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**Study on Economic Measurement and Control of
Coal Supply Chain's Carbon Emissions**

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Abstract: In the next 20 years, coal still is a major energy to promote China's economic growth and also a main source of carbon emissions. Research of the economic relations among coal supply chain's carbon emissions, cost and benefit generated by the activities coupled with carbon emissions has an important significance for controlling coal supply chain's carbon emissions from an economic point. Firstly, we present a typical structural model of coal supply chain. Secondly, we analysis the relations among carbon emissions, cost and benefit of this structural model, and then construct a carbon emissions economic measurement (CEEM) model of coal supply chain. Our research shows that controlling coal supply chain's carbon emissions from an economic point can achieve good results.

Keywords: coal supply chain; carbon emissions; economic measurement; control

1. Introduction

In December 2009, Premier Wen Jiabao announced Chinese carbon emissions targets in Copenhagen climate summit: By 2020 carbon dioxide emissions of unit GDP will drop 40% to 45% than 2005. So it means China will bear more than a quarter of the world's total emissions reduction. Meanwhile, Chinese primary energy endowment structure is "rich in coal, oil-poor, less gas". Compared with oil, natural gas, water, nuclear energy and other primary energy resources, coal resource accounts for 85% of total proven reserves and accounts for about 70% in primary energy consumption structure. Therefore, the study of the corresponding relationship between carbon emissions in every link of China's coal supply chain and the cost, in order to achieve their effective measure and control, is of great significance for the "emissions reduction" goals.

2. The definition and connotation of coal supply chain

The exact definition of the supply chain is still in controversy [1] [2] [3] [4], but its content generally consists of three aspects:

(1) Supply chain is the operational activities that begins with the demand of customer (or consumer), run through from product design to raw material supply, production, wholesale, retail and other processes (it may contains transport and warehousing), deliver products to the end-user.

(2) The participants in supply chain include enterprises and departments within the enterprise. The supply chain is the interaction and the link between these units and co-operation between and within enterprises.

(3) The analysis of supply chain business processes and operations can be started from work flow, physical flow, information flow and funds flow.

In these three aspects, (1) illustrates the specific services of supply chain, (2) illustrates the boundary of the supply chain, and (3) illustrates the supply chain analysis method. These three aspects complement each other, and are indispensable.

Coal supply chain is a special case of the supply chain, not only with the general characteristics of the supply chain which contains business flow, physical flow, information flow, capital flow, but also with the specific characteristics of coal resources which contains coal production, consumption, regional, concentrated etc. Therefore this paper needs to re-define the services, boundary, and analysis method of coal supply chain. At present, the studies on the coal supply chain are not much. The definition of the coal supply chain mainly contains three aspects: the coal enterprise supply chain [5], the coal industry supply chain [6], the coal supply chain [7] [8], and these definitions have their own characteristics. However, these three categories to definition of the supply chain are still based on the services and do not give a good description to the boundary of the supply chain. According to the connotation of the supply chain, in this paper coal supply chain is defined as a complex activity, according to the requirement of consumers and the collaboration of the enterprise clusters comprised of core enterprises, from mining preparation to final product being consumed by customers, including a synthetic process of mining, transportation and storage in original places.

The definition shows that:

(1) Assure the specific services of the coal supply chain. Coal supply chain starts from the needs of electricity generation, construction, iron and steel, chemicals and others, through the coal mining, processing, transport, storage and so on, and includes various operational activities delivering the final consumer of coal to end-users.

(2) Defining the boundary of the coal supply chain. Participants of coal supply chain include enterprises and departments within the enterprises, specifically related to coal producers, coal processing enterprises, coal logistics enterprises, coal consumption enterprises and various departments within the enterprises.

(3) Pointing out the approach of analyzing coal supply chain. Coal supply chain contains four kinds of streams: logistics, business flow, capital flow and information flow. It coordinates with each other in all aspects and processes of coal supply chain, maximizes the potential for economic and social benefits by analyzing business flow, logistics, information flow and capital flows and changes in the entire coal supply chain.

