International Journal of Minerals, Metallurgy and Materials
Volume 28, Number 4, April 2021, Page 513
https://doi.org/10.1007/s12613-020-2155-4

Invited Review

Mitigation of greenhouse gases released from mining activities: A review

Li-yuan Liu[1,2], *Hong-guang Ji*[1,2], *Xiang-feng Lü*[1,2], *Tao Wang*[1,2], *Sheng Zhi*[3], *Feng Pei*[2], *and Dao-lu Quan*[2]

1) Beijing Key Laboratory of Urban Underground Space Engineering, University of Science and Technology Beijing, Beijing 100083, China
2) School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
3) Department of Energy and Mineral Engineering, EMS Energy Institute and G3 Center, Pennsylvania State University, University Park, PA 16802, USA
(Received: 27 May 2020; revised: 16 July 2020; accepted: 27 July 2020)

Abstract: Climate changes that occur as a result of global warming caused by increasing amounts of greenhouse gases (GHGs) released into the atmosphere are an alarming issue. Controlling greenhouse gas emissions is critically important for the current and future status of mining activities. The mining industry is one of the significant contributors of greenhouse gases. In essence, anthropogenic greenhouse gases are emitted directly during the actual mining and indirectly released by the energy-intensive activities associated with mining equipment, ore transport, and the processing industry. Therefore, we reviewed both direct and indirect GHG emissions to analyze how mining contributes to climate change. In addition, we showed how climate change impacts mineral production. This assessment was performed using a GHG inventory model for the gases released from mines undergoing different product life cycles. We also elucidate the key issues and various research outcomes to demonstrate how the mining industry and policymakers can mitigate GHG emission from the mining sector. The review concludes with an overview of GHG release reduction and mitigation strategies.

Keywords: greenhouse gas emission; greenhouse gas reduction; mining; climate change; life cycle assessment; mitigation strategy

1. Introduction

Worldwide population and economic growth demand more energy and raw resources. However, the extraction and delivery of these resources often negatively impact the environment. For example, greenhouse gases (GHGs) emitted from mining and processing activities currently cannot be avoided. Anthropogenic GHG emissions contribute to global climate change [1–2]. A fundamental role of GHGs is to act as a protective blanket that allows solar heat to reach the Earth but prevents it from escaping back into the deeper atmosphere [3]. According to the Intergovernmental Panel on Climate Change, the anthropogenic global GHG emission between 1970 and 2020 has been increasing annually by 78% [4].

Anthropogenic GHGs include CO_2 (76wt%), CH_4 (16wt%), N_2O (6wt%), and fluorinated gases (2wt%; see Fig. 1). The Paris Agreement was initiated to formalize the cooperation between the largest world countries to fight against climate changes and to commit themselves to stop global annual temperature increase at <2°C with the use of a pre-industrial level as a basis. To decrease GHG emissions, countries have adopted strict measures in terms of GHG emission control and also sponsored fundamental and applied programs to monitor GHGs and associated climate change [5].

Quantifying the actual GHG emissions from mining activities is difficult because they evolve as human activities, including their diversity and expansion rate, change. The International Energy Agency calculated that ~75wt% of anthropogenic CO_2 is emitted because of the burning of fossil fuels [6]. As part of an effort to monitor emissions from the mining sector, gases emitted from Caterpillar 797B haulers were measured and recalculated to obtain real-world fuel-based emission factors [7], which were then compared with hauler activities. For the GHGs, the emission factors for CO_2 were the highest and related directly to the quantity of fuel burned, as indicated by the low standard deviations and consistency among the different engines [7]. CH_4 emissions were detectable but low, constituting ~0.1wt% of CO_2 emissions. With their awareness of the significant emission of GHGs, many countries responded and took actions by making climate

Corresponding authors: Hong-guang Ji E-mail: jihongguang@ces.ustb.edu.cn;
Xiang-feng Lü E-mail: lvxiangfeng2006@126.com

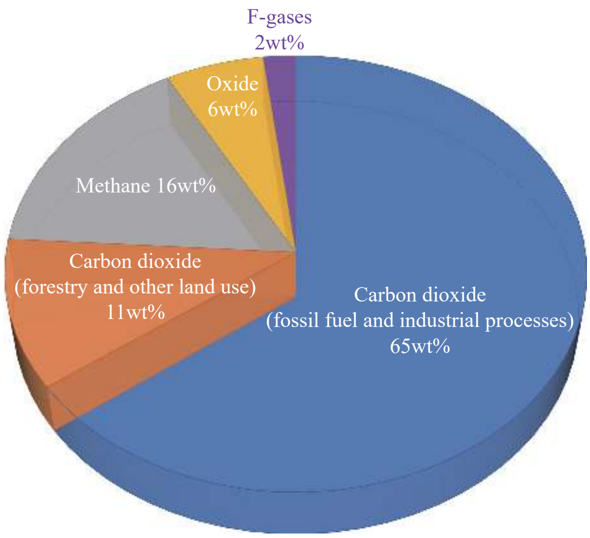

Fig. 1. Global GHG emissions (data collected from Ref. [4]). "F-gases" stands for fluorinated gases.

change-related policies and regulations even though environmental protection measures and regulations, as well as their execution, negatively affect the profitability and efficiency of mining projects [8]. Despite these negative impacts, regulations are needed, especially for countries that undertake extensive mining industries, such as Australia, China, and the United States. According to the National Bureau of Statistics of China [9], the production of coal and other energy sources continued to increase from 2000 to 2013. As shown in Fig. 2, coal production in 2013 is 2.7 times that in 2000. In recent years, the coal production of China was basically maintained at the level of 270 billion tons of standard coal. Undoubtedly, China is the world's largest coal miner. In essence, climate change due to the GHG emissions from mining has been quantified as one of the most acute environmental challenges in these countries [10].

