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Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines

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Abstract: At present, the carbon emissions in China's metal mining industry can be calculated based on the amount of energy consumed in the mining process. However, it is still difficult to predict the carbon emissions before implementation of mining engineering. There are no effective approaches that could reasonably estimate the amount of carbon emissions before mining. To this end, based on the 'Top–down' carbon emission accounting method recommended by the Intergovernmental Panel on Climate Change (IPCC), this study proposes a model to predict the greenhouse gases emitted in seven carbon-intensive mining stages, namely, drilling, blasting, ventilation, drainage, air compression, transportation, and backfilling. The contribution of this model is to enable a prediction of the accumulation of greenhouse gases based on the mining preliminary design of mine, rather than on the consumption of energy and materials commonly used in recent research. It also establishes the amount of carbon emissions generated by mining per unit cubic meter of ore rock as the minimum calculation unit for carbon emissions, which allows for the cost and footprint of carbon emissions in the mining process to become clearer. Then, a gold–copper mine is involved as a case study, and the greenhouse gas emissions were predicted employing its preliminary design. Among all the predicted results, the carbon emissions from air compression and ventilation are larger than others, reaching 22.00 kg CO_2/m^3 and 10.10 kg CO_2/m^3, respectively. By contrast, the carbon emissions of rock drilling, drainage, and backfilling material pumping are 5.87 kg CO_2/m^3, 6.80 kg CO_2/m^3, and 7.79 kg CO_2/m^3, respectively. To validate the proposed model, the calculation results are compared with the actual energy consumption data of the mine. The estimated overall relative error is only 5.08%. The preliminary predictions of carbon emissions and carbon emission costs in mining before mineral investment were realized, thus helping mining companies to reduce their investment risk.

Keywords: mining carbon emissions; metal mines; carbon emission prediction model; cost of carbon emission; carbon emissions

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Citation: Ren, G.; Wang, W.; Wu, W.; Hu, Y.; Liu, Y. Carbon Emission Prediction Model for the Underground Mining Stage of Metal Mines. *Sustainability* **2023**, *15*, 12738. https://doi.org/10.3390/su151712738

Academic Editors: Krzysztof Skrzypkowski, Faham Tahmasebinia, Jianhang Chen, René Gómez, Fhatuwani Sengani and Derek B. Apel

Received: 11 July 2023
Revised: 10 August 2023
Accepted: 21 August 2023
Published: 23 August 2023

1. Introduction

With the continuous emission of greenhouse gases, the frequency of extreme weather around the world has increased significantly, causing great economic losses and also posing a serious threat to human sustainable development [1–3]. Against the background of countries around the world having reached a consensus on the adjustment of the energy structure and control of greenhouse gas emissions, the impact of mining activities on climate change is often insufficiently considered. M. Azadi et al. [4] calculated a 130% increase in fuel consumption per unit of copper mined in Chile from 2001 to 2017 and a 32% increase in electricity consumption. Meanwhile, greenhouse gas emissions from metal and mineral production accounted for about 10% of global energy-related greenhouse gas emissions in 2018. Therefore, the large increase in energy consumption in the mining industry needs to be taken seriously, and regulators must consider greenhouse gas emissions more actively, accurately, and transparently to be able to implement effective mitigation strategies. According to the to the EU Green Deal fit for 55 packages [5], resource acquisition is also a strategic security issue in the process of realizing the Green New Deal. Therefore, accelerating the reduction of primary material production energy consumption caused by mining activities and ensuring the supply of sustainable raw materials are also prerequisites for achieving green transformation (EU 2018; Pelin and Mehmet 2022) [6,7]. At the same time, to further improve the initiative of enterprises in various industries to control greenhouse gas emissions, many countries and regions have successively formed their own carbon trading systems. China's carbon emission trading market was officially launched on December 19, 2017. In the long term, the carbon market will have a significant impact on the carbon emissions and investment decisions of various industries (X. Song et al., 2022) [8].

To date, numerous scholars have conducted extensive research on the problem of mining carbon emissions. With the goal of carbon emission reduction required in each production process of open-pit mines, Guoyu Wang et al. (2022) [9] used a multi-objective optimization algorithm to establish a multi-objective carbon emission distribution model for open-pit mines from the perspective of carbon quota allocation, and used this model to provide optimization suggestions for carbon emission quotas in each process link in the production process. Boyu Yang et al. (2021) [10] selected the Pingshuo open pit coal mine in Shanxi Province, China, as a case study object, analyzed the dynamic changes of carbon emissions based on the IPCC method, and used the IPAT equation to analyze the influencing factors of carbon emissions. It is concluded that the carbon emission sources of open-pit mines mainly include the use of fuel and explosives, methane escape from coal mines, spontaneous combustion of coal and gangue, power consumption, and other parts; at the same time, the carbon emissions caused by the open-pit coal mine increased year by year, with an average annual growth rate of 11.64%, of which the carbon emissions of fuel consumption and methane emissions accounted for 41.79% and 46.66%, respectively. This paper focuses on how to use the IPAT equation to analyze the influencing factors of carbon emissions in actual cases of mines. However, the dynamic change calculation of mine carbon emissions still uses the accounting model based on post-clearance provided by IPCC, and it is still difficult to solve the problem of how mining enterprises estimate the carbon emission intensity of mining before mining. Based on the life cycle concept, Benzheng Li et al. (2022) [11] established a carbon emission accounting model for each process link of a fully mechanized coal mine. And, according to the IPCC calculation method and the China Coal Production Enterprises Green Gas Emissions Accounting Methodology and Reporting Guide, producing the carbon emission model is feasible. However, the verification method of the model lacks the detailed data basis of real-time production statistics. Youshun Cui et al. (2015) [12] proposed a method for calculating the carbon emissions of diesel vehicles in underground mines using a geographic information system. The carbon emissions related to trucking work and were calculated by considering the carbon emission factors of the road and the distance as determined by the best-route analysis based on GIS. Lili Wei et al. (2021) [13] established a carbon emission estimation model to estimate the carbon emissions of the energy consumption of China's mining industry from 2000 to 2020, referring to the methods and parameters of the 2006 IPCC National Greenhouse Gas Inventory Guidelines. Then, using the extended Kaya identity and the LMDI model, analyzed the influencing factors of carbon emissions in the mining industry, including energy carbon emission intensity, energy structure, energy intensity, industrial structure, and output value. This paper analyzed the correlation between mining carbon emissions and economic output at the macro level, but ignored the significant differences in carbon emissions caused by different production processes among different types of mines.

Timothy Rijsdijk et al. (2022) [14] studied the impact of the change in carbon price on the mining economy of high-grade copper–cobalt mines in the Democratic Republic of Congo during mining and beneficiation processes. They came to the conclusion that the change in carbon price had little impact on the open-pit mining limit and cut-off grade. Yang Liu et al. (2022) [15] calculated the energy consumption of open-pit metal mines based on IPCC method and combined the traditional energy-saving supply curve analysis method with the open-pit mining boundary to evaluate the energy-saving potential and carbon emission costs caused by the application of energy-saving technologies. Sam Ulrich et al. (2022) [16] studied the interaction between greenhouse gas emissions from gold mining, abatement measures, and carbon prices. The impact of the carbon price varied markedly between countries, with a 100 USD/t CO_2-e price increasing gold production costs on average by 13 USD/oz in Finland and up to 275 USD/oz in South Africa. If the mine's primary energy source is replaced, the greenhouse gas emissions generated will be reduced by up to 46%. Further, by improving energy efficiency, the processes with the largest reductions in greenhouse gas emissions in underground mining are ventilation and cooling, going down by up to 24% (Sam Ulrich et al., 2022) [16]. From the perspective of carbon price, energy-saving technology application, and mining economy, the works above provide a reference for mineral development investors to make decisions by demonstrating the quantitative relationship between carbon emission costs and mining costs. However, mining is a huge and multi-process joint system. How to distinguish and clarify the carbon emission cost of various production processes is still a difficult problem.

In general, scholars have constructed a carbon emission accounting model for the whole life cycle of coal mine production, but research on carbon emission accounting models in the metal and non-metal mining stages is rare. At the same time, the current research in the mining field focuses on calculating carbon emissions based on the amount of energy consumed during the mining process, which is a method of post-liquidation. The disadvantage is that it can only passively calculate the carbon emissions generated after mining. If the prediction of mining carbon emissions can be realized before production, mining enterprises will be able to calculate the carbon emission cost in advance, thus reducing their investment risk. Table 1 shows the critical things such the parameter selection, modeling, analysis advantages, and limitations of existing literature. √ means the citation has used or studied the methods.