3. Structure of coal supply chain in the perspective of carbon emissions

Based on the definition of coal supply chain, carbon emissions in coal supply chain are mainly in coal mining, processing, logistics, and consumption. In the coal mining links, mining depth has a significant impact on carbon emissions of coal. When the coal-bed seam is broken, there are significant differences in CBM(coal bed gas) emissions(mainly contains CO_2, CH_4) between underground coal mines and surface coal mines.. In the coal processing links, anthracite, bituminous coal and lignite release a certain amount of CBM. In addition, coal handling, processing and

distribution will release CBM (also known as post-mining emissions). Based on the calculation method in "2006 IPCC Guidelines for National Greenhouse Gas Inventories"[9] (referred to as "2006 IPCC Guidelines"), this paper will deal with post-mining carbon emissions in coal processing links. In coal logistics links (exclude carbon emissions of logistics in the post-mining processing), coal transports from the producer to the consumer mainly in railways, highways, waterways, and intermodal transport. Usually, train transport coal which is fuelled by diesel, automotive transport coal which is fuelled by gasoline or diesel and ship transport coal which is fuelled by gasoline or diesel. Therefore, there are some differences in the carbon emissions resulting from these fuel combustions. In the coal consumption links, according to "2008 Annual Report of Chinese coal industry," the consumption of coal are mainly in electricity generation, iron and steel, construction, chemical industry, accounting for 87% of total coal consumption (of which electricity generation accounted for 49.85% ,construction accounted for 16.98%, iron and steel accounted for 14.20%, and chemicals accounted for 5.97%) [10].

Therefore, this paper builds the structure of coal supply chain in the perspective of carbon emissions, which is shown in Figure 1.

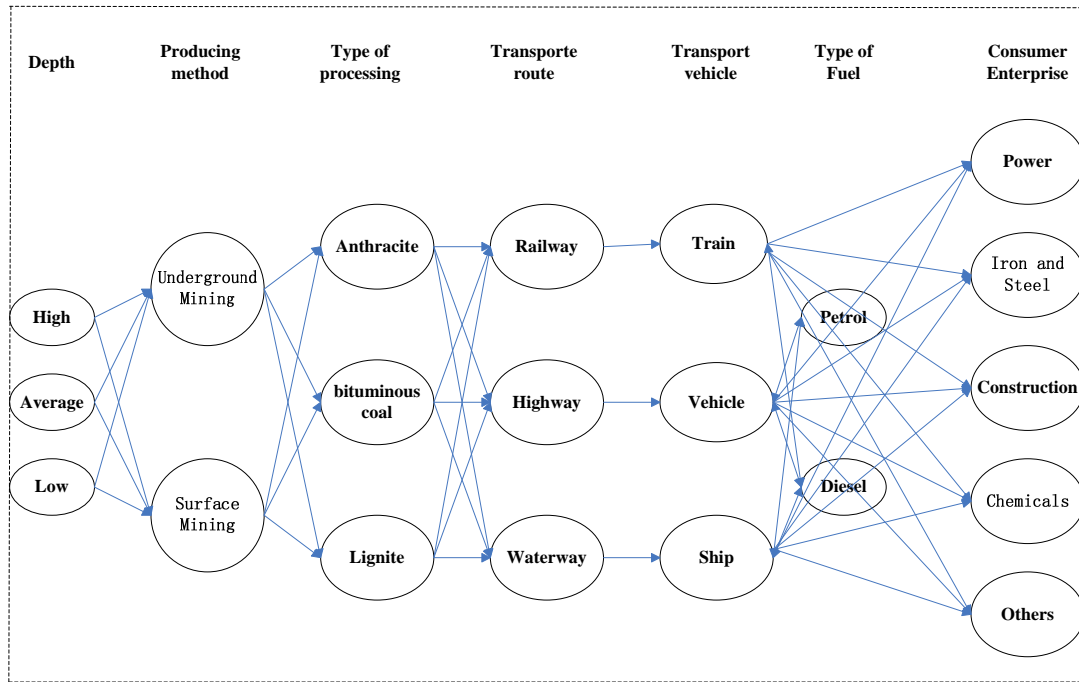


Figure-1 coal supply chain structure in the perspective of carbon emission

4 Carbon emissions economic measurement and control model in coal supply chain

According to the coal supply chain structure in the perspective of carbon emissions(Figure-1), this paper constructs CEEM model of coal supply chain based on the relationship between corresponding cost and coal mining ,coal processing, coal logistics ,coal consumption in coal supply chain.

