CARBON FLOW COST CONTROL OF COAL-FIRED POWER PLANT BASED ON “ENERGY FLOW–VALUE FLOW” ANALYSIS

PAN, Y. B.[1] – XIAO, X.[1] – LI, J. J.[1] – HUANG, Y.[1] – ZHOU, Z. F.[1,2*]

[1]*School of Business, Central South University, Changsha 410083, China*

[2]*Collaborative Innovation Center of Resource-Conserving and Environment-Friendly Society and Ecological Civilization, Central South University, Changsha 410083, China*

**Corresponding author*
e-mail: zzf3721@qq.com; phone: +86-139-7483-9572; fax: +86-731-265-6273

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Abstract. In response to the commitment that China will begin a comprehensive national carbon emissions trading system in 2017, and considering the needs of a green development strategy, in this paper we adopt a coal-fired power generation company as the research object to study its typical carbon emissions characteristics. Through theoretical analysis and modelling dominated by energy characteristics, the energy flow analysis is separated from the material flow analysis, and we construct an “energy flow—value flow” analysis model. Based on the link between energy use and carbon flow, we divide carbon flow cost into two parts: low carbon control costs and internal and external damage costs. A quality cost control idea is introduced to build a quantitative carbon flow cost control model, and we study the relationship between the total cost of carbon flow and the control of carbon pollution. The case calculation shows that coal enterprises should begin by examining their energy flow, invest reasonably in measures to control carbon, improve their energy efficiency, enhance their control of carbon flow costs and actively focus on relevant policies that control carbon flow effectively; following this process will allow them to be proactive in the new carbon market.

Keywords: *energy flow analysis, value flow analysis, carbon flow, cost control model, model application*

Introduction

Emitting greenhouse gases (primarily CO_2) cause externalities that have environmental effects on all of mankind (Cao and Zhang, 2010; Lodi et al., 2017). Since the Kyoto Protocol promulgated in 1997, the external costs of greenhouse gas emissions have been gradually internalized by market mechanisms (Liu and Huang, 2011). Thus, if today’s businesses ignore the costs associated with greenhouse gas emissions, they may face difficulties in terms of environmental payments (Zhang et al., 2005). After extensive long-term economic development, China has begun to emphasize the transformation and upgrading of its economic structure. In particular, industries that have traditionally emitted high levels of carbon dioxide, such as power generation, steel, and coal among others, are now being strictly regulated to protect the environment (Capoor and Ambrosi, 2009; Zhang, 2017). The National Development and Reform Commission announced in January 2016 that progress has been made toward implementing a national carbon emissions trading market (Lu et al., 2010; Tu and Ma, 2018), and China pledged in 2017 to begin its carbon emissions trading system. In this context, clarifying the cost of carbon flow for enterprises will help them control costs, enhance their corporate image, and enable them to occupy a strong competitive position in the new carbon market.

The 13th Five-Year Plan (2016-2020) emphasized the importance of low carbon development, required enterprises to take the initiative to control carbon emissions and

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strengthen control of their energy consumption. Controlling carbon emissions requires tracking the carbon flow path and calculating relevant costs. The core of studying carbon flow cost involves quantifying the flow of carbon energy inside the enterprise. From an economic standpoint, both carbon energy and value flow during an enterprise’s production and management, and both flows affect the enterprise’s financial costs (Wang, 2015). Therefore, we focus on the dual nature of energy and value flows, with high carbon emissions from coal-fired power generation enterprises as our research object. This paper constructs a simulation of carbon flow cost control based on “energy flow-value flow” to provide a model for the concrete implementation of carbon flow cost control.

Research methods

Energy flow, value stream analysis method

Energy flow analysis is a category of material flow analysis. During the 1980’s, scholars studied the interaction between economic systems and the natural environment and developed a system known as material and energy flow accounting (MEFA) (Chang, 2012). In 2001, through an analysis of the energy flow of national economic systems, Harberl and others put forward a material and energy flow accounting framework and applied it to analyze sustainable development problems (Helmut et al., 2004). Teresa Torres applied material and energy flow accounting to analyze the status of clay in roofing tiles (Torres et al., 2008). Chinese scholar Li Xingji, after analyzing the role of logistics in urban pollution, put forward the idea of using energy flow accounting to protect the urban environment (Li, 1979). Liu et al. (2011) and other scholars wrote that energy flow accounting helps reduce environmental pollutants, because it provides a theoretical basis for enterprises’ efforts to save energy and reduce emissions (Liu et al., 2017). The core of energy flow analysis is the concept of energy flow management (Bendriss et al., 2017; Makni et al., 2017). Quantitatively analyzing energy flows produced by social economic activities will help us to understand and best utilize the flow and flux of energy.

In 1997, the value stream concept was proposed by James Martin, an American management scientist, who believed that value streams exist in a group from the beginning to the end of continuous activities, and that customers were satisfied by consuming all kinds of resources as cost flows (James, 1997). Womack et al. (1997) and other scholars proposed that resources, time and costs could be saved by using value stream analysis to analyze production and maximize product values (Lalami et al., 2017). Xiao and Liu (2004) and others scholars wrote that “flow” can be used to reveal the direction, speed and strength of the interactions among different elements, and that the concept of “flow” could be used to measure the value of diverse elements dynamically. The practical application of value stream analysis requires the collection of information and the analysis of data. By managing value stream analysis, enterprises can gain a competitive advantage (Zhang and He, 2002).