Table 1. Key information comparison table of existing literature.

Ref.	Coal Mine	Open-Pit Metal Mine	Underground Metal Mine	IPCC Method	Model Reliability Verification	Predicting Carbon Emissions
[9]		√			√	
[10]	√			√		
[11]	√			√	√	
[15]		√		√		

In China, where underground mines account for 90 per cent of the total number of metal mines, there has been no review of the technical strategy needed by Chinese metal mines to achieve the goals of "carbon peak and carbon neutrality" (Q.F. Guo et al., 2022) [17]. With China's carbon emission trading market and mechanism becoming more and more mature and perfect, a more detailed carbon emission estimation model has been established for underground mines. According to the geological survey and preliminary design data obtained before mining, the carbon emission prediction will be realized after the mine is put into operation. At the same time, if the mine is in the exploitation stage, the method can provide a more accurate assessment of carbon emissions and energy-saving technology applications generated by different processes in the mine. The above two points are of great significance to the current developers of mineral resources.

2. Carbon Emission Prediction Model for the Metal Mine Underground Mining Stage

To calculate the carbon emissions in the underground mining stage of metal mines, the calculation boundary first needs to be determined (R. Chambi-Legoas et al., 2021) [18]. All production processes in the actual mining stage fit into nine categories: drilling, blasting, supporting, ventilation, transportation, lifting, drainage, air compression, and backfilling. It is necessary to point out that the carbon emission of the underground support process mainly results from cement. Since almost all of the carbon emission of cement is from its production process, its carbon emission has been included in the cement production industry (T. Du et al., 2020) [19]. Since the lifting process involves the transport of ores, personnel, and all kinds of materials required for underground construction, the factors considered to affect the carbon emissions of this process include mining depth, personnel scheduling, underground production schedule, etc., making it difficult to model the energy consumption of different mines during the lifting process. Therefore, this study aimed to establish the seven production processes of rock drilling, blasting, ventilation, air compression, drainage, transportation, and backfilling as the calculation boundaries, and to construct the corresponding carbon emission models.

When metal mines are mined underground, there are differences in the types of energy and working methods used by equipment in various production processes. If the carbon emission calculation results of each process are not based on the same indicators, a comparison of the carbon emissions of different processes will be very inconsistent. Since the purpose of all mining work is to mine ore, in order to further quantify and compare the carbon emission value of each mining production process, this study opted to use 'per cubic meter rock mass' as the calculation unit for the process of mining carbon emissions.

2.1. Carbon Emission Accounting Method for Each Process in the Mining Stage

The most widely used carbon emission accounting method is the carbon emission coefficient method recommended by the Intergovernmental Panel on Climate Change (IPCC), which can be classified into two types of calculation methods: 'Top–down' and 'bottom–up'. The 'Top–down' method refers to the classification of energy used within the defined boundary, and the carbon emissions are obtained by multiplying the corresponding carbon emission coefficients after measuring the consumption. The 'bottom–up' method is used for the direct, on-site measurement of the carbon emissions of all equipment in order to calculate the total carbon emissions. Due to factors such as changing operating conditions, numerous sources of carbon emissions, and complex measurement environments in mines, it is almost impossible to use the 'bottom–up' method for the complete measurement of emission data for each source and component.

In this study, the 'Top–down' method was used to calculate the carbon emissions in the underground mining stage of metal mines (G.Y. Wang and J.S. Zhou, 2022) [9]. The calculation formula is as follows:

$$E = \sum_{\psi=1}^{\psi'} \Delta_{\psi} \cdot EF_{\Delta} \tag{1}$$

where E represents the carbon emission per cubic meter rock mass in the process, ψ represents the number of equipment types used, Δ_{ψ} represents the energy consumption per cubic meter rock mass, and EF_{Δ} represents the corresponding carbon emission factor of the energy type consumed by the ψ type of equipment. The subsequent model calculation formulas will be based on Formula (1).

In this study, when selecting the main types of carbon emission energy—which refers to the energy that is classified by carbon emission accounting according to the guidelines for the greenhouse gas emissions of national mining enterprises—two types of energy were selected: electricity and diesel. These two types of energy are the main sources of carbon emissions in the mining stage. In addition, because blasting is an important underground mining process, the explosive consumption in the blasting process is also measured. The following Figure 1 is shown as the boundary chart of carbon emission prediction in underground mining stage of metal mine.

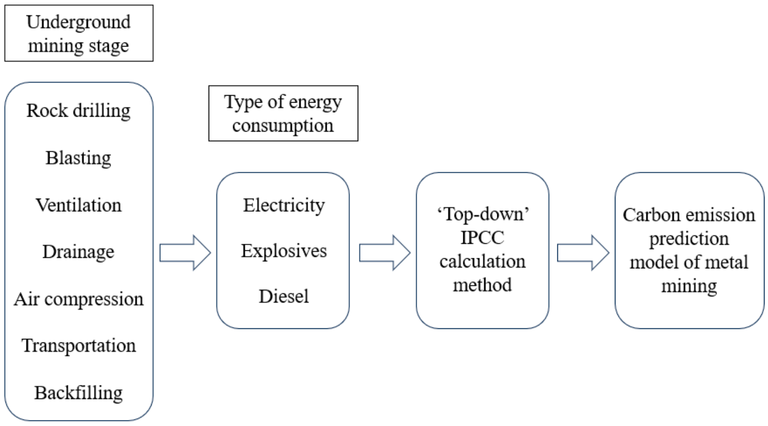

Figure 1. Carbon emission system boundary of the underground mining stage of a metals mine.

2.2. Carbon Emission Model in the Rock Drilling Process

The greenhouse gas emissions in the drilling process mainly result from the energy consumption of the drilling equipment. Underground drilling construction includes shaft and roadway excavation. The carbon emissions produced by different construction methods are not the same. To facilitate the calculation, it is assumed that drilling and blasting are used throughout the excavation of the mine, and, therefore, only the carbon emissions generated during the drilling process are considered. At present, the drilling tools used in underground mining are the pneumatic leg rock drill, tunneling trolley, and deep-hole trolley drilling. The pneumatic leg rock drill is used to drill shallow holes, and the tunneling and drilling trolleys are used to drill medium-depth and deep holes. Although the pneumatic leg rock drill is used for shallow-hole drilling work, its energy consumption is essentially different from the power and oil consumption of the tunneling and drilling trolleys. Its power results from the use of high-pressure air. The mine is equipped with several air compressors to supply compressed air to the underground pneumatic leg rock drill, air pick, and other rock drilling equipment by establishing a compressor station on the surface. Because the air compressor does not directly affect the rock drilling work, it is distinguished from the rock drilling work performed by the tunneling trolley drilling and deep-hole trolley drilling, and the carbon emissions from the shallow-hole drilling work of the pneumatic leg rock drill are calculated in the air pressure process.

The energy consumption of the drilling work carried out for medium-depth and deep holes depends on the rock breaking working time and the machine power of drilling tools. Machine power is usually a known quantity, and the time consumed by drilling work is related to factors such as drilling length, drilling number, and rock properties. The average drilling length, drilling number, and mechanical drilling efficiency required for mining are used to calculate the rock breaking working time per cubic meter rock mass of different drilling tools. Derived from Formula (1) above, when drilling medium-depth and deep holes, underground mines use the drilling and tunneling trolleys to drill different types of ore per cubic meter. The drilling carbon emissions per cubic meter rock mass are calculated as follows:

$$E_1^{dr} = \sum\nolimits_{j=1}^{j'} P_1 \cdot \frac{a_j^1 \cdot b_j^1}{\eta_1} \cdot EF_{electricity} + \sum\nolimits_{j=1}^{j'} P_2 \cdot \frac{a_j^2 \cdot b_j^2}{\eta_2} \cdot EF_{electricity} \quad (2)$$

where E_1^{dr} represents greenhouse gas emissions per cubic meter rock mass drilled by a rock drilling rig, t CO_2/m^3; j' represents the number of rock types with obvious differences in properties in the mine; P_1 and P_2 represent the rated power of the drilling trolley and deep-holetrolley at work, kW; a_j^1 and a_j^2 represent the average number of boreholes drilled by a drilling trolley and a deep-hole trolley in a certain type of rock mass; b_j^1 and b_j^2 represent the average borehole length per unit cube of a certain type of rock mass for the drilling and deep-hole trolleys, m/m^3; η_1 and η_2 represent the general drilling efficiency of tunneling drilling and deep-holetrolleys, m/h; $EF_{electricity}$ represents the greenhouse gas emission factor of electric energy, t CO_2/kWh.

