THE CURRENT SITUATION OF COAL AND COALBED METHANE DEVELOPMENT IN CHINA

According to recent statistics, the reserves of coal resources in China are approximately 249.23 billion tons, and the reserves of coalbed methane (CBM) resources, with a depth of 2000 m, are approximately 31.46 Tm$^3$. The latter is equivalent to the total amount of conventional onshore natural gas resources (30 Tm$^3$), of which the recoverable resources are 10.87 Tm$^3$. With the rapid development of China's economy and the increasing demand for resources, coal plays an important role in the national energy structure. Although the state has vigorously promoted the development of new energy and reduced the development and utilization of disposable energy (especially coal), according to the data released by the National Bureau of Statistics (given as Figure 1), coal still accounts for approximately 60% of China's primary energy structure.

Owing to the influence of economic structures, coal output decreased from 2012 to 2016 and rebounded immediately after 2016. Coal still accounts for a large proportion of China's energy consumption, and the proportion will not drop sharply in a short period of time. At the same time, with the...
development of green mining, the production of the CBM industry has greatly increased in recent years (see Figure 2).

The huge demand for coal has caused most shallow coal mines to be exhausted daily. Moreover, although the mining depth for coal has gradually increased, the safety measures adopted in shallow coal seams have been gradually restricted in the application of deep well practice, whereas the dangerous factors in coal mine production have increased. This has caused related technology for deep well safety measures to emerge, as the situation requires. As an unconventional natural gas, CBM has large reserves and can compensate for the shortage of energy supply and demand in China. Thus, the exploitation and utilization of CBM are of great significance to the economy and for environmental protection. As the depth of coal mining increases, the method for CBM extraction used in shallow coal seams cannot be directly applied in deep mining; thus, the situation requires targeted methods and means. Therefore, it is necessary to understand the current situations of coal and CBM development in China for the safe production of coal mines.

2 | COAL AND GAS COPRODUCTION SCHEMES

2.1 | Protective seam mining

Protective seam mining is a simple, economical, and effective method for using coal and gas co-mining technology measures (shown in Figure 3). Gaving zone, fractured zone, and bending zone were formed above the goaf. The advantages of protective mining measures include a uniform outburst prevention effect, high safety, and reliability. The disadvantage is that it requires coal seam group mining and is restricted to areas with conditions for protective seam mining. These areas only account for approximately 30% of the mining areas in China.

2.2 | Surface extraction well

Surface extraction well technology was originally developed on a large scale as a CBM technology and has achieved great success in the United States. In the 1990s, the Jincheng Coal Group introduced this technology for testing in the Qinshui Basin and achieved success, as shown in Figure 4. A large number of scholars researched the principles, methods, and practices of surface extraction. Surface well development had become an important means of coalbed methane development. The advantages of regional outburst prevention measures using the predrainage of coal seam gas by surface wells are as follows: (a) a long service period, (b) the fact that the multipurposing of a single well can be realized, effectively solving the time and space limitations of gas drainage, and (c) the aid in improving the effects of downhole drilling and extraction along the seam. The shortcomings of using surface wells are as follows: (a) a high investment cost, (b) a relatively slow reduction of coal seam gas content.
from predrainage, and (c) a long single-well construction period. The regional outburst prevention measures for the predrainage of coal seam gas in surface wells are suitable for areas exhibiting the geological conditions of moderate burial depth, good topography and geomorphology in the minefield, and high permeability of the coal seam.

2.3 | Crossing borehole extraction

This method for gas predrainage and outburst prevention comprises drilling holes through the full thickness of coal seam in the middle of the rock roadway to carry out gas premining, \(^{11}\). Many scholars summarized the development of gas extraction technology in coal mines of China. \(^{12-14}\) For enhancing the effect of coal extraction, permeability improvement measures such as hydraulic flushing, hydraulic fracturing, shock wave, and CO\(_2\) prefracturing are used in China. \(^{15-17}\) The advantages of the cross-layer boreholes are as follows: (a) the construction of cross-layer boreholes is flexible, convenient, and adaptable, (b) a high degree of safety, and (c) ease in testing the effects. The shortcomings of the cross-layer boreholes are that: (a) the rock roadway excavation and drilling construction progress are slow and (b) the construction cost for pumping engineering is high. Cross-layer boreholes are suitable for geological conditions with a high risk of outburst and complicated geological structure in the mining, and without a protective seam.

