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Invited Review

Technology strategies to achieve carbon peak and carbon neutrality for China’s metal mines

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Abstract: Greenhouse gas (GHG) emissions related to human activities have significantly caused climate change since the Industrial Revolution. China aims to achieve its carbon emission peak before 2030 and carbon neutrality before 2060. Accordingly, this paper reviews and discusses technical strategies to achieve the “dual carbon” targets in China’s metal mines. First, global carbon emissions and emission intensities from metal mining industries are analyzed. The metal mining status and carbon emissions in China are then examined. Furthermore, advanced technologies for carbon mitigation and carbon sequestration in metal mines are reviewed. Finally, a technical roadmap for achieving carbon neutrality in China’s metal mines is proposed. Findings show that some international mining giants have already achieved their carbon reduction targets and planned to achieve carbon neutrality by 2050. Moreover, improving mining efficiency by developing advanced technologies and replacing fossil fuel with renewable energy are two key approaches in reducing GHG emissions. Green mines can significantly benefit from the carbon neutrality process for metal mines through the carbon absorption of reclamation vegetations. Geothermal energy extraction from operating and abandoned metal mines is a promising technology for providing clean energy and contributing to the carbon neutrality target of China’s metal mines. Carbon sequestration in mine backfills and tailings through mineral carbonation has the potential to permanently and safely store carbon dioxide, which can eventually make the metal mining industry carbon neutral or even carbon negative.

Keywords: carbon emissions; carbon neutrality; China’s metal mines; deep mining; mining efficiency.

1. Introduction

The atmospheric concentrations of greenhouse gases (GHGs) have significantly increased since the industrial revolution began. GHG emissions related to human activities have caused a temperature increase of approximately 1.0°C above preindustrial levels [1]. Through the Intergovernmental Panel on Climate Change, governments around the world have approved a special report on limiting the temperature increase to 1.5°C above preindustrial levels [1]. Global emissions should be reduced by approximately 7.6% every year for the next decades to meet the 1.5°C increase target [1].

At the general debate of the 75th session of the United Nations General Assembly in September 2020, China announced to achieve carbon dioxide (CO_2) emission peak before 2030 and carbon neutrality before 2060 [2]. After China’s pledge to carbon neutrality before 2060, the roadmap to achieve the goal is becoming clearer than ever. By 2030, China aims to lower its CO_2 emissions per unit of GDP by over 65% from that in 2005 [3]. The “dual carbon” targets will bring an extensive and profound systemic reform for the economy and society. Moreover, technologies related to carbon neutrality have become research hotspots in China and other major economic countries. Therefore, it is necessary to review and discuss how to achieve the carbon peak and carbon neutrality for each industrial sector.

GHG emissions from mining can be divided into three scopes: Scope 1 is the direct emissions from mining operations, including the consumption of fossil fuel and GHG leaking; Scope 2 is the indirect emissions from electricity purchased and used by mining operations; Scope 3 is all other indirect emissions from upstream and downstream activities related to purchased or sold goods and services [4]. Scope 3 emissions occur from out-of-control sources (e.g., emissions from processing mined iron ore to steel). In the past decades, considerable research has been performed on estimating GHG emissions from the mining industry. Northey *et al.* [4] estimated GHG emissions for 19 copper mining companies in 11 countries and found that the range of GHG emissions was 1–9 t CO_2e/t Cu, with an average of 2.6 t CO_2e/t Cu (CO_2e—carbon dioxide equivalent). They pointed out that the large variation is mainly caused by the copper produced, ore grade, fuel sources, and electrical energy. A decline in the ore grade generally resulted in high GHG emission intensities [4]. Li [5] analyzed the current situation and development trends of coal consumption and carbon emissions in China and discussed the main problems associated with the green and low-carbon development and utilization of

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coal. Yang *et al.* [6] investigated GHG emissions in the Pingshuo coal mining area and found that coalbed methane emissions and fuel consumption accounted for 46.66% and 41.79% of the total emissions, respectively. Azadi *et al.* [7] estimated that GHG emissions from metal and mineral productions were equivalent to approximately 10% of the total global energy-related GHG emissions in 2018.

To achieve carbon neutrality in the mining industry, some researchers have examined the benefits of current mining technologies on carbon emission reduction. Liu *et al.* [8] compared the energy consumption and carbon emissions of different transportation modes in open-pit coal mines. They found that CO_2 emissions from truck transportations were 3 to 10 times higher than those from belt conveyors. Carmichael *et al.* [9] explored the relationship between the optimal unit cost and optimal unit carbon emissions of surface mining and found that mining operation optimizations on the truck size, payload, fuel use, and travel and loading times can coincidently reduce the unit cost and emissions. Zhang *et al.* [10] developed a model to calculate the carbon sink from mine land reclamations and found that the reclamation in the Huaibei mining area can absorb 1.68×10^5 t CO_2 per year.

