

Article

# Uncovering Cleaner Method for Underground Metal Mining: Enterprise-Level Assessment for Current and Future Energy Consumption and Carbon Emission from Life-Cycle Perspective

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**Abstract:** China has committed to peak its carbon emissions by 2030, which puts forward a new issue for underground metal mines—selecting a cleaner mining method which requires less energy and generates less carbon emissions. This paper proposes an enterprise-level model to estimate life-cycle energy consumption and carbon emissions, which takes more carbon sources (e.g., cement and carbon sink loss) into consideration to provide more comprehensive insights. Moreover, this model is integrated with the energy-conservation supply curve and the carbon abatement cost curve to involve production capacity utilization in the prediction of future performance. These two approaches are applied to 30 underground iron mines. The results show that (1) caving-based cases have lower energy consumption and carbon emissions, i.e., 673.64 GJ/kt ore, 52.21 GJ/kt ore (only considering electricity and fossil fuel), and 12.11 CO<sub>2</sub> eq/kt ore, as compared the backfilling-based cases, i.e., 710.08 GJ/kt ore, 63.70 GJ/kt ore, and 40.50 t CO<sub>2</sub> eq/kt ore; (2) caving-based cases present higher carbon-abatement potential (more than 12.95%) than the backfilling-based cases (less than 9.68%); (3) improving capacity utilization facilitates unit cost reduction to mitigate energy consumption and carbon emissions, and the energy-conservation and carbon-abatement potentials will be developed accordingly.

**Keywords:** metal mining; energy consumption; carbon dioxide emission; life cycle assessment; conservation supply curve; abatement cost curve



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## 1. Introduction

Under the driving effect of more than 1.4 billion people and fast-growing economy [1], China has been the largest carbon emitter since 2007, as well as the largest energy consumer since 2010 [2,3]. To mitigate global climate change, China announced a series of ambitious long-term targets, e.g., peaking carbon emission by 2030 [4], and carbon neutrality around 2060 [5]. This poses a new problem for China's underground metal mines—selecting a cleaner method to extract minerals, which requires less energy and generates fewer carbon emissions [6].

Open-stope, caving, and backfilling are three conventional and mainstream mining methods for underground metal mines [7–10]. The caving method is favored due to high cost efficiency [11], but the surface subsidence associated still heavily restricts its application [12,13]. Considering the increasing public concern for surface subsidence [14], more and more projects employ the backfilling method, because it can preserve the ground surface by backfilling and supporting the void after deposit excavation [15]. Moreover, many projects initially by open stope also backfill their voids subsequently, to protect the ground

surface, and the open-stope method is rarely employed individually in China's underground metal mines now [16,17]. Considering the advantage of ground surface preservation, some researchers have regarded the backfilling method (including conventional backfilling and subsequent backfilling after open stope) as the cleaner mining method [18,19]. However, such analysis is still inadequate, because cleaner production aims to mitigate environment impact of industrial production from a life-cycle perspective [20,21].

Life-cycle assessment (LCA) is a systematical framework to assess environmental impact of industrial production [22], and it has been applied to test energy consumption and carbon emissions in metal mining sector. Norgate and Haque [23] carried out an LCA on the energy consumptions and carbon emissions in the production for iron, bauxite, and copper concentrates in Australia. Farjana et al. [24] divided the life cycle of aluminum production into four steps, i.e., bauxite extraction, alumina production, smelting, and ingot casting, and the energy consumption of aluminum produced in China was estimated accordingly. Memary et al. [25] analyzed the variation of life-cycle carbon emissions of Australia's copper production between 1940 and 2008. Shao et al. [26] calculated the carbon emissions of China's ferrous and non-ferrous metal mining sector and five sub-sectors. Due to the challenges associated with both the engineering-based model on enterprise level, and the accessibility of input data required, previous life-cycle analysis is generally conducted based on economic or statistical data on the national, regional, or sectoral level. Evidently, such macroscale and rough assessments cannot provide detailed information to screen the cleaner mining method from open-stope, caving, and backfilling, e.g., life-cycle energy consumption and the carbon emissions from the metal minerals extracted from the deposit by various mining methods.

Due to the inevitable conflict between economic development, energy conservation and carbon emission reduction, predicting energy conservation and carbon-abatement potential has become a critical issue in numerous industrial sectors [27,28]. Such predictions are critically important for both government and enterprise, because macro-scale fiscal policy and enterprise-level investment strategies are based upon them [29–31]. The conservation supply curve (CSC) and abatement cost curve (ACC) are most popular bottom-up tools for such prediction, and they have been applied in some energy-intensive and carbon-intensive sectors, power generation, cement, iron and steel [32–35]. Chen et al. [36] analyzed the cost and potentials of energy conservation in China's coal-fired power sector under the uncertainties of coal and carbon price by the CSC involving 32 technologies. Toleikyte et al. [37] tested the contribution of 30 technologies to save energy, if they were deployed in the building sector in Lithuania, and a promotion portfolio was established by cost-effective analysis based on the ACCs of these technologies. Long et al. [38] utilized the CSC approach to predict the potential of China's iron and steel sectors to reduce the emissions of greenhouse gases by 2030 in multiple scenarios. Liu et al. [39] constructed a supply curve of energy and electricity for 23 technologies, and proposed a technology promotion roadmap for saving energy and reducing carbon emissions in China's cement sector.

Although the CSC and ACC approaches have been widely discussed, some drawbacks still restrict them from being used in this study. The first drawback is the absence of consideration for the difference between production capacity and actual output, i.e., capacity utilization. In previous studies, the investment in and the contribution of a technology to mitigate energy consumption and carbon emissions were calculated based on production capacity. However, it seems that such contributions heavily depend on the actual output, rather than production capacity, because the accumulated contributions of multiple technologies cannot exceed the energy consumed or carbon emissions generated on-site. Another drawback is that they assume the unit energy-conservation or carbon abatement cost of a technology is constant over the entire range of application. Due to the close relationship between the actual output and the contribution of a technology to saving energy and reducing carbon emissions, it can be expected that the unit cost should vary in the projects with different capacity utilization.

Therefore, due to the absence of either a detailed inventory or robust approach, it is still an intractable issue to uncover the cleaner mining method from open-stope, caving, and backfilling, especially under the consideration of both current and future performance regarding energy consumption and carbon emissions of metal miners from a life-cycle perspective. In order to bridge this research gap, we established an enterprise-level model to estimate present life-cycle energy consumption and carbon emissions. Moreover, this life-cycle model is integrated with the CSC and ACC approach to predict future performance. Eventually, 30 underground iron mines are involved as case studies to uncover the cleanest mining method. This work contributes to the existing literature from both theoretical and practical perspectives. Theoretically, it provides a robust approach to test the current and future life-cycle energy consumption and carbon emissions of metal mineral extraction by underground mining to guide policy design or improvement. In practice, this model can provide detailed predictions of various technologies to mitigate energy consumption and carbon emissions in different projects, which means it facilitates the determination of whether a technology should be employed.