Existing research has focused mostly on material flow and value stream analysis, without stripping out source analysis. This paper focuses on the costs of the carbon flow of coal-fired power enterprises, for which energy is the main input material. We argue that an energy flow and value stream analysis method is more targeted than a material flow and value stream analysis.

The relationship between energy utilization and carbon flow cost

Carbon element flows are the carrier of fossil energy. The energy input mainly consists of the combustion of coal in coal-fired power enterprises, and energy is released by the oxidation of carbon. Along the flow path of this fossil energy, carbon is transformed during the different production processes and eventually is fixed into products or becomes CO_2 emissions that are released into the external environment. Scholars such as Yin et al. (2013) wrote about a “low-carbon revolution” that would focus on energy saving and emission reduction; use less coal, oil and other carbon-containing energy sources; and ultimately reduce the negative effects on the external environment. Following the internal transport path of carbon energy and calculating the value stream may help enterprises understand the value of energy flows in their production processes and allow them to control the cost of their carbon flows. There are six strands energy flow that influence the unit process of carbon flows in coal-fired power enterprises, as shown in the following *Figure 1:*

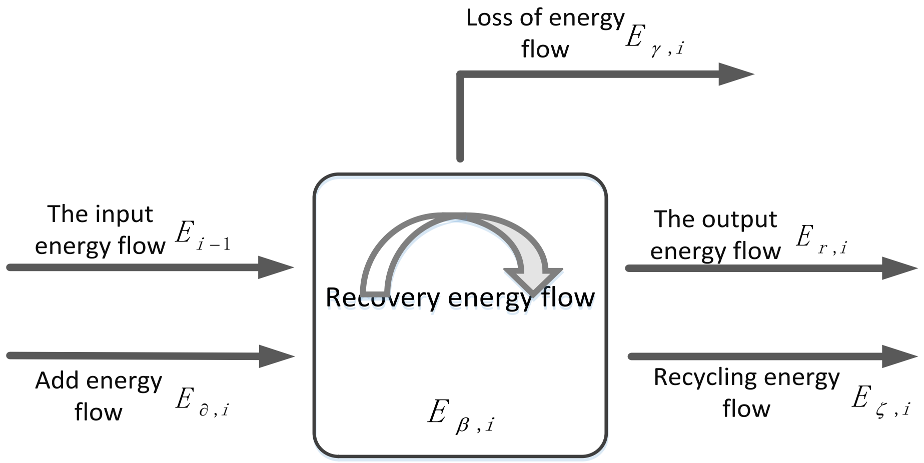

Figure 1. *Coal-fired power generation enterprise unit process flow diagram*

As *Figure 1* shows, the energy flow suggests that the process of the i-1 is the i process of energy flow, and it represents the flow of external added energy, including fuel, electricity, steam and other means. *Figure 1* also suggests that the output of energy is an energy flow loss. It shows that the recovery of energy refers to the process of recycling during the production of energy flow.

Concept and classification of carbon flow cost

Scholars of ecology, energy science and engineering have written that carbon flow draws on the resource flow cost and the concept of energy and value flow; however, they have not focused on carbon flows. Qi et al. (2010) proposed studying carbon flows from a homogeneous carbon source to carbon sequestration. In a coal-fired power generation enterprise, carbon energy is also produced in the process of the treatment.

Carbon flow cost may be evaluated by examining environmental and carbon costs. Gray and Bebbington (1993) used the concept of life cycle to argue that carbon costs include all costs associated with carbon emissions that may occur in the production process. Wang et al. (2011) wrote that carbon costs may be divided into ex ante costs, testing costs and loss costs. Considering the production cost, the cost of detection and prevention before and after the production of carbon flows, and the cost of these carbon flows, cost may be divided into four categories: the cost of carbon flow prevention, inspection costs, and the carbon emissions themselves (including carbon trading and carbon tax).

Model design

Content of carbon flow cost control

Carbon cost flow control is also dependent on the concepts of carbon costs and environmental cost control. USEPA introduced relevant environmental cost control tools and pointed out that government and enterprises should jointly bear the responsibility for controlling environmental costs. Gray and Bebbington (1993) wrote that comprehensive control should be based on the life cycle of carbon costs. Wang et al. (2011) proposed using the PDCA (plan, do, check, and action) method to control the environmental costs of enterprises. Zhou et al. (2016) believe in controlling the cost of carbon emissions and carbon emission reductions. He and Li (2015) proposed focusing on logistics to optimize energy flows and help companies control the cost of carbon energy.

The existing research on the cost control of carbon flows generally does not focus on the idea of "low carbon", and little research has been done on the development of China's carbon market and the specific characteristics of Chinese enterprises. This paper focuses on the quality cost control model and the characteristics of the carbon flow costs of coal-fired power generation enterprises to establish a carbon flow cost control model.