2.3. Carbon Emission Model for the Blasting Process

The greenhouse gas emissions in blasting operations mainly result from the consumption of industrial explosives; the consumption of explosives is the product of unit explosive consumption and blasting volume. For underground metal mines, blasting work can be classified into excavation blasting, preparatory blasting, and stopping blasting. For excavation blasting and preparatory blasting, there is only one free surface, the blasting conditions are difficult, and the unit consumption of the explosives is generally higher than that in stopping blasting.

The average explosive unit consumption of various types of rocks commonly used in mine blasting work (distinguished here by the rock general coefficient) is measured. The calculation model for greenhouse gas emissions per cubic meter rock mass in different blasting processes is as follows:

$$E_2^{ex} = \sum_{j=1}^{j'} \frac{\left[K_j^1 \cdot \alpha + K_j^2 \cdot (1-\alpha)\right] \cdot EF_{explosive}}{1000} \tag{3}$$

where E_2^{ex} represents greenhouse gas emissions per cubic meter rock mass mined during blasting, t CO_2/m^3; j' represents the number of rock mass types with obvious differences in rock properties in the mines; K_j^1 and K_j^2 represent the unit consumption of explosives for the same type of rock mass for preparation blasting and ore blasting, respectively, kg/m^3; α represents the proportion of preparatory work in the whole underground mine; $EF_{explosive}$ represents the greenhouse gas emission factor for industrial explosives used in mines, t CO_2/t.

2.4. Carbon Emission Model in the Ventilation, Drainage, and Air Compression Processes

The carbon emission attributes of the ventilation, drainage, and compressed air systems in underground mines are similar, mainly in the following aspects: the carbon emissions of the three systems are all derived from power consumption; the number of fans, drainage pumps, and compressors required for the mine increases with the expansion of the mining area; during production, the main fan, drainage pump, and compressor are kept uninterrupted at work. The purposes of the ventilation, drainage, and compressed air systems are to ensure the safe production of mines, and they are not strongly related to the amount of ore being mined. Therefore, in order to convert the carbon emissions produced by ventilation, drainage, and air compression into unit cubic ore, the ratio of the daily power consumption of the ventilation and drainage systems to the sum of the daily ore and waste rock production in mines is considered to be able to determine the carbon emissions caused by ventilation and drainage technology when mining rock masses. By calculating the ratio of the daily power consumption of the compressed air system to the daily average amount of rock mass mined by the compressed air equipment in the mine, the carbon emission produced by air compression when mining the unit cubic rock mass is determined.

The carbon emissions of related equipment can be calculated using the following formula:

$$E_3^{v-w-c} = \frac{\left(\sum_{\imath=1}^{\imath'} P_\imath^{ve} \cdot n^\imath \cdot t_\imath + \sum_{\mathscr{g}=1}^{\mathscr{g}'} P_\mathscr{g}^{wa} \cdot n^\mathscr{g} \cdot t_\mathscr{g}\right) \cdot \rho \cdot EF_{electricity}}{Q_{day} \cdot 1000} + \frac{\sum_{\mathscr{z}=1}^{\mathscr{Z}'} P_\mathscr{Z}^{CO} \cdot n^\mathscr{Z} \cdot t_\mathscr{z} \cdot \rho \cdot EF_{electricity}}{Q_{day}^1 \cdot 1000} \tag{4}$$

where E_3^{v-w-c} represents the greenhouse gas emissions from the ventilation, drainage, and pressurization processes when treating a unit cube of rock mass, t CO_2/m^3; $\imath$, $\mathscr{g}$, and $\mathscr{z}$

represent the number of types of ventilators, drainage pumps, and compressors; $P_{\mathscr{i}}^{ve}$, $P_{\mathscr{g}}^{wa}$, and $P_{\mathscr{z}}^{co}$ represent the respective working power of a certain type of fan, drain pump, and compressor, kW; $n^{\mathscr{i}}$, $n^{\mathscr{g}}$, and $n^{\mathscr{z}}$ represent the number of working units of ventilators, drainage pumps, and compressors of a certain type; $t^{\mathscr{i}}$, $t^{\mathscr{g}}$, and $t^{\mathscr{z}}$ represent the average daily working time of a certain type of ventilator, drainage pump, and compressor, h; ρ represents the average density of mine rock mass, kg/m^3; $EF_{electricity}$ represents greenhouse gas emission factor of electricity, t CO_2/kWh; Q_{day} represents the sum of daily ore and waste rock in the underground mine, t/day; Q_{day}^1 represents the daily average amount of rock mass excavated in the underground mine using compressed air equipment, t/day.

2.5. Carbon Emission Model in the Transportation Process

The transportation process in underground mines can be divided into stope transportation and bottom-hole yard transportation. At present, the commonly used equipment for stope transportation includes the electric scraper, diesel scraper, loader, etc., and the bottom-hole yard transportation equipment generally involves the use of an electric locomotive. The carbon emission during the transportation process of the stope is the most complex, mainly due to the following aspects: the location and scope of the stope are constantly changing, and the distance covered by the transportation equipment is also constantly changing; the power consumed by the mining equipment varies under different transportation conditions, such as no-load, heavy load, uphill, downhill, and vehicle performance. In the process of mine production, there are usually multiple stopes at the same time, and the transportation distance and working conditions for the mining and loading equipment in each stope are not consistent. Therefore, in order to provide data statistics and facilitate calculation, the following assumptions are made on the transport process of the stope: without considering the transport distance of different stopes, the slope of the stope and the performance of the vehicle itself and their influence on the mining and loading equipment, the transport distance parameter is converted into the average round-trip time required for mining and loading; the load of the underground scraper is usually about 3 tons. The power ratio coefficient λ of the engine is defined when the mining vehicle is empty and heavy, and the value of λ could be taken as 0.91 (Z.Y. Zhang et al., 2014) [20]. Because the electric locomotive uses the method of rail transportation, its characteristics include having a large capacity and a small running friction resistance. The running power of the empty and heavy load is regarded as the rated power of the supporting motor.

Different from the electric scraper, the carbon emission of the diesel scraper is the result of diesel consumption. Therefore, it is necessary to convert the engine power of the diesel scraper into diesel consumption. The greenhouse gas emission model for transporting a unit cube of rock mass by diesel scraper is as follows:

$$E_4^{di} = \sum\nolimits_{\hbar=1}^{\hbar'} \frac{P_{di}^{\hbar}(1+\lambda)\cdot t_{sc}^{av}\cdot EF_{diesel}}{2\cdot \alpha_{di}\cdot V_{bucket}^{\hbar}\cdot k_{sc}} \tag{5}$$

where E_4^{di} represents carbon emissions per unit cube of rock mass for diesel scrapers, t CO_2/m^3; $\hbar'$ represents the number of diesel scraper types used in the mine; $P_{di}^{\hbar}$ represents the engine rated power of a certain type of diesel scraper, w; λ represents the power ratio coefficient of an engine under no-load and heavy load, λ = 0.91; t_{sc}^{av} represents the average round-trip time of the scraper, s; EF_{diesel} represents the carbon emission factor of diesel, t CO_2/J; α_{di} represents the diesel combustion conversion efficiency; $V_{bucket}^{\hbar}$ represents the bucket capacity corresponding to a certain type of diesel scraper used in the mine, m^3; k_{sc} represents the full bucket coefficient of the scraper.

Based on the above assumptions, the greenhouse gas emission models for electric scrapers and electric locomotives during underground mine transportation are as follows:

$$E_5^{el} = \sum\nolimits_{\hbar=1}^{\hbar'} \frac{P_{el}^1(1+\lambda)\cdot t_{sc}^{av}\cdot EF_{electricity}}{2\cdot V_{bucket}^{el-1}\cdot k_{sc}\cdot 3600} + \sum\nolimits_{\ell=1}^{\ell'} \frac{P_{el}^2\cdot t_{el}^{av}\cdot EF_{electricity}}{V_{bucket}^{el-2}\cdot n'\cdot k_{train}} \tag{6}$$

where E_5^{el} represents the carbon emissions per unit cube of rock mass shoveled by electric scrapers and electric locomotives in the mine, t CO_2/m^3; $\mathcal{k}'$ and ℓ' represent the number of types of electric scrapers and electric locomotives used in the underground mine; $P_{el}^{\mathcal{k}}$ and P_{el}^{ℓ} represent the respective rated power of a certain type of electric scraper and electric locomotive, kW; t_{el}^{av} represents the average round-trip time of electric locomotives, h; V_{bucket}^{el-1} and V_{bucket}^{el-2} represent the bucket volume of the electric scraper and the carriage volume of the electric locomotive, respectively, m^3; n' represents the number of carriages in the electric locomotives; k_{train} represents the full bucket coefficient of the electric locomotive.