## 2. Materials and Methods

### 2.1. System Boundary Definition

The research scope of this study is the entire life cycle of minerals extraction in underground metal mines, from deposit discovery to raw ore being transported to dressing plants. This life cycle can be categorized into nine stages, e.g., ventilation, drilling, blasting, supporting, loading, haulage, crushing, backfilling, and dewatering. Three type of energy are considered in the life-cycle assessment for energy consumption, i.e., electricity, fossil fuels, and industrial explosives. In addition to these energies, we also take cement and carbon sink loss into account as carbon sources, which are rarely assessed as such in the existing literature. This system boundary defined is valid not only for assessing life-cycle energy consumption and carbon emissions at present, but also for predicting energy conservation and carbon abatement potential in the future. Additionally, it should be noted that the functional unit has been defined to be per kiloton extracted metal ore to unify the results of various indicators from different cases.

### 2.2. Life Cycle Assessment for Energy Consumptions and Carbon Emissions

The model to estimate life-cycle energy consumptions and carbon emissions by energy type (or carbon source) is described below.

#### 2.2.1. Electricity

Electricity is the predominant energy source in underground metal mines to maintain a favorable environment at the underground working faces [40]. Equations (1) and (2) are proposed to quantify the energy consumption and indirect carbon emissions from electricity-powered equipment, respectively.

$$EC^{EL} = \frac{\sum_i \alpha \cdot P_i \cdot t_i^{EL}}{Q^{Ore}} \quad (1)$$

$$CE^{EL} = \frac{\sum_i EF^{EL} \cdot P_i \cdot t_i^{EL}}{Q^{Ore}} \quad (2)$$

where  $EC^{EL}$  and  $CE^{EL}$  are the unit energy consumption and unit carbon emission from electricity-powered mining equipment, respectively;  $\alpha$  is a coefficient to standardize the unit of energy consumption;  $EF^{EL}$  is the carbon emission factor of electricity;  $P_i$  is the power of mining equipment  $i$ ;  $t_i^{EL}$  is the operating time of electricity-powered mining equipment  $i$  annually; and  $Q^{Ore}$  is the annual yield of minerals in a underground metal mine.

### 2.2.2. Fossil Fuel

Fossil fuel is another primary energy source, especially in the development engineering, due to its advantage of flexibility. Consuming fossil fuel leads to both direct and indirect carbon emissions which occur in their production and combustion, respectively [41–43]. The energy consumption and carbon emissions related to fossil fuels can be calculated by Equations (3) and (4), respectively.

$$EC^{FF} = \frac{\sum_j \sum_i (NCV_j)^{-1} \cdot Q_{i,j}^{FF} \cdot t_i^{FF}}{Q^{Ore}} \quad (3)$$

$$CE^{FF} = \frac{\sum_j \sum_i EF_j^{FF} \cdot Q_{i,j}^{FF} \cdot t_i^{FF}}{Q^{Ore}} \quad (4)$$

where  $EC^{FF}$  and  $CE^{FF}$  are the unit energy consumption and unit carbon emissions related to fossil fuels, respectively;  $NCV_j$  is the net calorific value of the fossil fuel  $j$ ;  $EF_j^{FF}$  is the carbon emission factor of fossil fuel  $j$ ;  $Q_{i,j}^{FF}$  is the consumption of fossil fuel  $j$  by mining equipment  $i$  in unit time; and  $t_i^{FF}$  is the annual operating time of mining equipment  $i$  powered by fossil fuel.

### 2.2.3. Industrial Explosive

Underground metal mines utilize the energy released by industrial explosives in blasting reactions to break intact hard rocks. Producing industrial explosives generates indirect carbon emissions, but the direct emissions depend on the proportion of blasting agents and additives [44]. Equations (5) and (6) are valid to estimate the energy released in blasting reaction and the carbon emissions, respectively.

$$EC^{IE} = \sum_j DH_j \cdot Q_j^{IE} \quad (5)$$

$$CE^{IE} = \sum_j EF_j^{IE} \cdot Q_j^{IE} \quad (6)$$

where  $EC^{IE}$  and  $CE^{IE}$  are the unit energy consumption and unit carbon emission due to industrial explosives, respectively;  $DH_j$  is the detonation heat of the industrial explosive  $j$ ;  $EF_j^{IE}$  is the carbon emission factor of the industrial explosive  $j$ ; and  $Q_j^{IE}$  is the consumption of industrial explosive  $j$  to break unit quantity of rocks.

### 2.2.4. Cement

Cement is required in underground metal mines using either the open-stope, caving or backfilling methods to enhance the stability of shafts, tunnels, and chambers. But backfilling-based mines require much more cement to cement the materials backfilled into the void after deposit excavation [45]. Although no energy consumption related to cement takes place in the mining site, indirect carbon emissions still occur, such as carbon dioxide emitted in limestone quarries and clinker plants [46,47]. Such indirect carbon emissions can be quantitatively described by Equation (7).

$$CE^C = \frac{\sum_i EF^C \cdot Q^C}{Q^{Ore}} \quad (7)$$

where  $CE^C$  is the unit carbon emission due to consumed cement;  $EF^C$  is the carbon emission factor of cement; and  $Q^C$  is the annual consumption of cement.

### 2.2.5. Carbon Sink Loss

In the underground metal mines using the open stope or caving methods, large-scale subsidence is commonly observed on ground surface [48]. The destruction of vegetation raises

direct carbon emissions, which can be quantitatively described by the net primary production (NPP) [49,50]. And the carbon emission can be calculated by Equation (8), accordingly.

$$CE^{CSL} = \frac{\beta \cdot (NPP' - NPP_0) \cdot S}{Q^{Ore}} \quad (8)$$

where  $CE^{CSL}$  is the unit carbon emission due to carbon sink loss;  $\beta$  is a coefficient to convert the NPP to carbon emissions;  $NPP_0$  and  $NPP'$  are the NPPs of the vegetation on the ground surface before and after subsidence, respectively; and  $S$  is the area of the pit formed after surface subsidence.

If the inputs listed in Equations (1)–(8) have been provided, the life-cycle unit energy consumption and unit carbon emission in an underground metal mine can be estimated by Equations (9) and (10), respectively.

$$EC = \sum_k EC^k \quad (9)$$

$$E = \sum_k CE^k \quad (10)$$

where  $EC$  and  $CE$  are the unit energy consumption and unit carbon emission of the minerals in the life cycle from deposit to the gate of dressing plants, respectively; and  $EC^k$  and  $CE^k$  are the unit energy consumption and unit carbon emission due to the energy or carbon source  $k$ .

Equations (1)–(10) are the model proposed to assess the life-cycle energy consumption and carbon emission of the minerals extracted from underground metal mines.

Compared with existing models, this approach extends the scope of energy and carbon sources by taking industrial explosive, cement, and carbon sink loss into consideration. Hence, it can be expected to provide comprehensive insight into the environmental impact of underground metal mining sector. Moreover, this approach utilizes engineering-based data as inputs, this enables it to relate energy consumption and carbon emission directly to the mining equipment and stage. This means it has the potential to be integrated with the CSC and ACC approach to include production capacity utilization in assessments of energy-conservation and carbon-abatement potentials.