Classification of carbon flow cost control factors

In the middle of twentieth century, American quality management experts Feigenbaum (1961) and Juran (1988) put forward the concept of "total quality management" for the purpose of achieving high quality products with few defects. In this paper, we regard damage to the internal and external environment as a quality defect. Combined with considering the characteristics of carbon flow costs incurred by coal-fired power generation enterprises, this paper divides the carbon flow cost control model into two categories: low carbon control costs and internal and external costs, specific classification as shown in *Table 1*.

Low carbon control costs

Low carbon control costs are mainly divided into two categories: prevention costs and testing costs. The prevention cost is what the enterprise must spend in order to improve energy efficiency, reduce carbon waste emissions, and achieve a "low carbon" design. In a certain range, the cost of prevention is inversely proportional to the cost of the carbon. Detection of cost measures the cost of carbon flows, including training costs and labor costs; these element of the cost remains relatively stable.

Internal and external damage costs

This section contains two factors: the internal loss cost of carbon flow and the external environmental damage cost. The carbon flow internal loss costs include loss cost, processing cost, resource utilization cost and profit loss. Negative cost relative to the cost of products includes the output of the products. Processing cost refers to the use of carbon emission reduction devices and the cost of processing. Resource utilization cost and income includes enterprise measures and carbon recycling resources. Carbon flow external environmental damage cost includes 5 elements: (1) carbon waste emissions cost; (2) carbon trading costs and benefits (enterprises must buy emissions quotas issued by the government according to their actual carbon emissions); (3) costs or gains from the sale of surplus quota; (4) carbon taxes, and (5) fines.

If the penalties (costs incurred) for not controlling carbon emissions are increased, then pollution will be reduced, and the cost of internal and external loss will be reduced. However, the cost of internal and external losses will increase. In order to better express the relationship between the two, this paper introduces the quality cost control model.

Table 1. *Classification of carbon cost control model factors in coal-fired power generation enterprises*

Carbon flow cost control model factor classification		
Low carbon control cost	Preventive cost	Design labor cost Equipment purchase Surrounding greening Equipment update and maintenance
	Detection cost	Testing training fee Detection of labor costs
Internal and external damage cost	Internal loss cost of carbon	Lost cost Treatment cost Resource utilization cost and benefit
	Carbon and sulfur external environment loss cost	Carbon waste disposal costs CO_2 Emission cost Carbon trading costs and benefits Carbon tax Fine

Construction of carbon flow models of cost control

Conventional quality cost control models

Mathematical models express the quantitative relationship between quality cost based: C: Quality costs, C_1: Cost identification of prevention, C_2: Quality loss cost, q: average rate of products $(0 \leq q \leq 1)$, F: Unit cost of nonconforming, d: Unqualified product rate $[d = 1 - q(0 < d < 1{,}0 < q < 1)]$, x: and thus Output.

From *Equation 1, Equation 2* is obtained.

$$Fdx = C_2qx \qquad \text{(Eq.1)}$$

$$C_2 = \frac{Fd}{q} = \frac{F(1-q)}{q} \qquad \text{(Eq.2)}$$

Set: K for C_1 with $\frac{d}{p}$ scale factor, then *Equations 3-4* are obtained.

$$C_1 = \frac{Kq}{d} = \frac{Kq}{1-q} \qquad \text{(Eq.3)}$$

$$C = C_1 + C_2 = \frac{Kq}{1-q} + \frac{F(1-q)}{q} \qquad \text{(Eq.4)}$$

C is minimized, that is $C_1 = C_2$, when *Equations 5-6* are obtained.

$$q = \frac{1}{\sqrt{\frac{K}{F}}+1} \qquad \text{(Eq.5)}$$

$$C = C_1 + C_2 = 2\sqrt{KF} \qquad \text{(Eq.6)}$$

Early quality cost control models for quality and cost control and management thinking. However, in practice there are quality limitations and problems such as lack of theoretical calculations, such that the intersection curves represent only the low total cost and are contrary to the actual situation. Based on Japan's successful zero defects theory, there has been improvement in quality cost control models.

Improving cost control model of carbon flow

Japan scholar Dr's study points out that: "the concept of quality usually refers to the same utility function under products to users with less failure, low energy consumption, long life, high efficiency characteristics, comprehensive loss." Thus, a product can be drawn to society brought about by the total loss of a function expression, provided with $T_{(q)}$ said. $T_{(q)} = C_{(q)} + L_{(q)}$, Which $C_{(q)}$ the cost function for the enterprise, $L_{(q)}$loss function, $q$the quality characteristics of the product vector. When quality level $q = 1 - d$ ($d$is the carbon losses and the pollution of the environment), then the carbon emissions control level is equal to the success rate of carbon emissions. Taking into account the recent coal-fired power plant investment and production decisions made for long-term economic benefit, we can establish the following mathematical model (*Eq. 7).*

$$T_{(q)} = C_{(q)} + L_{(q)} \qquad \text{(Eq.7)}$$

$T_{(q)}$ represents the total cost of the carbon flow and for low carbon costs under control, $L(q)$ is the internal and external damage costs.

