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Research on a Carbon Emission Calculation Model and Method for an Underground Fully Mechanized Mining Process

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Abstract: With the ratification of the Paris Agreement at the Paris Climate Conference, reducing carbon emissions has become a global interest. Coal is one of the main industries causing carbon emissions; thus, quantifying carbon emissions from coal mining is an important step in reducing these emissions. Firstly, based on the life cycle idea, in this paper, we define the Carbon Emission Boundary of the fully mechanized coal mining method. Secondly, the carbon emission accounting model (B-R model) of fully mechanized coal mining is established, which includes the total amount of carbon emissions and the carbon emissions of each mining link during the mining process. The Fifth-II mining area of the Jinda Coal Mine in Tengzhou City is taken as an example. We collect the relevant data on carbon emissions in the mining process of the Jinda Coal Mine, and the B-R model is used to obtain the carbon emissions in the mining process of this mining area. Finally, the feasibility of the B-R model is further verified according to the international authoritative carbon emission IPCC calculation method and the *China Coal Production Enterprises Greenhouse Gas Emissions Accounting Methodology and Reporting Guide*. The results show that the B-R model in this paper is feasible and that the greatest amount of carbon emissions arises from the coal breaking link and coal transportation, which provides a basis for other coal mines to calculate carbon emissions. The B-R model lays a foundation for coal mines to formulate a carbon emission reduction system.

Keywords: carbon emissions; fully mechanized mining; calculation model; underground mining

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1. Introduction

Due to the development of the economy, technology, and population growth, human consumption of coal is increasing day by day, which is causing damage to the carbon balance of the environment [1–3]. In recent years, the Chinese Communist Party and the government have attached great importance to environmental issues, and in September 2020, they proposed to adopt stronger policies and measures to achieve the "double carbon target" [4–6]. The double carbon target, which takes into account carbon peaking and carbon neutrality, requires that China strives to achieve carbon peaking by 2030 and carbon neutrality by 2060. According to statistics, coal accounted for 56.7% of China's energy mix in 2020, and coal mining, as the upstream link in coal consumption, plays an important role in the overall carbon emissions generated by coal consumption [7]. With the continuous development of technology, the underground coal mining process has gradually been mechanized and developed into fully mechanized coal mining technology, which is now widely used [8–10]. At present, there is very little research on carbon emission accounting for fully mechanized coal mines, and there is no accounting model to quantify the carbon emissions of each process in a fully mechanized working face. Firstly, this paper uses life cycle thinking to analyze the carbon emission sources of each process step in the mining process. Secondly, this paper establishes a carbon emission accounting model for each process step and finally uses real cases to verify the feasibility of the model and calculate

the carbon emissions of each step in the example. This paper is of great significance for the realization of low carbon fully mechanized coal mining.

2. Fully Mechanized Carbon Emission Boundary Establishment

This paper uses the life cycle idea to determine the carbon emission boundary of the fully mechanized process under different geological conditions. The carbon emission boundary cannot be determined without the identification of carbon emission sources [11,12]. The purpose of this study was to calculate the amount of CO_2 released by each source of carbon emissions throughout the underground coal mining process, so the carbon emissions were calculated using functional units of CO_2 which has the advantage of allowing all parts of the mining system to be analyzed and compared on the same basis. A uniform unit of tons (t) is used in this paper.

2.1. Carbon Emission Source Determination

The main components of the CO_2 emission boundary of underground coal mining include: energy use, escape of greenhouse gases, and spontaneous combustion of coal gangue and raw coal [13]. The CO_2 emission boundary also contains some auxiliary elements: the drainage system, ventilation system, energy consumption for staff daily work, office area consumption, transportation system, etc. (as shown in Table 1).

Table 1. Carbon emission source analysis of coal mines.

Direct Emissions		
Process Linkage	**Type of Source**	**Main Greenhouse Gases**
Diesel, gasoline, and other fuels for equipment power	Emergency power generation equipment, mine transportation, etc.	CO_2, N_2O, CH_4
Production system	Spontaneous combustion caused by stacking of coal gangue and raw coal Vaporize	CO_2, N_2O, CH_4, H_2S
Transportation system	Transportation in the mine Staff transportation	CO_2, N_2O, CH_4
Subsidiary production system	Fossil raw coal used in staff bathhouse	CO_2, N_2O, CH_4
Indirect emissions		
Process linkage	Type of source	Main greenhouse gases
Production system	Coal mining process related to the use of machine power (specifically, purchased power)	CO_2, N_2O, CH_4
Auxiliary production systems	Drainage system, ventilation system, gas emissions, and other power use (specifically, purchased power)	CO_2, N_2O, CH_4
Subsidiary production systems	Transmission and distribution processes Personnel and building consumption	CO_2, N_2O

2.2. Carbon Dioxide Emission Boundary Establishment

According to the information in Table 1, the carbon dioxide emission boundary of coal mining based on life cycle thinking is shown in Figure 1, combined with the specific coal mining processes and the preparation stage, operation stage, and closing stage of the coal mining process.