The quantity of drainage can be calculated by Equation (1) through crossing borehole extraction. \(^{18,19}\) The original gas pressure and permeability coefficient are the most important factors affecting the gas drainage volume.

\[
q = 3.14m^{0.9}p_0^{1.85}R_1^{0.2}d^{0.1}t^{-0.1}
\]  

Here, \(q\) is the gas drainage amount (m\(^3\)/min), \(m\) is the coal seam thickness (m), \(\lambda\) is the gas permeability coefficient (m\(^3\)/MPa\(^2\) d), \(p_0\) is the gas pressure (MPa), \(R_1\) is the drainage hole radius (mm), \(d\) is the attenuation coefficient, and \(t\) is the drainage time (d).
2.4 | Drilling along seam extraction

Coal seam gas predrainage using bedding boreholes is a predrainage technology for achieving regional outburst elimination through the construction of bedding boreholes in coal seam roadways, as shown in Figure 6. In recent years, long bedding directional drilling borehole used in Jincheng coal area. Many scholars pointed out that 1000 m length drill hole was a new technology which applied to area prevention of gas outburst and underground coalbed methane drainage in gassy mine.20-22 The advantages of antioutburst measures using bedding boreholes are as follows: (a) all bedding boreholes are coal holes, and the utilization rate of boreholes is very high, (b) the distribution of the hole is uniform and can effectively avoid the blank zone, (c) the cost of the pumping project is low, and (d) pre-extraction of adjacent planned areas can be realized. The shortcomings of the measures using bedding boreholes are as follows: (a) all bedding boreholes are significantly susceptible to collapse, owing to the low strength of coal, and (b) the construction safety is low. The measures for predrainage of coal seam gas by drilling along the seam are mainly applicable to areas with coal seams exhibiting stable occurrence and good permeability.

The quantity of drainage can be calculated by Equation (2) through drilling along seam extraction.18,19 Numerator of the equation represents the absolute extraction amount, and denominator is the drainage time. In general, gas drainage efficiency is the most important factor decides the gas drainage volume.

\[
q = \frac{k \cdot L_1 \cdot L_2 \cdot M \cdot \gamma \cdot X \cdot \eta}{365 \times 1440t}
\]

Here, \(q\) is the gas drainage amount (m³/min), \(k\) is the coefficient, \(L_1\) is the coal face length (m), \(L_2\) is the coal face width (m), \(M\) is the coal seam thickness (m), \(\gamma\) is the coal body density (t/m³), \(X\) is the gas content (m³/t), \(\eta\) is the gas drainage efficiency (%), and \(t\) is the drainage time (a).

3 | CO-MINING MODE FOR COAL AND GAS IN CHINA

At present, for most coal mining areas in China, effective gas extraction has become an urgent problem. The characteristics of “three low and one strong,” meaning low pressure, low permeability, low saturation, and strong heterogeneity (especially low permeability and heterogeneity), make the effects of direct gas extraction significantly less than ideal. Moreover, the previously adopted method of “pumping first, then mining” can no longer be applied. After years of scientific and technological research, technology for a co-mining mode for coal and gas has been proposed, helping to cope with the current challenges for coal mines in China. With the development and engineering application of coal and gas co-mining modes in recent years, three modes have gradually formed: the Huainan mode, based on pressure relief mining of the protective seam; the Jincheng mode, based on directional long borehole mining; and the Yangquan/Songzao mode, based on cross-layer borehole mining. At the same time, research continues to progress, and development trends for coal and gas co-mining in the future are being discussed (see Figure 7).
3.1 Huainan mode based on pressure relief mining of protective seam

In the past, gas (as a harmful gas in coal mines) was basically released into the atmosphere, via emission during construction and production. However, gas has a high calorific value and causes pollution; thus, its rational development and utilization have become a trend in coal mine development. The proposal of “co-exploitation of coal and CBM” concerns the development and utilization of coal and CBM together as resources.