Low-carbon model

We used the Cobb Douglas function to represent the relationship between preventive costs C_1 and testing costs C_2 (*Eq. 8*).

$$q = AC_1^{\alpha}C_2^{\beta} \qquad \text{(Eq.8)}$$

Constraint conditions (*Eq. 9*):

$$C_1 + C_2 = C_{(q)} \qquad \text{(Eq.9)}$$

Using the Lagrange multipliers method provides *Equation 10*.

$$\varphi(C_1, C_2, q) = AC_1^{\alpha}C_2^{\beta} - \lambda[C_{(q)} - (C_1 + C_2)] \quad \text{(Eq.10)}$$

where λ is the Lagrange multiplier and *Equation 11* can be obtained.

$$C_{(q)} = q^{\frac{1}{\alpha+\beta}}/[A(\frac{\alpha}{\alpha+\beta})^{\alpha}(\frac{\beta}{\alpha+\beta})^{\beta}]^{\frac{1}{\alpha+\beta}} \quad \text{(Eq.11)}$$

Let $a_1 = [A(\frac{\alpha}{\alpha+\beta})^{\alpha}(\frac{\beta}{\alpha+\beta})^{\beta}]^{\frac{-1}{\alpha+\beta}}$, $b_1 = \frac{1}{\alpha+\beta}$, *Equation 12* can be obtained.

$$C_{(q)} = a_1 q^{b1} \quad \text{(Eq.12)}$$

Internal and external damage cost model

Businesses must pay for ecological damages caused by the pollution they emit. When the deviation $|q - 1| = 0$ shi, then internal and external losses are at a minimum, and constant $L(1) = a_2$ and $a_2 \neq 0$. In$q = 1$, we have the Cheng Tailei series, *Equation 13* can be obtained.

$$L_{(q)} = L(1) + \frac{L^{'}(1)}{1!}(q-1) + \frac{L^{''}(1)}{2!}(q-1)^2 + \frac{L^{'''}(1)}{3!}(q-1)^3 + \ldots \quad \text{(Eq.13)}$$

$L_{(q)}$ in $q = 1$ obtains the extreme-one derivative $L'(1) = 0$. In addition, taking into account the deviation $|q - 1|$ value minimum, and the Taylor expansions, we find that the fourth and following are much smaller than the third, and the internal and external damage cost functions $L_{(q)}$ yield the approximate expression (*Eq. 14*):

$$L_{(q)} = L(1) + \frac{L^{''}(1)}{2!}(q-1)^2 \quad \text{(Eq.14)}$$

Order $a_2 = L(1)$, $b_2 = \frac{L''(1)}{2!}$, *Equation 15* can be obtained:

$$L_{(q)} = a_2 + b_2(q-1)^2 \quad \text{(Eq.15)}$$

Total cost of carbon control model

As mentioned above, the total cost of carbon $T_{(q)}$ comprises low carbon, control costs and external costs, and thus *Equation 16* can be obtained from *Equations 12* and *15:*

$$T_{(q)} = C_{(q)} + L_{(q)} = a_1 q^{b1} + a_2 + b_2(q-1)^2 \quad \text{(Eq.16)}$$

where $a_1 = [A(\frac{\alpha}{\alpha+\beta})^{\alpha}(\frac{\beta}{\alpha+\beta})^{\beta}]^{\frac{-1}{\alpha+\beta}}$, $b_1 = \frac{1}{\alpha+\beta}$, $a_2 = L(1)$, $b_2 = \frac{L^{''}(1)}{2!}$.

Equation 16 shows the total cost of carbon $T_{(q)}$. Numerically, it is low carbon cost $C_{(q)}$ with internal and external damage costs $L_{(q)}$ overlaid. $C_{(q)}$ has a relationship with q in the form of indices, Therefore, the logarithmic processing on both sides of *Equation 17* is obtained.

$$log(C_{(q)}) = log^{a_1} + b_1\, log^q \qquad \text{(Eq.17)}$$

$log(C_{(q)})$ with log^q constitutes a slope b_1. The intercept of log^{a_1} A is a linear relationship, yielding a different$q$. $C_{(q)}$ values can be obtained by linear regression a_1 and b_1. The values obtained $C_{(q)}$ with q have a relationship.

On the other hand, $L_{(q)}$with$q$provides a functional quadratic expression, but when $(1-q)^2 = q_1$ are the variables, we get *Equation 18*.

$$L_{(q_1)} = a_2 + b_2 q_1 \qquad \text{(Eq.18)}$$

As can be seen in the $L_{(q_1)}$ with log^q formation of slope b_2, the intercept a_2 is a linear relationship, and the different values for q, $L_{(q)}$, a_2 and b_2 can be obtained by linear regression.

For the $C_{(q)}$, $L_{(q)}$ and $L_{(q_1)}$ expressions, we can discuss q and the $T_{(q)}$ impact of its extremes.

Application of carbon flow models of cost control

Data collection and processing

This paper takes a large coal-fired power plant as its study object; such plants use inputs like water, coal, oil, natural gas and other types of raw energy, convert them into electric secondary energy forms, which become inputs in the power grid and provide energy to users. A typical energy conversion of a coal-fired power plant consumes many resources. Power plants convert the chemical energy of fuels (mainly coal into electrical energy via the transformation process shown in *Figure 2*. *Table 2* provides carbon cost data for a coal-fired power plant during the period from 2010 to 2015. *Table 3* shows more data for the same time period.