2.6. Carbon Emission Model in the Backfilling Process

The carbon emission in the backfilling stage is the result of the large amount of electricity consumed during the preparation and transportation of the backfilling material. At present, there are many kinds of backfilling processes. Due to the different formation and geological conditions, the mineral processing technology used, and other factors, the backfilling process, backfilling material ratio, and backfilling material preparation equipment used in different mines are also different. The equipment utilized in the backfilling process includes filter presses, mixers, and pumps.

The carbon emission in the backfilling process is the sum of the preparation of the backfilling material and the hydraulic transportation. The source of carbon emissions during preparation is the equipment power consumption during the pressure filtration and mixing processes, while the carbon emissions in the hydraulic transportation process are the result of the equipment power consumption during the pumping process. Thus, the carbon emission accounting model for the backfilling unit cubic cavity process is obtained as follows:

$$EF_8^{fi} = \sum_{\mathcal{w}=1}^{\mathcal{w}'} \frac{P_{pr}^{\mathcal{w}} \cdot t_{pr}^{av} \cdot n_{pr}^{\mathcal{w}} \cdot EF_{electricity}}{V_{pr}^{av}} + \sum_{\mathcal{r}=1}^{\mathcal{r}'} \frac{P_{st}^{\mathcal{r}} \cdot t_{st}^{av} \cdot n_{st}^{\mathcal{r}} \cdot EF_{electricity}}{V_{st}^{av}} + \sum_{\mathcal{u}=1}^{\mathcal{u}'} \frac{P_{pu}^{\mathcal{u}} \cdot t_{pu}^{av} \cdot n_{pu}^{\mathcal{u}} \cdot EF_{electricity}}{V_{pu}^{av}} \quad (7)$$

where EF_8^{fi} represents the carbon emissions produced during the backfilling of each cubic cavity, t CO_2/m^3; $\mathcal{w}'$, $\mathcal{r}'$, and $\mathcal{u}'$ represent the types of filter presses, mixers, and pumps used in the processes of pressure filtration, mixing, and pumping, respectively; $P_{pr}^{\mathcal{w}}$, $P_{st}^{\mathcal{r}}$, and $P_{pu}^{\mathcal{u}}$ represent the rated power of each type of filter press, mixer, and pump, kW; t_{pr}^{av}, t_{st}^{av}, and t_{pu}^{av} represent the average working time of the filter press, mixer, and pump to complete a workflow, h; $n_{pr}^{\mathcal{w}}$, $n_{st}^{\mathcal{r}}$, and $n_{pu}^{\mathcal{u}}$ represent the number of presses, mixers, and pumps for each type, respectively; V_{pr}^{av}, V_{st}^{av}, and V_{pu}^{av} represent the treatment volume of the filter press, mixer, and pump in their respective single workflow time, m^3.

2.7. Summary of Section 2

In the Section 2, based on the IPCC 'Top–down' calculation method, we construct a carbon emission prediction model for different processes in the mining stage of underground metal mines. The calculation results of different processes are unified as the carbon emissions per cubic meter of ore, the core modeling idea is to decompose the mining process and divide the process into direct production processes and auxiliary production processes. The direct production processes include drilling, blasting, transportation, and filling process, their carbon emission models were constructed by calculating the energy consumption per unit cubic ore of direct production equipment. The auxiliary production processes include ventilation, drainage, and air pressing process, and their modeling method was to calculate the ratio of daily energy consumption of auxiliary production equipment to daily output of ore. The advantage of this modeling is that all input parameters in the model can be obtained in advance in the preliminary design, and it is easy to compare the differences in carbon emissions between different production processes. The disadvantage is that the model calculation results cannot be accurately adjusted according to the changes in the actual production plan of the mine, and when the production equipment is faced with changes in working capacity caused by migration and failure, it will lead to deviations in the model prediction results.

3. Case Study

This study selected an underground gold and copper mine located in Daye, Hubei Province, China (114°54′42″~114°55′45″ E, 30°04′45″~30°05′50″ N), and the total area is about 2.4 km^2. The underground mine is mined by the filling method. The main mineral products are gold copper ore, sulfur ore, and associated iron ore. At present, the mining depth has reached 500 m underground. Its actual production was investigated and measured, and the carbon emission accounting model designed above was utilized to calculate the carbon emission of each unit cube of ore body treated by each process flow. In calculating the carbon emissions of each process, the electric energy carbon emission factor used was 0.581 t CO_2/MWh, as given in the Enterprise Greenhouse Gas Emission Accounting Method and Reporting Guide Power Generation Facilities (Environmental Climate No. 111) (2022) [21], and the selected diesel carbon emission factor was 74.1 t CO_2/TJ, as given in the International Greenhouse Gas Emission Factor Guide provided by the IPCC in 2006 (IPCC, 2006) [22].

3.1. Carbon Emissions during Rock Drilling

The drilling parameters (drilling length and drilling number) for each unit cube of rock mass with different lithology were determined in this underground gold–copper mine, as shown in Table 2. The technical parameters of the excavation and drilling trolleys selected for the mine are shown in Table 3.

Table 2. Technical parameters of the drilling trolley under different rock masses.

Common Rock Mass Types in the Mine	Average Borehole Length (m/m^3)	Average Number of Boreholes
(Orebody) Skarn	0.83	5
(Orebody) Marble	0.83	5
(Wall-rock) Quartz diorite porphyrite	0.94	5
(Wall-rock) Diorite	0.94	5.4

Table 3. Technical parameters of the tunneling and drilling trolleys.

Drill Type	Model of Drill	Nominal Power (kW)	Rock Breaking Efficiency (m/h)	Equipment Size (m)	Equipment Weight (t)
Tunneling trolley	Huatai HT82	62	30	$11 \times 1.45 \times 2.08$	10
Deep-hole drilling	Huatai HT72	62	60	$9.05 \times 1.45 \times 2.08$	11.5

Substitute the data into Formula (2) to calculate:

When the tunneling trolley was used for rock drilling, the carbon emission of quartz diorite porphyrite was 5.64×10^{-3} t CO_2/m^3, and the carbon emission of diorite was 6.09×10^{-3} t CO_2/m^3.

When the deep-hole trolley was used for rock drilling, the general carbon emission of the ore rock with the lithology of skarn and marble was 2.49×10^{-3} t CO_2/m^3.

3.2. Carbon Emissions during Blasting

The explosive used in the mine production process is modified amine oil explosive, and its carbon emission factor is 0.2 t CO_2/t. The average density of skarn and marble is 2700 kg/m^3 and 2600 kg/m^3, respectively. The proportion of preparatory cutting work to the whole project is about 0.2. The average explosive unit consumption of various types of rocks in different blasting work of the mine (here, distinguished by the general coefficient of rock) is counted. The statistical results are shown in the Table 4.

Table 4. Explosive blasting parameters.

Rock Mass Types	Solid Coefficient of Rock (*f*)	Unit Explosive Consumption of Preparatory Cutting Work	Unit Explosive Consumption of Ore Blasting Work
Skarn	8~10	1.62~1.89 kg/m^3	1.49 kg/m^3
Marble	10~12	1.84~2.11 kg/m^3	1.58 kg/m^3

Substitute the data into Formula (2) to calculate:

When the rock is skarn, the carbon emission of blasting is about 3.03 $\times$ 10^{-4} t CO_2/m^3~3.14 $\times$ 10^{-4} t CO_2/m^3. When the rock is marble, the carbon emission of blasting is about 3.26 $\times$ 10^{-4} t CO_2/m^3~3.37 $\times$ 10^{-4} t CO_2/m^3.