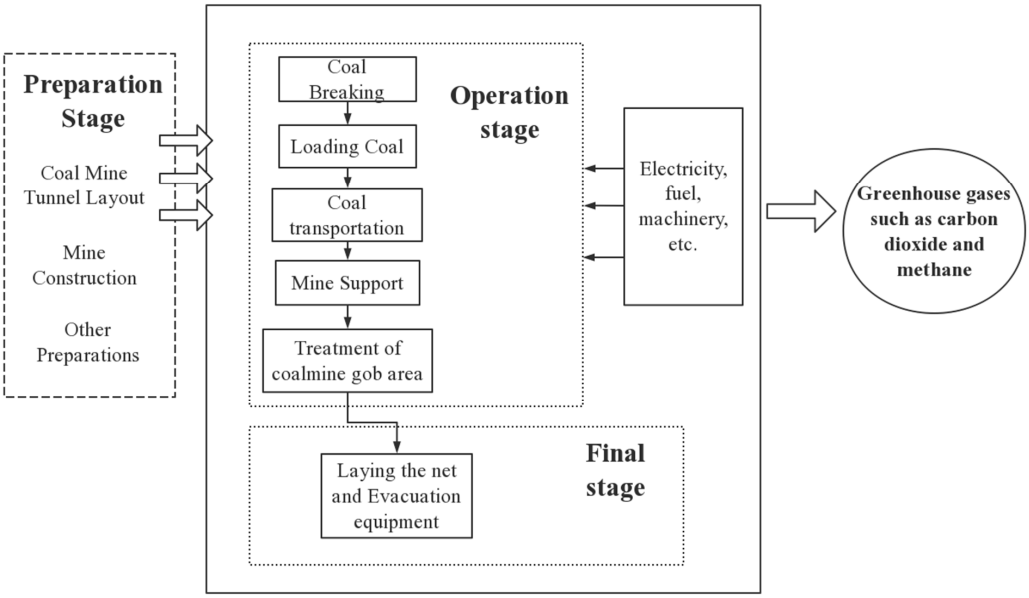

Figure 1. The carbon dioxide emission boundary of coal mining.

Based on the CO_2 boundary, this paper will focus on the energy use aspects of the system, which are as follows:

(1) Preparation stage. The preparation stage includes the up-and-down hill mining area type, panel area type, strip type, and other preparation methods, in which the main materials used are concrete, steel, etc., and also related pioneering machines (road header, excavator, etc.). Such carbon emissions can be calculated by carbon emission factors.
(2) Operation stage. The operation phase includes the entire coal mining process: coal breaking, coal loading, coal transportation, roof support, and treatment of the coal mine gob area. The entire process generates large amounts of carbon dioxide. CO_2 is produced by the use of machines, electricity, escape, and spontaneous combustion under different geological conditions. The machines often used in the process are coal mining machines, scraper conveyors, and hydraulic pillars, which use electricity and produce some carbon emissions. Lubricants are also applied to the machines, which also produce small amounts of CO_2 emissions [14–16].
(3) Final stage. A lot of equipment and machinery are dismantled or removed during this phase and the net is laid in the mine. All of these construction phases generate some greenhouse gas emissions.

3. Accounting for Carbon Emissions from Underground Coal Mining

Through the above-mentioned analysis of CO_2 emission boundary establishment, combined with the actual situation of underground coal mining, this paper simplifies the establishment of the model.

(1) The preparation stage mainly involves coal mine tunnel layout and mine construction. There are many factors to consider in coal mine tunnel layout: roadway design, policy, funding, geology, and labor. The greenhouse gas emissions from these factors are negligibly small. The main sources of carbon emissions considered for mine construction are machine use and fugitive emissions. There are overlaps between mine construction and coal mining machine use and the carbon emissions from fugitive emissions are low. Therefore, they are not included in the calculation of carbon emissions in this paper.
(2) Emissions from the finishing phase of netting, evacuation, or removal of the equipment are small and difficult to quantify, therefore, they are not included in the calculation.

3.1. Accounting for Carbon Emissions from Fully Mechanized Processes

Based on the above analysis, the B-R model is established in this paper. The B-R model proposed in this paper is an accounting model for the carbon emissions generated in the fully mechanized processes.

The fully mechanized mining process consists of four specific processes: falling and mining coal, transporting coal, roof support, and treatment of the coal mine gob area [17]. The geological conditions of a coal mine are an important factor affecting all aspects of underground coal mining. Different geological conditions can lead to different mining methods [13] and thus have an impact on carbon emissions, therefore, this paper needed to analyze the four processes based on geological conditions before building the model in order to ensure the correct source of carbon emissions. The idea was to account for the total carbon emissions and then find the carbon equivalent emissions per ton of coal mined. The total carbon emission accounting model (B-R model) for the entire fully mechanized mining process was based on:

$$E = E_f + E_t + E_s + E_g \tag{1}$$

where E refers to total carbon emissions from underground fully mechanized mining processes (t/t); E_f refers to carbon emissions from falling and mining coal (t/t); E_t refers to carbon emissions from transporting coal (t/t); E_s refers to carbon emissions from roof support (t/t); and E_g refers to carbon emissions from the treatment of the coal mine gob area (t/t).

3.2. Carbon Emissions from Falling and Mining Coal

As shown in Table 2, this paper analyzed the sources of carbon emissions from falling and mining coal. In general, the shearer completes the cutting and loading of coal, and on the working face, the coal miner cuts the top coal in the front roller and the bottom coal in the rear roller [17,18]. The advantages of this method are safe operation, less coal dust, and a good coal loading effect, therefore, it is widely used. Spray pumping stations are also used in this process. The spraying pumping stations provide a power source for the coal breaking and loading process where the dust needs to be sprayed. Electricity is used extensively in the processes of falling and mining coal. Falling coal causes the seam to fracture, which in turn leads to the release of stored gas from the surrounding rock seam; this is known as spillage. The fugitive gases are essentially methane, therefore, the calculation is based on methane. Lubricants are used as auxiliary supplies in the operation of machines and are omitted in this article due to their small quantity. In this paper, a classification of the calculated electricity carbon emissions of the B-R model is presented. There are two sources of electricity for coal mines: self-generation and purchased electricity, and different sources of electricity have different impacts on carbon emissions.

Table 2. Analysis of sources of carbon emissions from falling and mining coal.

Major Carbon Emission Sources	Role	Geological Condition	
Shearer	Coal breaking	Thickness of coal seam	A thin seam shearer is suitable for mining coal seams with minimum seam thickness below 1.3 m. A medium–thick coal seam mining machine is suitable for mining coal seams with a thickness from 1.3 to 3.5 m, and is the mainstream shearer, with many varieties and wide uses. A thick seam shearer is suitable for mining coal seam with a highest seam thickness of more than 3.5 m; the model basically was derived from a medium–thick seam shearer and the maximum cutting height can reach 4.5~5 m at present.
		Dip angle of the coal seam	According to the applicable coal seam, the inclination angle can be divided into three types of shearers: gently inclined seam, pitching seam, and steeply pitching seam. A gently inclined seam mining machine is applicable to coal seams with inclination angle below 25°, and most of the shearers belong to this category. A pitching seam mining machine is suitable for coal seams with inclination angle of 25 to 45°, and this kind of shearer is generally modified on the basis of a slow-slope coal seam mining machine, in the process of development of a steeply pitching seam shearer.
Spray pumping stations	Dust spraying	Geological requirements are not obvious.	
Spillage	Methane spill	Geological requirements are not obvious.	