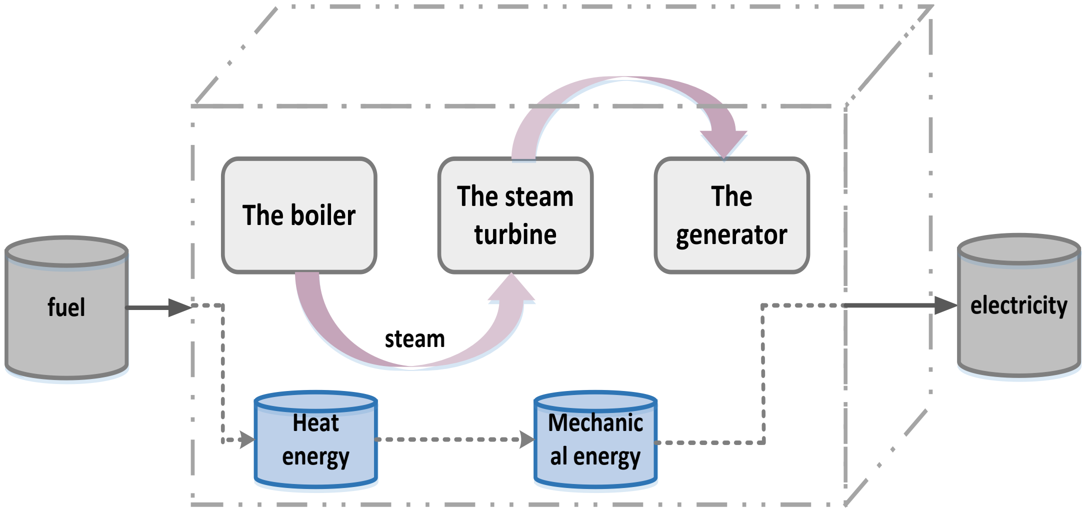

Figure 2. *Energy transformation diagram of a coal-fired power plant*

Table 2. *Carbon costs of a coal-fired power plant from 2010~2015*

Cost of carbon flow classification	**Cost items**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Low carbon cost	The cost of prevention	94.40	109.50	129.20	140.50	186.51	259.40
	Testing costs	19.07	27.20	40.30	63.80	72.70	88.90
	Subtotal (C)	113.47	136.70	169.50	204.30	259.21	348.30
Internal and external damage costs	Carbon flow loss cost	629.80	553.01	420.76	358.90	320.80	301.60
	Carbon external environmental damage costs	361.69	326.04	252.04	179.24	125.12	102.09
	Subtotal (L)	991.49	879.05	672.80	538.14	445.92	403.69
Total (T)		1,104.96	1,015.75	842.30	742.44	705.13	751.99
Comprehensive compliance rate (%)		87.27	88.98	90.72	92.14	93.71	95.46

Table 3. *Statistics for a coal-fired power plant for the period 2010~2015*

Vintage	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Energy-saving Total (tce)**
Electricity generation (million kWh)	5,401.48	6,505.38	6,000.00	6,000.00	6,000.00	6,000.00	437.57
Power supply coal consumption (g/kWh)	310.32	309.47	307.94	305.70	303.90	302.13	
Standard coal (tce)	41.27	62.10	91.80	134.40	108.00	106.20	

From *Tables 2* and *3*, one may see the relationship among energy-saving, internal and external damage costs and the costs of low carbon control (see *Fig. 3*). The increase in energy-saving, source reduction, and low carbon control cost allows for a reduction in carbon-containing waste material and in internal and external damage costs.

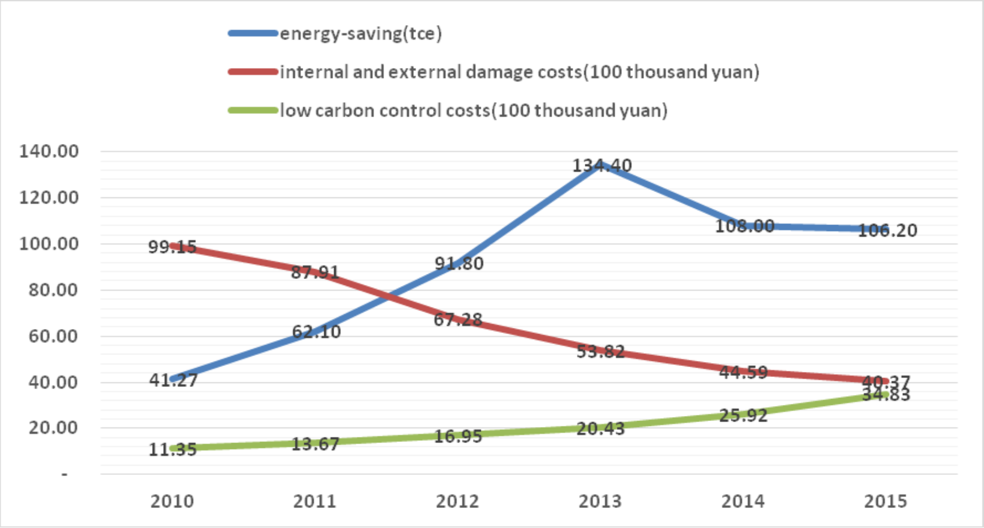

Figure 3. *The relationship among energy-saving, internal and external damage costs and low carbon control costs*

