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# Technology Strategies to Achieve Carbon-peak and Carbon-neutrality for Chinese 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 emissions peak before 2030 and carbon neutrality before 2060. This paper attempts to review and discuss technical strategies to achieve the “dual-carbon” targets in Chinese metal mines. First, global carbon emissions and emission intensity from metal mining industries are analysed. The metal mining status and carbon emissions in China are then examined. Further, advanced technologies for carbon mitigation and carbon sequestration in metal mines are reviewed. Finally, a technical roadmap for achieving carbon-neutrality in Chinese metal mines are proposed. It has been found that some international giants have already made 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 to reducing GHG emissions. Green mines can significantly benefit the carbon neutrality process for metal mines through carbon absorption of reclamation vegetation. The geothermal energy extraction from operating and abandoned metal mines is a promising technology for providing clean energy and contributing to the carbon neutrality target for Chinese metal mines. Carbon sequestration by mining backfill and tailing through mineral carbonation has the potential to permanently and safely store carbon dioxide, which can eventually transform the metal mining industry to become carbon neutral or even carbon negative.

**Keywords:** carbon emissions; carbon neutrality; Chinese metal mines; deep mining; mining efficiency.

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## 1. Introduction

The atmospheric concentrations of greenhouse gas (GHG) have increased significantly since the industrial revolution began. GHG emissions related to human activities have caused approximately 1.0°C of global warming above pre-industrial levels [1]. The world's governments have approved a special report through the Intergovernmental Panel on Climate Change (IPCC) on limiting the temperature increase to 1.5°C above pre-industrial levels [1]. It was estimated that global emissions should be reduced by 7.6% every year for the next decades to meet the 1.5°C increase target [1].

China announced to have $CO_2$ emissions peak before 2030 and achieve carbon neutrality before 2060 at the general debate of the 75th session of the United Nations General Assembly in September 2020 [2]. After China's pledge to carbon neutrality before 2060, the roadmap to achieve the goal is getting clearer. By 2030, China aims to lower its carbon dioxide 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 has 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]. The scope 3 emissions occur from sources out of control (e.g., emissions from processing mined iron ore to steel). In the past decades, considerable researches have been carried out on estimating GHG emissions from the mining industry. Northey et al. estimated GHG emissions for 19 copper mining companies in

11 countries and found the range of GHG emissions was 1–9 t $CO_2$e/t Cu, with an average of 2.6 t $CO_2$e/t Cu [4]. They pointed out that the large variation is mainly caused by the copper produced, ore grade, fuel sources, and electrical energy. A decline in ore grade generally resulted in higher GHG emissions intensity [4]. Li [5] analysed 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 utilisation of coal. Yang et al. [6] investigated GHG emissions in the Pingshuo coal mining area and found coalbed methane emissions and fuel consumption accounted for 46.66% and 41.79% of the total emissions, respectively. Azadi et al. [7] estimated GHG emissions from metal and mineral productions were equivalent to approximately 10% of the total global energy-related greenhouse gas emissions in 2018.

To achieve the carbon-neutrality for the mining industry, some researchers studied the benefit of current mining technologies on carbon emission reduction. Liu et al. [8] compared the energy consumption and carbon emissions for different modes of transportation in open-cut coal mines. They found the $CO_2$ emissions from truck transportation were three to ten times higher than that from the belt conveyor. Carmichael et al. [9] explored the relationship between the optimal unit cost and the optimal unit carbon emissions for surface mining and found that mining operations optimisations on truck size, payload, fuel use, and travel and loading times can coincidently reduce the unit cost and emissions. Zhang et al. developed a model to calculate the carbon sink from mine land reclamation and found that the reclamation in the Huaibei mining area can absorb $1.68\times10^5$ t $CO_2$ per year [10].