Currently, the USA and China, which are the leaders in heavy industrial activities, are investigating how released CO_2 can be stored underground to solve the GHG emission problem [11]. Undoubtedly, climate change is an issue for mining activities and needs to be addressed from a variety of aspects. To address this matter, many countries incorporate regulations that, unfortunately, often negatively affect mining industries, especially those that emit large amounts of GHGs [12]. Countries such as Finland, Sweden, Denmark, and the Netherlands introduced an obligatory carbon energy tax [13], while the United Kingdom created a climate change tariff even for the production sector [14].

2. GHG emissions caused by mining

The mining industry is both a direct and an indirect GHG emission because it uses very energy-intensive processes (e.g., mining itself followed by ore transport and processing) [12]. This section summarizes both direct and indirect GHG emissions caused by mining activities.

2.1. Direct emissions of GHGs

Direct GHG emission sources are commonly classified into (1) those that correspond to process emissions and (2) those that produce emissions from energy consumption needed to perform mining-related activities.

2.1.1. On-site direct emissions

During mining and ore processing, GHGs are mainly released as a result of the consumption of energy produced by fossil fuel combustion during mining activities. More than 65wt% of the energy consumed during these stages is due to the burning of fossil fuel, emitting mostly CO_2. For instance, surface mining, including overburden removal on a large

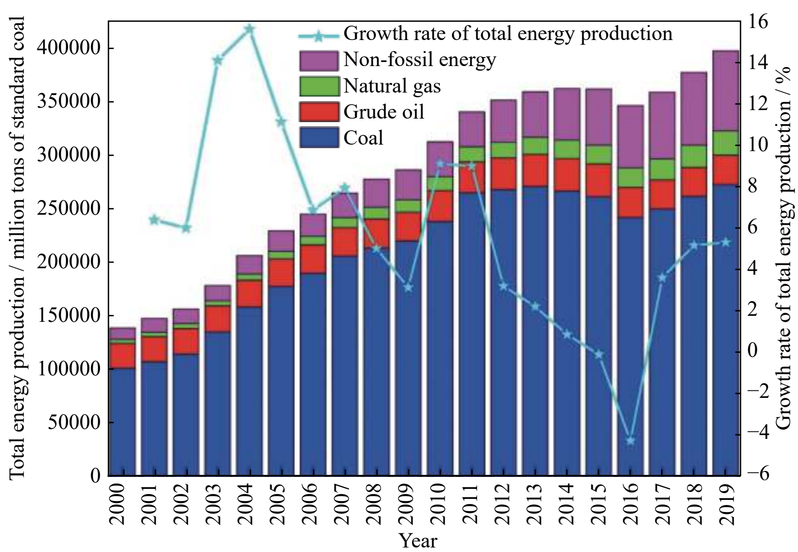

Fig. 2. Changes in energy productions in China from 2000 to 2019.

scale, is all performed by machinery, which uses diesel, thereby consuming a large amount of energy [15]. The primary emission sources during smelting and refining are both energy and process related. For example, the clinker-making process in the cement industry uses coal [16]. Thus, GHG emissions mainly originate from operating equipment such as diesel, blasting, and conveying motors.

However, some GHGs, such as CH_4, originate from the mineral deposits themselves. Mining, as a result of ore excavation, clearing, crushing, removal, and loading, also produces significant amounts of aerosols and particulates, which are then emitted into the air, thereby worsening its quality. Operations such as drilling and blasting also release CO_2. Both operations are very vigorous and energetic processes, producing toxic gases such as carbon monoxide (CO) and nitric oxide (NO) aside from stable gases, such as CO_2 and N_2. In addition, a significant amount of NO_2 are released as a result of blasts, judging by its characteristic orange-colored smoke [17].

The desorption or release of coalbed methane also contributes to GHG emissions. GHGs are also generated by coal burning by consumers and coal usage to provide centralized heating and for electricity [18]. Coal fires around coal mines are frequent, yet coal transport from these mines and their remote storage spread and propagate these fires beyond their natural occurrence, thus spreading them spatially and to different territories, thereby further worsening the environmental pollution problem [19]. Burning coal releases not only CO_2 due to the carbon reaction with oxygen but also toxic sulfur- and nitrogen-containing oxides; rain will worsen this situation even more by forming acidic precipitation. Coal burning also releases particulate matter (PM) and flying ash, a variety of organic chemicals, and hazardous trace elements such as As, Hg, and Se [20]. However, not all carbon from the coal converts to CO_2. As the fire temperature increases, other GHGs such as CO, H_2, and even hydrocarbons such as ethylene (C_2H_4), propylene (C_3H_6) and acetylene (C_2H_2) form. Sometimes, mining industries have their own power plants, which also emit GHGs and should be considered as direct emissions.

2.1.2. Fugitive emissions as a result of coal mining

Fugitive emissions refer to GHGs that escaped from the ores themselves in their natural environment and during their mining, storage, and transport. For example, the geological formation of CH_4 co-occurs with coal. In essence, methane forms and becomes absorbed by the surrounding ore during coalification, which is a process in which plants are consumed by anaerobic microorganisms followed by their long-term burial under the pressure of the surrounding rock strata [21]. CH_4 escapes when coal is exposed and broken [22] as a result of the following situations associated with mining: (1) surface mines with seams exposed to the surrounding open areas; (2) degasification of the underground mines through vertical or horizontal wells; (3) underground mine ventilation; (4) coal broken and disturbed during storage, transportation, and post-mining processing; (5) leakages from vent holes or fissures of abandoned or closed mines.

The amount of released CH_4 strongly depends on its content in the coal seam and the coal buried depth. Coals with higher carbon ranks typically contain more CH_4. Deep-lying coals, when undisturbed, do not release a large amount of methane because CH_4 simply cannot escape thick strata above the coal layers. However, although natural CH_4 migration from these deep layers is hindered, nothing stops these vast amounts of CH_4 from escaping when coal is mined and brought to the surface [23]. Surface coal mining does not release a large amount of CH_4 (compared with its deeper counterparts) because of its lower rank and deposition depth. Ventilation emissions from shallow and deep coal mines are the most significant contributors to the total global CH_4 release related to coal mines. The total CH_4 released from abandoned mines is also significant, but it varies from mine to mine and strongly depends on (1) when the mine was abandoned, (2) whether it was flooded prior to the closure, (3) overall CH_4 content in the coal, and (4) network of escape passages (e.g., mine seals and vents).