Furthermore, some new mining concepts and technologies have been recently proposed to achieve carbon neutrality in the mining industry. Martens *et al.* [11] developed an electrokinetic in-situ leaching method for copper mining, which can significantly reduce environmental carbon footprints. Wu *et al.* [12] proposed the concept of in-situ fluidization mining for deep metal mines. Xie *et al.* [13] and Yuan *et al.* [14] proposed the utilization of abandoned coal mines as underground spaces for mining garden construction, oil and gas storage, underground laboratory, hospital, planting, and pumped-storage power. Li and Hitch [15] developed technologies to sequestrate carbon via mine tailings. Shao [16] proposed an integrated system for underground mining–processing–dressing in Angang mines, which can significantly reduce the mining cost. Bao *et al.* [17] investigated the geothermal energy extraction from an abandoned copper mine in the USA and introduced a demonstration project to use mine water for heating a 1394 m^2 building.

In China, underground metal mines account for 90% of the total metal mines, and the mining depth is becoming increasingly deep [18–20]. Moreover, the average ore grades of some key minerals (e.g., iron) are significantly lower than the global average grades [19]. These conditions could pose a huge challenge for achieving carbon neutrality in China's metal mines. To date, there is no review on technical strategies to achieve "dual carbon" targets in China's metal mines. Accordingly, this paper attempts to review and discuss GHG emissions and carbon-related technologies for metal mining. The global GHG emissions from metal mining and GHG emissions targets from some international mining giants are collected and discussed. Then, China's deep mining status and mining GHG emissions are analyzed. Furthermore, advanced technologies for carbon mitigation in metal mines are reviewed. The key philosophy and common technologies on GHG emission reduction are provided. Moreover, advanced technologies for carbon sequestration in metal mines, including green mines and mineral carbonation, are examined. Finally, a technical roadmap for carbon neutrality in China's metal mines is proposed.

2. GHG emissions from global metal mining

Generally, metal mining industries have caused significant environmental issues, e.g., vegetation destruction, water pollution, and soil contamination. In the past century, great achievements were made to solve the environmental issues caused by metal mining. Moreover, metal mining activities will continue to develop and increase to provide more metals for human demands. To tackle the huge challenge of climate change, the reduction in GHG emissions from metal mining has been attracting increasing attention from researchers and industries. Fig. 1 illustrates the global mineral and metal productions and estimated GHG emissions related to metal mining in 2018. The production data are obtained from the US Geological Survey and British Geological Survey, and the GHG emission data are obtained from the emission contributions of mining to the emissions of metal life cycle stages, including mining, purification, and refining [7,21]. Data show that iron mining of approximately 1200 Mt contributed 1800 Mt of CO_2 equivalent (CO_2e), which is the largest emissions for metal mining in 2018. The estimated GHG emissions from metal mining (approximately 3.6 Gt CO_2e) are approximately 10% of the total energy-related GHG emissions [7]. The ratio of GHG emissions to the corresponding production varies from different minerals and metals. For example, GHG emission from the production of 1 t iron is much smaller than that for producing 1 t Al, Au, and Mg. The differences are caused by the mining processes and ore grades. For iron mining, diesel consumption for hauling and loading is a major contributor to its GHG emissions. However, for gold mining, more energy is consumed for crushing and grinding, which contributes to more GHG emissions. Aside from the difference in GHG emissions per unit mass, the values or prices of minerals are significantly different. Therefore, GHG emissions per unit value should also be considered. The World Gold Council [22] summarized the rank of emission intensity per unit value for primary metals from high to low

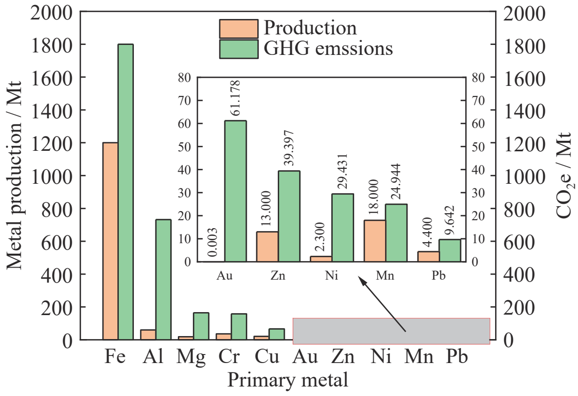

Fig. 1. Productions and GHG emissions of primary minerals and metals in 2018 (data collected from Ref.[7]).