Further, some new mining concepts or technologies were recently proposed to achieve the carbon-neutrality of the mining industry. Martens et al. developed an electrokinetic in-situ leaching method for copper mining, which can significantly reduce the environmental carbon footprint [11]. Wu et al.

proposed a conception of in-situ fluidisation mining for deep metal mines [12]. Xie et al. [13] and Yuan et al. [14] proposed to utilise abandoned coal mines as underground spaces for mining garden construction, oil and gas storage, underground laboratory, hospital, planting, pumped-storage power, etc. Li and Hitch developed technologies to sequestrate carbon by mine tailings [15]. Shao et al. proposed to establish an integrated system for underground mining-processing-dressing in Angang mines, which can significantly reduce the mining cost [16]. Bao et al. 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 1,394 $m^2$ building [17].

In China, underground metal mines account for 90% of the total metal mines and the mining depth is becoming deeper [18]–[20]. Moreover, the average ore grades of some key minerals (e.g., iron) are significantly lower than the global average grades [19]. These could pose a huge challenge for achieving carbon-neutrality in Chinese metal mines. To date, there is no review on technical strategies to achieve "dual carbon" targets in Chinese metal mines. 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 Chinses deep mining status and mining GHG emissions are analysed. Further, advanced technologies for carbon mitigation in metal mines are reviewed. The key philosophy and common technologies on GHG emissions reduction are given. 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 Chinese metal mines is proposed.

## 2. GHG emissions from global metal mining

It is well-known that metal mining industries have cuased significant environmental issues, e.g., vegetation destruction, water pollution, soil contamination, etc. In the past century, great achievements were made to solve the environmental issues caused by metal mining. In the meantime, metal mining activities will continue to develop and increase to provide more metal for human demands. To tackle the huge challenge of climate change, the reduction of GHG emissions from metal mining are attracting more attention from researchers and industries. Figure 1 illustrates the global mineral and metal productions and estimated GHG emissions related to metal mining in 2018. The production data are from the US Geological Survey, the British Geological Survey and the GHG emission data are from the emission contributions of mining to emissions of metal life cycle stages including mining, purification, and refining [7], [21]. It can be seen that iron mining of around 1,200 million tonnes contributed carbon dioxide equivalent ($CO_2e$) of 1,800 million tonnes, which was the largest emissions for metal mining in 2018. The estimated GHG emissions from metal mining (about 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, the GHG emissions for producing one-tonne iron is much smaller than that for producing one-tonne 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. Besides the difference in GHG emissions per unit mass, the values or prices of minerals are significantly different. Therefore, the GHG emissions per unit value should also be considered. World Gold Council [22] summarised the rank of emissions intensity per unit value for primary metals from high to low: aluminium, steel, zinc, gold, copper and lead, and the rank of emissions intensity per unit mass from high to low: gold, aluminium, copper, zinc, steel and lead. Therefore, GHG mitigation of metal mining is an important part of global carbon neutrality, and the policies on GHG emissions should vary from minerals.

Under the pressure of GHG emissions mitigation, some international mining giants have proposed their GHG emission targets. Table 1 lists the GHG emission targets for some mining companies. It should be mentioned the data are collected from their published annual reports [23]–[27]. Their lastest GHG emissions amounts in 2020 are about 10.3-31.5 million tonnes. And their medium-term targets are reducing GHG emissions by 10-33% in 2025-2030 based on baselines from 2016-2020. For long-term targets, Glencore aims to achieve carbon neutrality in 2050 for all Scopes. And the other companies strive to achieve carbon neutrality in 2050 for Scopes 1 and 2. The main actions for reducing GHG emissions include renewable power, electric mining equipment, battery electric vehicles, smart mining, etc. Proposing carbon targets and managing the carbon footprint are becoming necessary actions for metal mining corporations.