Approximately 28 billion cubic meters of CH_4 (or 420 million tons if the corresponding carbon content is recalculated to the CO_2) enter the atmosphere annually as a result of coal mining [24]. Thus, we not only pollute our planet with this GHG, but our wastefulness and lack of utilization of this useful energy resource also contribute to global temperature increase [25].

2.2. Indirect emissions of GHGs

The indirect emissions of GHGs include those that result from fuel consumption during mining operations, production of electricity, and detonation of explosives. Evidently, more GHGs are emitted as more fuel is consumed [26]. Mining, including open-cast mining, requires a large-scale excavation to recover ore from the subsurface, which is typically accompanied by deforestation activity and, as a result, significant depletion of CO_2 fixation source. A typical example of process-related emissions is the Al processing industry, which releases CO_2 and perfluorocarbons because of the way aluminum is recovered from Al_2O_3. Another example is cast iron and steelmaking, which generates significant CO_2 and CH_4 amounts during ore sintering.

Surprisingly, loading and hauling are the most significant contributors to the total GHGs emitted during mining and processing of iron and bauxite ores, totaling more than 50wt% (see Figs. 3(a) and 3(b), respectively). For copper ore processing, the steps of crushing and grinding contributed the most GHGs (see Fig. 3(c)) [27]. Usage of explosives during mining added only small amounts (1wt%–8wt%) of GHGs to the atmosphere, contributing 0.4, 0.7, and 0.6 kg CO_2 equi-

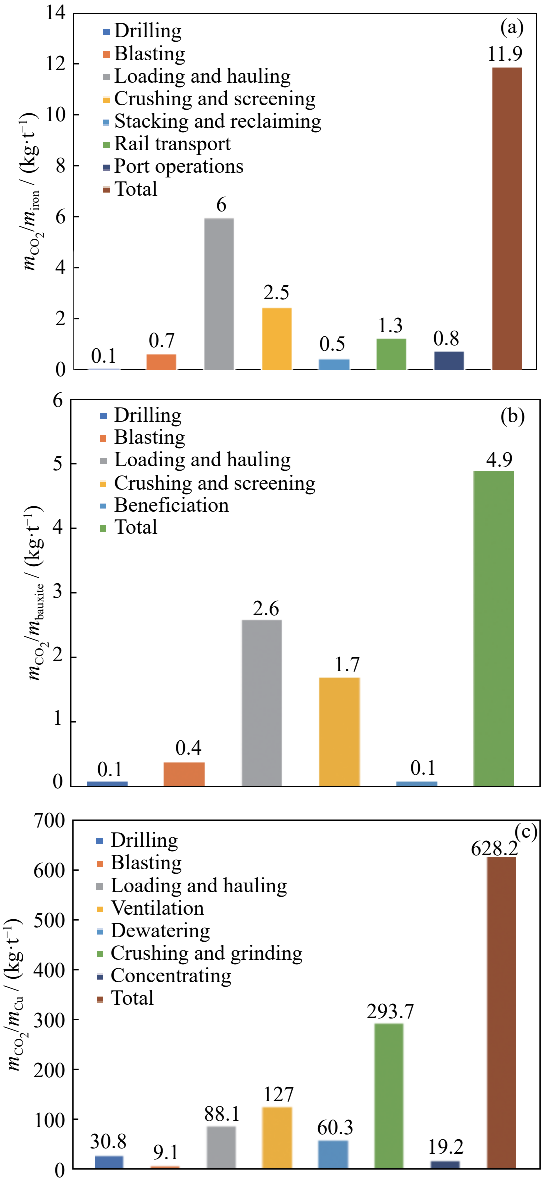

Fig. 3. CO_2 release during different stages of (a) iron ore, (b) bauxite, and (c) Cu concentrate processing. (m_{CO_2} is the mass of released CO_2 in kg; m_{iron}, $m_{bauxite}$, and m_{Cu} are the weights of iron ore, bauxite, and Cu concentrate in t, respectively) (data collected from [27]).

valent per ton (e/t) out of the total GHGs for activities related to bauxite, iron ore, and Cu concentrate mining, respectively [27]. After analyzing aluminum production in 29 countries, Paraskevas *et al.* [28] concluded that it released 0.45 Gt CO_2 equivalent (eq.) in 2012.

3. Mining contribution to climate change

Without a doubt, mining affects the climate and health of our planet. However, this influence is much more diverse than many might realize. One example is the expansion of mining in forested areas, which leads to an overall increase in GHGs because of the loss of CO_2-absorbing forests [15,29]. To slow down the negative impact of mining on the environment, many governments introduce measures and incentives to make sustainable mining attractive to industries. Yet, some industrial areas, such as ones in Australia, still face challenges. More prime ore deposits in Australia become gradually depleted, and the remaining ore has a significantly lower grade than those in as-yet undeveloped deeper deposits. However, the development of deeper mines might face sustainability and environmental issues. On the other side, the processing of poor-quality ore will require more water and energy. That might also increase GHG emissions even more and present an additional burden on already scarce Australian water resources [30].

Complex and multistage cast iron and steel production requires a tremendous amount of resources. Out of the total energy consumed by the cast iron and steel making, coal-based energy accounts for 69.9wt%, while electricity and oil account for 26.4wt% and 3.2wt%, respectively [31]. The energy and coal consumption by China's cast iron and steel industry during the recent decade has been increasing substantially (Fig. 4). Cast iron and steel metallurgy is believed to remain one of the largest CO_2 emitters, not quite surpassing the chemical and construction industries [31]. Thus, an analysis and understanding of how CO_2 release into the atmosphere from the heavy metallurgy can be decreased are extremely important. This scientific data could then be efficiently used as a basis for relevant government policies.