E_f of the B-R model is expressed as:

$$E_f = \frac{h(N+M)\alpha + S_{CH_4} \cdot GWP_{CH_4}}{hQ_m} \tag{2}$$

where N refers to the power of the spray pumping stations (kw); M refers to the power of the shearer (kw); α refers to carbon emission factors for electricity (t/kwh); S_{CH_4} refers to the total amount of fugitive CH_4 over time h (t); GWP_{CH_4} refers to the Global Warming Potential of CH_4 (t/t); and Q_m refers to the average coal mining capacity of the shearer (t/h). In B-R, the power of spray pumping stations [18] is expressed as:

$$N = \frac{(2.75 \cdot R \cdot H)}{\eta} \tag{3}$$

where R refers to the flow rate of the spray pumps (m^3/h); H refers to the head of the spray pump (m); η refers to the efficiency of the spray pumps. In B-R, the power of spray pumping stations is expressed as:

$$M = 60k_b \cdot B \cdot D \cdot V_{max} \cdot \varphi \tag{4}$$

where k_b refers to the shearer cutting efficiency factor; B refers to the dinting depth of the shearer (m); D refers to the cutting height of the shearer (m); and V_{max} refers to the maximum velocity of the shearer (m/min). In B-R, the average coal mining capacity of the shearer is expressed as:

$$Q_m = \frac{60 \cdot P \cdot [L \cdot (1+i) - 2i \cdot L_m]}{((K \cdot T_1 \cdot L \cdot C) - 2T_d \cdot P)/(B \cdot H \cdot \gamma)} \tag{5}$$

where P refers to the daily production of the working face (t); L refers to the length of the working face (m); i refers to the ratio of the coal cutting speed and haulage speed of the shearer; L_m refers to the center distance between two drums (m); K refers to the average daily shearer start rate; T_1 refers to the daily production time of the working face (min); C refers to the recovery rate of the working face; T_d refers to the return time of shearer (min); H refers to the mining height (m); and γ refers to the coal seam capacity (t/m^3).

The global warming potential is a parameter of the radiative impact of a certain mass of greenhouse gases with an equal mass of CO_2 over a period of time. Generally speaking, it means that the mass of greenhouse gases other than CO_2 is converted into a uniform accounting for the mass of CO_2. The specific GWP values for each GHG are specified in the IPCC report.

3.3. Carbon Emissions from Transporting Coal

As shown in Table 3, the main equipment of the coal transportation link of fully mechanized coal mining is the scraper conveyor to transport coal, followed by the loader conveyor. The mining equipment train is also a piece of equipment for coal transportation, which is installed on the main road or secondary road of the coal mining face. Spillage will continue to occur in the coal transportation segment in general, although it is slower than emissions from the coal seam crushing stage.

E_t of the B-R model is expressed as:

$$E_t = \frac{h\alpha(F+W+G+Z) + S \cdot GWP}{hQ_m} \tag{6}$$

where F refers to the power of the scraper conveyor, (kw); W refers to the power of the band conveyor (kw); G refers to the power of the hoister (kw); and Z refers to the power of

the mining equipment train (kw). In B-R, the power of each transporter and the mining equipment train [16] is expressed as:

$$F = 0.003Q_m \cdot L + 0.004Q_m \cdot H_a + 1.1 \tag{7}$$

$$W = \varepsilon Q_m \cdot L + 0.0032Q_m \cdot H_a + 1.5 \tag{8}$$

$$G = 0.005Q_m H_a + 1.1. \tag{9}$$

$$Z = \frac{(\omega' + \omega_i)Y_a + (\omega'' + \omega_i)Y_b}{3600\xi} \times 9.81v \tag{10}$$

$$\omega = \frac{Y_a\omega' + Y_b\,\omega''}{Y_a + Y_b} \tag{11}$$

where L refers to the length of working face (m); H_a refers to the vertical lifting height (m); Y_a refers to the adhesive gravity of the mining equipment train, (t); Y_b refers to the weight of the mining equipment train (t); ξ refers to the utilization factor of the mining equipment train; and v refers to the operating speed of the mining equipment train (km/h). ω refers to the unit basic resistance of the mining equipment train (N). In general, $\omega = a + bv + cv^2$; a and b are the mechanical resistance, and c is the air resistance.

Table 3. Analysis of the sources of carbon emissions from transporting coal.

Major Carbon Emission Sources	Role	Geological Condition	
Scraper conveyor	Coal transportation, pivot point of the front section of hydraulic support, etc.	Thickness of coal seam	Suitable for thin, medium–thick, thick coal seam
		Dip angle of coal seam	Upward transport inclination does not exceed 25°, downward transport does not exceed 20°
Band conveyor	Coal transportation	Tilt angle up to 29–35° possible	
Loader conveyor	The coal transported by the scraper on the mining face is transferred to the band conveyor after being raised by the bottom plate of the roadway	Geological requirements are not obvious	
Mining equipment train	Installed in the main and secondary alleys	Geological requirements are not obvious	
Spillage	-	-	

3.4. Carbon Emissions from Roof Support

As shown in Figure 2, the main equipment used to support the roof is the self-moving hydraulic bracket, which has corresponding models for simple, complex, and extremely complex geological types according to the geological conditions. As the main carbon-emitting equipment in this segment, the emulsion power pack provides energy for the hydraulic support, which is mainly used for the high-pressure fluid supply of the hydraulic bracket in the underground fully mechanized coal mining working face and is also used for spray cooling and dust removal of the coal mining machine and bracket. The use of lubricants is significant in this segment, which has an impact on carbon emissions. Negligible spillage in the support links occurs.