Results and discussion

Based on the expression of functions $C_{(q)}$ and $L_{(q)}$ in combination with the data in *Table 2*, we used MATLAB software and an analysis of statistical regression models to calculate the variable parameters of our model. The results of the main performance parameters of the model are shown in *Table 4*. As calculated by *Equations 19* and *20*, the original scattered data points and the fitting result curves are shown in *Figure 4*. From *Table 1*, we can see the equivalent substitutions for $C_{(q)}$ and $L_{(q)}$ and the significant linear relationship q. The R^2values were 0.986 and 0.978, and the significance levels F were 422.26 and 261.932. The F values show that the statistical equations and the calculated P order of magnitude 10^{-6} were far less than the criterion value of 0.05. This proves that this paper constructed a regression model with high reliability.

Table 4. *Calculation results of* $C_{(q)}, L_{(q)}$ *and* $T_{(q)}$

	R²	**F**	**P**	**MSE**
C(q)	0.986	422.26	8.6e-7	17.7885
L(q)	0.978	261.932	3.53e-6	29.1789
T(q)	--	--	--	46.5544

$$C_{(q)} = 669.73q^{13.74} \quad \text{(Eq.19)}$$

$$L_{(q)} = 337.5 + 40460(1\text{-q})^2 \quad \text{(Eq.20)}$$

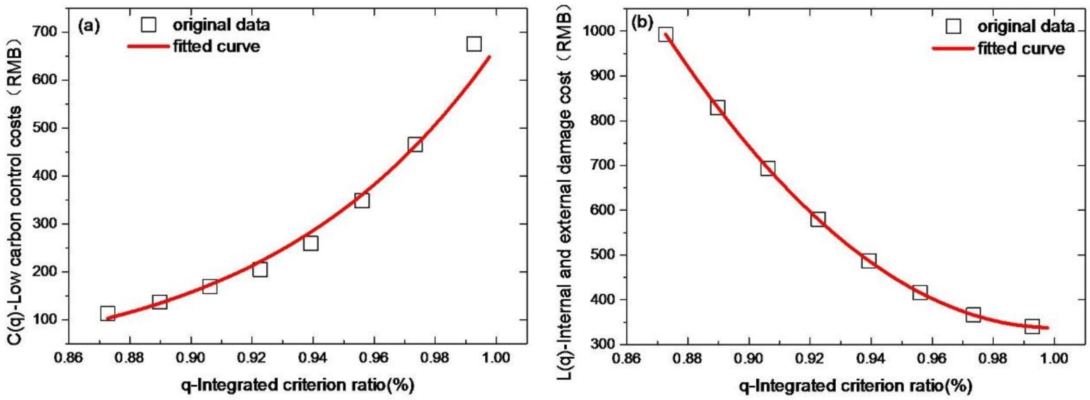

Figure 4. *Comparison of scatter plots and fitting curves*

As can be seen from *Figure 4*, *Equations 19* and *20* fit the regression of low carbon cost control, and of the internal and external damage costs, with the original plot value and the change trend of q. When the variable q is gradually increased, the corresponding function $C_{(q)}$ (low carbon control costs) gradually increased, and $L_{(q)}$ (the value of internal and external damage costs) gradually decreased.

According to the relationship between $C_{(q)}$ and $L_{(q)}$, the total carbon flow cost control function is obtained (*Eq. 21*).

$$T_{(q)}=C_{(q)}+L_{(q)}=669.73q^{13.74}+337.5+40460(1-q)^2 \qquad \text{(Eq.21)}$$

We then combine *Equations 19* and *20* to draw $C_{(q)}$, $L_{(q)}$, $T_{(q)}$ and q with the change of the curve, as shown in *Figure 5*.

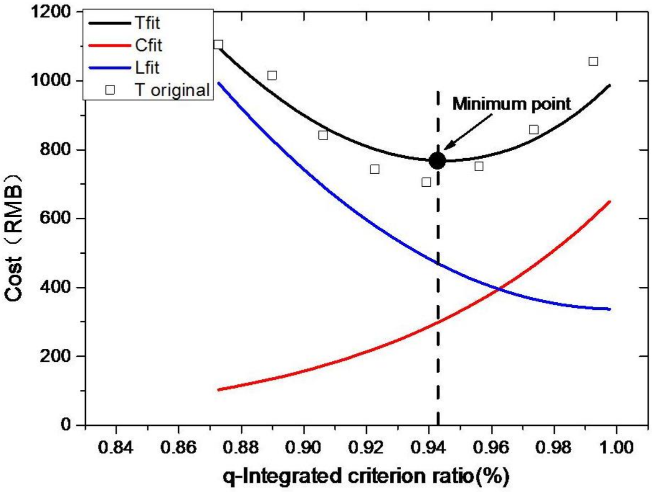

Figure 5. *Comparison of scatter plots and fitting curves*

Figure 5 shows that q has different effects on $C_{(q)}$ and $L_{(q)}$ trends, and $T_{(q)}$ decreases gradually with the increase of q, and after reaching its lowest point, it then increases gradually again. The minimum value as the black circle in the x = 0.942 graph represents the position and the corresponding gross $T_{(q)}$ is 768.0516.