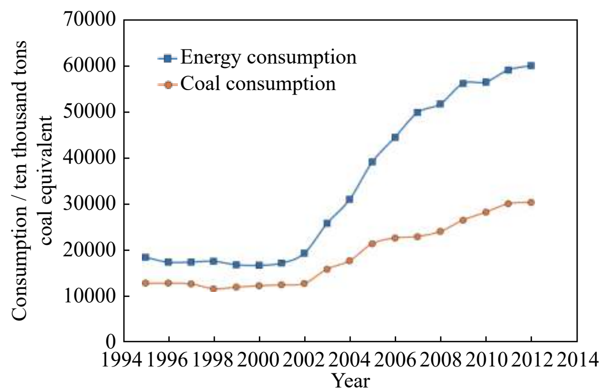

Fig. 4. Energy and coal consumption by China's cast iron and steel industry (data collected from [31]).

Among various mining activities, coal excavation is considered the main contributor to GHG release and buildup. CO_2 emitted from coal-operated power plants was predicted to rise by 75% between 1970 and 2010 [32]. According to the 2015 data, 93wt% of the GHGs in the United States were emitted from electricity generated by burning coal [33]. CH_4 emissions from coal mines correspond to 3wt% [33]. Spontaneous coal combustion, which is severely aggravated by human activities around coal deposits (also known as coal fires), also releases a variety of GHGs [34] and toxic gasses. Products of incomplete combustion (PICs) released from burning coals contain both solid particles and gases, thereby making separation and capture of GHGs complicated. Some of these PICs are so toxic and dangerous (e.g., SO_2, NO_2, CO, PM, and As-, Hg-, and F-based compounds) that their release and contents are heavily regulated [35].

Coal mining extracts ore from the strata to the Earth's surface. A coal life cycle assessment (LCA), which was performed using underground coal mining in southern Brazil as a subject [36], showed that 0.0856 kg CO_2 equivalent per kilogram of coal was emitted during mining. A similar model, which was performed for China's iron ore mining and processing industries to estimate GHG emissions, showed that 270 kg CO_2 e/t of iron ore was released and that the two most significant contributors to overall GHG emissions were the agglomeration (60wt%) and ore processing (23wt%) steps [37].

The strong correlation between the climate change and mining industry raises a question about the total CO_2 or other GHGs released at the global level. The International Council on Mining & Metals (ICMM) was founded in 2001 to enhance performance with respect to sustainable development within the mining industry. ICMM calculations suggest that the mining and metal industries contribute ~2wt% of global anthropogenic GHG emissions [30]. The mining, mineral processing, and metal production sector, like other industrial sectors, is coming under increased pressure to reduce GHG emissions.

4. Strategies in mitigating GHG emissions from mining activities

Many aspects need to be considered and adjusted, including mining activity, to slow down climate changes caused by anthropogenic activities. To address this matter, various countries requested other nations to collaborate on controlling and limiting GHG emissions and initiated programs and policies to monitor the progress [5]. Such major initiatives require well-thought-out coordination of climate policymakers and for investors to agree on what merit the energy technology innovations can bring to reduce GHG emissions. A deep understanding of the potential impact of policies and investment strategies in relationship to GHGs will guide governments to establish anthropogenic GHG reduction targets and human-caused climate change goals. For example, an analysis of the truck energy consumption and associated GHG emissions showed that regular truck engine maintenance could significantly reduce their fuel consumption and, as a consequence, CO_2 and other gas emissions [2]. Thus, one of the implemented regulatory policies needs to be an equipment and machinery maintenance policy. Another sustainable way to reduce fossil fuel energy use and GHG release is to incorporate renewable energy sources in mining sites [38–39]. The next four sections in this chapter provide more details on significant strategies to mitigate GHG emissions caused by mining.

4.1. Mitigation and utilization of methane emitted from coal mines

Targeted drainage of coal bed methane (CBM) is a very efficient strategy to reduce CH_4 release in the atmosphere. As illustrated in Fig. 5, sequestration of CO_2 in unminable coal seams is an option to combat climate change and an opportunity to enhance CBM production [40–43]. Gaseous CO_2 enters a supercritical state when temperature and pressure are above the critical point (31.1°C and 7.38 MPa), which is a typical state for CO_2 storage for carbon sequestration and CO_2 injection in enhanced CBM recovery [44–45]. CBM drainage also improves mine safety and provides a raw source of clean energy and carbohydrate materials in this case where CH_4 is captured [46–49].

However, capture and further commercial use of CBM are currently impractical from both technical and economic points of view. Therefore, drained CBM is removed from the mine and then simply discarded into the atmosphere through blowers or vents. One option is to burn this CH_4 in a controlled manner. In fact, CBM flaring is widely used in Europe and Australia but has not found widespread application in the United States. Mining conditions often change frequently; thus, gas supply parameters (produced amounts or its purity) can change, which might result in failure or planned shutdown of the corresponding equipment. If the released methane is not trapped because of these issues, then it can still be flared to minimize its emission into the atmosphere. Another option (especially if dilution or flaring cannot be achieved) is to dilute CH_4 in the air to oxidize it using ventilation air methane (VAM) technology.

Released coal bed methane may be collected and sold to existing natural gas companies. Current pipelines require methane to be 90wt%–95wt% concentrated. Gas drained from vertical frac wells, horizontal wells, and in-seam boreholes contains >90wt% of methane; thus, a satisfactory approach is to inject it into existing pipelines with limited additional processing [50]. If methane quality is unsatisfactory, one way to improve it is to redesign wells and boreholes for efficient gas recovery by mixing low- and high-quality CBM together and/or by spiking the CBM with hydrocarbon gases with a higher molecular weight. Another way is to remove gas impurities in a special central facility, in which CBM will be sent through several treatment stages to remove hydrogen sulfides gradually (if present), then excess water, O_2, CO_2, and nitrogen. According to the United States Environmental Protection Agency, other technologies include the usage of volatile organic compound concentrators, lean gas fuel turbines, and VAM as ancillary fuels.