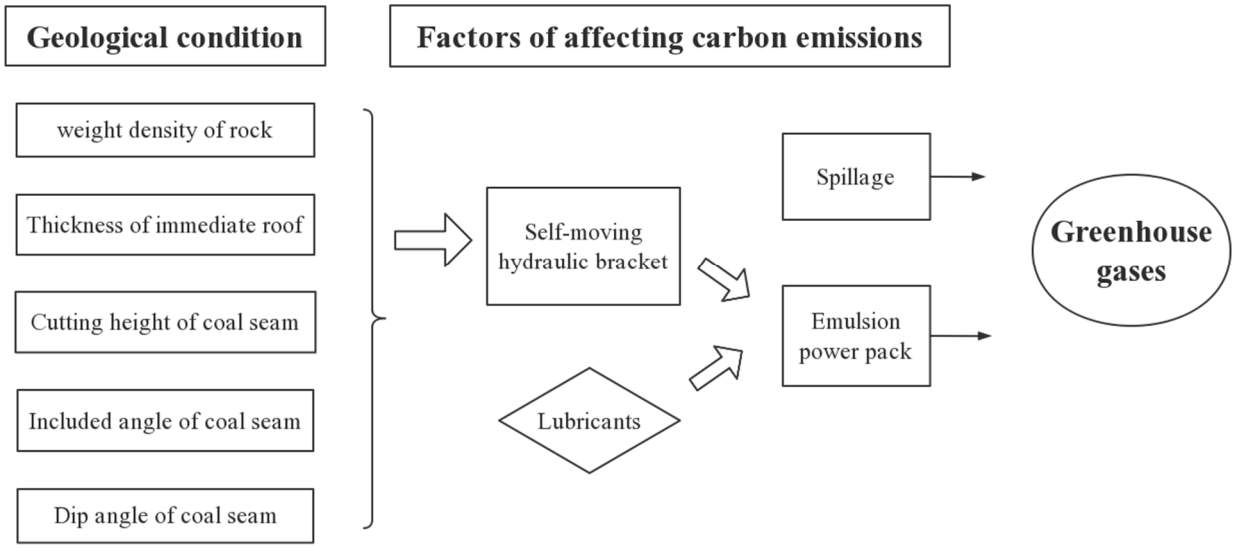

Figure 2. Analysis of the sources of carbon emissions from roof support.

E_s of the B-R model is expressed as:

$$E_s = \frac{\alpha(h \cdot P_b \cdot Q_b)/612\rho + S_{CH_4} GWP_{CH_4} + I(\lambda_1 + \lambda_2) \cdot 10^{-3}}{hQ_m} \tag{12}$$

where P_b is the pressure of the emulsion power pack (MPa); Q_b refers to the measured flow rate of liquid from the emulsion pumps (L/min); ρ refers to the total efficiency of the emulsion power pack (value range 0.7–0.8); I refers to the supply of lubricants (L); λ_1 refers to the carbon emission factor of the lubricant use process (kg/L); and λ_2 is carbon emission factor of the waste process treatment of the lubricant (kg/L).

The working pressure of the emulsion pump can be calculated according to the requirements of the initial bracing force, the pulling force, and the push-conveyor force. The pressure of the emulsion power pack is expressed as:

$$P_i = \frac{P_1 \cdot K'}{\frac{\pi}{4} \cdot D_1^2 \cdot a} \quad P_f = \frac{P_2}{\frac{\pi}{4} D_2^2} \quad P_c = \frac{P_3}{\frac{\pi}{4} \cdot \left(D_2^2 - d^2\right)} \tag{13}$$

$$P_b = \{P_i \, P_f \, P_c\}_{max} \tag{14}$$

$$P_b \geq P_b' \cdot \sigma \tag{15}$$

where P_i refers to the working pressure of the emulsion pump calculated according to the initial support force requirement; P_1 refers to the initial support force of the hydraulic support (kN); K' refers to the correction factor of the column, $K' \approx 1/\cos\theta$, where θ refers to the inclination of the column; D_1 refers to the column bore of the hydraulic support (m); a refers to the number of columns of the bracket; P_f refers to the working pressure of the emulsion pump calculated according to the pulling force (MPa); P_2 refers to the pulling force of the hydraulic bracket (kN); D_2 refers to the column bore of the pulling force (m); P_c refers to the working pressure of the emulsion pump, calculated according to the push-conveyor force (MPa); P_3 refers to the push-conveyor force of hydraulic bracket (kN); d refers to the piston rod diameter of the push–pull cylinder (m); and σ refers to the pressure loss factor (1.1~1.2). The measured flow rate of the emulsion power pack is expressed as:

$$t = \frac{\pi}{4}\left[\frac{{d_1}^2 l_1 + \left({d_2}^2 l_2 + q{d_3}^2 l_3\right)}{Q_b}\right] \times 10^3 \tag{16}$$

$$t = t_1 - t_2 \; V_y = \frac{We}{t_1} \geq V_c \tag{17}$$

where t refers to the fluid supply time (min); d_1 refers to the cylinder diameter of the lifting jack (m); l_1 refers to the moving distance of the moving frame jack (m); l_2 refers to the short column bore of beam support (m); d_3 refers to the column bore (m); l_3 refers to the distance of column shift frame (m); q refers to the number of columns raised and lowered; We refers to the support width of one stand (m); t_1 refers to moving rack time (min); t_2 refers to the operation adjustment time (min); V_y refers to the shift speed of the bracket (m/min); and V_c refers to shearer working traction speed (m/min).