Because of the congenital shortages of the coal industry in China, permeability enhancement measures have become necessary links in gas extraction. In the process of coal mining, owing to strata movement and stress redistribution, a concentrated stress zone, original stress zone, and stress relief zone will be formed in the coal seam. According to the law of strata movement, the stress relief zone can be determined, and an extraction system can be arranged to optimize the drainage scheme and improve the extraction efficiency. At present, regional gas control technologies such as pressure relief of the protective layer and enhanced predrainage technology have gradually formed, referred to together as the “Huainan Mode.” In that regard, with the developments in deep mining trends, some technologies and means for shallow mining may no longer be applicable. Gas extraction technology is in a bottleneck period, and gas becomes a roadblock in the extraction process, threatening mine safety and production. Faced with this challenge, many experts and scholars have tackled key problems and carried out significant scientific research.

Yuan et al. and Guo analyzed the laws of gas migration after pressure relief by using rock mechanics, and O-ring and gas flow theories, providing a scientific theoretical basis for coal and gas co-mining. Advanced gas control and management concepts in the Huainan mining area were suggested, and the technology of no-pillar mining was applied to the engineering implementation of coal and gas co-mining theory. Using numerical and physical simulations, the distribution characteristics of the stress field, displacement field, and seepage field after pressure relief mining were studied, and the variation rules of the relevant gas and permeability parameters were analyzed by Tu and Ni and Guo interpreted coal and gas co-mining theory in terms of connotation and form. Taking the Huainan mining area as an example, the key technologies in coal and gas co-mining were summarized. Yao considered the field working face as an example and studied the distribution laws of gas and air pressure in a goaf under the conditions of “Y”-shape ventilation and no-pillar mining, successfully realizing the efficient mining of the working face and the comprehensive elimination of outburst in adjacent strata. Based on the methods of theoretical analysis, numerical simulation, and field measurement, Qi et al. conducted a feasibility analysis for a protective layer mining mode in a working face. Qian et al. based on the structure theory of mining rock mass and the seepage theory of mining rock mass, systematically discussed the main progress in the basic research of green mining of coal resources. The “O” ring principle of co-mining of coal and gas and the technology of mining pressure relief gas drainage are used for gas drainage, which can greatly improve the drainage effect and reduce the occurrence of gas explosion accidents in coal mines.

Based on the experience in gas prevention and control at home and abroad, with the aim of achieving a high gas and low permeability coal seam group in China, Yuan Liang (as the representative of scientific and technological personnel) created a method for gob-side entry retention without coal pillars. First, when a key pressure relief stratum is first mined, a high-strength support body is constructed along the edge of the goaf of the first mining face to retain the mining roadway and allow for continuous mining without pillars. Thus, it is possible to realize the coal and gas co-mining mode in the working face and air return roadway. The process of coal seam mining inevitably leads to changes of strata stress. With the advance of the working face, the strata above and below the goaf and around the goaf are affected by stress and self-weight, resulting in movement and breakage, and the formation of mining cracks in the strata.

Owing to the influence of the mining, the roof and floor strata of the goaf will expand and deform, causing overburden. The surrounding strata of the roof and floor of the coal seam will fully relieve the pressure, and the permeability of the coal seam will increase by orders of magnitude. Therefore, the pressure relief area of the goaf is analyzed and studied, and the migration laws and enrichment area of the pressure relief gas in the coal seam are explored. By using the borehole method in a retaining roadway, the area rich in gas is sufficiently drained, eliminating the threat of gas exceeding the limit and causing an outburst in the process of mining and excavation. Accordingly, it is possible to realize continuous gas drainage synchronously with mining in a working face and form (or generate) no-pillar mining, a gob-side retaining roadway, Y-type ventilation, and pressure relief drainage. Thus, coal co-mining and gas co-mining are practiced with a series of technologies.

Through the application and popularization of Y-type ventilation technology in gob-side entry retention without coal pillar mining, it is possible to not only effectively eliminate the safety threat caused by gas gushing into the working face in a traditional U-type ventilation mode but also to improve the output of coal and gas, and eliminate the outburst danger of the working face in the protective layer. In this regard, the continuous extraction and utilization of high-concentration gas have realized safe production and good economic benefits in coal mines.
3.2 Jincheng mode based on directional long boring technology