### 2.3. Bottom-Up Assessment for Energy-Conservation and Carbon-Abatement Potential

Mining method selection is a strategic decision, which means not only the current but also the future performance of energy consumption and carbon emissions are critical concerns. To develop the accuracy of the assessment for energy-conservation and carbon-abatement potentials on enterprise level, we integrate the LCA model proposed with the ECSC and CACC approaches to take capacity utilization into account. The contribution of energy-saving technology and reduced carbon emissions can be estimated by Equations (11) and (12), respectively.

$$ECM_{n,t} = \frac{EC_t^i}{EC^{CAP}} \cdot UECM_n^0 \cdot CAP_n^i \quad (11)$$

$$CEM_{n,t} = \frac{CE_t^i}{CE^{CAP}} \cdot UCEM_n^0 \cdot CAP_n^i \quad (12)$$

where  $ECM_{n,t}$  and  $CEM_{n,t}$  are the potentials of technology  $n$  to mitigate energy consumption and carbon emission in year  $t$ , respectively;  $EC_t^i$  and  $CE_t^i$  are the energy consumption and carbon emissions due to mining equipment  $i$  in year  $t$  occurring on-site, which can be estimated by the LCA model proposed;  $EC^{CAP}$  and  $CE^{CAP}$  are the energy consumption and carbon emissions in the original design, respectively;  $UECM_n^0$  and  $UCEM_n^0$  are unit contribution of technology  $n$  to saving energy and reducing carbon emissions, which can be derived from the illustrative examples employing this technology; and  $CAP_n^i$  is the installed capacity of mining equipment  $i$ , to which that technology  $n$  will be deployed.

On the other hand, the investment in a technology still depends on the installed capacity, and the associated cost to save unit energy or reduce unit carbon emissions can be calculated by Equations (13) and (14), respectively.

$$C_n^{ECM} = \frac{\sum_t^{t_n} \left[ \frac{(\gamma \cdot UI_n \cdot CAP_n^i + \Delta OM_{n,t})}{(1+r)^t} \right] - P^C \cdot \sum_t^{t_n} CEM_{n,t}}{\sum_t^{t_n} ECM_{n,t}} \quad (13)$$

$$C_n^{CEM} = \frac{\sum_t^{t_n} \left[ \frac{(\gamma \cdot UI_n \cdot CAP_n^i + \Delta OM_{n,t})}{(1+r)^t} \right] - P^E \cdot \sum_t^{t_n} ECM_{n,t}}{\sum_t^{t_n} CEM_{n,t}} \quad (14)$$

where  $C_n^{ECM}$  and  $C_n^{CEM}$  are the unit cost to mitigate energy consumption and carbon emission by employing technology  $n$ ;  $t_n$  is the lifetime of technology  $n$ ;  $\gamma$  is a coefficient to spread investment for technology  $n$  over its lifetime, which can be calculated by  $\gamma = r \cdot [1 - (1+r)^{-t_n}]$ ;  $r$  is the discount rate;  $UI_n$  is the unit investment for technology  $n$ , which can be calculated derived from the illustrative examples;  $\Delta OM_{n,t}$  is the additional cost for operating and maintaining technology  $n$ ;  $\gamma$  is a coefficient to spread investment for technology  $n$  over its lifetime, which can be calculated by  $\gamma = r \cdot [1 - (1+r)^{-t_n}]$ ;  $r$  is the discount rate; and  $P^C$  and  $P^E$  are the price of carbon and energy, respectively.

Equations (13) and (14) enable the break-even analysis to determine the employment of a technology [51], such as Equations (15) and (16).

$$\Delta_n^E = C_n^{ECM} - P^E \quad (15)$$

$$\Delta_n^C = C_n^{CEM} - P^C \quad (16)$$

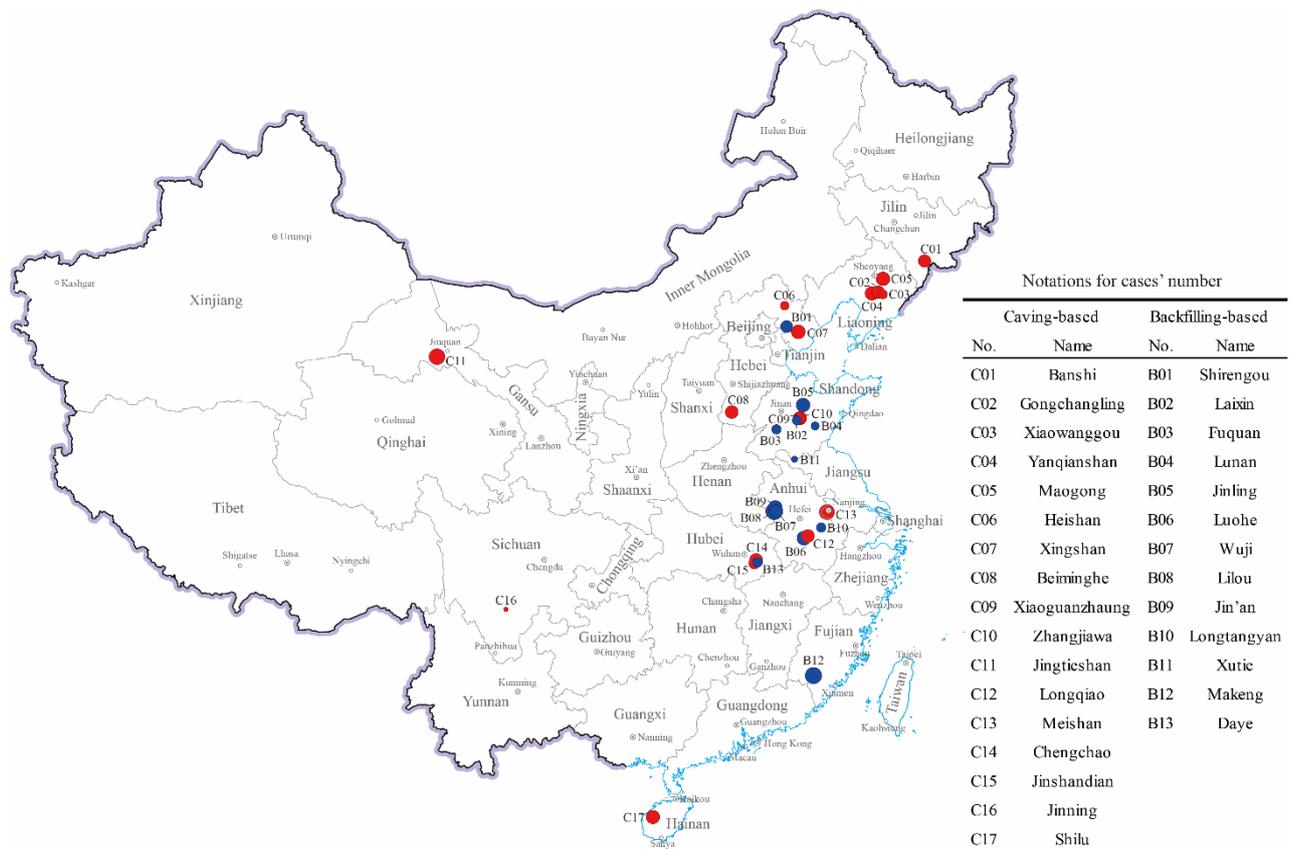
where  $\Delta_n^E$  and  $\Delta_n^C$  are the indicators for the cost-effectiveness of technology  $n$ ; and the employment of a technology can be determined by testing whether  $\Delta_n^E > 0$  or  $\Delta_n^C > 0$  is satisfied.