4.1 Relationship between the fugitive carbon emissions in coal mining links and the corresponding cost

In the coal mining links, because the geological process of coal generation will generate CH₄ and there may also be CO₂ in some coal seam, CH₄ and CO₂ will release along with the exposure and broken of coal seam in the coal mining,. For underground coal mines, CH₄ and CO₂ are mainly from coal mine ventilation air and coal mine degasification systems. For the surface coal mines, CH₄ and CO₂ are mainly from

breakage of coal and associated strata and leakage from the pit floor and highwall.

According to the "2006 IPCC Guidelines"[11], in the condition of "global average method -coal mining-before adjustment for any methane utilization or flaring", CH₄ emissions = CH₄ Emission Factor · Coal Production · Conversion Factor.

$$DA_{1j} = EF_{km(n)j} \times CP_k \times TF_j \quad (1)$$

$$\frac{DA_{1j}}{CP_k} = EF_{km(n)j} \times TF_j \quad (2)$$

$$A_{1j} = \frac{DA_{1j}}{CP_k \times C_1} = \frac{EF_{km(n)j} \times TF_j}{C_1} \quad (3)$$

So the formula of the relationship between the fugitive carbon emissions in coal mining links and the corresponding cost is:

$$A_{1j} = \frac{EF_{km(n)j} \times TF_j}{C_1} \quad (4)$$

Where,

A_{1j} -the amount of j gas emissions corresponds to the cost of mining one ton coal in

the coal mining links, $j = 1$ is CH₄, $j = 2$ is CO₂, the units is Kg / Yuan ;

DA_{1j} -the amount of j gas emissions in the mining links, the units is Kg ;

CP_k -coal production, CP_1 means underground coal production, CP_2 means surface coal production, the units is t;

C_1 -the cost of mining one ton coal, the units is Yuan / t ;

$EF_{km(n)j}$ -j gas emissions factor of k-type coal mining in the m-type depth, underground coal mines is $k = 1$, surface coal mines is $k = 2$. $k = 1, m = 1$ means that the average mining depth of underground coal mines is less than 200 meters; $k = 1, m = 2$ means that the average

depth mining of underground coal mines is more than 200 meters, less than 400 meters; $k = 1, m = 3$ means that the average mining depth of underground coal mines is more than 400 meters. $k = 2, n = 1$ means that the average mining depth of surface coal mines is less than 25 meters; $k = 2, n = 2$ means that the average mining depth of surface coal mines is more than 25 meters, less than 50 meters; $k = 2, n = 3$ means that the average mining depth of surface coal mines is more than 50 meters. CH₄ emission factor: $EF_{111} = 10m^3/t$, $EF_{121} = 18m^3/t$, $EF_{131} = 25m^3/t$, $EF_{211} = 0.3m^3/t$, $EF_{221} = 1.2m^3/t$, $EF_{231} = 2.0m^3/t$;

TF_j -the density of gas j and converts volume of gas j to mass of gas j . The density is taken at 20°C and 1 atmosphere pressure and has a value of $0.67 \text{ Kg} / m^3$ of CH₄ and has a value of $0.8 \text{ Kg} / m^3$.

4.2 Relationship between the fugitive carbon emissions in coal processing links and the corresponding cost

Normally, after coal being mined, it will continue to release gases, but slowly than the phase of coal seams broken. Based on the "2006 IPCC Guidelines", this paper will calculate carbon emissions of post-mining processing in coal processing link. According to the "2006 IPCC Guidelines"[11], in the condition of "global average method - coal mining – before adjustment for any methane utilization or flaring", CH₄ emissions = CH₄ Emission Factor · Coal Production · Conversion Factor.

$$DA_{2j} = EF_{km(n)j} \times CP_k \times TF_j \quad (5)$$

$$\frac{DA_{2j}}{CP_k} = EF_{km(n)j} \times TF_j \quad (6)$$

$$A_{2j} = \frac{DA_{2j}}{CP_k \times (C_2 + C_3)} = \frac{EF_{km(n)j} \times TF_j}{C_2 + C_3} \quad (7)$$