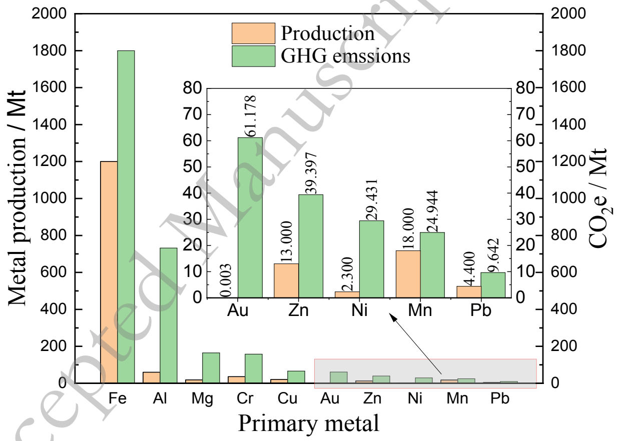


**Fig. 1. Productions and GHG emissions of primary minerals and metals in 2018 (Date collected from [7]).**

**Table 1. GHG emission targets for some international mining companies**

| Mining companies | 2020 GHG emissions | Medium-term target | Long-term target |
|---|---|---|---|
| Anglo American[23] | 16.08 Mt | GHG emissions reduction by 30% by 2030 (vs 2016 baselines 17.9 Mt) | Carbon neutrality by 2040 |
| BHP [24] | 15.8 Mt | GHG emissions reduction by 30% by 2035 (vs 2020 baselines 15.8 Mt) | Carbon neutrality by 2050 |
| Glencore [25] | 24.3 Mt | GHG emissions reduction by 10% by 2025 (vs. 2016 baselines 36 Mt) | Carbon neutrality by 2050 (Scopes 1, 2 & 3) |
| Rio Tinto [26] | 31.5 Mt | GHG emissions reduction by 15% by | Carbon neutrality by 2050 |

| | | | |
|---|---|---|---|
| | | 2030 (vs 2018 baselines 32.6 Mt) | |
| Vale [27] | 10.3 Mt | GHG emissions reduction by 33% by 2030 (vs 2017 baselines 14.1 Mt) | Carbon neutrality by 2050 |

## 3. Current status of Chinese metal mines

China is one of the most historical countries on 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 ore but fewer mines with rich ore in China [28][29]. For example, the average iron ore grade in China is 33.5% which is smaller than that in the world by 10%. Moreover, 90% of Chinese metal mines are underground mines, and the proportion of underground mining is still increasing due to the exhaustion of shallow resources. Figure 2 shows sixteen Chinese 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 iron mine and others are non-ferrous mines. It is predicted that one-third of non-ferrous metal mines will 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 also be increased due to longer 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 larger challenge for carbon neutrality in Chinese metal mines.

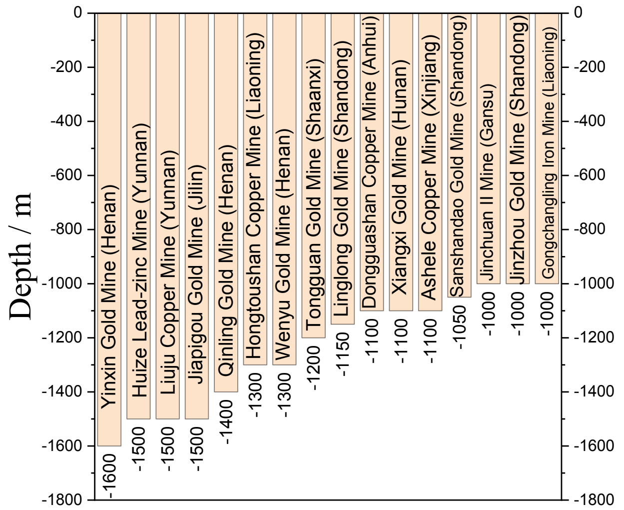


**Fig. 2. Chinese metal mines with the mining depth larger than 1000 m.**

Figure 3 illustrates the GHG emissions and emission intensity from the Chinese mining industry. The emission intensity is the ratio of GHG emissions (million tonnes) to the value (billion Chinese Yuan). According to the literature, the GHG emissions data from Chinese metal mining are limited. Therefore, the data include GHG emissions from five resource extraction parts: coal mining and dressing, petroleum and natural gas extraction, ferrous metals mining and dressing, non-ferrous metals mining and dressing, nonmetal minerals mining and dressing. The emissions data are from Chinese CEADs (Carbon Emission Accounts and Datasets) and the calculation is mainly based on the energy-related method [30]. It can be seen that, the total GHG emissions from resources mining increased from 224 Mt in 2005 to 380 Mt in 2012. With the efforts of reducing production capacity, the 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 emission-trading system has started on 16th July 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, it is of great significance to reduce the carbon emissions and achieving net-zero or negative emissions in Chinese metal mines in terms of value and climate change.