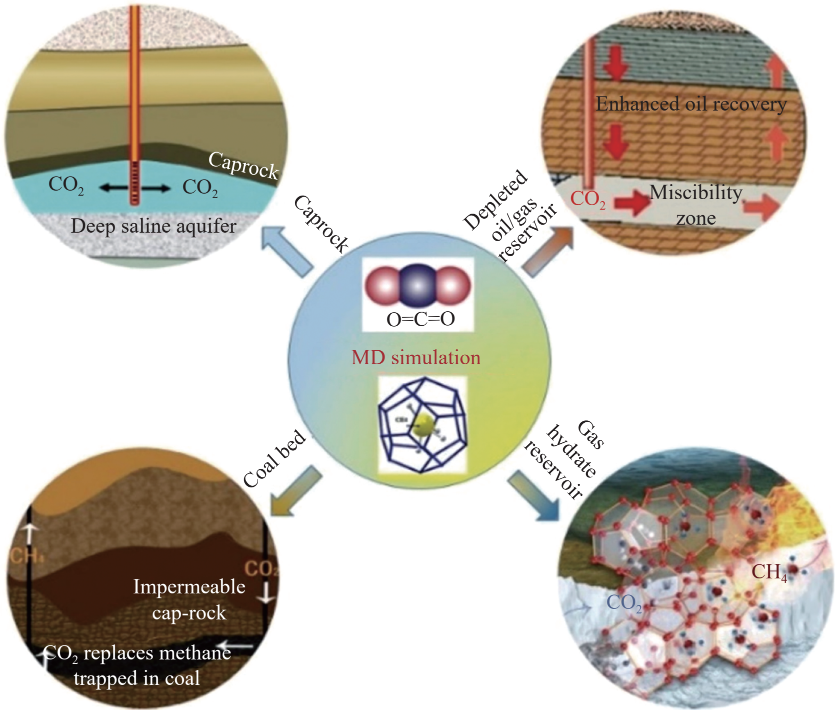

Fig. 5. Schematic diagram showing possible deposits for geologic carbon sequestration. Reprinted from *Fuel*, 255, Z.Y. Ma and P.G. Ranjith, Review of application of molecular dynamics simulations in geological sequestration of carbon dioxide, 115644, Copyright 2019, with permission from Elsevier.

4.2. CO_2 capture and storage

Capturing CO_2 and then storing it underground is a novel approach that can relieve the ever-increasing anthropogenic CO_2 emissions. Geological CO_2 sequestration is based on a strategy used during oil and natural gas production, as well as underground CBM and natural gas storage. These approaches are reasonable in terms of short-term CO_2 sequestration. In addition, CO_2 storage in geological formations offers reduced costs, increased capacity, and enhanced safety, among other benefits [51]. The process of injecting and storing CO_2 in unmineable coal seams to enhance methane recovery is called enhanced coalbed methane recovery. Enhanced coalbed methane recovery parallels enhanced oil recovery (EOR) because it provides an economic benefit from the recovery and sale of the methane gas, helping to offset the cost of CO_2 storage. Novel CO_2 storage technologies include but are not limited to (1) mineral trapping assisted by catalysts or additives, (2) CO_2 sequestration into composites containing multilayered geological formations of rocks capable of dispersing CO_2 plume [52], (3) usage of empty or depleted oil reservoirs or coal seams through EOR and enhanced coalbed methane (ECBM) programs, and (4) injection of CO_2 into methane hydrate formations, which not only provides CO_2 storage but also generates new methane hydrate clusters [53–56].

Geological sequestration involves the injection of captured CO_2 into the geological subsurface. The geosequestration technique was established by EOR and enhanced gas recovery initiatives. For example, the Southwest Regional Partnership on Carbon Sequestration (SWP) is one of seven regional partnerships funded by the United States Department of Energy. SWP aims at examining the long-term CO_2 storage potential in partially depleted oil and gas reservoirs and extracting a prolific volume of hydrocarbon fluids [57]. The global capacity of underground sequestration was assessed to be equal to 1000–1800 Gt CO_2 [58]. However, the biocomplexity of the underground environment makes underground CO_2 storage less reliable and more dangerous than ocean CO_2 sequestration [59].

CO_2 capture and storage (CCS) could reduce the lifecycle of CO_2 emissions from power plants that use fossil fuel for their operations. CCS power plants could thrive, but significant incentives would be needed before this technology becomes competitive. For instance, additional investments and operational costs caused in part by efficiency improvements would be compensated by high carbon prices (or direct financial support) [60]. CCS can be implemented with gas production from biomass to enhance the CO_2 mitigation potential further [61].

4.3. Life cycle assessment of mining and further processing

A relatively newly developed LCA of the environmental impact of various activities and products uses interconnected stages of various processes, starting from the purchase of raw materials or excavation and ending with their final disposal.

Yellishetty *et al.* [62] reviewed the LCA methods used for mining and metal sectors. Suppen *et al.* [63] summarized the Mexican mining industry and its strategies of sustainable principle incorporation, including the creation of a national base metals life cycle inventory. Adachi and Mogi [64] focused on GHG emissions while developing a mining life cycle inventory database for Cu and Zn production. LCA reported by Mangena and Brent [65] used a "cradle-to-gate" study to analyze coal produced at mine sites in South Africa. Liang *et al.* [66] developed life cycle models for four electricity-generating and coal-using technologies in China: integrated gasification combined cycle and subcritical, supercritical, and ultra-supercritical steam generation. LCA of Awuah-Offei *et al.* [67] showed that GHG emissions from belt conveyors were significantly higher than those produced from truck haulage considering the same functional unit (hauling 4000 t/h of ore). However, their assessment of the acid rain gas emissions obtained the opposite result. Some of these data were obtained from the LCA cases on the basis of experimental data. However, none of them analyzed the exact contributions of different mining and mineral processing steps with regard to GHG release.

4.4. Carbon trading

According to the Kyoto Protocol Clean Development Mechanism (CDM), GHGs released from mining can be decreased by carbon trading, which is an economic activity that involves buying and selling environmental services and commodities, including GHGs from the atmosphere. These commodities are then identified and purchased by eco-consulting firms, after which they are sold to individuals or corporations to offset their harmful emissions [68]. Some regions, most notably the EU, have already initiated cooperation on mitigation performed using a carbon trading scheme and binding regulations on GHG emissions. Similar to the established EU carbon trading system, other countries and territories (e.g., New Zealand, Australia, South Korea, California, northeastern United States, Quebec province in Canada, Japan, and several areas in China) adopted and followed this practice to control GHG emissions.