So the formula of the relationship between the fugitive carbon emissions in coal processing links and the corresponding cost is:

$$A_{2j} = \frac{EF_{km(n)j} \times TF_j}{C_2 + C_3} \quad (8)$$

Where,

A_{2j} -the amount of j gas emissions corresponds to the cost of mining one ton coal in the coal processing links, $j = 1$ is CH_4 , $j = 2$ is CO_2 , the units is $Kg / Yuan$;

DA_{2j} -the amount of j gas emissions in the processing links, the units is Kg ;

CP_k -coal production, CP_1 means underground coal production, CP_2 means surface coal production, the units is t;

C_2 -the cost of processing one ton coal, the units is $Yuan / t$;

C_3 -the cost of transporting one ton coal, the units is $Yuan / t$;

$EF_{km(n)j}$ -j gas emissions factor of k-type coal mining in the m-type depth, underground coal mines is $k = 1$, surface coal mines is $k = 2$. $k = 1, m = 1$ means that the average mining depth of underground coal mines is less than 200 meters; $k = 1, m = 2$ means that the average depth mining of underground coal mines is more than 200 meters, less than 400 meters; $k = 1, m = 3$ means that the average mining depth of underground coal mines is more than 400 meters. $k = 2, n = 1$ means that the average mining depth of surface coal mines is less than 25 meters; $k = 2, n = 2$ means that the

average mining depth of surface coal mines is more than 25 meters, less than 50 meters; $k = 2, n = 3$ means that the average mining depth of surface coal mines is more than 50 meters. CH₄ emission factor: $EF_{111} = 0.9m^3 / t$, $EF_{121} = 2.5m^3 / t$, $EF_{131} = 4.0m^3 / t$, $EF_{211} = 0m^3 / t$, $EF_{221} = 0.1m^3 / t$, $EF_{231} = 0.2m^3 / t$.

TF_j -the density of gas j and converts volume of gas j to mass of gas j . The density is taken at 20°C and 1 atmosphere pressure and has a value of $0.67 Kg / m^3$ of CH₄ and has a value of $0.8 Kg / m^3$.

4.3 Relationship between the carbon emissions in coal logistics links and the corresponding cost

Chinese coal-mining and consumption is obvious regional, coal logistics is characterized by long transportation route and complex weather conditions and so on. In the transport links of coal logistics, railway transport is dominant and road transport plays a supporting role. In China, railway and shipping joint transport is very common. These vehicles are usually fuelled by gasoline or diesel, and also release a certain amount of CH₄ and CO₂.

According to the "2006 IPCC Guidelines"[12], in the condition of "global average method -gas emissions from mobile combustion", j gas emissions= $\sum_a Fuel_a \cdot Emission Factor_a$.

Then, CO₂ or CH₄ emissions in transport= the quality of fuel in transport · combustion value · emission factor=density · volume · combustion value · emission factor,

$$DA_{3iaj} = \rho_a \times q_a \times V_a \times EF_a \quad (9)$$

$$\frac{DA_{3iaj}}{V_a} = \rho_a \times q_a \times EF_a \quad (10)$$

$$A_{3iaj} = \frac{DA_{3iaj} / V_a}{P_a} = \frac{\rho_a \times q_a \times EF_a}{P_a} \quad (11)$$

As coal logistics employs at least one kind of transport vehicle, the formula of the relationship between the carbon emissions in coal logistics links and the corresponding cost is:

$$A_{3iaj} = \frac{DA_{3iaj} / V_a}{P_a} = b \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) + c \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) + d \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) \quad (12)$$

(b, c, d is 0 or 1, they can not be 0 at the same time)

Where,

A_{3iaj} -the amount of j gas emissions corresponds to the cost of transporting one tone coal through i-type transportation using a-type fuel, $i = b$ is railway, $i = c$ is highway, $i = d$ is waterway, $a = 1$ is gasoline, $a = 2$ is diesel, $j = 1$ is CH₄, $j = 2$ is CO₂, the units is Kg / Yuan ;