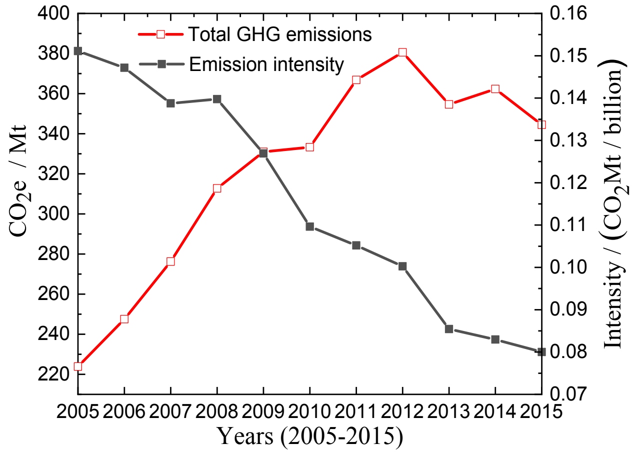


**Fig. 3. GHG emissions from Chinese mining industries (Data collected from [31]).**

## 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 [32]. While 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. Figure 4 illustrates the pathways for carbon mitigation by improving energy efficiency. From the construction to operations of metal mines, improving mining efficiency and using more low-carbon energy should be thoroughly considered. More sustainable mining methods, including backfill mining, in-situ leaching mining, etc., should be employed with priority [33]–[35]. Backfill mining can avoid surface movement, which reduces the impact of land footprint. Wu et al. [36] and Martens et al. [11] proposed advanced in-situ leaching methods, which markedly reduced environmental footprint. Further, the carbon cost could be calculated to determine the cut-off grade. Moreover, production processes of raw materials, including cement, concrete, bolts and supports, will generate carbon emissions. Reasonably reducing the raw materials consumption will also benefit carbon mitigation. For drilling and blasting, drilling optimisation 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 rock dynamic mechanics and blasting mechanics, which reduced the energy and cost from follow-up mining processes [37], [38]. For loading and hauling, the diesel trucks and equipment not only produce more carbon but also affect the air of working faces. The GHG emissions can be significantly mitigated by electrification, automation, and intelligence of mining equipment and trucks. Fankou Lead-Zinc Mine tested the intelligent mining technology with an unmanned underground scraper, a mining truck, a rock-drilling jumbo, and a down to hole drill and found intelligent mining can reduce the number of field operations and the discharge of mine solid waste [39]. For transportation and hoist, continuous transportation can reduce the mining cost, especially for deep open-pit and underground mines. Cai et al. developed a truck-belt conveyor semi-continuous in Shuichang iron deep open-pit mine and found the developed method can significantly reduce the transportation cost by 30% [40]. Zhangjiawan iron Mine integrated the mining-processing by constructing an underground beneficiating plant near the stope [41]. Wu et al. proposed a concept of in-situ fluidisation mining for deep metal mines and pointed out the integration equipment of mining-processing-backfilling should be developed in the future [12].