3.3. Carbon Emissions during Ventilation, Drainage, and Air Compression

In the production process of the mine, the daily ore output was about 3000 t, the amount of waste rock was about 250 t per day, the average density of ore and rock was 3200 kg/m^3, and the proportion of the compressed air equipment used as power source to the mine ore accounts for about 70% of the total output of the mine. The mine made use of a frequency conversion fan, with the energy-saving effect reaching 40% (Z.X. Zeng et al., 2020) [23]; the fan was kept open for 24 h. The number of working tables with the same type of drainage pump was 2, and the rest were on standby. The average daily working time was 3 h. The working arrangement of the air compressor was as follows: 8:00–16:00 all open, 16:00–8:00 three open. This is because the working mechanism of the air compressor is meant to stop the air pressure when it reaches the required air pressure value, and when it is lower than this value, it is programmed to resume operation. Mine technicians found that the actual full-power working time of the air compressor in this gold–copper mine could be multiplied by the utilization coefficient of 0.8. The mine fan and drainage pump data are shown in Tables 5 and 6, while the surface air compressor data are shown in Table 7.

Table 5. Fan data.

Type of Fan	Operating Capacity (kW)	Number of Working Devices	Fan Air Volume (m^3/min)	Static Pressure (Pa)	Fan Speed (r/min)
K40-6-№14	30	1	984~2064	150~695	960
K45-6-№14	45	1	1434~2718	500~959	980
FCDZ-6-№22	370	3	2400~7600	750~2750	990
K40-4-№12	37	1	882~1926	242~1118	1450

Table 6. Drainage pump data.

Type of Pump	Operating Capacity (kW)	Number of Working Devices	Pumping Capacity (m^3/h)	Fan Speed (r/min)
200D43*6	300	1	280	1480
MD280-65*7	630	2	280	1480
MD280-43*5	250	2	280	1480
MD280-65*9	800	2	280	1480

Table 7. Air compressor data.

Type of Compressor	Operating Capacity (kW)	Number of Working Devices	Operating Time	Rated Exhaust Pressure (MPa)	Nominal Volume Flow (m^3/min)
TS325-400	300	8	8 h	0.7	41.8
TS325-400	300	3	16 h	0.7	61.7

Bring the above data into Formula (4), and the calculation results are as follows:

In the process of mine production, the carbon emission produced by the ventilation process is about 1.01×10^{-2} t CO_2/m^3, the carbon emission produced by the drainage process is about 6.80×10^{-3} t CO_2/m^3, and the carbon emission from the compressed air process is about 2.20×10^{-2} t CO_2/m^3.

3.4. Carbon Emissions during Transportation

The average round-trip time of the diesel scraper is 200 s; diesel engine efficiency is generally between 34% and 45%; here, 40% was used for the calculation. It is assumed that only one type of diesel scraper is used in the whole process of transporting the same rock mass. Data on diesel scrapers used in mines are shown in Table 8.

Table 8. Diesel scraper data.

Type of Diesel Scraper	Rated Power (kW)	Number of Working Devices	Bucket Capacity (m^3)	Full-Bucket Coefficient
WJ-1.5	63	8	1.5	1.12
WJ-0.75	58	4	0.75	1.09
WJ-1	58	7	1	1.10

Substitute the above diesel engine-related production data into Formula (5), and the calculation results are as follows:

When the WJ-1.5 diesel scraper was selected, the carbon emission produced by the process of scraping ore was about 1.33×10^{-4} t CO_2/m^3.

When the WJ-0.75 diesel scraper was used, the carbon emission produced by the process of scraping ore was about 2.51×10^{-4} t CO_2/m^3.

When the WJ-1 diesel scraper was used, the carbon emission produced by the process of scraping ore was about 1.87×10^{-4} t CO_2/m^3.

The average round-trip time of the electric scraper and the electric locomotive in the mine was 200 s and 600 s, respectively. Similarly, it is assumed that only one type of electric scraper and electric locomotive is used in the whole process of transporting the same rock mass. The electric scraper and electric locomotive equipment parameters are shown in Tables 9 and 10, respectively.

Table 9. Electric scraper data.

Types of Electric Scraper	Rated Power (kW)	Number of Working Devices	Bucket Capacity (m^3)	Full-Bucket Coefficient
WJD-1.5	55	20	1.5	1.12
WJD-1	45	13	1	1.10

Table 10. Electric locomotive production data.

Types of Electric Locomotive	Rated Power (kW)	Number of Working Devices	Number of Carriages and Capacity	Full-Bucket Coefficient
CJY5/6GB 250	15	16	96 (0.75 m^3)	0.91
CJK7/6GB 250	42	8	28 (1.2 m^3)	0.95
CTY5/6G	15	4	10 (1.2 m^3)	0.95

Substitute the above data into Formula (6), and the calculation results are as follows:

When the WJD-1.5 electric scraper was selected, the carbon emission produced by the process of scraping ore was about 1.01×10^{-3} t CO_2/m^3.

When the WJD-1 electric scraper was used, the carbon emission produced by the process of scraping ore was about 1.26×10^{-3} t CO_2/m^3.

In the transportation process of the CJY5/6GB 250 electric locomotive, the carbon emission produced by ore transportation was about 2.22 × 10^{-5} t CO_2/m^3.

In the CJY7/6GB 250 locomotive transport process, the carbon emissions produced by the ore handling process was about 1.27 × 10^{-4} t CO_2/m^3.

In the transportation process of the CTY5/6G electric locomotive, the carbon emission produced by ore transportation was about 1.27 × 10^{-4} t CO_2/m^3.

3.5. Carbon Emission during the Backfilling Process

In the process of mine production, the backfilling process is converted into 3000 T/day according to the ore, and to 800 m^3/day according to the backfilling amount. The specific parameters of the equipment involved in the backfilling process are shown in Table 11.

Table 11. Backfilling equipment parameter table.

Equipment	Number of Types	Number of Working Devices	Rated Power (kW)	Operating Time (h)
Filter press	KGZ600/2000-U	3	20.7	24
Mixer	φ2000*2200	1	30	16
	SJ6*6	2	30	16
	SJ6*8	1	30	16
Pump	100ZJ-I-A46	1	55	8
	100ZJ-I-A50	3	90	8
	100ZJ-I-A50	2	55	8
	150D30*3	1	75	8
	80ZBYL-450	7	90	8
	150ZJ-I-A70	1	200	8

Substitute the data into Formula (7), and the calculation results are as follows:

In the process of mine backfilling, the carbon emission produced by the pressure filtration process was about 1.08 × 10^{-3} t CO_2/m^3, the carbon emission produced by the agitation process was about 1.39 × 10^{-3} t CO_2/m^3, and the carbon emission produced by the pumping process was about 7.79 × 10^{-3} t CO_2/m^3.

3.6. Data Analysis

(1) Comparative analysis of the theoretical calculation and actual production

In the production process of the gold–copper mine in Hubei Province, the power consumption of the main departments of the mine is monitored and measured on a monthly basis. However, due to the relatively stable energy consumption, equipment operation positions, and working conditions in the mine's ventilation, drainage, compressed air, and backfilling departments, the energy consumption data for these departments were more accessible and accurate than those from other departments. Therefore, the monthly power consumption data of the ventilation, drainage, compressed air, and backfilling departments of the mine from January to June 2022 were averaged separately to eliminate the contingency of the monthly data. And the following Table 12 is the actual monthly energy consumption of the four departments of the mine.

Table 12. Actual monthly energy consumption data (January to June 2022).

Department	January (1.0 ×10^4 kwh)	February (1.0×10^4 kwh)	March (1.0 ×10^4 kwh)	April (1.0 ×10^4 kwh)	May (1.0×10^4 kwh)	June (1.0 ×10^4 kwh)	Average (1.0×10^4 kwh)
Ventilation	56.5684	52.7422	47.7846	51.5141	50.8204	51.7728	51.87
Drainage	28.8745	27.7241	22.0039	25.2564	24.3321	25.6627	25.64
Compressed air	83.7515	72.6625	74.2611	79.0424	83.2553	82.0065	79.16
Backfilling	44.6089	38.6525	39.6776	44.5871	39.0314	45.3569	41.99

The model calculates the carbon emission per cubic rock mass by calculating the ratio of the daily average carbon emission to the daily average production. The daily average carbon emission of each process is the product of the daily average energy consumption and the corresponding energy carbon emission factor in each process. Since the average daily output of the mine and the energy carbon emission factor can be regarded as fixed values, the reliability of the carbon emission model can be verified by ensuring that the theoretical energy consumption calculated by the model for each process is consistent with the actual energy consumption. Therefore, the theoretical monthly energy consumption of the above process is calculated and compared with the actual monthly energy consumption of the mine, as shown in Figure 2.