3.5. Carbon Emissions from the Treatment of the Coal Mine Gob Area

As shown in Figure 3, there are four main methods to deal with the coal mine gob area: the total fallen method, support method, slow sinking method, and filling method [19]. The carbon emissions from the support method and the slow sinking method are too small and difficult to quantify, therefore, they are not included in the calculation of carbon emissions from the process of treatment of the coal mine gob area. Explosives are used in the total collapse method to perform blasting, which generates some carbon emissions. Equipment is used to fill the extraction area in the filling method. Treatment of the coal mine gob includes the extraction of gas from the extraction zone, which causes some gas spillage, which also contributes to the carbon emissions. The process of the treatment of the coal mine gob will result in some spontaneous combustion.

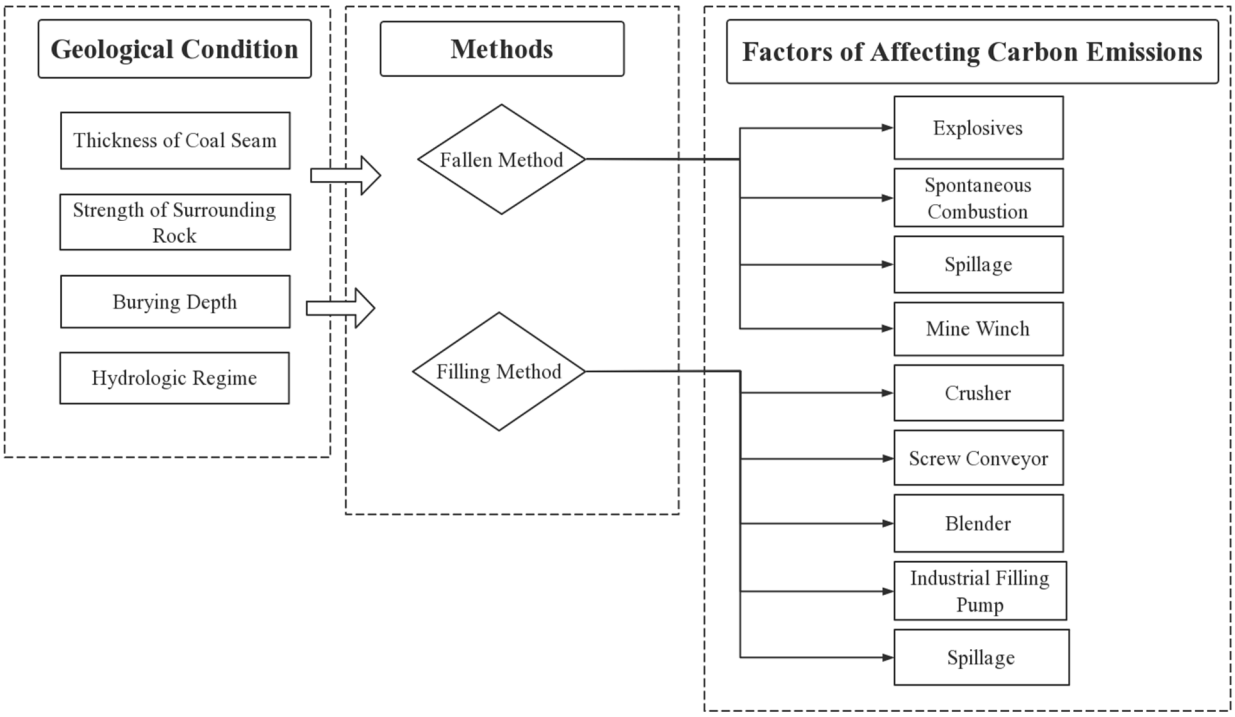

Figure 3. Analysis of the sources of carbon emissions from the coal mine gob area.

(1) Treatment of the coal mine gob area in the total fallen method.

E_g of the B-R model in the total fallen method is expressed as:

$$E_g = \frac{\sum_{i=1}^{n} \theta_i U_i + \sum_{j=1}^{n} \frac{44}{12} \cdot NCV_j \cdot CR_j \cdot CL_j \cdot \beta \times 10^{-6} + S_{CH_4} GWP_{CH_4} + \frac{F_q V_q \cdot \alpha}{\gamma}}{Q_m} \tag{18}$$

where θ_i refers to the carbon emission factors for explosives i (t/t); U_i refers to the amount of explosives i (t); NCV_j refers to the net calorific value of j spontaneously combusted

raw materials j (typically gangue or raw coal) (TJ/Gg); CR_j refers to the carbon content of spontaneous combustion raw materials j (kg/TJ); CL_j refers to the quantity of spontaneous combustion raw materials j (t); β refers to the carbon oxidation factor (usually the default is 1); S_{CH_4} refers to the total amount of gas emissions (t); GWP_{CH_4} refers to the gas GWP (CO_2 t/t); F_q refers to mine winch traction (kN); V_q refers to the winch speed for towing heavy vehicles (m/s); and γ refers to the transmission efficiency of the winch (0.8).

A carbon balance method is used to calculate the carbon emission factors for explosives. The specific steps are as follows [20–23]:

① Calculating the chemical equation for the explosive. The chemical formula of explosives is mainly composed of four elements: carbon, hydrogen, oxygen, and nitrogen. As coal mines mostly use a mixture of explosives, calculations are based on a mixture of explosives.

a. Let the chemical equation of mixed explosives be $C_cH_hO_oN_n$;

b. Assuming that the mixed explosive is composed of n components, the chemical equation of each component is $C_{c_i}H_{h_i}O_{o_i}N_{n_i}$ ($i \in n$,), and the proportion of component i is ϑ_i (%).

② Through the chemical equation of the above explosive, the carbon emission factor was calculated. The formula is expressed as:

$$d = \sum_{i=1}^{n} \frac{1000\vartheta_i c_i}{12c_i + h_i + 16o_i + 14n_i} \tag{19}$$

$$\theta_i = \frac{44}{1000} d \tag{20}$$

where c_i refers to the number of moles of carbon elements in the i-th group (1 mol); h_i refers to the number of moles of hydrogen elements in the i-th group (1 mol); o_i refers to the number of moles of oxygen elements in the i-th group (1 mol); and n_i refers to the number of moles of nitrogen elements in the i-th group (1 mol).