(i.e., aluminum, steel, zinc, gold, copper, and lead) and the rank of emission intensity per unit mass from high to low (i.e., gold, aluminum, copper, zinc, steel, and lead). Therefore, the GHG mitigation of metal mining is an important part of global carbon neutrality, and policies on GHG emissions should vary per mineral.

Under the pressure of GHG emission mitigation, some international mining giants have proposed their GHG emission targets. Table 1 lists the GHG emission targets of some mining companies. The data are collected from their published annual reports [23–27]. Their latest GHG emission amounts in 2020 are approximately 10.3–31.5 Mt. Moreover, their medium-term targets are reducing GHG emissions by 10%–33% in 2025–2030 based on baselines from 2016 to 2020. For long-term targets, Glencore aims to achieve carbon neutrality in 2050 for all scopes while Anglo American, BHP, Rio Tinto and Vale strive to achieve carbon neutrality in 2050 for Scopes 1 and 2. The main actions for reducing GHG emissions include the use of renewable power, electric mining equipment, battery electric vehicles, and smart mining. Proposing carbon targets and managing carbon footprints are becoming necessary actions for metal mining corporations.

Table 1. GHG emission targets for some international mining companies

Mining companies	2020 GHG emissions / Mt	Medium-term target	Long-term target
Anglo American [23]	16.08	GHG emission reduction of 30% by 2030 (vs. 2016 baseline of 17.9 Mt)	Carbon neutrality by 2040
BHP [24]	15.8	GHG emission reduction of 30% by 2035 (vs. 2020 baseline of 15.8 Mt)	Carbon neutrality by 2050
Glencore [25]	24.3	GHG emission reduction of 10% by 2025 (vs. 2016 baseline of 36 Mt)	Carbon neutrality by 2050 (Scopes 1, 2, and 3)
Rio Tinto [26]	31.5	GHG emission reduction of 15% by 2030 (vs. 2018 baseline of 32.6 Mt)	Carbon neutrality by 2050
Vale [27]	10.3	GHG emission reduction of 33% by 2030 (vs. 2017 baseline of 14.1 Mt)	Carbon neutrality by 2050

3. Current status of China's metal mines

China is one of the most historical countries that perform metal mining and is also one of the few countries in the world with complete types and abundant reserves of metal mineral resources. However, there are more mines with lean ores but fewer mines with rich ores in China [28–29]. For instance, the average iron ore grade in China is 33.5%, which is smaller than that in the world by 10%. Moreover, 90% of China's metal mines are underground mines, and the proportion of underground mining is still increasing due to the exhaustion of shallow resources. Fig. 2 shows 16 China's metal mines with a mining depth larger than 1000 m [19]. The deepest mine is located in Henan Province, with a mining depth of 1600 m. Only one of the deep mines is an iron mine, whereas others are non-ferrous mines. One-third of non-ferrous metal mines are expected to reach or exceed the mining depth of 1000 m [19]. The high in-situ stress and high temperature in deep mines will unavoidably increase the construction and maintenance cost and the consumption of materials. Moreover, the energy consumed by hauling and loading will be increased due to the long transportation and hoist distances. Therefore, the energy consumption intensity for metal mining in China may continue to grow under the current mining technologies, posing a large challenge for carbon neutrality in China's metal mines.

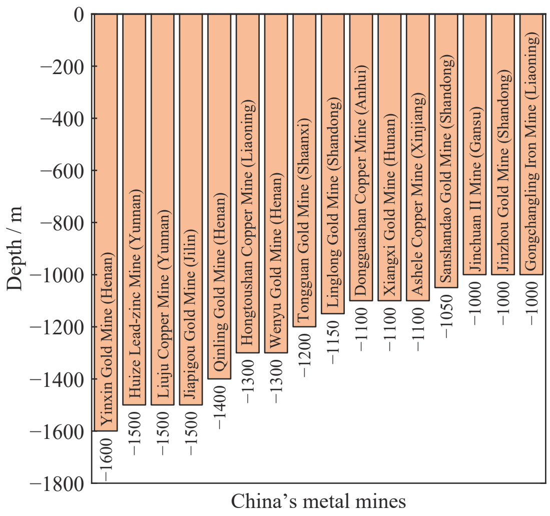

Fig. 2. China's metal mines with mining depths larger than 1000 m.