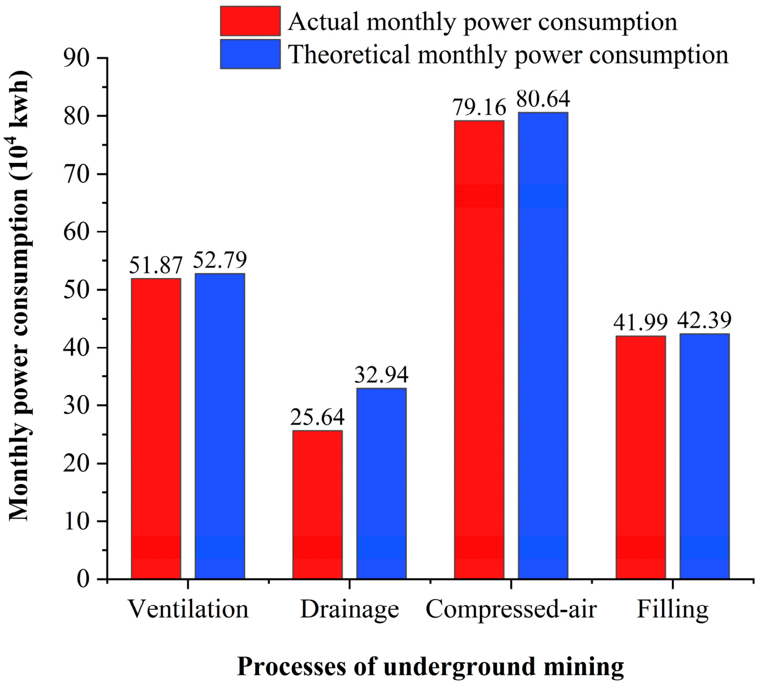

Figure 2. Comparison of the theoretical calculation and the actual energy consumption.

The analysis results show that the relative error between the overall calculation results of the model and the actual production statistics is 5.08%. For the ventilation process, the theoretically calculated power consumption of the model is 9200 kWh higher than the average monthly consumption of the mine, and the relative error is 1.77%. For the drainage process, the power consumption calculated by the model is 73,000 kWh higher than the average monthly consumption of the mine, and the relative error is 28.5%. For the air compression process, the power consumption calculated by the model is 14,800 kWh higher than the average monthly consumption of the mine, and the relative error is 1.87%. For the backfilling process, the power consumption calculated by the model is 4600 kWh higher than the average monthly consumption of the mine, and the relative error is 0.94%. It can be seen that the difference between the theoretical calculation and the actual consumption of the drainage process is the biggest. The main reason for this is that the mine drainage is affected by seasonal climate change. The precipitation is different for each month, resulting in different water inflows during the mine production process. The working time of the drainage pump is also different. In the theoretical model, this working time is a fixed value, and the statistical data in the previous paper were taken from the period of January–June, which is the dry season and when the rainfall is low; these produced a high relative error between the theoretical calculation and the actual energy consumption in the drainage process. In contrast, the relative errors between theory and practice in the ventilation, compressed air, and backfilling processes are less than 2%. Thus, the reliability of the model is well-verified, making it capable of conducting the accounting and estimation of the carbon emissions of each process in mine production.

(2) Analysis of carbon emission differences between different processes

The results of the calculation of carbon emissions for the different processes above are shown in Figure 3.

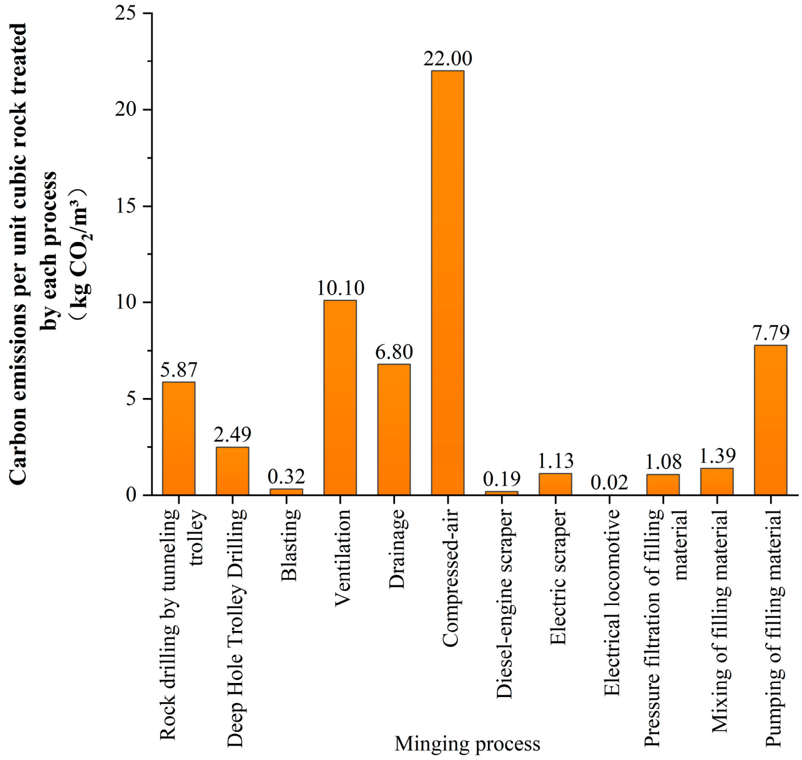

Figure 3. Carbon emission per unit cube of ore rock treated by each process.

In the diagram, it can be seen that there are obvious differences between the carbon emissions of different processes. The carbon emissions of the rock treated with compressed air and ventilation are the highest, reaching 22.00 kg CO_2/m^3 and 10.10 kg CO_2/m^3, respectively, and accounting for 54.24% of the whole process. The carbon emissions of rock drilling, drainage, and backfilling pumping of the heading trolley also reached 5.87 kg CO_2/m^3, 6.80 kg CO_2/m^3, and 7.79 kg CO_2/m^3, respectively; these are the key processes that need energy saving and carbon reduction. It is possible to start the energy-saving and carbon-reduction work of the compressed air process by reducing the use of the pneumatic leg rock drill and increasing the use of the tunneling trolley and the middle–deep-hole rock drilling trolley. The other processes can be applied based on economic rationality. New energy-saving and carbon-reducing technologies are used for equipment transformation.

For the underground transportation, although the direct carbon emission value of the rock from the diesel scraper is lower than that from the electric scraper, the use of the diesel scraper will increase the burden of the underground ventilation system, thus resulting in increased energy consumption. The indirect carbon emissions produced by this are not calculated, and other toxic and harmful gases produced by diesel combustion are not converted into CO_2 for the statistics. On the other hand, the carbon emission value of a unit cube of ore rock transported by the underground electric locomotive is only 0.02 kg CO_2/m^3, which is the lowest in the whole process. The large capacity of the underground electric locomotive fully reduces the carbon emission cost per cubic ore rock, which also demonstrates that the promotion and use of large-scale and intelligent equipment in underground mines indeed promotes a reduction in carbon emissions in production.

(3) Carbon emission cost calculation

The China Carbon Price Survey 2020 predicted the prices in the national carbon emission trading market and provided the following average expected price of carbon quotas: 49 CNY/t in 2020, 71 CNY/t in 2025, 93 CNY/t in 2030, and 167 CNY/t in 2050 (H. Shi, 2022) [24]. In the Carbon Emissions Trading Management Measures (Trial) issued by the Ministry of Ecology and Environment, the distribution of carbon quotas is mainly free in the early stage, while paid distribution is introduced in the later stage (B. Cox et al., 2022) [25]. The proportion of free carbon quotas has a great impact on the development of the industry. To compare the impact of different free quota ratios of carbon emission rights on the cost of carbon emissions per ton of ore mined, the gold–copper mine in Hubei Province is again used as an example. The total carbon emission per cubic ore and rock in underground mining is 59.18 kg CO_2/m^3, and the average density per ore and rock is 3200 kg/m^3. Different free quota ratios are set at 100%, 90%, 80%, 70%, 60%, and 50% of carbon emissions per ton of ore produced, and the cost of carbon emissions per ton of ore mined is calculated, as shown in Figure 4.