The Jincheng area of Shanxi Province is mostly a single coal seam. The gas pressure and gas content are high. The potential safety hazards caused by the gas in the process of mining are very prominent. The method of pressure relief and extraction by mining the protective seam is evidently inapplicable. If a protective seam is laid in the rock stratum, the amount of engineering required is large, the effective engineering rate is low, and the mining cycle is increased. At the same time, a large amount of gangue can seriously damage the environment. As compared with the United States, and under the condition of the “congenital insufficiency” of the coal seams in China, only the coal seams in Jincheng and other individual areas have relatively stable occurrence conditions, well-developed fissures, good permeability, and conditions for CBM extraction above and below wells. Therefore, the realization of combined extraction in the well and underground can be divided into the coal mine planning area, development preparation area, and production area. A relatively mature “three-zone” combined three-dimensional extraction technology for CBM has been formed, and this is called the “Jincheng mode,” as shown in Figure 8.44,45

Using the laws of pressure relief and gas migration in combination with a kilometer directional drilling rig imported from Germany, Xie et al.46 realized the application of directional long borehole coal and gas co-mining in engineering. Considering the Si-he Coal Mine as an example, Du et al.47 introduced a three-dimensional spatial “three-level” comprehensive gas management mode for realizing combined surface and underground gas extraction. Based on the imported kilometer directional drilling rig, Fang48 suggested a new method for kilometer directional drilling in the roof fracture zone of a working face. He et al.49 introduced the gas control mode of “integration of coal mining and gas production” and proposed directions for future efforts and problems to be urgently solved. Gao50 proposed a three-area linkage coal and gas co-mining mode suitable for the GuJiao mining area to solve problems regarding the shortage of drainage, excavation, and mining succession, according to the drainage modes of Huainan, Jincheng, Songzao, and other mining areas, combined with the production characteristics of the GuJiao mining area. Li,51 Li, 52 and Jin53 analyzed the distribution and dominant factors of CBM by mastering the geological conditions of the Jincheng mining area and summarized the effects and existing problems in three-dimensional combined extraction of CBM in the Jincheng mining area. Wang, Fan et al.54,55 introduced the main problems faced by gas mining in China and discussed the current gas mining mode in China. In view of the difficulties in drilling along the formation and poor drainage effect in the process of gas predrainage, the permeability enhancement measures such as hydraulic reaming and deep hole presplitting blasting are adopted to improve the effect of gas predrainage, and an integrated drainage system of “one well, three uses” surface drilling comprehensive gas drainage technology is constructed.56,57

Before the construction and operation of a mine, the mining sequence is reasonably divided, according to the geological distribution conditions of the coal seam and the planning of the mine.58 For the planned area, the coal resources will not be exploited in a short period of time; in fact, the time allotted for mining and excavation will exceed 8 years. Therefore, sufficient time will be left for conducting pre-extraction of gas, eliminating the dangerous disasters that gas may bring and realizing the effective coordination of coal and gas resources. In the preparation area, the coal resources will be converted into a coal production area in a relatively short period of time (usually within 5-8 years). If the time is more than 5 years, the maintenance cost will increase; however, if the time is too short, the gas content and pressure will not meet the required standard because of insufficient gas desorption time, and the purpose and task of gas extraction will not achieve the expected results. The establishment of the combined extraction technology for ground and underground holes combines the application of fracturing technology in the ground drilling and the crossing-layer technology of directional long borehole extraction in the underground, that is, “ground fracturing” and “underground orientation,” respectively (shown in Figure 9).59 The organic combination of the long drilling technology creates the conditions for the accelerated conversion of the preparation area to the production area.

3.3 Songzao/Yangquan mode based on cross-layer drilling technology

As the main coal-producing area in Chongqing, the Songzao mining area has become a key mining area, owing to its abundant coal and gas reserves, simple geological structure, stable coal seam occurrence, and superior geographical position. In

![FIGURE 8](image-url) The model of three zones linkage 3D gas drainage in coal mining

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the initial stages, owing to the frequent occurrence of gas disasters during the construction and production processes, resulting in casualties and huge economic losses, solving gas disasters was the primary task of mining area development. Through years of unremitting efforts, research gradually developed a technology for drilling through layers as the main adjacent layer cross-layer extraction + coal seam bedding extraction + goaf extraction. The multidirectional and three-dimensional comprehensive extraction method for rock extraction is called the “Songzao mode” or “Yangquan mode.”