(2) Treatment of the coal mine gob area in the filling method.

Filling methods to treat goaf can be divided into two categories: (similar) paste filling technology and (super) highwater filling technology. Both technical methods will produce fugitive carbon emissions during the process.

① (Similar) Paste filling technology

Paste filling is used to process several materials into a mixture using a conveying system to enter the gob to complete the filling, as shown in Figure 4.

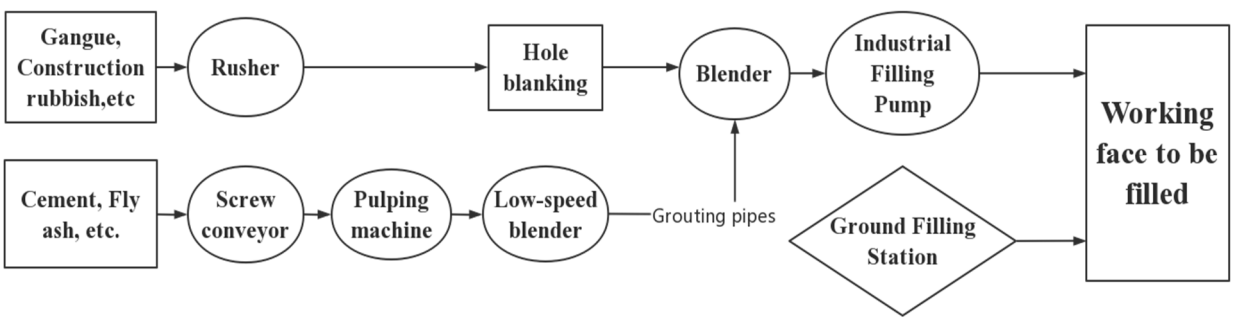

Figure 4. Process of paste filling technology.

E_g of the B-R model in paste filling technology is expressed as:

$$E_g = \frac{h\left(\frac{\rho \cdot Q_p \cdot r_p}{\delta_a \delta_b} + N_p \cdot \rho_d \cdot V_j^3 \cdot d_j^5 + \frac{k_1 \cdot q_b \cdot p_k}{1000 \varepsilon_v \cdot \varepsilon_j}\right) \cdot \alpha + S_{CH_4} GWP_{CH_4}}{Q_m} \tag{21}$$

where ρ refers to the energy factor of the crusher; Q_p refers to crusher productivity (t/h); r_p refers to the crushed product particle size coefficient; δ_a refers to the belt conveying efficiency; δ_b refers to the crusher efficiency; N_P refers to the criterion number of the blender power; ρ_d refers to the system density; V_j refers to stirring speed (r/s); d_j refers to the paddle diameter (m); k_1 refers to the pump station motor reserve factor; q_b refers to the flow rate conveyed by the pumping station (L/s); p_k refers to the total head of filling paste conveying (m); ε_v refers to pump station volumetric efficiency; and ε_j refers to the total mechanical efficiency.

② (Super) Highwater filling technology

The flow of high-water filling is shown in Figure 5.

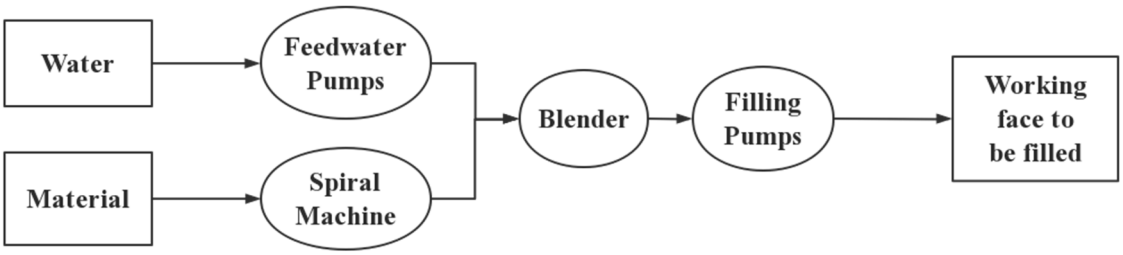

Figure 5. Process of highwater filling technology.

E_g of the B-R model in highwater filling technology is expressed as:

$$E_g = \frac{h\left[\frac{Q_g(\omega_g \cdot L_g + H_g)}{367} + \frac{D_g \cdot L_g}{20} + \frac{k_1 \cdot q_b \cdot p_k}{1000\varepsilon_v \varepsilon_j}\right]\alpha + S_{CH_4} GWP_{CH_4}}{Q_m} \tag{22}$$

where Q_g refers to the spiral machine conveying capacity (t/h); ω_g refers to the spiral machine resistance coefficient; L_g refers to conveying length (m); H_g refers to vertical height in inclined arrangement (m); D_g refers to the spiral diameter (m).

4. Case Study

4.1. Case Introduction

The Fifth-II mining area of the Jinda Coal Mine is located in Tengzhou City, Shandong Province, China (as shown in Table 4). The average east–west width of the Fifth-II mining area is about 0.66 km, the average north–south length is about 2.9 km, and the total area is about 1.94 km^2.

Table 4. The coordinates of the inflection point in the fifth-II mining area.

Serial Number	Inflection Point Number	x-Coordinate	y-Coordinate
1	S1	3,886,513.85	39,499,649.00
2	S2	3,884,994.12	39,499,064.54
3	S3	3,883,571.4	39,498,574.81
4	S4	3,883,327.15	39,499,284.18
5	S5	3,884,297.95	39,499,618.46

The Fifth-II mining area is a wide and gentle monoclinic structure, and the dip angle of the coal bed is 2–10°, with an average of 6°. The faults with a drop of less than 5 m in this mining area are relatively developed, and they are all normal faults. According to the above geological conditions, the Fifth-II mining area adopts the fully mechanized coal mining method (toward longwall mining). In the calculation process, the selected time was 24 h working time, and four digits after the decimal point were reserved. In the Fifth-II mining area, the roof management of the working face adopts the full caving method and adopts hydraulic support to control the roof.