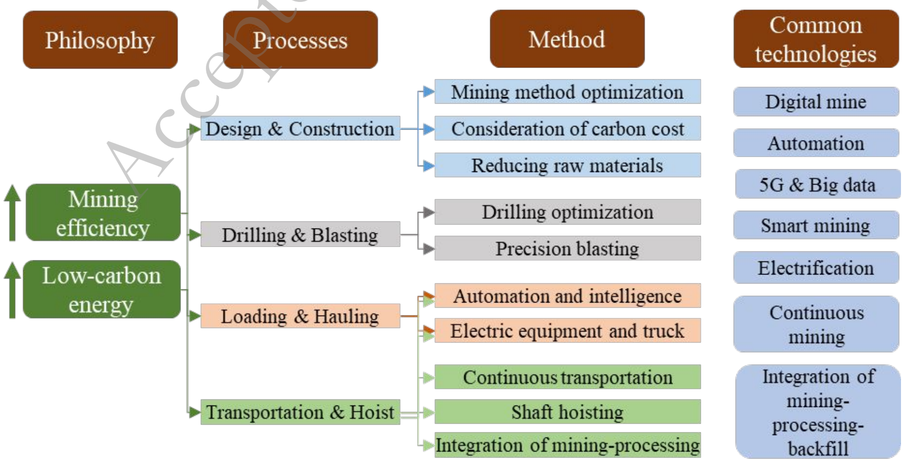


**Fig. 4. Pathways for carbon mitigation by improving energy efficiency.**

There are some common technologies to improve the energy efficiency in metal mining: digital mine, automation, 5G, big data, digital twin, smart mining, electrification of mining equipment and trucks, continuous mining, integration of mining-processing-backfilling, etc. The techniques or concepts were previously proposed to achieve safe and efficient mining. Here we are focused on considering the low-carbon benefits induced by the above technologies.

**4.2. Simultaneous extraction of mining resources and geothermal energy**

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

Further, we propose to simultaneous extract mining resources and geothermal energy. Figure 5 illustrates the concept of simultaneous extraction of resources and geothermal energy. First, the heat resources are surveyed in the deep mines. A cavern-like space is excavated as the heated water reservoir to store the heat energy in the tunnels. Under the cavern, a number of parallel wells are drilled. Then the rocks surrounding these wells are fractured to generate the controllable fracture network for maximining the heat-conducting supply for the reservoir. A pulsating fracking technique can be employed to optimise the fracture netwroks and reduce the risk of seismicity [48], [49]. The heated water reservoir is then connected with heat-conducting pipes to harvest the 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 the abundant heat for energy will significantly mitigate GHG emissions in Chinese metal mines.

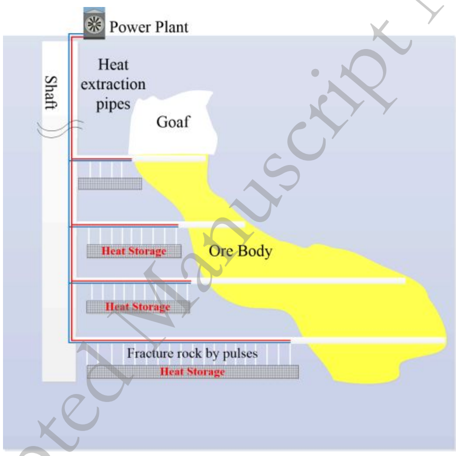


**Fig. 5. A concept model for the simultaneous extraction of resources and geothermal energy.**

**4.3. Utilisation of abandoned metal mines**

With the exhaustion of resources after mining for a long period, many mines will be closed or abandoned. It was estimated there are more than 40,000 closed coal mines in China [50]. Abandoned mines can be treated as a kind of resource. Xie et al. proposed to employ abandoned underground mines as special underground spaces for mining garden construction, oil and gas storage, underground laboratory, hospital, planting, pumped-storage power, etc. [13], [50]. Yuan et al. proposed concepts for precision exploitation and utilisation of abandoned mines [14]. Further, Xie et al. concluded three key technologies for the utilisation of abandoned mines, i.e., safety assessment of abandoned mines, construction of abandoned mines for different utilisation purposes and comprehensive control of subsurface environment [50]. Moreover, the long-term durability and stability of underground structures should be carefully considered for utilising abandoned mines. The proposed concepts and practices significantly enhanced the development of abandoned coal mines utilisation in China [13], [14], [50], [51].

Besides the utilisation of abandoned mines mentioned in [13], [14], [50], [51], extracting geothermal energy from abandoned mines also attracts much 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 utilising the mine water from the Goyer Quarry was developed to supply 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]. And it was estimated around 2.2 million GWh of heat could be provided by the flooded abandoned coal mines, which will contribute to a net-zero carbon society [53]. Moreover, the UK government has funded more than 10 million pounds to study extracting geothermal energy from the flooded abandoned mines since 2020. It is worth investigating how to utilise abandoned metal mines for geothermal energy in China. The utilisation of abandoned metal mines will contribute to a low-carbon metal mining industry.