Lei and others summarized the characteristics and applicable conditions of the exploitation mode of the Songzao mining area in terms of geological conditions, space-time coordination, and technical approaches. Xue simulated the change law of overburdened rock and fissures under mining in a high-mining face using fast Lagrangian analysis of continua (FLAC) software. Through the development channels of fissures and pores, the gas enrichment area was determined. A new method of gas extraction using large-diameter inclined boreholes instead of a high-drainage roadway has also been proposed. Considering the Songzao Mining Bureau as an example, Wu introduced the current situation of gas extraction in the Songzao area and introduced scientific research achievements in coal and gas co-mining. Cheng introduced the application of gas extraction technology in the Qinan coal mine of the Huaibei mining area by drilling through strata in a floor rock roadway and the application of technology in the Yangquan mining area by combining a roof strike high-extraction roadway with an internal staggered tail roadway. This was performed during the process of mining under the conditions of a super-long distance protective layer and pressure relief gas. Due to the pressure relief effect of the overlying gas-bearing coal rock layer, gas is flooded into the fully mechanized caving face through the mining fracture network, restricting the safety of coal mine production. Yu et al. proposed to adopt a “high pumping alley” technical scheme, which not only ensured the safe production of coal, but also achieved the efficient extraction of gas. According to the results of simulation test, Lu et al. determined the evolution rule of roof cover rock fracture and the area of pressure relief gas enrichment, put forward the technical scheme of pressure relief gas extraction by mining, and tested the extraction effect. Taking Yuyu mine as an example, Li et al. optimized a new pattern of underground space-time tridimensional gas drainage and observed the treatment effect.

For a mine with a coal seam group, mining the protective seam is the most effective means for preventing outbursts in the region. In the process of mining the protective layer, with the advance of the working face, the overburdened strata in the goaf can achieve the effect of pressure relief and permeability enhancement owing to the influence of the mining, breaking the original dynamic balance of free gas and adsorption, and releasing a large amount of gas. A high-concentration gas extraction roadway was excavated in the overlying strata of the coal seam, and boreholes were drilled into adjacent relief seams in the high-concentration gas extraction roadway to continuously extract high-concentration gas resources. Gas reaches the ground through the extraction pipeline, instead of passing through the coal face, and the threat of gas overflow caused by the gas gushing into the coal face is eliminated. This ensures the normal operation of production, so as to realize efficient and safe coal and gas co-mining.

The first extraction mode is mainly applicable to the mining of coal seam group, with high efficiency and good economy. Only 30% of the mining areas in China meet the requirements. The second extraction mode is mainly applicable to thick coal seam, which requires high permeability and hardness of coal seam, and only less than 10% of coal mines in China meet the requirements. The third extraction mode can be used in different geological conditions, but its economy is poor.

4 | FUTURE DEVELOPMENT TRENDS

4.1 | Fluidized mining technology

With the gradual exhaustion of shallow coal resources, China’s coal resource development continues to move deeper into the earth. However, as limited by the deep stratum environment and mining depth, traditional mining technologies and methods may not be suitable for the development and utilization of deep resources and may face difficulties and challenges, as described below. Xie et al. summarized and analyzed the current research status and progress of coal and gas co-mining technologies under different mining modes in China; they also proposed new methods and measures to...
solve the problems. In that regard, “fluidized mining technology” refers to the in situ conversion of deep solid mineral resources into gaseous, liquid, or gas-liquid mixed substances, and realizes intelligent digging, crushing, and transportation/transformation/imagining for underground oil and gas development.

Liu et al.71 and Xie et al.72-74 proposed the subversive scientific idea of fluidized coal resource mining and defined its connotation and goal. By adopting physical, chemical, and biological means, the transformation of a coal resource mining mode from a solid state to a fluidized state can be realized. According to this concept, the grand blueprint of China’s coal resource mining can be planned for the next 30 years. Taking time as the node and under the gradual progress and upgrade of science, technology, and mining equipment, the development stage of the coal revolution can gradually develop and transition from level 3.0 or 4.0 to 5.0. Niu et al.75 conducted a feasibility analysis on the biological fluidization mining of coal based on existing studies on the biological transformation of coal and proposed the development of efficient strains that can react with coal through biological and genetic engineering, so as to realize the liquefaction and gasification of solid coal.