Table 2 shows that in 2010, coal-fired power plants implemented certain low carbon control cost measures, and while the effect on the cost of carbon flow control was not obvious, the potential for a reduction in emissions is enormous. Beginning in 2011, power plant shave been gradually screened for small energy sources. Significant increases have been made in the research and development of low carbon technology, and energy utilization rates have improved. In 2014, the total carbon flow cost reduction was 3,998,300 yuan, compared with a 2010 decrease of about 36.18%. Low carbon control costs doubled, compared to the cost of internal and external damage, which decreased to 44.97% in 2010. In particular, the reduction of coal consumption reduced the cost of carbon flow. Improved technology, low carbon control costs, and energy conservation clearly help to reduce the total carbon flow cost. When the pollution control level is more than 94.2%, the rate of the enterprise’s low carbon cost increases more than the rate of internal and external damage costs declines, which leads to an increase in the total carbon flow cost. Therefore, in the long run, low carbon cost control is not possible for coal-fired power generation enterprises. Enterprises should avoid excessive investment in low carbon balance, and in the control of costs, because these measures result in unnecessary waste. *Figure 5* shows that the carbon flow cost curve improves, according to the specific situation of enterprises, depending on the low carbon control and damage cost functions. The lowest total cost of carbon flow is calculated on this basis, and likely the two intersection functions may also be offset, if we used an improved model data to compensate for the lack of the original model.

Conclusion

Against the background of climate warming, the analysis and control of carbon flow cost is an important condition to understand in order for industrial enterprises to realize sustainable development. In this paper, based on the concept of “energy flow and value flow,” and using an improved model of carbon flow cost control, the following conclusions and implications are obtained:

Coal-fired power generation enterprises should take the initiative to control the cost of carbon flow, at a reasonable increase in the cost of low carbon control inputs. Low carbon control costs should reduce the cost of carbon flow, which is an important guarantee for an enterprise. However, because low carbon cost control is not possible, enterprises should aim to achieve the optimal emissions compliance rate to control their carbon flow cost, as well as to avoid losing control because of a lack of investment, and to avoid wasting resources by focusing too much on low carbon investment control.

Further increasing R&D investment and power will maximize the utilization rate of energy and reduce the coal consumption. Based on the “energy flow, value flow” concept, enterprises should pay attention to the optimization and control of carbon flow cost from the source. First, they should choose low pollution sources of energy and materials and reduce their unit energy flow. Second, they should increase low carbon technology development and invest more in carbon flow loss processing equipment to ensure the transition to becoming green, low carbon enterprises.

Coal-fired power generation enterprises should combine their own characteristics to improve the cost control system of their carbon flow. The key to improving carbon flow cost curves is determined according to the actual situation of the enterprises, as well as to their low carbon control and damage cost functions. Given this, in this paper, we used statistical analysis software to find a comprehensive compliance rate for the control of carbon flow in a coal-fired power enterprise; this rate is of practical significance for the enterprise’s cost control.

The accounting of carbon flow costs in coal-fired power generation enterprises is relatively wide-ranging. To accurately calculate and achieve carbon flow cost control, a lot of in-depth and meticulous research is needed. Future research can consider the following aspects. (1) It is relatively easy to quantify the cost of low carbon control and the internal loss of carbon flow. However, the technology that can be used to determine the external loss cost according to the degree and type of energy damage needs to be further improved. In addition, accurate accounting of carbon emissions remains a challenge. These will affect the collection of cost data, which in turn affects the model analysis. (2) We may have different classifications for various cost items of coal-fired power generation enterprises. After accurate accounting of carbon flow costs, it is necessary to further study the classification according to what standards. (3) When testing the model, the target company needs a large amount of carbon flow cost data for many years. The lack of data will affect the model rationality test. In the future, more data can be collected to test the model.

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REFERENCES

[1] Bendriss, A., Kezrane, C., Lasbet, Y., Awad, S., Loubar, K., Makhlouf, M. (2017): Experimental investigation on the influence of a biodiesel (waste cooking oil) on the performance and exhaust emissions of a compression ignition engine. – Journal Européen des Systèmes Automatisés 50(4-6): 361-378.

[2] Cao, H. X., Zhang, F. (2010): Low-carbon economy research progress at home and abroad. – Productivity Research 3: 1-6.

[3] Capoor, K., Ambrosi, P. (2009): Carbon Market Development Status and Trends in 2006 (1st to 3rd Quarters). – World Bank, Wahington, DC.

[4] Chang, Z. (2012): Carbon Pulse Analysis Based on Energy Utilization. – Fudan University, Shanghai.

[5] Chou, J. S., Yeh, K. C. (2015): Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. – Journal of Cleaner Production 101: 137-147.

[6] EPA. (1995): Environmental Accounting Case Studies: Green Accounting at AT&T. – EPA, Washington, DC

[7] EPA. (1997): Applying Environmental Accounting to Electroplating Operations：An In-Depth Analysis. – United States Environmental Protection Agency, Washington, DC.