EF_a -emission factor of a-type fuel, the units is Kg / TJ ;

ρ_a -density of a-type fuel, $a = 1$ means gasoline, $a = 2$ means diesel, the units is Kg / L ;

V_a -volume of a-type fuel, $a = 1$ means gasoline, $a = 2$ means diesel, the units is L ;

DA_{3iaj} -the amount of j gas emissions when transport one ton coal through i-type transportation using a-type of fuel;

q_a -combustion value of a-type fuel, the units is TJ / Kg ;

P_a -price of a-type fuel, the units is Yuan / L .

4.4 Relationship between the carbon emissions in coal consumption links and the corresponding cost

According to "2008 Annual Report of Chinese coal industry"[10], coal consumption of electric power industry accounts for about 49.85% of nationwide consumption, so electricity generation plays the dominant role in coal consumption and gas emissions. This paper studies the relationship between the carbon emissions of the power sector coal consumption and the corresponding cost.

According to the "2006 IPCC Guidelines"[13], in the condition of "greenhouse gas emissions from stationary combustion", Emissions_{GHG, fuel} = Fuel Consumption_{fuel} • Emission Factor_{GHG, fuel}. Then CO₂ (CH₄) Emissions Released by Power Plant = Fuel Consumption_{fuel} • Emission Factor • Generator Efficiency = Quality of Steam Coal Consumption • Combustion Value • Generator Efficiency • Emission Factor

$$A_{4j} = \frac{DA_{4j}}{C_4} = \frac{m_e \times q_e \times \eta_a \times EF_e}{C_4} \quad (13)$$

So the formula of the relationship between the carbon emissions in coal consumption links and the corresponding cost is:

$$A_{4j} = \frac{\sum_e m_e \times q_e \times \eta \times EF_e}{C_4} \quad (14)$$

Where,

A_{4j} -the amount of j gas emissions corresponding to the unit cost of electricity industry in coal consumption links, the units is $Kg / Yuan$;

DA_{4j} -the amount of j gas emissions in coal consumption links, the units is Kg ;

m_e -the quality of every component in units of steam coal, composed of lean coal, 1 /

2 stick of coal, weak sticky coal, long flame coal, lignite, the units is Kg ;

q_e -the combustion value of different coal, the units is TJ / Kg ;

EF_e -the emission factor of different coal, the units is Kg / LJ ;

η -generator efficiency;

C_4 -the cost of generating one kilowatt hour electricity, the units is $Yuan / Kwh$;

From the above analysis, coal eventually reaches the consumer through mining, processing and logistics. This paper takes power plant as an example and calculates the carbon emissions economic measurement and control (CEEM) model of the relationship between carbon emissions and cost in coal supply chain model. The calculation process and the results are as formula (15) shows:

$$A_j = \frac{EF_{km(n)j} \times TF_j}{C_1} + \frac{EF_{km(n)j} \times TF_j}{C_2 + C_3} + b \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) + c \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) + d \left(\frac{\rho_a \times q_a \times EF_a}{P_a} \right) + \frac{\sum m_e \times q_e \times \eta \times EF_e}{C_4} \quad (15)$$

(b, c, d is 0 or 1, they can not be 0 at the same time)

5. Conclusion

This paper proposes the definition of the coal supply chain, interprets the definition from services, boundary and research methods of coal supply chain and builds the coal supply chain structure in the perspective of carbon emissions which theoretically solves the carbon emissions's boundary and research methods in coal supply chain research. Meanwhile, the paper constructs economic measurement model and overall measure model for the corresponding cost of coal mining, coal processing, coal logistics and coal consumption in coal supply chain. These models

provides efficient method for the in-depth analysis of the relationships between carbon emissions of the coal supply chain and corresponding cost and achieves control effect of relatively high links of carbon emissions in coal supply chain.

As a follow-up study of this paper, the CEEM model of carbon emissions in coal supply chain under different modes of transport is simulating. Simulation tries to find low-carbon emissions and more efficient coal supply chain system. In addition, the study of iron and steel, construction, chemicals through CEEM model is also of great significance.

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