## 5. Advanced technologies in carbon sequestration for metal mines

### 5.1. Green mines

It is necessary to sequestrate carbon for metal mining achieving carbon neutrality. The concept of “green mining” and “green mines” have already existed since the 19th century in many countries [54]. Green mines have also been practised in Chinese metal mines for many years. Green mines improve environmental efficiency and maintain the mining industry's competitiveness over the entire life cycle

[54]. Here, we focus on the effect of the land reclamation in green mines on carbon sequestration capacity. The amount of carbon stored in terrestrial vegetation is a key component of the global carbon cycle [55]. Trees and other vegetation in green mines can absorb a considerable amount of carbon. Since 2011, more than 600 mines have been recognised as green mines construction pilot programs, of which 303 are metal mines [56]. Zhang et al. developed a model to calculate the carbon sink from mine land reclamation and found a square hectometer ($hm^2$) of reclamation woodland can absorb $1.44\times10^5$ kg $CO_2$ per year [10]. Table 2 lists the areas of reclamation and estimated carbon sequestration capacity in some Chinese metal mines. The carbon sequestration capacity is calculated based on the unit absorbability of reclamation woodland (i.e., $1.44\times10^5$ kg/$hm^2$) [10]. By multiplying the carbon price of 50 Yuan/ton, the total value of the mine land reclamation on carbon emission can reach 27.7 million Yuan every year. Therefore, carbon targets attribute new values to green mines. More efforts should be taken to construct green mines from Chining metal mining industry.

**Table 2. Land reclamation areas and carbon sequestration in some Chinese metal mines**

| Mine area name | Type | Reclamation area / $m^2$ | Sequstrated carbon / (t/a) |
|---|---|---|---|
| Baiyunebo | Iron | $3.2\times10^5$ [57] | $4.7\times10^3$ |
| Zijinshan | Copper-gold | $2.4\times10^6$ [58] | $3.5\times10^4$ |
| Malanzhuang | Iron | $7.6\times10^6$ [59] | $1.1\times10^5$ |
| Jinchang | Nickel | $3.1\times10^6$ [60] | $4.5\times10^4$ |
| Anshan | Iron | $1.5\times10^7$ [61] | $2.2\times10^5$ |
| Tongling | Copper | $1.0\times10^7$ [62] | $1.4\times10^5$ |

### 5.2. Carbon sequestration by backfill and tailing

Carbon capture and storage (CCS) is believed the primary option to limit the temperature rise to 1.5 ℃ relative to pre-industrial 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]:

$$\text{Metal oxide} + CO_2 \rightarrow \text{Metal carbonate} + \text{Heat} \quad (1)$$

Mineral carbonation can utilise Mg, Ca or Fe silicates minerals to stably store carbon dioxides [66]:

$$Mg_2SiO_4 + 2CO_2 + 2HO_2 \rightarrow 2MgCO_3 + H_4SiO_4 \quad (2)$$

$$Fe_2SiO_4 + 2CO_2 + 2HO_2 \rightarrow 2FeCO_3 + H_4SiO_4 \quad (3)$$

$$CaSiO_3 + CO_2 + 2HO_2 \rightarrow CaCO_3 + H_4SiO_4 \quad (4)$$

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]. Since the mineral carbonation concept was proposed, many researchers have tried to store $CO_2$ by different minerals from different industries. Xie et al. proposed to use $MgCl_2$ to store $CO_2$ and produce magnesium carbonate and hydrochloric acid [67]. Moreover, the heat produced by mineral carbonation can also be collected as power [67]. Xi et al. 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) [68]. Chen et al. employed fly ash to absorb $CO_2$ and found the modified sorbents achieved a $CO_2$ capture capacity of 0.27 g $CO_2$/g sorbent [69]. Forkers developed accelerated carbonation equipment to cure cemented-based materials and the equipment can process 50 tonnes of construction materials every hour [70]. Moreover, the concrete cured in $CO_2$ had a 45% higher strength than that cured in the $N_2$ atmosphere [70]. Most mining backfill is a kind of cement-based materials consisting of cement, fly ash, tailings and solid waste. According to existing researches on mineral carbonation in concrete, geopolymer and other construction materials, there may be a great potential to store $CO_2$ in mining backfill. If the carbon dioxide can be stored in the backfill, metal mines will be possible to become negative carbon mines.