4.2. Calculation Results of Carbon Emissions in the Fifth-II Mining Area Based on the B-R Model

The coal mining capacity of the Fifth-II mining area is 59.47 t/h, and the electricity consumption depends on the purchase of electricity from the grid. Tables 5 and 6 show the carbon emissions calculated according to the actual situation of the Fifth-II mining areas using the B-R model established above.

Table 5. Summary of carbon emissions from major carbon emission sources in the mining areas.

Project	Carbon Emissions (t)	Project	Carbon Emissions (t)
Shearer	458.64295	Emulsion Pump	402.76
Spray Pump Station	45.3105	Crusher	110.759
Scraper Conveyor	402.76	Winch	55.3795
Belt Conveyor	93.681976	Spillover	21.7635
Mine Train	55.3795	Transfer Machine	110.759

Table 6. Carbon emissions in all stages of fully mechanized mining.

Production Processes	Carbon Emissions (t)	Accounting Results (t/t)	Production Processes
Falling and Mining Coal	12,115.4078	8.48885	Falling and Mining Coal
Transporting Coal	15,901.9797	11.1415	Transporting Coal
Roof Support	9666.24	6.7724	Roof Support
Treatment of the Coal Mine Gob Area	3987.3253	2.7936	Treatment of the Coal Mine Gob Area
Total	41,670.9528	29.19635	Total

4.3. Result and Discussion

The total carbon emission in the five mining areas is 41,670.953 tons, and the carbon emissions per ton of coal mining amount to 29.196 tons. As Figure 6 shows, in the whole process of coal mining, carbon emissions are mainly concentrated in the coal drop and coal transportation links, accounting for 29% and 38% of the total carbon emissions, respectively, the other links account for 33%. Relevant administration departments can start from these two links to reduce greenhouse gas emissions. The most effective way is to control the use of electricity by making secondary use of coal gas or methane gas generated in the coal mines and using it for power generation through technological innovation.

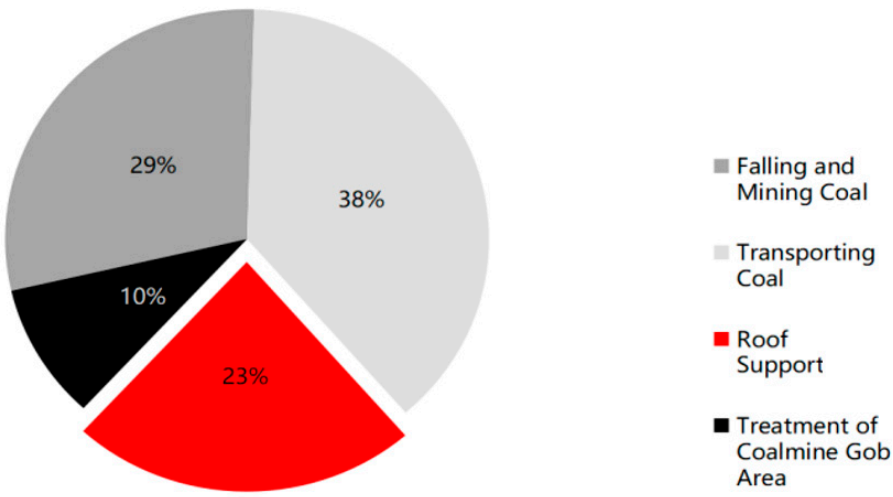

Figure 6. Results analysis chart.

The main source of carbon emissions in the Fifth-II mining areas is from equipment use according to the calculation results. Shearers, emulsification pumps, and scraper conveyors are the main high carbon emission equipment. If carbon emissions are reduced from the perspective of the equipment, these three kinds of equipment can be used to formulate relevant indicators to regulate the equipment.

4.4. Model Feasibility Verification

In this paper, two common carbon emission accounting methods are used to validate the B-R model based on relevant data from the Fifth-II mining areas: the IPCC method and the *China Coal Production Enterprises Greenhouse Gas Emissions Accounting Methodology and Reporting Guide*.

The IPCC method is an internationally authoritative carbon accounting model. The basic idea of the IPCC method is shown in Figure 7. According to the relevant content of the "IPCC Energy Volume", the main sources of carbon emissions from underground coal mining are: energy consumption, dynamite, spillover, and spontaneous combustion. The IPCC model is as follows:

$$E_{ipcc} = \sum_j CO_{2j}^t = \frac{44}{12} \cdot \sum_j EF_j^t \cdot OF_j O_j \tag{23}$$

where E_{ipcc} refers to CO_2 emissions calculated by the IPCC model (t); co_{2j}^t refers to total CO_2 emissions of fuel j in time t; $\frac{44}{12}$ refers to the molecular weight of carbon dioxide; EF_j^t refers to the energy consumption of fuel j (t); OF_j refers to the CO_2 emission factor; and O_j refers to the carbon oxidation rate of j.

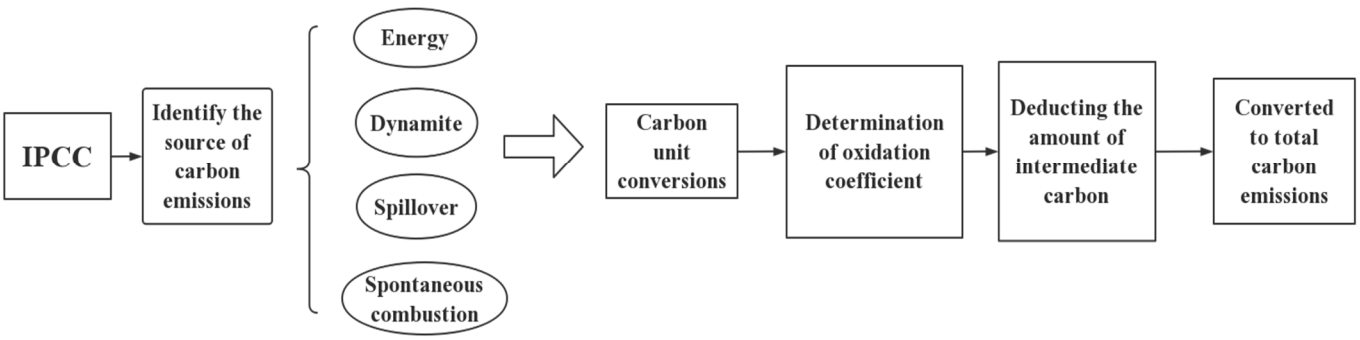

Figure 7. Flow chart of the IPCC method.