Initial CDM sponsorship by governments or large industries could make them more economically feasible and eventually create a technology market worldwide, including China. CDM statistical analysis shows that CH_4 is expected to be reduced by ~74.6 million tons of CO_2 eq. per year through recovery and utilization, accounting for 10.6wt% of the total number of approved CDM projects in China [69].

5. Summary and conclusions

This paper reviewed how mining activities affect climate change and summarized strategies reported in the literature on how to mitigate GHG emissions released by the mining industry. GHGs can be released as a result of direct or indirect mining activities. Without a doubt, mining affects climate change severely. Thus, this review provided an overview of the specific factors that contribute to global warming. A GHG inventory assessment of mines covered all relevant product life cycle stages. The review also discussed the key issues and outcomes that need to be navigated by the mining industry to continue to satisfy policymakers and produce needed raw resources in a sustainable and environmentally friendly way. This review concluded with a description of possible mitigation strategies to reduce GHG emissions into the atmosphere.

Climate change is indeed real. Thus, internationally collaborative efforts are needed to assess how the mining industry, which is one of the significant contributing players, can be guided to slow down or even eliminate irreversible damage done to our climate. Definitively, the urgent need for a further elaborated research field that couples mining activities and climate change is evident.

Acknowledgements

This work was financially supported by the Beijing Natural Science Foundation (No. 2204084), the National Science Foundation of China (Nos. 52004015 and 51874014), the Major Scientific and Technological Innovation Project of Shandong Province, China (No. 2019SDZY02), and the Fundamental Research Funds for the Central Universities of China (No. FRF-TP-19-027A1).

References

[1] J.D. Figueroa, T. Fout, S. Plasynski, H. McIlvried, and R.D. Srivastava, Advances in CO_2 capture technology—The U.S. department of energy's carbon sequestration program, *Int. J. Greenhouse Gas Control*, 2(2008), No. 1, p. 9.

[2] S. Peralta, A.P. Sasmito, and M. Kumral, Reliability effect on energy consumption and greenhouse gas emissions of mining hauling fleet towards sustainable mining, *J. Sustainable Min.*, 15(2016), No. 3, p. 85.

[3] N. Mirovitskaya and W.L. Ascher, *Guide to Sustainable Development and Environmental Policy*, Duke University Press, Durham, NC, 2002.

[4] T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda, and T. Troxler, *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*, the Intergovernmental Panel on Climate Change, Switzerland, 2014.

[5] M. Meinshausen, N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, and M.R. Allen, Greenhouse-gas emission targets for limiting global warming to 2°C, *Nature*, 458(2009), No. 7242, p. 1158.

[6] International Energy Agency, *Beyond Kyoto: Energy Dynamics and Climate Stabilisation*, OECD Publishing, Paris, 2002.