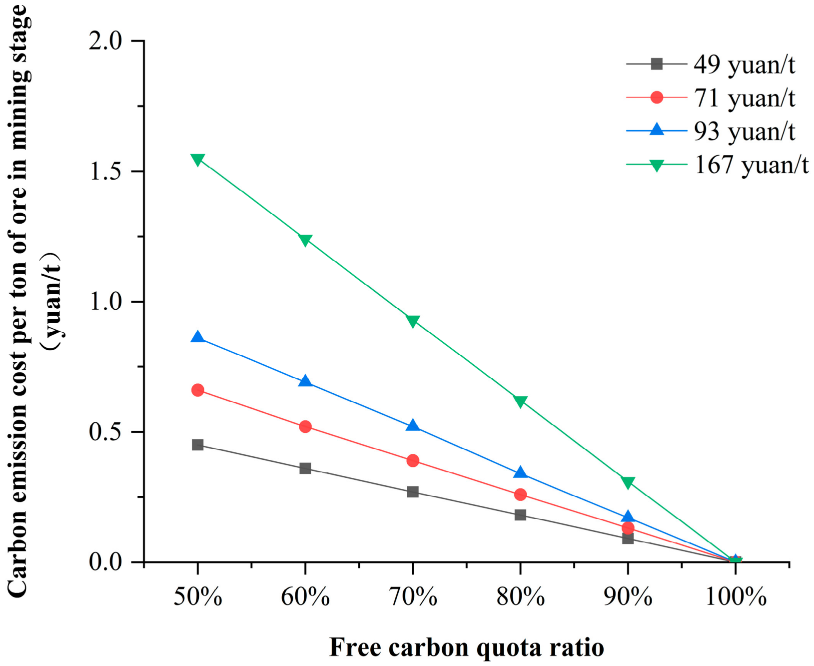

Figure 4. Carbon emission costs per ton of mining under different carbon quota ratios.

It can be seen in the figure that the carbon emission cost per ton of ore in the underground mining stage is positively correlated with the carbon price and negatively correlated with the free carbon quota ratio. When the ratio of the free carbon quota is 50%, according to the current carbon price forecast, the carbon emission cost interval of one ton of ore mined underground in this gold–copper mine is CNY 0.45–1.55. The gold grade of the ore is 1.74 g/t, and the carbon emission cost interval of one gram of gold mined underground is CNY 0.27–0.89. At the same time, after mining, it is necessary to crush and produce a concentration of the ore in the concentrator, and the energy consumption in this part is also huge. It is foreseeable that with the comprehensive improvement of China's carbon market and the continuous rise of the carbon price, mining enterprises will pay more and more attention to the cost increase caused by carbon emissions. Therefore, at this stage, mining enterprises should have the ability to make a preliminary estimate of the carbon emission cost in the mining production process before making an investment so as to reduce investment risk. For mines in the process of mining, an accounting of carbon emissions for various processes should also be carried out to provide a basis for decision making with respect to the application of energy-saving and carbon-reduction technology.

4. Conclusions

Based on the principle of the IPCC carbon emission calculation, this study utilized the carbon emission of a unit cube of rock mass as the calculation index; determined the drilling, blasting, ventilation, drainage, compressed air, transportation, and backfilling processes as the boundaries of carbon emission calculation; and established the carbon emission prediction model for each process. Taking a gold–copper mine in Hubei Province, China, as an example, the proposed model was verified. The following conclusions were drawn:

(1) The accuracy of the carbon emission accounting model was verified using the actual production energy consumption data from the ventilation, drainage, compressed air, and filling processes. The relative error between the overall calculation results of the model and the actual values was 5.08%, which verifies the practicability of the model and has a popularization value in underground mines using the same production processes. But among them, the prediction error of the drainage model is quite different from the actual one, reaching 28.5%. Although there are signs that this is due to the fact that the mine drainage situation is greatly affected by seasonal factors, it also shows that the model still has uncertainty in some aspects. Therefore, we still recommend that mining companies use models to predict and evaluate the average, and try to avoid the pursuit of accurate prediction at a certain stage;
(2) The existing post-liquidation method for calculating carbon emissions based on the amount of energy consumed in the mining industry was improved, and the preliminary prediction of carbon emissions and carbon emission costs in mining before mineral investment was realized;
(3) In the process of underground mining, the carbon emission per unit of cubic rock treated with compressed air and ventilation was the highest, reaching 22.00 kg CO_2/m^3 and 10.10 kg CO_2/m^3, respectively, accounting for 54.24% of the whole process. Our analysis showed that using the rock-drilling trolley instead of the pneumatic leg rock drill and increasing the proportion of the large transport equipment can effectively reduce carbon emissions.

Further Study

(1) Conduct a sensitivity analysis on the model's predictions, to study the influence of different input parameters on mining carbon emissions, so as to provide more clear decision-making suggestions for the subsequent application of energy saving and emission reduction technology in mines;
(2) Carbon emission prediction models still have many limitations, such as limited accounting boundaries, difficulty of making timely adjustments according to actual production plan changes of the mine, equipment production capacity, and working parameters not being immutable. Subsequent research should try to improve these defects, expanding the scope of research, considering cross-validation of different types of mines, and further improving the accuracy and generalization of the model.

Author Contributions: All authors contributed to the study concept and design. G.R. guided the topic selection and writing ideas of the article, W.W. (Wenbo Wu) proposed the prediction model and wrote this article, W.W. (Wei Wang) and Y.H. collected and proofread the actual mine data utilized in the article, W.W. (Wei Wang) completed the analysis of selected cases, and Y.L. provided help in the modeling process of the carbon emission prediction model in this article. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Department of Science and Technology of Hubei Province (grant number 2022BEC040). The project name is Research on Key Technologies for Optimal Mining and Carbon Emission Accounting of Close-Range Multi-Layer Phosphate Ore.

Institutional Review Board Statement: This study did not require ethics approval, thus this declaration is not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data and materials used in this work have been permitted by all participants and published in the article.

Conflicts of Interest: The authors have no relevant financial or non-financial interests to disclose.

Abbreviations

The main notations comparison list is as follows:

Notations	Meaning	Unit
E_1^{dr}	greenhouse gas emissions per cubic meter rock mass drilled by a rock drilling rig	t CO_2/m^3
$j^{'}$	the number of rock types with obvious differences in properties in the mine	
P_1	the rated power of the drilling trolley	kw
P_2	the rated power of the heading trolley	kw
a_j^1	the average number of boreholes drilled by a drilling trolley in a certain type of rock mass	
a_j^2	the average number of boreholes drilled by a heading trolley in a certain type of rock mass	
b_j^1	the average borehole length per unit cube of a certain type of rock mass for the drilling trolleys	m/m^3
b_j^2	the average borehole length per unit cube of a certain type of rock mass for the heading trolleys	m/m^3
η_1	the general drilling efficiency of drilling trolleys	m/h
η_2	the general drilling efficiency of heading trolleys	m/h
$EF_{electricity}$	greenhouse gas emission factor of electric energy	t CO_2/kwh
E_2^{ex}	greenhouse gas emissions per cubic meter rock mass mined during blasting	t CO_2/m^3
K_j^1	the unit consumption of explosives for the same type of rock mass for preparation blasting	kg/m^3
K_j^2	the unit consumption of explosives for the same type of rock mass for ore blasting	kg/m^3
$EF_{explosive}$	the greenhouse gas emission factor for industrial explosives used in mines	t CO_2/t
E_3^{v-w-c}	the greenhouse gas emissions from the ventilation, drainage, and pressurization processes when treating a unit cube of rock mass	t CO_2/m^3
i	the number of types of ventilators	kW
g	the number of types of drainage pumps	kW
z	the number of types of compressors	kW
n^{i}	the number of working units of ventilators of a certain type	
n^{g}	the number of working units of drainage pumps of a certain type	
n^{z}	the number of working units of compressors of a certain type	
t^{i}	the average daily working time of a certain type of ventilator	h
t^{g}	the average daily working time of a certain type of drainage pump	h
t^{z}	the average daily working time of a certain type of compressor	h
ρ	the average density of mine rock mass	kg/m^3
Q_{day}	the sum of daily ore and waste rock in the underground mine	t/day
Q_{day}^1	the daily average amount of rock mass excavated in the underground mine using compressed air equipment	t/day
E_4^{di}	carbon emissions per unit cube of rock mass for diesel scrapers	t CO_2/m^3
$\hbar$	the number of diesel scraper types used in the mine	
$P_{di}^{\hbar}$	the engine rated power of a certain type of diesel scraper	kw
λ	the power ratio coefficient of an engine under no-load and heavy load	
t_{sc}^{av}	the average round-trip time of the scraper	h
EF_{diesel}	the carbon emission factor of diesel	t CO_2/J
α_{di}	the diesel combustion conversion efficiency	
$V_{bucket}^{\hbar}$	the bucket capacity corresponding to a certain type of diesel scraper used in the mine	m^3
k_{sc}	the full bucket coefficient of the scraper	
E_5^{di}	carbon emissions per unit cube of rock mass shoveled by electric scrapers and electric locomotives in the mine	t CO_2/m^3