Eventually, the potential of an underground metal mine to save energy or reduce carbon emissions can be predicted by accumulating the contributions of these cost-effective technologies. Compared with the conventional ECSC and CACC approaches, this approach eliminates the negative impact of some assumptions on the results. Firstly, the production capacity utilization is considered in accordance with the difference between on-site energy consumption (or carbon emissions) and the value in original design. Secondly, the assumption of constant unit cost is avoided.

#### 2.4. Data Source

In total, 30 of China's underground iron mines from 11 provinces were selected for this study, including 17 caving-based and 13 backfilling-based cases, as illustrated in Figure 1. The total yield is more than 70 million t iron ore per year, comprising ~34% of China's iron ore production from underground projects in 2019. The results proposed in this work can be expected to represent the national common level. An inventory analysis was conducted to obtain the inputs for estimating life-cycle of energy consumptions and carbon emissions, as presented in Appendix A.

We applied the developed ECSC and CACC approaches to 8 projects from these 30 cases to uncover the difference between caving-based or backfilling-based cases to save energy and reduce carbon emissions. Table 1 lists 15 the energy conservation and carbon abatement (ECCA) technologies, promoted to the underground mining sector by China's NDRC [52]. More detailed information is provided in Appendix B. Additionally, some assumptions should be noted, i.e., the discount rate is 15% [53], and the energy and carbon prices equal to 100 CNY/GJ and 100 CNY/t CO<sub>2</sub> eq, respectively.



**Figure 1.** Distribution of underground iron mines involved in this study. The marks for case positions are colored according to the mining method they utilized, i.e., red and blue represent caving and backfilling methods, respectively. The size of the marks indicates their yields in 2019.

**Table 1.** Energy conservation and carbon abatement technologies.

No.	Name of Technologies	Affiliation
T01	Curved blade series centrifugal fan technology	Fan system
T02	Permanent magnet eddy current flexible transmission	Fan system
T03	Two-stage oil injection high efficiency screw air compressor	Drills
T04	Cleaner and efficiency-enhanced fuel for vehicle	Fossil-fueled LDH
T05	Intelligent engine cooling	Fossil-fueled LDH
T06	Potential Energy Recovery in Excavators	Electric LDH
T07	Speed control for frequency converter	Crusher
T08	Cast copper rotors for electric motors	Vibration feeder
T09	Hybrid AC drive shunting locomotive	Electric locomotive
T10	Frequency conversion system for belt conveyor	Belt conveyor
T11	Three-phase sampling and fast response electromotor	Hoister
T12	High voltage variable frequency modulated speed system	Hoister
T13	Frequency conversion optimization control system	Water pump
T14	Optimizing user-side voltage quality by electromagnetic balance regulation	Backfilling equipment
T15	Energy-saving copper-clad aluminum tube bus	Power bus

### 3. Results

#### 3.1. Energy Consumptions and Carbon Emissions

##### 3.1.1. Life-Cycle Energy Consumption

Figure 2 provides the results of life cycle assessment for energy consumption in 30 underground iron mines. We calculated the average energy consumption in either caving-based or backfilling-based cases to test the difference, and the results were 673.64

and 710.08 GJ/kt, respectively. However, such results are still insufficient to demonstrate that the caving method is more effective in energy consumption than the backfilling, due to the predominant role of explosive-related energy. For instance, the energy consumption in Jin'an (B09, 605.83 GJ/kt) is higher than that in Xiaoguanzhuang (C09, 595.73 GJ/kt). But if the explosive-related energy is ruled out, Jin'an's energy consumption (36.14 GJ/kt) falls below that in Xiaoguanzhuang (64.97 GJ/kt). Thus, we compared only the energy consumption involving electricity and diesel between the caving-based and backfilling-based cases, to eliminate the interference of industrial explosives, as listed in Table 2.

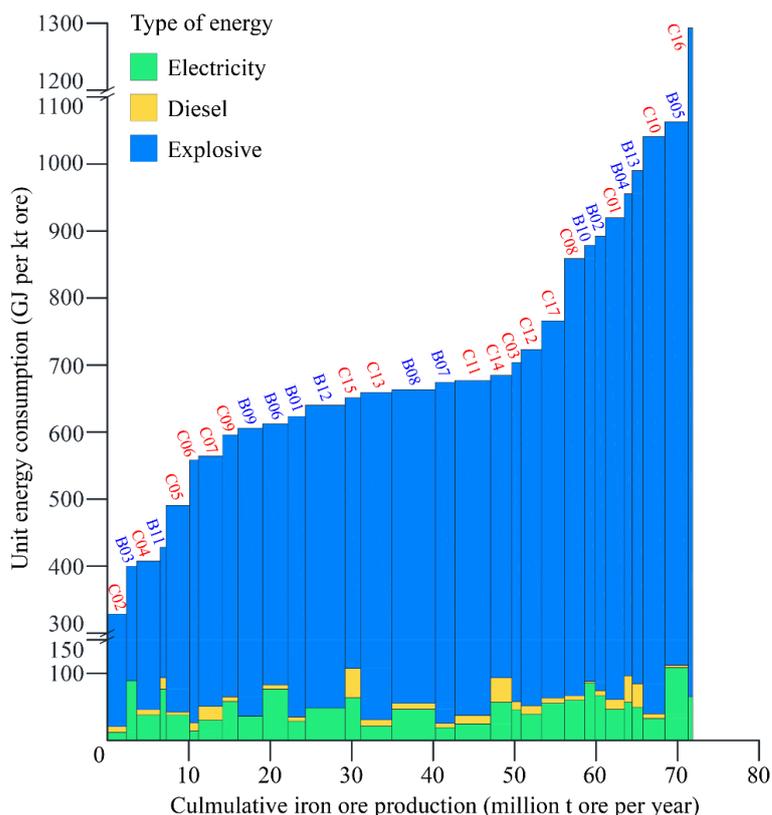


Figure 2. Energy intensity supply curve of the involved underground iron mines.

