	C_{12}: External damage value per unit of output	0.5396
			C_{13}: Carbon emission reduction rate	0.297
			C_{14}: Low carbon economy increase	0.1634
	Enterprise carbon management index B_4	0.0954	C_{15}: Carbon emission reduction per unit energy saving investment	0.5936
			C_{16}: Staff's post skill training	0.2493
			C_{17}: Carbon emission reduction results recognition	0.1571

Table 11 Calculation of the distance between the classical domains of the material to be evaluated

	Excellent (D_j)	Good (D_j)	Fair (D_j)	Poor (D_j)
c_1	0.065	−0.065	0.135	0.185
c_2	−0.022	0.178	0.478	0.678
c_3	0.281	0.106	−0.011	0.011
c_4	0.022	−0.022	0.060	0.140
c_5	0.119	−0.081	0.081	0.281
c_6	−0.052	0.052	0.234	0.431
c_7	−0.063	0.063	0.363	0.563
c_8	−0.067	0.067	0.367	0.567
c_9	0.363	0.063	−0.063	0.137
c_{10}	0	0.030	0.100	0.200
c_{11}	0	0.030	0.100	0.200
c_{12}	−0.009	0.009	0.209	0.509
c_{13}	0.464	0.264	−0.036	0.036
c_{14}	0.035	−0.035	0.165	0.349
c_{15}	0.095	−0.095	0.105	0.305
c_{16}	0.300	0.100	−0.100	0.100
c_{17}	0.300	0.100	−0.100	0.100

5 Conclusions and policy implications

This article differs from other existing traditional carbon performance evaluation research that combines the evaluation index system with the 3R principle of circular economy and applies them to micro-enterprises — a potential breakthrough point for emissions reduction. Through the analysis of the production process of thermal power enterprises along with resource value stream calculation theory which includes the carbon resource (energy) input, cycle, output, and carbon management, this work produces 4 index dimensions with 17 indicators of tertiary carbon management indexes. Then, the carbon performance of enterprises is evaluated comprehensively, scientifically, reasonably, and systematically, and the comprehensive consideration of carbon-containing resources in production entry, circulation stages, emission stages and cost management is realized. As such, a previous shortage of the research literature on enterprise level carbon performance evaluation has been addressed.

In addition, in selecting evaluation methods, this paper first uses the matter–element extension model and the AHP, which is a subjective and objective comprehensive assignment method based on calculation of the weight of each index; establishes multi-level and multi-index evaluation model; and quantifies a large number of multi-factor and multi-level qualitative indicators. The classical and physical domains, as well as the calculation of correlation, is used to improve the comprehensive correlation degree and assess the enterprise that belongs to each carbon performance grade. This method can represent the correlation between the assessment result and the rank set by quantitative value, judge the level of the object according to it to reflect the comprehensive level of enterprise carbon performance and widen the matter–element model application boundary.

Finally, this paper uses the model to conduct a case study on the carbon performance evaluation of a thermoelectric enterprise and analyzes whether the carbon performance of the enterprise belongs to the “good” grade. According to the evaluation results, this enterprise has a low investment in resource recycling and a low utilization rate of carbon-containing resources in the production process. This paper proposes corresponding solutions for this enterprise. Through case application, the feasibility of the method proposed in this paper is verified in the carbon performance evaluation. This work also provides new methods and ideas for the carbon performance evaluation of other industries or enterprises.

According to the research conclusions, we present the following suggestions. First, in terms of reducing unit coal consumption, the enterprise can optimize the coal bunker setting, improve the conveying efficiency, and strengthen the management to prevent the occurrence of coal quality adulteration. The enterprise can also improve the combustion efficiency of the boiler and reduce the combustibles of fly ash and slag. Second, to reduce the cost loss rate of materials, enterprises should improve the utilization rate of materials, the pass rate of one-time inspection, the pass rate of batches, and the reuse rate of waste leftover materials. Third, in terms of reducing the external damage value of the output, the enterprise should monitor and evaluate the surrounding environmental quality timely, optimize the production process of the enterprise, reduce the generation of waste, realize the resource utilization of waste, reduce the discharge of pollutants, and take pollutant purification measures to reduce the content of pollutants in the production waste. Finally, to reduce the carbon emission reduction of unit energy saving investment, enterprises should introduce new technology and equipment to achieve energy saving and emission reduction, strengthen environmental protection and low-carbon training, increase research and development investment, and improve resource utilization.

Some shortcomings still exist in this work. First, because of the difficulty of data acquisition, part of the data used to calculate the index weight is calculated by experts. Thus, a certain degree of subjective judgment can be observed. The future study may obtain sufficient sample, adopt the method of statistics, determine the weight of each index, and make the index more representative and scientific. Second, the case study fails to analyze and evaluate the carbon performance of each production link in the production process. In the future, the research can be refined to evaluate the carbon performance of each production link comprehensively.

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