Fig. 3 illustrates the GHG emissions and emission intensity from the Chinese mining industry. The emission intensity is the ratio of GHG emissions (million tons) to the value (billion Chinese Yuan). According to the literature, GHG emission data from China's metal mines are limited. Therefore, the data include GHG emissions from five resource extraction parts: coal mining and dressing, petroleum and natural gas extraction, ferrous metal mining and dressing, non-ferrous metal mining and dressing, and nonmetal mineral mining and dressing. The emission data are obtained from China Carbon Emission Accounts and Datasets, and the calculation is mainly based on the energy-related method [31]. The results show that the total GHG emissions from resource mining increased from 224 Mt in 2005 to 380 Mt in 2012. With the efforts of reducing the production capacity, GHG emissions decreased to 344 Mt in 2015. Moreover, the emission intensity gradually decreased from 0.15 in 2005 to 0.08 in 2015. The reduction of emission intensity is mainly contributed to the development of technologies. The weighted carbon price from the Chinese national emissions trading system started on July 16, 2021. Based on the current price of 50 Yuan per ton, the value for net-zero emissions in the mining industry can be estimated to be 17 billion Yuan, and the carbon price will increase in the future. Therefore, the reduction of carbon emissions and achieving net-zero or negative emissions in China's metal mines is of great significance in terms of value and climate change.

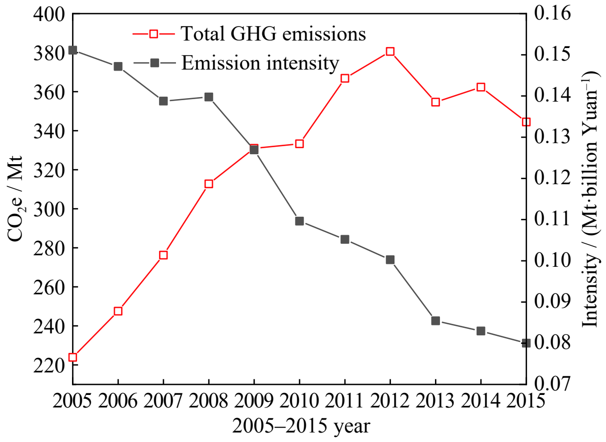

Fig. 3. GHG emissions from Chinese mining industries (data collected from Ref. [30]).

4. Advanced technologies in carbon mitigation for metal mines

4.1. Carbon mitigation by improving energy efficiency

For coal mining, GHG emissions from methane can account for nearly half of the total emissions [6,32]. Meanwhile, for metal mining, most GHG emissions are energy-related emissions. Therefore, a fundamental philosophy to carbon mitigation in metal mining is improving mining efficiency and replacing fossil fuels with renewable energy. Fig. 4 illustrates the pathways for carbon mitigation by improving energy efficiency. From the construction to operations of metal mines, improving the mining efficiency and using more low-carbon energy should be thoroughly considered. More sustainable mining methods, including backfill mining and in-situ leaching mining, should be employed with priority [33–35]. Backfill mining can avoid surface movement, which reduces the impact of land footprints. Wu *et al.* [36] and Martens *et al.* [11] proposed advanced in-situ leaching methods, which markedly reduced environmental footprints. Furthermore, the carbon cost could be calculated to determine the cut-off grade. Production processes of raw materials, including cement, concrete, bolts, and supports, will generate carbon emissions. Reasonably reducing raw material consumption will also benefit carbon mitigation. For drilling and blasting, drilling optimization and precision blasting can save the cost and energy for rock excavation and ore processing. Yang *et al.* developed precision blasting techniques for mining based on dynamic rock mechanics and blasting mechanics, which reduced the energy and cost in follow-up mining processes [37–38]. For loading and hauling, diesel trucks and equipment not only produce more carbon but also affect the air of working faces. GHG emissions can be significantly mitigated by electrification, automation, and intelligence of mining equipment and trucks. The Fankou Lead-Zinc Mine tested the intelligent mining technology with an unmanned underground scraper, a mining truck, a rock-drilling jumbo, and a down-the-hole drill and found that intelligent mining can reduce the number of field operations and the discharge of solid mine waste [39]. For transportation and hoist, continuous transportation can reduce the mining cost, especially for deep open pits and underground mines. Cai *et al.* [40] developed a truck-belt conveyor semi-continuous hauling system in Shuichang iron deep open-pit mine and found that the developed method can significantly reduce the transportation cost by 30%. Zhangjiawan iron mine integrated mineral processing by constructing an underground beneficiation plant near the stope [41]. Wu *et al.* [12] proposed a concept of in-situ fluidization mining for deep metal mines and pointed out that the integration equipment of mining–processing–backfilling should be developed in the future.