When only the energy consumption related to electricity and fossil fuel are considered, Table 2 shows more that caving-based cases (9 of 17) present lower energy consumption (colored by blue), than backfilling-based cases (5 of 13). Particularly, the energy consumption due to electricity was much lower in the caving-based (38.85 GJ/kt, average-weighted), than in the cases using the backfilling method (56.68 GJ/kt, average-weighted). This accounts for the phenomenon that caving-based cases require less energy (52.21 GJ/kt, average-weighted) than the backfilling-based (63.70 GJ/kt, average-weighted), although they consume more fossil fuels (13.36 GJ/kt and 7.02 GJ/kt for the caving-based and backfilling-based average-weighted, respectively). Thus, the results of the LCA illustrated in Figure 2 and Table 2 demonstrate that caving method is superior to backfilling in energy consumption.

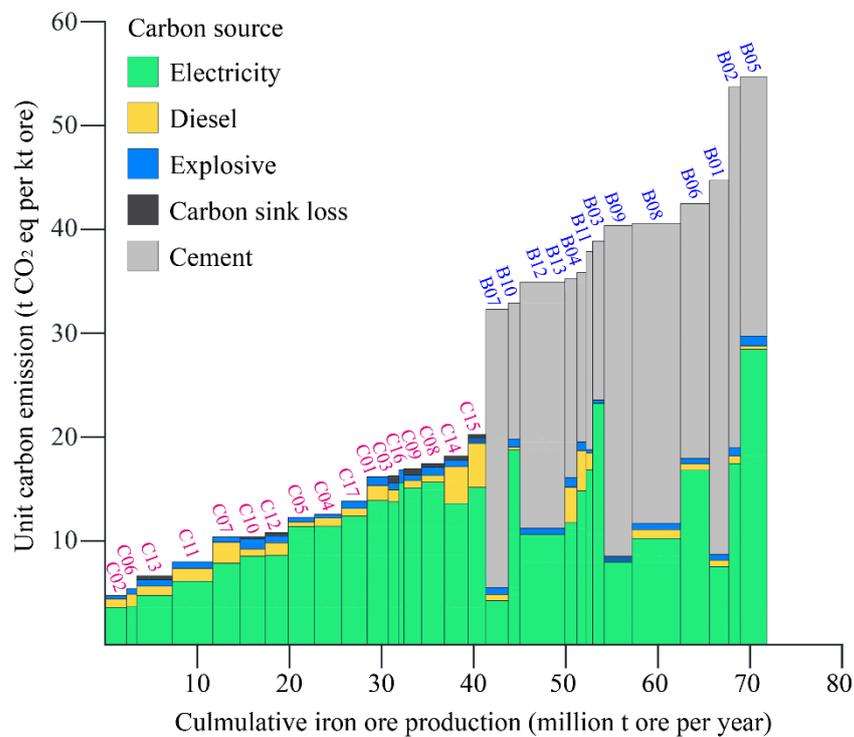
### 3.1.2. Life-Cycle Carbon Emissions

Figure 3 provides the carbon intensity supply curve of the 30 underground iron mines, and it explicitly shows that the carbon emissions in caving-based cases are much lower than that in the backfilling-based cases. In the caving-based cases, the carbon emissions varied between 4.73 t CO<sub>2</sub> eq/kt (C02, Gongchangling) and 20.25 t CO<sub>2</sub> eq/kt (C15, Jinshandian), and the weighted average was 12.11 t CO<sub>2</sub> eq/kt. Meanwhile, these values in the backfilling-based increases from 32.30 t CO<sub>2</sub> eq/kt (B07, Wuji) to 50.47 t CO<sub>2</sub> eq/kt (B05, Jinling), and

the weighted average was 40.50 t CO<sub>2</sub> eq/kt. This means that the caving method is also superior to backfilling in carbon emissions.

**Table 2.** Energy consumption without the consideration of industrial explosives. The results are colored by red and blue in varying intensity to indicate the difference between the results of each case and the average overall, i.e., 46.42, 10.67, and 57.09 GJ/kt for  $EC^{EL}$ ,  $EC^{FF}$ , and sum of  $EC^{EL}$  and  $EC^{FF}$ , respectively.

No.	Caving-Based Cases			No.	Backfilling-Based Cases		
	$EC^{EL}$	$EC^{FF}$	Sum		$EC^1$	$EC^2$	Sum
C02	11.92	8.69	20.61	B07	19.26	6.15	25.41
C06	14.08	12.16	26.24	B01	28.76	6.19	34.96
C13	21.49	9.29	30.78	B09	36.14	—	36.14
C11	24.66	12.74	37.4	B12	48.31	—	48.31
C10	32.58	7.14	39.72	B08	46.48	8.73	55.21
C05	37.87	4.42	42.29	B02	66.71	7.55	74.26
C04	37.98	7.91	45.89	B06	76.36	6.37	82.73
C07	29.95	20.84	50.79	B13	49.32	35.14	84.46
C12	39.06	12.6	51.66	B10	85.25	2.77	88.02
C03	45.79	11.82	57.61	B03	88.81	—	88.81
C01	46.15	14.87	61.02	B11	76.5	16.82	93.32
C17	55.37	7.7	63.07	B04	56.66	39.66	96.33
C09	57.67	7.3	64.97	B05	108.72	3.49	112.21
C16	65.45	—	65.45				
C08	59.83	6.64	66.47				
C14	57.02	36.44	93.47				
C15	63.47	43.8	107.27				



**Figure 3.** Carbon intensity supply curve of 30 underground iron mines.

The contribution of each carbon source is also illustrated in Figure 3, which explains the underlying drivers for the difference of carbon emission in either the caving-based or backfilling-based cases. It can be observed that the carbon emissions in the caving-based cases were dominated by electricity (more than 68.32%), and the contribution of carbon sink loss was less than 5.67%. In some caving-based cases, such as C01 (Banshi), C02 (Gongchangling), C04 (Xiaowanggou), C05 (Maogong), C06 (Heishan), C07 (Xingshan), C11 (Jingtieshan), C16 (Jining), and C17 (Shilu), no carbon emissions related to carbon sink loss occurred, because the underground mining was implemented after surface mining. Surface mining, rather than underground caving, is responsible for the destruction of ground vegetation and the associated carbon sink loss.

In the backfilling-based cases, cement is another primary contributor to carbon emission, besides electricity. And cement's contribution heavily depends on the cement-sand ratio of the slurry backfilled into the void after deposit excavation. For instance, in cases utilizing a lower cement-sand ratio slurry, e.g., B03 (Fuquan, cement-sand ratio is 1:12) and B10 (Longtangyan, cement-sand ratio is 1:10), the contribution is obviously lower than that in other cases (cement-sand ratio higher than 1:8). This reveals that lowering the cement-sand ratio is a robust approach to mitigate carbon emissions in backfilling-based underground metal mines, in addition to the conventional approaches focused on conserving electricity and fossil fuel.