Notations	Meaning	Unit
$\mathscr{k}'$	the number of types of electric scrapers	
$\mathscr{l}'$	the number of types of electric locomotives	
$P_{el}^{\mathscr{k}}$	the respective rated power of a certain type of electric scraper	kw
$P_{el}^{\mathscr{l}}$	the respective rated power of a certain type of electric locomotive	kw
t_{el}^{av}	the average round-trip time of electric locomotives	h
V_{bucket}^{el-1}	the bucket volume of the electric scraper	m^3
V_{bucket}^{el-2}	the carriage volume of the electric locomotive	m^3
n	the number of carriages in the electric locomotive	
k_{train}	the full bucket coefficient of the electric locomotive	
EF_8^{fi}	the carbon emissions produced during the backfilling of each cubic cavity	$t\ CO^2/m^3$
$\mathscr{w}'$	the types of filter presses used in the processes of pressure filtration, mixing, and pumping	
$\mathscr{r}'$	the types of mixers used in the processes of pressure filtration, mixing, and pumping	
$\mathscr{u}'$	the types of pumps used in the processes of pressure filtration, mixing, and pumping	
$P_{pr}^{\mathscr{w}}$	the rated power of each type of filter press	kW
$P_{st}^{\mathscr{r}}$	the rated power of each type of mixers	kW
$P_{pu}^{\mathscr{u}}$	the rated power of each type of pumps	kW
t_{pr}^{av}	the average working time of the filter press to complete a workflow	
t_{st}^{av}	the average working time of the mixer to complete a workflow	
t_{pu}^{av}	the average working time of the pump to complete a workflow	
$n_{pr}^{\mathscr{w}}$	the number of presses for each type	
$n_{st}^{\mathscr{r}}$	the number of mixers for each type	
$n_{pu}^{\mathscr{u}}$	the number of pumps for each type	
V_{pr}^{av}	the treatment volume of the filter press in their respective single workflow time	m^3
V_{st}^{av}	the treatment volume of the mixer in their respective single workflow time	m^3
V_{pu}^{av}	the treatment volume of the pump in their respective single workflow time	m^3

References

1. Zhou, A.; Hu, J.; Wang, K. Carbon emission assessment and control measures for coal mining in China. *Environ. Earth Sci.* **2020**, *79*, 1–15. [CrossRef]
2. Yuan, Y.; Chuai, X.; Xiang, C.; Gao, R. Carbon emissions from land use in Jiangsu, China, and analysis of the regional interactions. *Environ. Sci. Pollut. Res.* **2022**, *29*, 44540. [CrossRef] [PubMed]
3. Clarke, B.J.; Otto, F.E.L.; Jones, R.G. Inventories of extreme weather events and impacts: Implications for loss and damage from and adaptation to climate extremes. *Clim. Risk Manag.* **2021**, *32*, 100285. [CrossRef]
4. Azadi, M.; Northey, S.A.; Ali, S.H.; Edraki, M. Transparency on greenhouse gas emissions from mining to enable climate change mitigation. *Nat. Geosci.* **2020**, *13*, 100–104. [CrossRef]
5. European (EU) Commission. *European Green Deal 2021 Fit for 55 Package: The EU's Fit for 55 Package—Key Takeaways from Bernstein Renewables, Chemical, Airlines & Energy Teams*; European (EU) Commission: Brussels, Belgium, 2021.
6. European (EU) Commission. *European Green Deal 2018 A Clean Planet for All*; European (EU) Commission: Brussels, Belgium, 2018; p. 773.
7. Yapıcıoğlu, P.; Yeşilnacar, M.I. Economic performance index assessment of an industrial wastewater treatment plant in terms of the European Green Deal: Effect of greenhouse gas emissions. *J. Water Clim. Chang.* **2022**, *13*, 3100–3118. [CrossRef]
8. Song, X.; Wang, D.; Zhang, X.; He, Y.; Wang, Y. A comparison of the operation of China's carbon trading market and energy market and their spillover effects. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112864. [CrossRef]
9. Wang, G.; Zhou, J. Multiobjective Optimization of Carbon Emission Reduction Responsibility Allocation in the Open-Pit Mine Production Process against the Background of Peak Carbon Dioxide Emissions. *Sustainability* **2022**, *14*, 9514. [CrossRef]
10. Yang, B.Y.; Bai, Z.K.; Zhang, J.J. Environmental impact of mining-associated carbon emissions and analysis of cleaner production strategies in China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 13659. [CrossRef]
11. Li, B.; Shi, Y.; Hao, J.; Ma, C.; Pang, C.; Yang, H. Research on a Carbon Emission Calculation Model and Method for an Underground Fully Mechanized Mining Process. *Energies* **2022**, *15*, 2871. [CrossRef]
12. Park, B.; Park, S.F.; Choi, Y.; Park, H.-S. Calculation of a Diesel Vehicle's Carbon Dioxide Emissions during Haulage Operations in an Underground Mine using GIS. *Tunn. Undergr. Space* **2015**, *25*, 373–382. [CrossRef]
13. Wei, L.; Feng, X.; Jia, G. Construction and Application Analysis of Carbon Emission Influence Factor Model of Energy Consumption in Mining Industry. *Adv. Civ. Eng.* **2021**, *2021*, 1–12. [CrossRef]
14. Rijsdijk, T.; Nehring, M. The effect of carbon pricing on cut-off grade and optimal pit limits in a high grade copper-cobalt deposit. *J. Clean. Prod.* **2022**, *356*, 131766. [CrossRef]

15. Liu, Y.; Zhang, C.; Xu, X.; Ge, Y.; Ren, G. Assessment of energy conservation potential and cost in open-pit metal mines: Bottom-up approach integrated energy conservation supply curve and ultimate pit limit. *Energy Policy* **2022**, *163*, 112809. [CrossRef]
16. Ulrich, S.; Trench, A.; Hagemann, S. Gold mining greenhouse gas emissions, abatement measures, and the impact of a carbon price. *J. Clean. Prod.* **2022**, *340*, 130851. [CrossRef]
17. Guo, Q.; Xi, X.; Yang, S.; Cai, M. Technology strategies to achieve carbon peak and carbon neutrality for China's metal mines. *Int. J. Miner. Metall. Mater.* **2022**, *29*, 626–634. [CrossRef]
18. Chambi-Legoas, R.; Ortega Rodriguez, D.R.; Figueiredo, M.D.; Pena Valdeiglesias, J.; Zevallos Pollito, P.A.; Marcelo-Pena, J.L.; Rother, D.C. Natural Regeneration After Gold Mining in the Peruvian Amazon: Implications for Restoration of Tropical Forests. *Front. For. Glob. Chang.* **2021**, *4*, 594627. [CrossRef]
19. Du, T.; Wang, J.; Wang, H.; Tian, X.; Yue, Q.; Tanikawa, H. CO^2 emissions from the Chinese cement sector: Analysis from both the supply and demand sides. *J. Ind. Ecol.* **2020**, *24*, 923–934. [CrossRef]
20. Zhang, Z.; Song, G.; Chen, J.; Zhai, Z.; Yu, L. Development of a Simplified Model of Speed-Specific Vehicle-Specific Power Distribution Based on Vehicle Weight for Fuel Consumption Estimates. *Transp. Res. Rec.* **2020**, *2674*, 52–67. [CrossRef]
21. Ministry of Ecology and Environement of the People's Republic of China. Enterprise Greenhouse Gas Emission Accounting Methods and Reporting Guidelines Power Generation Facilities (2022 Revision). Available online: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202203/W020220315357528424119.pdf (accessed on 20 March 2022). (In Chinese)
22. Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Calculate Inventories*; IPCC: Geneva, Switzerland, 2006.
23. Zeng, Z.X.; Guo, J.M.; Wei, X.Y.; Lü, E.; Liu, Y. The Analysis of Cooling Time and Energy Consumption of VAV Fan-pad Evaporative Cooling Systems in a Greenhouse. *Hortscience* **2020**, *55*, 812–818. [CrossRef]
24. Shi, H. The value assessment of copper mining right from the perpective of carbon emission cost. *Sci. Technol. Ind.* **2022**, *22*, 198–203. (In Chinese)
25. Cox, B.; Innis, S.; Kunz, N.C.; Steen, J. The mining industry as a net beneficiary of a global tax on carbon emissions. *Commun. Earth Environ.* **2022**, *3*, 17. [CrossRef]