Besides mineral carbonation in cemented-based materials, some researchers proposed to sequestrate carbon in tailings. Li and Hitch pointed out that the 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. carried out experiments to investigate the carbonation of a chrysotile mine tailings in Canada and found that about 10% wt of tailings to carbonate minerals could offset the greenhouse gas emissions from many ultramafic-hosted mining operations [71]. McGrail found relatively rapid chemical reactions of $CO_2$-saturated pore water with basalts to form stable carbonate minerals [72]. Therefore, mineral carbonation in mining backfill or tailings can be relatively inexpensive for carbon storage, which will significantly benefit metal mining to be carbon neutrality. More researches should be carried out to investigate the carbon storage capacity and technologies to store $CO_2$ in mining backfill and tailings.

## 6. Technical roadmap for carbon-neutrality in Chinese metal mines

Chinese metal mining industry and research community should take effective actions to achieve China's "dual carbon" targets. Figure 6 illustrates a brief technical roadmap for achieving carbon-neutrality in Chinese metal mines. Some existing and mature technologies should be taken as current actions. First, the GHG emissions data for 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 management and plan. Further, advanced mining methods and technologies can be employed to improve mining efficiency, including backfill mining, digital mine, automation, 5G, big data, smart mining, electrification of mining equipment and trucks, continuous mining, and integration of integration mining-processing-backfilling, etc. 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 utilised by metal mines. Importantly, more attention should be paid to green mines during the whole life-cycle of mines. By the above actions, Chinese 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 extract geothermal energy in metal mines is great. Therefore, researches on simultaneous extraction of mining resources and geothermal energy and extraction of geothermal energy from abandoned metal mines should be carried out. The clean energy from mines will benefit the construction of carbon neutrality. Moreover, carbon sequestration by mining backfill and tailing through mineral carbonation is a promising way to permanently and safely store carbon dioxide. Through mineral carbonation in metal mines, it is possible to transmit metal mines to negative carbon mines and bring new values to the metal mining industry. The related future technologies will contribute to the carbon-neutrality in Chinese metal mines before 2060.

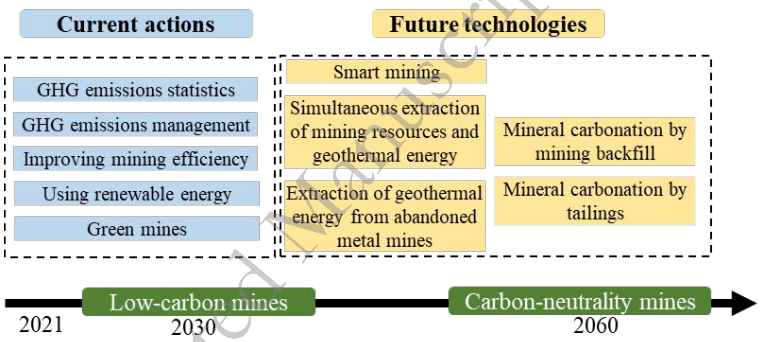


**Fig. 6. Technical roadmap for carbon-neutrality in Chinese metal mines.**

## 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 reviewed GHG emissions from metal mining industries and discussed the technical strategies for carbon-peak and carbon-neutrality in Chinese metal mines.

Conclusions can be drawn as follows:

(1) GHG mitigation of metal mining is essential for achieving carbon neutrality in China. The GHG emissions and its intensity vary from the mineral types. Iron mining contributed to the largerst amount of carbon emission in metal mining. The emission intensity per tone ore for gold mining is the highest.

(2) Some international 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 Chinese metal mine sector.

(3) Improving mining efficiency is the fundemantal way to reducing GHG emissions. Some common technologies (e.g., digital mine, automation, 5G, big data, smart mining, electrification of mining equipment and trucks, continuous mining, integration of mining-processing-backfilling, etc.) should be explored further to achive the 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 carbon absorption of reclamation vegetations. 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 by mining backfill and tailing through mineral carbonation is a also promising way to permanently and safely store carbon.

## Declaration of Competing Interest

The authors declare no competing interests.

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