The specific ideas of the "Greenhouse Gas Emissions Accounting Methodology and Reporting Guide for China's Coal Producers" (referred to as Method G) are shown in Figure 8. The Methodology and Reporting Guide for Greenhouse Gas Emissions of Chinese Coal Producers was commissioned by the China Development and Reform Commission and prepared by the National Center for Strategic Research and International Cooperation to address climate change. The compilation team drew on the research results and practical experience of GHG accounting reports of relevant enterprises at home and abroad and completed the compilation after field research and in-depth study. The Methodology and Reporting Guide on GHG Emissions of Chinese Coal Producers considers that there are five main sources of carbon emissions in the coal mining process: fuel combustion, flare combustion, GHG fugitive, net purchased electricity, and net purchased heat.

$$E_{GHG} = E_{fuel} + E_{flare} + E_{fugitive} \cdot GWP_{fugitive} + E_{electricity} + E_{heat} \tag{24}$$

where E_{GHG} refers to the total GHG emissions of an enterprise (t); E_{fuel} refers to the carbon emissions from fuel combustion (t); E_{flare} refers to carbon emissions from flare combustion (t); $E_{fugitive}$ refers to carbon emissions from GHG fugitive (t); $GWP_{fugitive}$ refers to the Global Warming Potential of GHG; $E_{electricity}$ refers to carbon emissions from net purchased electricity (t); and E_{heat} refers to carbon emissions from net purchased heat (t).

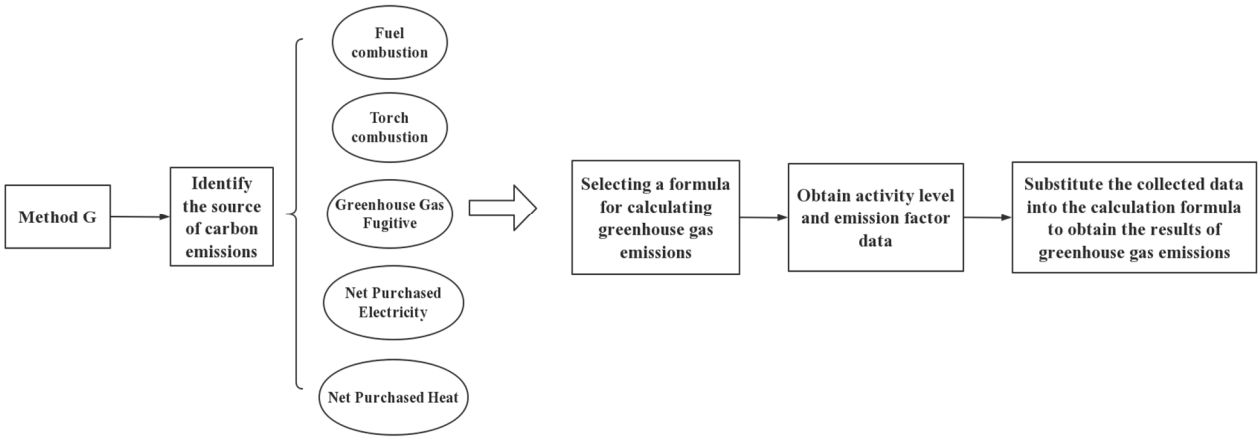

Figure 8. Flow chart of Method G.

In this paper, the carbon emissions of the Fifth-II mining areas were calculated according to the IPCC method and Method G, and the specific results are shown in Table 7.

Table 7. Results of IPCC, Method G, and the B-R model in the Fifth-II mining area.

Carbon Accounting Methodology	Total Carbon Emissions (t)
IPCC Model	41,675.8198
Method G	40,560.2071
The B-R model	41,670.9528

The IPCC method calculates that the total carbon emission of the Fifth-II mining areas is about 41,675 tons. The usual international error range is ±5%. A difference of 5 tons is within a reasonable range from the 41,670 tons calculated by the B-R model established in this paper. Method G calculated that the total carbon emissions of the Fifth-II mining areas are about 40,560 tons. The difference of 1110 tons is within a reasonable range from the other method's finding of 41,670 tons. It can be concluded that the B-R model established in this paper is feasible.

5. Conclusions and Further Work

5.1. Conclusions

In this paper, the carbon emission boundary of fully mechanized mining was determined based on the idea of the life cycle, and a carbon emission calculation model based on each link of fully mechanized mining is proposed. For the fully mechanized mining process in the area, the following conclusions were drawn:

(1) Among the four links of fully mechanized mining, the two links of coal transportation and coal drop contribute to a relatively high proportion of carbon emissions. The carbon emission sources were analyzed, and the main carbon emission source was equipment.
(2) The IPCC method and *The Methodology and Reporting Guide for Greenhouse Gas Emissions of Chinese Coal Producers* were introduced to verify the B-R model, and we found that the error of the calculation results was small and the B-R model is feasible.
(3) In order to better reduce carbon emissions, coal mines should control the use of electricity and improve the ability to transform and upgrade equipment. The secondary utilization of coal gas or methane gas generated inside the coal mine for power generation through technological innovation would be useful.

5.2. Further Work

(1) The carbon emission boundary in this paper assumes that, in the process of coal mining, there is no evaluation and calculation of related auxiliary systems. In the

future, this angle could be expanded to extend the calculation of carbon emissions to the entire production chain of coal products [24].

(2) Software for calculating coal mine carbon emissions could be developed to monitor the carbon emissions of all aspects of the entire coal mine.

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