Common technologies have been proposed to improve the energy efficiency in metal mining: digital mining, automation, 5G, big data, digital twinning, smart mining, electrification of mining equipment and trucks, continuous mining, and integration of mining–processing–backfilling. The techniques or concepts were previously proposed to achieve safe

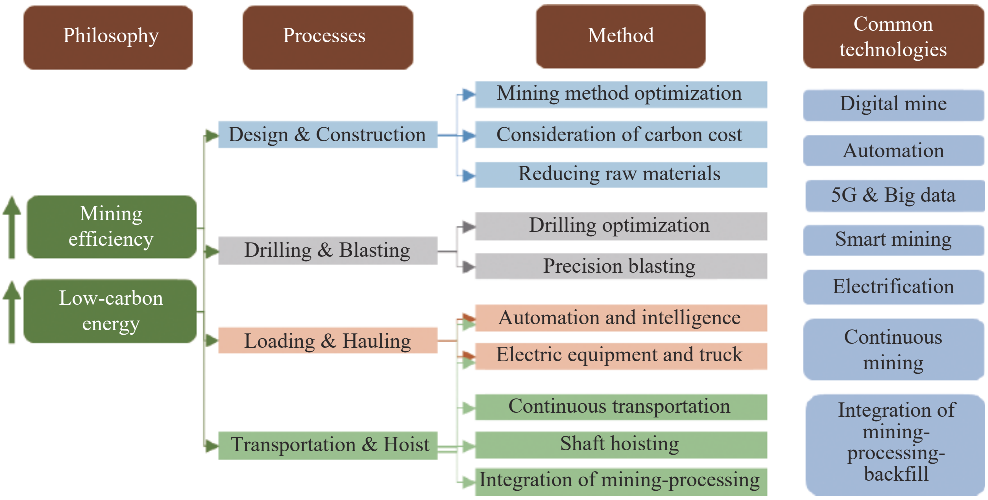

Fig. 4. Pathways for carbon mitigation by improving energy efficiency.

and efficient mining. Here, we focus on considering the low-carbon benefits induced by the above technologies.

4.2. Simultaneous extraction of mining resources and geothermal energy

As introduced in Fig. 2, underground mining in China has experienced increasing exploitation depth. In the next decade, many metal mines will have a depth of 1000 m, and the deepest is expected to be between 2000 and 3000 m. As a consequence, mining activities have encountered elevated heat problems. Heat can negatively impact the performance, overall productivity, and safety of the workforce. Accordingly, many efforts have been made to reduce mine temperature, such as improving the ventilation system, transferring ice to the working face, or even using high-temperature protective apparel [19]. However, the existing methods are all very costly or inefficient. Heat in deep metal mines is also a kind of green energy, i.e., geothermal energy. Some researchers have proposed the extraction of geothermal energy from deep mines. Preene and Younger [42] introduced existing geothermal systems in mines and suggested potential heat reservoirs associated with mine sites. He *et al.* [43] developed a high-temperature exchange machinery system for heat-harm control in deep mines. Zhao *et al.* [44] proposed an excavation-based enhanced geothermal system to extract geothermal energy with deep rock excavation, enhanced heat extraction, and enclosed heat transmission. Tang and other researchers [45–46] developed a coupled thermal–hydraulic–mechanical rock failure modeling method with application to deep geothermal wells. Liu *et al.* [47] proposed mine backfilling to store and exchange heat for geothermal energy extraction.

Furthermore, we propose the simultaneous extraction of mining resources and geothermal energy, as illustrated in Fig. 5. First, heat resources are surveyed in deep mines. A cavern-like space is excavated as a heated water reservoir to store heat energy in tunnels. Under the cavern, a number of parallel wells are drilled. Then, rocks surrounding these wells are fractured to generate a controllable fracture network for maximizing the heat-conducting supply for the reservoir. A pulsating fracking technique can be employed to optimize fracture networks and reduce the risk of seismicity [48–49]. The heated water reservoir is then connected with heat-conducting pipes to harvest heat through the pipes to the power station. The extracted geothermal energy can be used for local heating or collected to generate electricity. Actively controlling the mining temperature and using abundant heat for energy will significantly mitigate GHG emissions in China's metal mines.