[7] X.L. Wang, J.C. Chow, S.D. Kohl, K.E. Percy, A.H. Legge, and J.G. Watson, Real-world emission factors for Caterpillar 797B heavy haulers during mining operations, *Particuology*, 28(2016), p. 22.
[8] M. Tuusjärvi, I. Mäenpää, S. Vuori, P. Eilu, S. Kihlman, and S. Koskela, Metal mining industry in Finland – Development scenarios to 2030, *J. Cleaner Prod.*, 84(2014), p. 271.
[9] National Bureau of Statistics of China [2020-07-15]. http://data.stats.gov.cn/easyquery.htm?cn=C01
[10] G.M. Mudd, The environmental sustainability of mining in Australia: Key mega-trends and looming constraints, *Resour. Policy*, 35(2010), No. 2, p. 98.
[11] M. Davarazar, D. Jahanianfard, Y. Sheikhnejad, B. Nemati, A. Mostafaie, S. Zandi, M. Khalaj, M. Kamali, and T.M. Aminabhavi, Underground carbon dioxide sequestration for climate change mitigation – A scientometric study, *J. CO2 Util.*, 33(2019), p. 179.
[12] R. Irarrázabal, Mining and climate change: Towards a strategy for the industry, *J. Energy Nat. Resour. Law*, 24(2006), No. 3, p. 403.
[13] B. McDonald and Neil Hawke, Environmental Policy: Implementation and enforcement, *Int. Environ. Agreements Polit. Law Econ.*, 3(2005), No. 3, p. 293.
[14] A.J. Bradbrook, R. Lyster, R.L. Ottinger, and X. Wang, *The Law of Energy for Sustainable Development*, Cambridge University Press, Cambridge, 2005.
[15] E.D.C. Rodovalho and G. de Tomi, Simulation of the impact of mine face geometry on the energy efficiency of short-distance haulage mining operations, *Min. Technol.*, 125(2016), No. 4, p. 226.
[16] E. Worrell, L. Price, N. Martin, C. Hendriks, and L.O. Meida, Carbon dioxide emissions from the global cement industry, *Ann. Rev. Energy Env.*, 26(2001), p. 303.
[17] M.I. Attalla, S.J. Day, T. Lange, W. Lilley, and S. Morgan, NO*x* emissions from blasting operations in open-cut coal mining, *Atmos. Environ.*, 42(2008), No. 34, p. 7874.
[18] B. Pandey, M. Gautam, and M. Agrawal, Greenhouse gas emissions from coal mining activities and their possible mitigation strategies, [in] S.S. Muthu, ed., *Environmental Carbon Footprints: Industrial Case Studies*, Elsevier, Oxford, 2018, p. 259.
[19] J.D.N. Pone, K.A.A. Hein, G.B. Stracher, H.J. Annegarn, R.B. Finkleman, D.R. Blake, J.K. McCormack, and P. Schroeder, The spontaneous combustion of coal and its by-products in the Witbank and Sasolburg coalfields of South Africa, *Int. J. Coal Geol.*, 72(2007), No. 2, p. 124.
[20] R.B. Finkelman, Potential health impacts of burning coal beds and waste banks, *Int. J. Coal Geol.*, 59(2004), No. 1-2, p. 19.
[21] D.A. Kirchgessner, S.D. Piccot, and S.S. Masemore, An improved inventory of methane emissions from coal mining in the United States, *J. Air Waste Manage. Assoc.*, 50(2000), No. 11, p. 1904.
[22] Y.W. Ju, Y. Sun, Z.Y. Sa, J.N. Pan, J.L. Wang, Q.L. Hou, Q.G. Li, Z.F. Yan, and J. Liu, A new approach to estimate fugitive methane emissions from coal mining in China, *Sci. Total Environ.*, 543(2016), p. 514.
[23] United States Environmental Protection Agency, *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030* [2012-12-31]. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OAP&dirEntrId=268252
[24] P. Franklin, *Methane from Coal Mines Presents Opportunity to Recover Energy and Generate Revenues*, Oilfield Technology [2009-09-30]. https://www.oilfieldtechnology.com/exploration/30092009/methane_from_coal_mines_presents_opportunity_to_recover_energy_and_generate_revenues/#tags
[25] S. Su, J.Y. Han, J.Y. Wu, H.J. Li, R. Worrall, H. Guo, X. Sun, and W.G. Liu, Fugitive coal mine methane emissions at five mining areas in China, *Atmos. Environ.*, 45(2011), No. 13, p. 2220.
[26] A. Soofastaei, S.M. Aminossadati, M.S. Kizil, and P. Knights, Simulation of payload variance effects on truck bunching to minimise energy consumption and greenhouse gas emissions, [in] *The 15th Coal Operators' Conference*, University of Wollongong, Wollongong, 2015, p. 337.
[27] T. Norgate and N. Haque, Energy and greenhouse gas impacts of mining and mineral processing operations, *J. Cleaner Prod.*, 18(2010), No. 3, p. 266.
[28] D. Paraskevas, K. Kellens, A.V.D. Voorde, W. Dewulf, and J.R. Duflou, Environmental impact analysis of primary aluminium production at country level, *Procedia CIRP*, 40(2016), p. 209.
[29] M.G. da Silva, A.R.C. Muniz, R. Hoffmann, and A.C.L. Lisbôa, Impact of greenhouse gases on surface coal mining in Brazil, *J. Cleaner Prod.*, 193(2018), p. 206.
[30] S.D. Odell, A. Bebbington, and K.E. Frey, Mining and climate change: A review and framework for analysis, *Extr. Ind. Soc.*, 5(2018), No. 1, p. 201.
[31] L. Li, Y.L. Lei, and D.Y. Pan, Study of CO_2 emissions in China's iron and steel industry based on economic input–output life cycle assessment, *Nat. Hazard.*, 81(2016), No. 2, p. 957.
[32] J. Conti, P. Holtberg, J. Diefenderfer, A. LaRose, J.T. Turnure, and L. Westfall, *International Energy Outlook 2016: With Projections to 2040*, Technical Report, U.S. Energy Information Administration, Washington, 2016.
[33] United States Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks* [2020-03-10]. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
[34] P. van Dijk, C. Kuenzer, J.Z. Zhang, K.H. Wolf, and J. Wang, *Scientific Assessment and Policy Analysis: Fossil Fuel Deposit Fires: Occurrence Inventory, Design and Assessment of Instrumental Options*, Netherlands Research Programme on Scientific Assessment and Policy Analsisfor Climate Change (WAB), the Netherlands, 2009.
[35] J.F. Zhang and K.R. Smith, Household air pollution from coal and biomass fuels in China: Measurements, health impacts, and interventions, *Environ. Health Perspect.*, 115(2007), No. 6, p. 848.
[36] A. Restrepo, E. Bazzo, and R. Miyake, A life cycle assessment of the Brazilian coal used for electric power generation, *J. Cleaner Prod.*, 92(2015), p. 179.
[37] Y. Gan and W.M. Griffin, Analysis of life-cycle GHG emissions for iron ore mining and processing in China—Uncertainty and trends, *Resour. Policy*, 58(2018), p. 90.
[38] L.Y. Liu, H.G. Ji, D. Elsworth, S. Zhi, X.F. Lv, and T. Wang, Dual-damage constitutive model to define thermal damage in rock, *Int. J. Rock Mech. Min. Sci.*, 126(2020), art. No. 104185.
[39] K. Parameswaran, Sustainability considerations in innovative process development, [in] V.L. Lakshmanan, R. Roy, and V. Ramachandran, eds., *Innovative Process Development in Metallurgical Industry*, Springer, Cham, 2016, p. 257.
[40] Z.Y. Ma and P.G. Ranjith, Review of application of molecular dynamics simulations in geological sequestration of carbon dioxide, *Fuel*, 255(2019), art. No. 115644.
[41] L. Liu, *Damage Mechanics Model for Dual Porosity Medium and Its Application on Hydraulic Fracturing* [Dissertation], Northeastern University, Shenyang, 2018.

[42] L.M. Qiu, D.Z. Song, X.Q. He, E.Y. Wang, Z.L. Li, S. Yin, M.H. Wei, and Y. Liu, Multifractal of electromagnetic waveform and spectrum about coal rock samples subjected to uniaxial compression, *Fractals*, 28(2020), No. 4, art. No. 2050061.

[43] L.Y. Liu, W.C. Zhu, C.H. Wei, and X.H. Ma, Mechanical model and numerical analysis of mechanical property alterations of coal induced by gas adsorption, *Rock Soil Mech.*, 39(2018), No. 4, p. 1500.

[44] S. Zhi, D. Elsworth, and L.Y. Liu, W-shaped permeability evolution of coal with supercritical CO_2 phase transition, *Int. J. Coal Geol.*, 211(2019), art. No. 103221.

[45] L.Y. Liu, W.C. Ma, and W.D. Wang, Dual damage mechanism of supercritical CO_2 adsorption-induced weakening effect on coal, *J. Shandong Univ. Sci. Technol.* (*Nat. Sci.*), 39(2020), No. 4, p. 79.