[8] Feigenbaum, A. V. (1961): Total quality control: engineering and management: the technical and managerial field for improving product quality, including its reliability, and for reducing operating costs and losses. – McGraw-Hill.

[9] Gray, R., Bebbington, J. (1993): Corporate accountability and the physical environment: social responsibility and accounting beyond profit. – Business Strategy and the Environment 2: 1-11.

[10] He, W. B., Li, Q. S. (2015): Pay attention to logistics “energy flow” and build China’s “ecological logistics”. – Modern State-Owned Enterprise Research 8: 96-97.

[11] Helmut, H., Marina, F. K., Fridolin, K. (2004): Progress towards sustainability What the conceptual framework of material and energy flow accounting (MEFA) can offer. – Land Use Policy 21: 199-213.

[12] Juran, J. M. (1988): Juran's Quality Control Handbook. – McGraw-Hill.

[13] Lalami, I., Frein, Y., Gayon, J. P. (2017): Demand variability and value of information sharing in the supply chain. A case study in the automotive industry. – Journal Européen des Systèmes Automatisés 50(1-2): 157-186.

[14] Li, X. J. (1979): Logistics energy flow and urban environmental protection. – Environmental Protection 5: 11-13.

[15] Liu, T., Huang, G. L. (2011): Study on the theory and practice of the internalization of carbon emission cost in low carbon economy. – Accounting Friend 5: 68-69.

[16] Liu, W., Ju, M. T., Chu, C. L., Shao, C. F., Tian, W. X. (2011): System of regional environmental and economic material flow and energy flow analysis method and empirical research. – Journal of Natural Resources 8: 1435-1445.

[17] Liu, Y., Tian, Y., Chen, M. (2017): Research on the prediction of carbon emission based on the chaos theory and neural network. – International Journal Bioautomation 21(S4): 339-348.

[18] Lodi, C., Malaguti, V., Contini, F. M., Sala, L., Muscio, A., Tartarini, P. (2017): University energy planning for reducing energy consumption and GHG emissions: the case study of a university campus in Italy. – International Journal of Heat and Technology 35(S1): S27-S32.

[19] Lu, S. J., Yang, S. X., Lin, Y. T. (2010): Research on Development of Electric Power Industry under Low-carbon Economy. – National School of Administration 2: 82-86.

[20] Makni, A., Haouam, A., Favergeon, J., Lahoche, L., Moulin, G. (2017): Characterization by acoustic emission of the oxides scales obtained on the steel loaded in bending at high

temperature under controlled atmosphere. – Revue des Composites et des Matériaux Avancés 27(1-2): 209-226.

[21] Qi, S., Ju, M. T., Wang, Q. (2010): Starting from carbon sources, carbon flows and carbon sinks to develop a low-carbon economy. – Environmental Protection 16: 41-42.

[22] Shen, L., Liu, X. J. (2006): Theory and methods of resource flow study. – Resource Science 5: 9-16.

[23] Torres, M. T., Frieiro, C. B., Bugallo, P. M. B., Long, J. J. C., Rodríguez-Blas, J. M. (2008): Energy and material flow analysis: application to the storage stage of clay in the roof-tile manufacture. – Energy 33: 963-973.

[24] Tu, J. Z., Ma, D. L. (2018): A spatial economics perspective on convergence research of carbon emissions performance in China. – International Journal of Heat and Technology 36(3): 962-972.

[25] Wang, L., Xiao, X., Xiong, F. (2011): Research on path coordination model of energy saving and emission reduction for government and enterprise. – 2011 International Conference on Electric Technology and Civil Engineering (ICETCE).

[26] Wang, P. X., Liu, S. W. (2006): A comparative study of quality cost control model. – Journal of Harbin Institute of Technology (Social Science Edition) 9: 98-102.

[27] Wang, Y. Q. (2015): A Method for Analyzing the Flow Process of Carbon-Based Energy Resources. – Nanjing Normal University, Nanjing.

[28] Womack, J. P., Jones, D. T. (1997): Lean thinking—banish waste and create wealth in your corporation. – Journal of the Operational Research Society 48(11): 1148-1148.

[29] Xiao, X., Liu, S. H. (2004): Based on element flow–value flow analysis of environmental management accounting. – Journal of Accounting Research 3: 79-87.

[30] Yin, J., Cao, H. J., Du, Y. B., Tao, T. (2013): Energy carbon flow model of ceramic production process based on generalized fuzzy Petri net. – System Engineering Theory and Practice 33: 1035-1040.

[31] Zhang, J., Li, Y. P., Jing, C. Y. (2005): Research on environmental cost management of enterprises based on environmental quality cost model. – Soft Science 6: 49-55.

[32] Zhang, S. E. (2017): Study on dynamic performance modeling for carbon emission of machinofacture system based on mixed space model. – Academic Journal of Manufacturing Engineering 15(2): 87-94.

[33] Zhang, X. L., He, Y. W. (2002): Value stream - the foundation for enterprises to build a quality management system. – Journal of Southeast University (Philosophy and Social Science Edition) 4: 28-31.

[34] Zhou, Z. F., Huang, Y., Li, S. H. (2016): Carbon cost process of manufacturing enterprises: classification, calculation and control. – World Science and Technology Research and Development 2: 403-408.