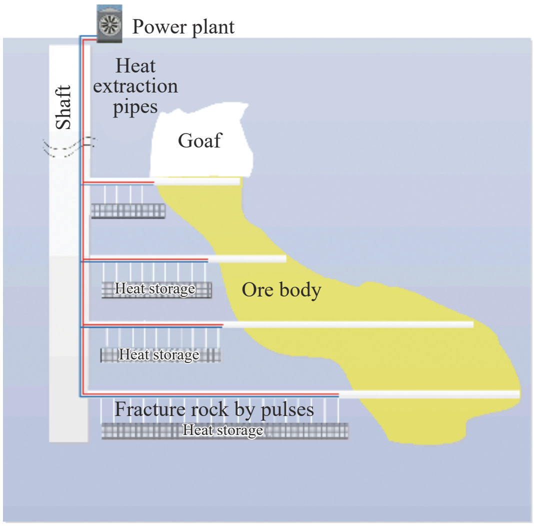

Fig. 5. Concept model for the simultaneous extraction of resources and geothermal energy.

4.3. Utilization of abandoned metal mines

With the exhaustion of resources after mining for a long period, many mines will be closed or abandoned. There are approximately more than 40000 closed coal mines in China [50]. Abandoned mines can be treated as a kind of resource. Xie *et al.* [13,50] proposed the use of abandoned underground mines as special underground spaces for mining garden construction, oil and gas storage, underground laboratory, hospital, planting, and pumped-storage power. Yuan *et al.* [14] proposed concepts for precision exploitation and utilization of abandoned mines. Furthermore, Xie *et al.* [50] introduced three key technologies for the utilization of abandoned mines, i.e., safety assessment of abandoned mines, construction of abandoned mines for different utilization purposes and comprehensive control of subsurface environments. Moreover, the long-term durability and stability of underground structures should be carefully considered in utilizing abandoned mines. The proposed concepts and practices significantly enhanced the development of abandoned coal mine utilization in China [13–14,50–51].

Besides the utilization of abandoned mines mentioned in [13–14,50–51], extracting geothermal energy from abandoned mines has also attracted much research attention. In the USA, a geothermal energy station was built in an abandoned copper mine located in the Upper Peninsula of Michigan for house heating [17]. In Canada, an open-loop geothermal system utilizing mine water from the Goyer Quarry was developed to provide heating and cooling to 36 apartments [52]. In the UK, the British Geological Survey and Coal Authority fully investigated the heat potential from abandoned coal mines in 2020 [53]. Moreover, approximately 2.2 million GWh of heat could be provided by flooded abandoned coal mines, which will contribute to a net-zero carbon society [53]. The UK government has funded more than 10 million pounds to study the extraction of geothermal energy from flooded abandoned mines since 2020. The utilization of abandoned metal mines for geothermal energy in China is worth investigating as it will contribute to a low-carbon metal mining industry.

5. Advanced technologies in carbon sequestration for metal mines

5.1. Green mines

The sequestration of carbon for metal mining is imperative to achieve carbon neutrality. The concepts of "green mining" and "green mines" have already existed since the 19th century in many countries [54]. Green mines have also been practiced in China's metal mines for many years. They improve environmental efficiency and maintain the mining industry's competitiveness over the entire life cycle [54]. Here, we focus on the effect of land reclamations in green mines on the carbon sequestration capacity. The amount of carbon stored in terrestrial vegetation is a key component of the global carbon cycle [55]. Trees and other vegetations in green mines can absorb a considerable amount of carbon. Since 2011, more than 600 mines have been recognized as green mine construction pilot programs, of which 303 are metal mines [56]. Zhang *et al.* [10] developed a model to calculate carbon sinks from mine land reclamation and found that a square hectometer (hm^2) of reclamation woodland can absorb 1.44×10^5 kg CO_2 per year. Table 2 lists the reclamation areas and estimated carbon sequestration capacity in some China's metal mines. The carbon sequestration capacity is calculated based on the unit absorbability of reclamation woodland (i.e., 1.44×10^5 $kg \cdot hm^{-2}$) [10]. By multiplying the carbon price of 50 Yuan/ton, the total value of the mine land reclamation on the carbon emission can reach 27.7 million Yuan every year. Therefore, carbon targets attribute new values to green mines. Hence, more efforts should be put into constructing green mines in China's metal mining industry.