It should be noted that the energy consumption in China's caving-based iron mines (Table 2) is similar to the inventory in the existing literature. For instance, the energy consumption in Kiruna iron mine, Sweden, is 46.728 GJ/kt, and contribution of electricity and fossil fuel are 41.4 and 5.328 GJ/kt, respectively [54]. Such results validate the results in this study, although it is difficult to compare the results of carbon emissions directly because the carbon emission factor of electricity significantly varies in different countries. The results of life cycle assessments for energy consumption and carbon emissions in 30 underground metal mines demonstrate that caving is cleaner than backfilling for deposit excavation. This phenomenon is opposite to the view in the existing literature [18,19], because those studies only considered environmental impacts due to surface destruction, rather than from a life cycle perspective. This indicates a one-sided preference is very likely to mislead policy decisions. For instance, the promotion of the backfilling method will raise the energy consumption and carbon emissions of China's metal mining sector. On the other hand, the results also indicate that energy conservation and carbon abatement actions for underground metal mines should primarily focus on mitigating electricity consumption, but additional attention is required to reducing the cement-sand ratio of backfilling slurry in backfilling-based mines.

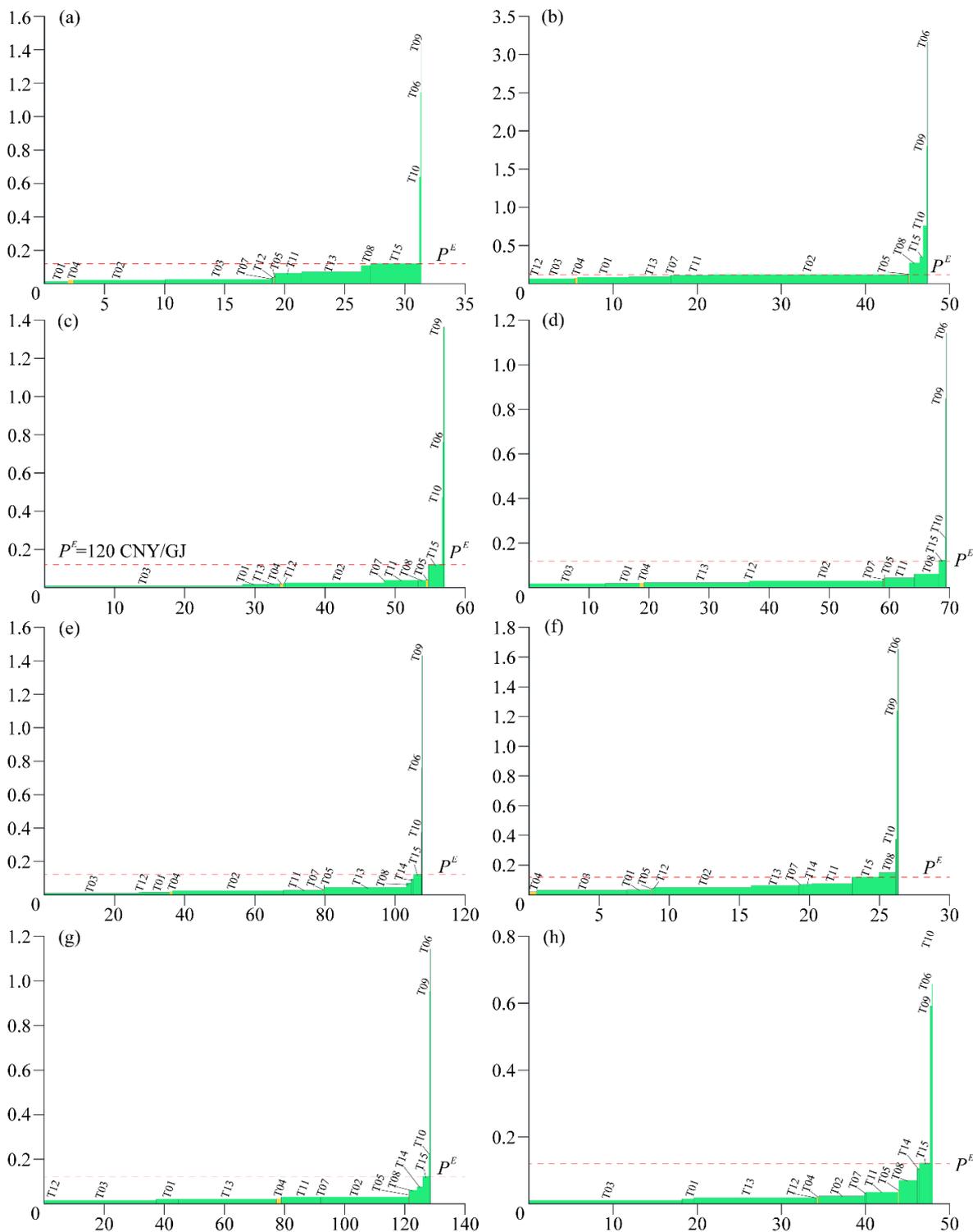
### 3.2. Energy Conservation and Carbon Abatement Potentials

#### 3.2.1. Energy Conservation Potentials

Figure 4 shows the ECSCs of 15 ECCA technologies (Table 2), when they are applied to the selected caving-based (i.e., Xiaowanggou (C03), Yanqianshan (C04), Maogong (C05), and Shilu (C17)), and backfilling-based cases (i.e., Luohe (B06), Wuji (B07), Lilou (B08), and Longtangyan (B10)). The production capacity utilization was calculated based on the energy consumption and carbon emissions occurring in 2019.

As can be seen from Figure 4, the unit costs to save energy present significant variations in the different cases. Yanqianshan (Figure 4b) present a much higher unit cost than other cases, because Yanqianshan's capacity utilization is lower than all the other cases, i.e., production capacity is 8 million t/a, and the outputs in 2019 is 2.9 million 8 million t/a. Such a low capacity utilization raises the unit cost to conserve energy, and further reduces the potential of Yanqianshan to save energy. When the prices of energy and carbon are equal to 120 CNY/GJ and 100 CNY/t CO<sub>2</sub> eq, Yanqianshan has the potential to reduce its energy consumption from 45.89 GJ/kt (without the consideration for the energy released in blasting reactions by industrial explosives, as listed in Table 2) to 38.47 GJ/kt, 16.17%. Meanwhile,

the energy-conservation in other cases was 40.97% (Xiaowanggou), 44.64% (Maogong), 38.48% (Shilu), 40.52% (Luohe), 37.56% (Wuji), 43.16% (Lilou), and 40.56% (Longtangyan).



**Figure 4.** Energy conservation supply curve for the underground iron mines by either the caving ((a) Xiaowanggou, (b) Yanqianshan, (c) Maogong, and (d) Shilu), or backfilling methods ((e) Luohe, (f) Wuji, (g) Lilou, and (h) Longtangyan). The vertical axis is the unit cost for saving energy, in k CNY/GJ, and the horizontal axis is the cumulative energy conservation potential, in TJ/a. The dotted line in red represents the break-even price of energy (PE), which equals 120 CNY/GJ. The colors indicate the type of energy that the ECCA technology targets for conservation, i.e., green and yellow represent electricity and fossil fuel, respectively.