[46] C.S. Zheng, Z.W. Chen, M. Kizil, S. Aminossadati, Q.L. Zou, and P.P. Gao, Characterisation of mechanics and flow fields around in-seam methane gas drainage borehole for preventing ventilation air leakage: A case study, *Int. J. Coal Geol.*, 162(2016), p. 123.

[47] S.J. Schatzel, C.Ö. Karacan, H. Dougherty, and G.V.R. Goodman, An analysis of reservoir conditions and responses in longwall panel overburden during mining and its effect on gob gas well performance, *Eng. Geol.*, 127(2012), p. 65.

[48] C.Ö. Karacan, F.A. Ruiz, M. Cotè, and S. Phipps, Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction, *Int. J. Coal Geol.*, 86(2011), No. 2-3, p. 121.

[49] C.S. Zheng, B.Y. Jiang, S. Xue, Z.W. Chen, and H. Li, Coalbed methane emissions and drainage methods in underground mining for mining safety and environmental benefits: A review, *Process Saf. Environ. Prot.*, 127(2019), p. 103.

[50] United States Environmental Protection Agency, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Profiles of Selected Gassy Underground Coal Mines 2002-2006* [2009-01-30]. https://www.epa.gov/sites/production/files/2016-03/documents/profiles_2008_final.pdf

[51] L.Y. Liu, W.C. Zhu, C.H. Wei, D. Elsworth, and J.H. Wang, Microcrack-based geomechanical modeling of rock–gas interaction during supercritical CO_2 fracturing, *J. Pet. Sci. Eng.*, 164(2018), p. 91.

[52] B.L. Preston and R.N. Jones, *Climate Change Impacts on Australia and the Benefits of Early Action to Reduce Global Greenhouse Gas Emissions*, Commonwealth Scientific and Industrial Research Organisation, Aspendale, Victoria, 2006.

[53] C.M. White, D.H. Smith, K.L. Jones, A.L. Goodman, S.A. Jikich, R.B. LaCount, S.B. DuBose, E. Ozdemir, B.I. Morsi, and K.T. Schroeder, Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery – A review, *Energy Fuels*, 19(2005), No. 3, p. 659.

[54] S. Harpalani, B.K. Prusty, and P. Dutta, Methane/CO_2 sorption modeling for coalbed methane production and CO_2 sequestration, *Energy Fuels*, 20(2006), No. 4, p. 1591.

[55] M.J. Mavor, W.D. Gunter, J.R. Robinson, D.H.-S. Law, and J. Gale, Testing for CO_2 sequestration and enhanced methane production from coal, [in] *SPE Gas Technology Symposium*, Calgary, 2002.

[56] W.C. Zhu, L.Y. Liu, J.S. Liu, C.H. Wei, and Y. Peng, Impact of gas adsorption-induced coal damage on the evolution of coal permeability, *Int. J. Rock Mech. Min. Sci.*, 101(2018), p. 89.

[57] J.Y. You, W. Ampomah, Q. Sun, E.J. Kutsienyo, R.S. Balch, Z.X. Dai, M. Cather, and X.Y. Zhang, Machine learning based co-optimization of carbon dioxide sequestration and oil recovery in CO_2-EOR project, *J. Cleaner Prod.*, 260(2020), art. No. 120866.

[58] J.J. Dooley, R.T. Dahowski, C.L. Davidson, M.A. Wise, N. Gupta, S.H. Kim, and E.L. Malone, *Carbon Dioxide Capture and Geologic Storage: A Core Element of a Global Energy Technology Strategy to Address Climate Change*, Global Energy Technology Strategy Program, College Park, MD, 2006.

[59] S. Bachu, Sequestration of CO_2 in geological media: Criteria and approach for site selection in response to climate change, *Energy Convers. Manage.*, 41(2000), No. 9, p. 953.

[60] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, J.C. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, and T. Zwickel, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2014.

[61] M.C. Carbo, R. Smit, B. van der Drift, and D. Jansen, Bio energy with CCS (BECCS): Large potential for BioSNG at low CO_2 avoidance cost, *Energy Procedia*, 4(2011), p. 2950.

[62] M. Yellishetty, P.G. Ranjith, A. Tharumarajah, and S. Bhosale, Life cycle assessment in the minerals and metals sector: A critical review of selected issues and challenges, *Int. J. Life Cycle Assess.*, 14(2009), No. 3, art. No. 257.

[63] N. Suppen, M. Carranza, M. Huerta, and M.A. Hernández, Environmental management and life cycle approaches in the Mexican mining industry, *J. Cleaner Prod.*, 14(2006), No. 12-13, p. 1101.

[64] T. Adachi and G. Mogi, Life cycle inventory for base metal ingots production in Japan including mining and mineral processing processes by cost estimating system database, *Trans. Nonferrous Met. Soc. China*, 17(2007), Suppl. 1, p. 131.

[65] S.J. Mangena and A.C. Brent, Application of a life cycle impact assessment framework to evaluate and compare environmental performances with economic values of supplied coal products, *J. Cleaner Prod.*, 14(2006), No. 12-13, p. 1071.

[66] X.Y. Liang, Z.H. Wang, Z.J. Zhou, Z.Y. Huang, J.H. Zhou, and K.F. Cen, Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China, *J. Cleaner Prod.*, 39(2013), p. 24.

[67] K. Awuah-Offei, D. Checkel, and H. Askari-Nasab, Valuation of belt conveyor and truck haulage systems in an open pit mine using life cycle assessment, *CIM Bull.*, 102(2009), p. 1.

[68] R. Sada, *Carbon Trading* [Dissertation], HNB Garhwal University, Uttarakhand, 2007.

[69] F.T. Wang, T. Ren, S.H. Tu, F. Hungerford, and N. Aziz, Implementation of underground longhole directional drilling technology for greenhouse gas mitigation in Chinese coal mines, *Int. J. Greenhouse Gas Control*, 11(2012), p. 290.