Table 2. Land reclamation areas and carbon sequestration in some China's metal mines

Mine area name	Type	Reclamation area / m^2	Sequestrated carbon / ($t \cdot a^{-1}$)
Baiyunebo	Iron	3.2×10^5 [57]	4.7×10^3
Zijinshan	Copper–gold	2.4×10^6 [58]	3.5×10^4
Malanzhuang	Iron	7.6×10^6 [59]	1.1×10^5
Jinchang	Nickel	3.1×10^6 [60]	4.5×10^4
Anshan	Iron	1.5×10^7 [61]	2.2×10^5
Tongling	Copper	1.0×10^7 [62]	1.4×10^5

5.2. Carbon sequestration by backfill and tailing

Carbon capture and storage (CCS) is the primary option used to limit the temperature rise to 1.5°C relative to preindustrial levels because CCS could reduce 85%–90% of CO_2 from large-emission sources and energy-intensive emitters [63–64]. Seifritz first proposed the mineral carbonation concept to accelerate the reaction between CO_2 and alkaline minerals in 1990 [65]. The reaction process of mineral carbonation can be generally expressed as follows [66]:

$$\text{Metaloxide} + CO_2 \rightarrow \text{Metalcarbonate} + \text{Heat} \tag{1}$$

Mineral carbonation can utilize Mg, Ca, or Fe silicate minerals to stably store CO_2 [66]:

$$Mg_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2MgCO_3 + H_4SiO_4 \tag{2}$$

$$Fe_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2FeCO_3 + H_4SiO_4 \tag{3}$$

$$CaSiO_3 + CO_2 + 2H_2O \rightarrow CaCO_3 + H_4SiO_4 \tag{4}$$

Mineral carbonation is regarded as a permanent and safe way for carbon storage because it will not cause carbon leakage. The potential of mineral carbonation is estimated to be 10%–15% of the total carbon emissions [66]. Because the mineral carbonation concept was proposed, many researchers have tried to store CO_2 using different minerals from different industries. Xie *et al.* [67] proposed the use of $MgCl_2$ to store CO_2 and produce magnesium carbonate and hydrochloric acid. Moreover, the heat produced from mineral carbonation can be collected as power. Xi *et al.* [68] found that the carbonation of cement materials over their life cycle represents a large and growing net sink of CO_2 (0.25 Gt in 2013). Chen *et al.* [69] employed fly ash to absorb CO_2 and found that the modified sorbents achieved a CO_2 capture capacity of 0.27 g CO_2/g sorbent. Forkers developed accelerated carbonation equipment to cure cemented-based materials, and the equipment can process 50 t of construction materials every hour. Moreover, concrete cured in CO_2 had a 45% higher strength than that cured in the N_2 atmosphere [70]. Most mining backfills are cement-based materials consisting of cement, fly ash, tailings, and solid waste. According to existing research on mineral carbonation in concrete, geopolymers, and other construction materials, storing CO_2 in mining backfills may have great potential. If CO_2 can be stored in the backfill, then metal mines may become negative-carbon mines.

Besides mineral carbonation in cement-based materials, some researchers have proposed the sequestration of carbon in tailings. Li and Hitch pointed out that suitable mines for mineral carbonation are the ultramafic rock-hosted ore deposits of chrysotile, nickel, chromium, diamond, and platinum [15,63]. They experimentally found that the CO_2 sequestration conversions of mechanically activated olivine and mine waste are 22.5% and 31.5%, respectively [15]. Wilson *et al.* [71] conducted experiments to investigate the carbonation of a chrysotile mine tailing in Canada and found that approximately 10wt% of tailings to carbonate minerals could offset GHG emissions from many ultramafic-hosted mining operations. McGrail *et al.* [72] found relatively rapid chemical reactions of CO_2-saturated pore water with basalts to form stable carbonate minerals. Therefore, mineral carbonation in mining backfills or tailings can be relatively inexpensive for carbon storage, which will significantly result in metal mining becoming carbon neutral. Nonetheless, more research should be performed to investigate the carbon storage capacity and technologies of storing CO_2 in mining backfills and tailings.