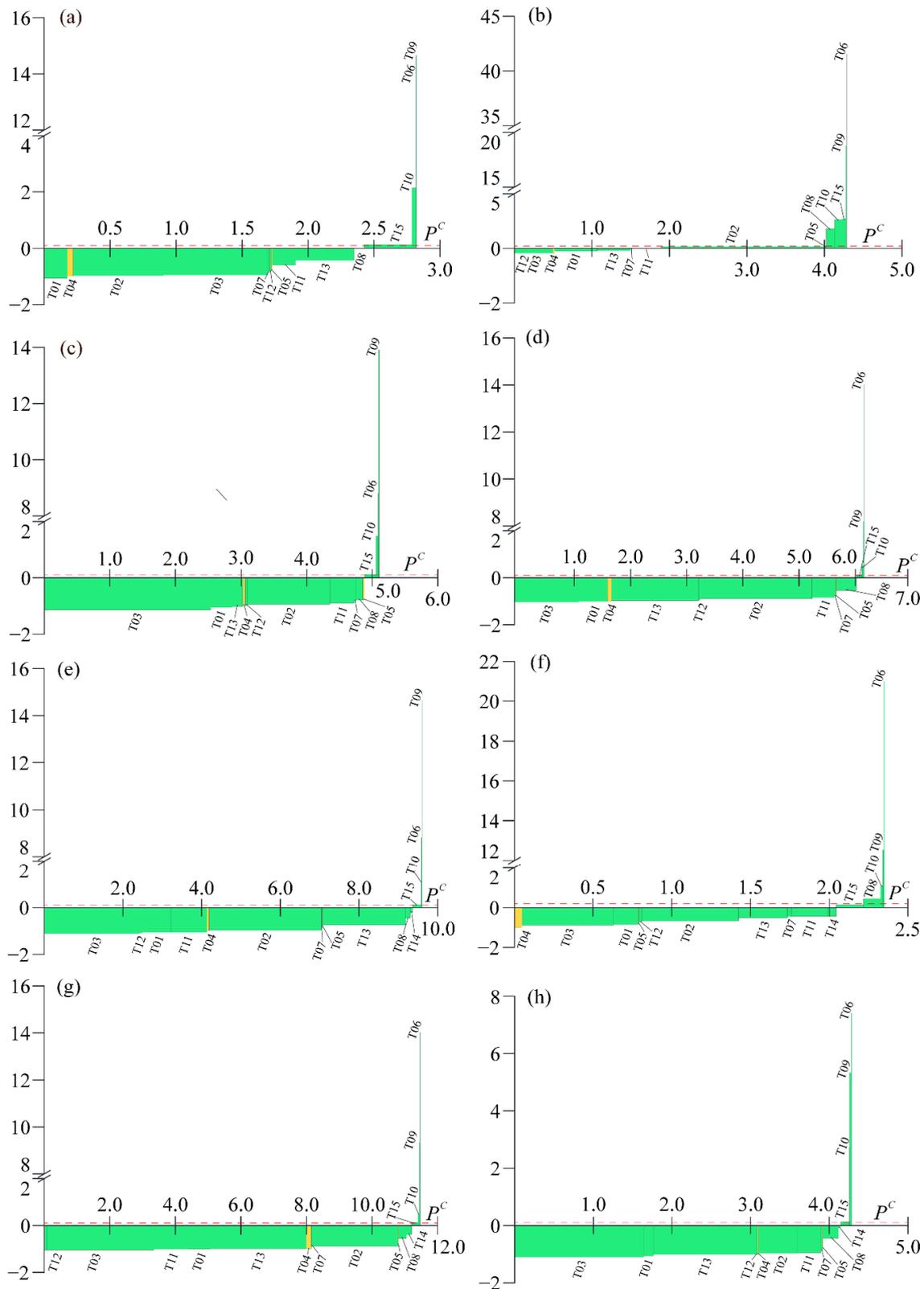
Apart from the case of Yanqianshan, the energy conservation potentials of the involved cases all varied around 40%, although the ECSCs present significant variation in each case. This reveals no significant difference of energy conservation potential can be observed between the caving-based and backfilling-based cases. However, because backfilling-based cases requires more energy to extract unit minerals at present, it can be expected the higher energy consumption in the projects using the backfilling method will continue in the future.

### 3.2.2. Carbon Abatement Potentials

Figure 5 provides the CACCs of 15 ECCA technologies, when they were deployed to the caving-based (i.e., Xiaowanggou (C03), Yanqianshan (C04), Maogong (C05), and Shilu (C17), or backfilling-based cases (i.e., Luohe (B06), Wuji (B07), Lilou (B08), and Longtangyan (B10)). Because the benefit from conserved energy surpasses the investment and additional operating and maintenance cost for employing these technologies, the unit carbon abatement cost of some technologies presents a negative value, such as T01 in Xiaowanggou (−1063.33 CNY/t CO<sub>2</sub> eq), T12 in Yanqianshan (−468.12 CNY/t CO<sub>2</sub> eq), T03 in Luohe (−1119.57 CNY/t CO<sub>2</sub> eq), and T04 in Wuji (−994.98 CNY/t CO<sub>2</sub> eq). This means these technologies will be utilized, no matter how high the carbon price.

The CAACs illustrated in Figure 5 enable the prediction of the future performance of carbon emissions in underground iron mines. When the prices of energy and carbon are equal to 120 CNY/GJ and 100 CNY/t CO<sub>2</sub> eq, the caving-based cases have the potentials to reduce the carbon emissions by 12.95% (in Xiaowanggou, from 14.38 to 12.52 t CO<sub>2</sub> eq/kt), 5.20% (in Yanqianshan, from 12.55 to 11.89 t CO<sub>2</sub> eq/kt), 13.73% (in Maogong, from 12.26 to 10.58 t CO<sub>2</sub> eq/kt), and 15.70% (in Shilu, from 13.81 to 11.64 t CO<sub>2</sub> eq/kt), respectively. The lower production utilization in Yanqianshan is responsible for this difference, because it raises the unit cost to reduce carbon emissions. Consequently, if Yanqianshan's production were to reach its designed capacity, its carbon abatement potential will significantly increase, because more ECCA technologies will be effective in the break-even analysis.

On the other hand, backfilling-based cases presented significant lower carbon-abatement potential than the caving-based cases, except Yanqianshan. For instance, the cases of Luohe, Wuji, Lilou, and Longtangyan had the potential to reduce their carbon emissions by 7.02% (from 42.51 to 39.62 t CO<sub>2</sub> eq/kt), 2.62% (from 32.30 to 31.45 t CO<sub>2</sub> eq/kt), 5.23% (from 40.56 to 38.44 t CO<sub>2</sub> eq/kt), and 9.68% (from 32.90 to 29.72 t CO<sub>2</sub> eq/kt), respectively. The absence of technology to lower the cement–sand ratio in backfilling slurry accounts for this phenomenon. As depicted in Table 1, ECCA technologies in the mining sector primarily work by saving electricity and fossil fuels, but the predominant role of cement in the carbon emissions from caving-based mining eliminates their potential to reduce carbon emissions. This demonstrates that technologies which can save cement and cement consumption in the backfilling stage are necessary for backfilling-based underground metal mines, in addition to the conventional ones promoted by China's NDRC.