6. Technical roadmap for carbon neutrality in China's metal mines

China's metal mining industry and research community should take effective actions to achieve the "dual carbon" targets. Fig. 6 illustrates a brief technical roadmap for achieving carbon neutrality in China's metal mines. Some existing and mature technologies should be taken as current actions. First, GHG emission data in metal mines should be studied and collected. Every large- and medium-sized mine can establish its GHG emission database, which is the basis for GHG man-

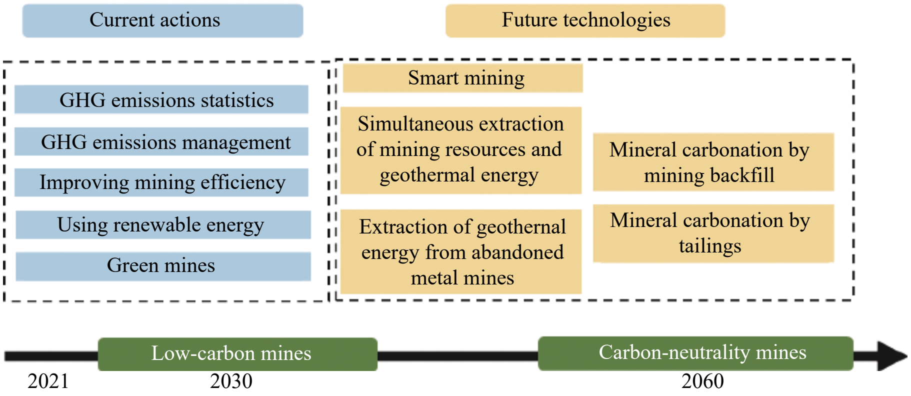

Fig. 6. **Technical roadmap for carbon neutrality in China's metal mines.**

agement and plan. Furthermore, advanced mining methods and technologies can be employed to improve mining efficiency, including backfill mining, digital mining, automation, 5G, big data, smart mining, electrification of mining equipment and trucks, continuous mining, and integration of integration mining–processing–backfilling. Moreover, the consumption amount of fossil fuel should be reduced, and more renewable energy can be used. For example, wind energy and solar energy can be in-situ developed and utilized by metal mines. Importantly, more attention should be paid to green mines during the whole life cycle of mines. Considering the above actions, China's metal mines can be constructed as low-carbon mines before 2030.

In the next 10–20 years, some key advanced technologies should be developed to improve energy efficiency and sequestrate carbon in metal mines. More smart mining will significantly improve energy efficiency and ensure mining safety. Moreover, the potential for extracting geothermal energy in metal mines is great. Therefore, research on the simultaneous extraction of mining resources and geothermal energy and extraction of geothermal energy from abandoned metal mines should be performed. Clean energy from mines will benefit the construction of carbon neutrality. Moreover, carbon sequestration by mining backfilling and tailing through mineral carbonation is a promising way to permanently and safely store CO_2. Through mineral carbonation in metal mines, metal mines can be transformed into negative-carbon mines and bring new values to the metal mining industry. Consequently, related future technologies will contribute to carbon neutrality in China's metal mines before 2060.

7. Conclusions

The "dual carbon" targets, i.e., carbon peak before 2030 and carbon neutrality before 2060, are a solemn promise of the Chinese government to the world. The metal mining industry and research community should effectively contribute to the "dual carbon" targets by constructing and maintaining low-carbon and carbon-neutrality mines. This paper reviews GHG emissions from metal mining industries and discusses technical strategies for achieving carbon peak and carbon neutrality in China's metal mines. The following conclusions were drawn in this study:

(1) The GHG mitigation of metal mining is essential for achieving carbon neutrality in China. GHG emissions and their intensities vary in each mineral type. Iron mining contributes to the largest amount of carbon emission in metal mining. The emission intensity per ton of ore for gold mining is the highest.

(2) Some international mining giants, including Anglo American, BHP, Glencore, Rio Tinto, and Vale, have made carbon targets and plans to achieve carbon neutrality before 2050. With the metal mining depth increasing in China, the energy consumption intensity may continue to grow under the current mining technologies, posing an even bigger challenge for carbon neutrality in the China's metal mining industry.

(3) Improving mining efficiency is the fundamental way to reduce GHG emissions. Some common technologies (e.g., digital mining, automation, 5G, big data, smart mining, electrification of mining equipment and trucks, continuous mining, and integration of mining–processing–backfilling) should be further explored to achieve safe mining and carbon mitigation. Metal mines can develop and use more renewable energy to replace fossil fuels in mining operations.

(4) Green mines can significantly benefit carbon neutrality for metal mines through the carbon absorption of reclamation vegetations. The simultaneous extraction of mining resources and geothermal energy and extraction of geothermal energy from abandoned metal mines are promising techniques for developing clean energy in metal mines, which can provide clean energy and contribute to carbon neutrality. Carbon sequestration via mining backfilling and tailing through mineral carbonation is also a promising way to permanently and safely store carbon.

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Conflict of interest

The authors declare no potential conflict of interest.

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