**Figure 5.** Carbon abatement cost curve for the underground iron mines by either caving ((a) Xiaowanggou, (b) Yanqianshan, (c) Maogong, and (d) Shilu), or backfilling method ((e) Luohe, (f) Wuji, (g) Lilou, and (h) Longtangyan)). The vertical axis is the unit cost for mitigating carbon emissions, in k CNY/t CO<sub>2</sub> eq, and the horizontal axis is the cumulative carbon abatement potential in kt CO<sub>2</sub> eq/a. The dotted line in red represents the break-even price of carbon emissions (P<sup>C</sup>), which equals to 100 CNY/t CO<sub>2</sub> eq. The colors indicate the type of carbon source that the ECCA technology targets to save, e.g., green and yellow represent electricity and fossil fuel, respectively.

#### 4. Policy Implications

From the analysis in this work, we propose the following suggestions for policy design and implementation.

Firstly, before the policy-making process, a standardized model is necessary to assess the environmental impact of the underground metal mining sector, comprehensively. Existing studies regard backfilling as the cleaner mining method [18,19], because it can protect the ground surface from large-scale destruction. However, the quantitative results from a life-cycle perspective (Figures 2–5) explicitly show caving is cleaner. This phenomenon reveals that this one-sided preference is very likely to mislead the policy decisions, especially in the absence of sufficient inventory. Thus, policymakers need a series of standardized models to assess the various impacts of underground metal mines on the environment, which should emphasize indicator selection, system boundary definition, and the preference of policies.

Secondly, Chinese governments can promote the caving method for peaking the carbon emissions from underground metal mining sector by 2030. The results from 30 underground iron mines (Figures 3 and 4) show the caving-based mining has lower unit carbon emissions and higher carbon-abatement potential. If the productivity by the backfilling method is replaced by the caving method, the overall carbon emissions of China's metal supply will decrease accordingly.

Thirdly, China's government can implement a mandatory policy to define a threshold of production capacity utilization for underground metal mining sector. The results in Section 3.2 explicitly demonstrate that developing production capacity utilization facilitates a reduction to the unit cost of ECCA technologies to save energy and reduce carbon emissions. This means the threshold of production capacity utilization is an indirect but robust approach to motivate the enthusiasm of underground metal mines, because employing cost-effective ECCA technologies is a profitable decision.

#### 5. Conclusions

To peak the carbon emissions in underground mining sector by 2030, uncovering a cleaner method has been a critical concern for both mining enterprise and China's government. This paper proposes an enterprise-level model under the LCA framework to estimate the energy consumption and carbon emissions of underground metal mines, integrated with CSC and ACC, to include production capacity utilization in predictions of future performance. Detailed data from 30 underground iron mines are provided, which is a contribution due to the absence of sufficient inventory in the existing literature.

The results of the LCA demonstrate that caving is the cleaner method for deposit excavation from a life-cycle perspective. These cases require less energy (673.64 GJ/kt, 52.21 GJ/kt without industrial explosive) and generate less carbon emissions (12.11 t CO<sub>2</sub> eq/kt), than backfilling-based mines, i.e., 710.08 GJ/kt, 56.68 GJ/kt without industrial explosive, and 40.50 t CO<sub>2</sub> eq/kt. Additionally, although no significant difference of energy conservation potential can be seen among the cases using either the caving or backfilling methods, the carbon abatement potential in the caving-based method is much higher (from 5.20% to 15.70%) than in the backfilling-based cases (from 2.62% to 9.68%). These results show that backfilling is the cleaner mining method, and that the existing literature is no longer valid from life-cycle perspective, because they demonstrate a one-sided preference very likely to mislead policy decisions.

In accordance with the engineering-based data from 30 underground iron mines, some implications for policy design can be summarized. Firstly, a comprehensive inventory and standardized model, especially from a life-cycle perspective, is suggested to be employed for policy decisions, to mitigate the effect of the one-sided preference. Secondly, to peak the carbon emissions from China's metal mining sector, the promotion of the caving method is suggested. Thirdly, a mandatory policy to improve production capacity utilization is also proposed, because this tactic facilitates energy savings and reduces carbon emissions of underground metal mines by reducing the unit cost for employing ECCA technologies.

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## Appendix A

**Table A1.** Heat values and carbon emission factors of energy or carbon sources.

Carbon Source	Heat Values	Carbon Emission Factors	Note
Electricity	3.6 GJ/MWh	1.0826 tCO <sub>2</sub> /MWh [55]	Jilin, Liaoning
		0.9419 tCO <sub>2</sub> /MWh [55]	Hebei, Shandong
		0.8922 tCO <sub>2</sub> /MWh [55]	Gansu
		0.7921 tCO <sub>2</sub> /MWh [55]	Anhui, Jiangsu, Fujian
		0.8587 tCO <sub>2</sub> /MWh [55]	Hubei, Sichuan
Diesel	45.766 GJ/t	0.8042 tCO <sub>2</sub> /MWh [55]	Hainan
		4.4409 tCO <sub>2</sub> /t	
Industrial explosive	1438 GJ/t	1.4251 tCO <sub>2</sub> eq/t	Emulsion explosive
Cement		0.442 t CO <sub>2</sub> eq/t	
		0.590 kg C/m <sup>2</sup> ·a	Deciduous needleleaf forest
		0.759 kg C/m <sup>2</sup> ·a	Deciduous broadleaf forest
Carbon sink loss		1.058 kg C/m <sup>2</sup> ·a	Evergreen broadleaf forest

## Appendix B

**Table A2.** Inputs required for the energy conservation supply curve and carbon abatement cost curve of different ECCA technologies.

No.	Lifetime (a)	$UI_n$ (k CNY/unit)	$UES_n$ (TJ/unit)	$UCR_n$ (t CO <sub>2</sub> /unit)	Unit
T01	10	0.413	4.728	0.426	kW·a
T02	20	2.703	18.376	1.654	kW·a
T03	8	2.080	38.449	3.464	kW·a
T04	1	0.043	1.631	0.146	t diesel
T05	10	10.258	58.553	5.275	LDH·a
T06	15	0.200	0.114	0.008	kt ore·a
T07	5	0.193	3.006	0.271	kW·a
T08	20	6.000	37.511	3.380	kW·a
T09	15	0.870	2.064	0.186	kW·a
T10	20	3.571	4.396	1.119	kW·a
T11	20	0.500	3.941	0.315	kW·a
T12	20	0.022	0.272	0.024	kW·a

Table A2. Cont.

No.	Lifetime (a)	$UI_n$ (k CNY/unit)	$UES_n$ (TJ/unit)	$UCR_n$ (t CO <sub>2</sub> /unit)	Unit
T13	10	0.995	10.982	0.989	kW·a
T14	20	0.769	3.607	0.323	kW·a
T15	30	3310.345	7680.193	691.724	km·a

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