Fluidized mining technology for deep coal resources has subverted the traditional coal mining concepts and technology system, and represents a great revolution in deep solid mineral resources mining technology, providing new direction for the future development of coal resources in China.

4.2 Intelligent unmanned mining technology

The demand for economic development in China has changed from quantity to quality. Under the new situation regarding the deep integration of emerging network technologies and traditional industries, various industries are in a critical period of transformation, upgrading, and structural adjustment. This will soon usher in tremendous changes in the industry. Insofar as the traditional coal industry, it must also keep pace with the times, and the research and development of advanced technology and equipment are essential. Among them, the integration of intelligent unmanned mining technology and traditional complete sets of equipment to, thereby, achieve industrial transformation and upgrading is becoming an important development trend. Intelligent unmanned mining refers to a mining operation process independently completed by mining equipment through intelligent sensing of the mining environment, intelligent regulation of the mining equipment, and autonomous cruising of mining operations, without manual intervention. In recent years, research on intelligent unmanned mining technology has been continuously promoted at home and abroad, achieving certain results.

Fan76 discussed intelligent unmanned fully mechanized technology, relying the success of unmanned fully mechanized mining technology, relaying the success of Huangling Mining in this venture, the advanced technology and equipment necessary to advance in the process from intellectualized to fully mechanized, realizations from the theoretical analysis to the practical application of the science and technology innovations, and the factors restricting intelligent drilling technology in the future. Ge77 pointed out the direction for the breakthrough of a key technology, according to the development status of coal mining equipment in intelligent unmanned mining technology. Wang et al.78,79 analyzed the development process for intelligent unmanned mining technology in recent years, summarized the technical ideas for intelligent mining at home and abroad, and proposed developmental directions for key technologies composed of intelligent detection, intelligent navigation, and intelligent control. By introducing the concept of a near-zero ecological environment impact in the development and utilization of coal, the development route of “2025 technology upgrade and replacement, 2035 technology expansion and transformation, and 2050 technology guidance and exploration” can be expounded, with time as the node.80 To solve the technical problems in working face tilt adjustment control, Zhang et al.81 adopted a method of combining theoretical analysis, field investigation, and industrial tests to lay a foundation for intelligent tilt adjustment control. Through the introduction of the development status of intelligent mining technology and equipment for a comprehensive excavation face, the future direction and the effort for key technologies for the intelligent mining process of a comprehensive excavation face are emphasized.82 Considering Huangling Mining as an example, Liu83 and Yuan84 elaborated on the expected targets and technical difficulties in intelligent mining at large mining heights in China. They drew lessons from the successful experience of the intelligent unmanned mining of a no. 1 coal mine to provide a basis and guarantee for the overall plan of a No. 2 coal mine. Wang et al.85,86 proposed that coal mine intelligence is the core technical support for adapting to the development trend of modern industrial technology revolution, ensuring national energy security, and realizing high-quality development of the coal industry. Based on the status quo of intelligent development of coal mines in China and the strategic direction and development goals of the transformation and upgrading of the coal industry, several issues of intelligent development of coal mines are discussed.87

With the deep integration and application of the fields of intelligence, digitization, and “informatization” to the coal industry, it is necessary to accelerate the intelligent and unmanned construction of coal mines, promote the scientific and technological innovation and development of the coal industry, and realize the concerns in labor-intensive low-end industries. The high-tech industry transformation to talent-intensive technology has greatly reduced the number of
casualties caused by accidents in coal mines and the occupational diseases (e.g., pneumoconiosis, silicosis) caused by poor working conditions. Ultimately, we will achieve the goal of “intelligent and safe” mining and the goal of intelligent unmanned mining.

4.3  Precision mining technology

For a long time, owing to limitations in technology and equipment, the exploitation of traditional coal in China was mostly based on experience and qualitative analysis. The uncertainty, lag, and intensive use of underground workers for mining methods based on theory caused China to lag far behind other developed countries in terms of accidents, casualties, and severity.

Yuan Liang et al.88,89 proposed using advanced technology and equipment, and multifunctional and multiparameter intelligent sensors supported by intelligent perception, intelligent control, the internet of things, large data cloud computing, and disposal functions for risk identification, monitoring, and early warning. Traditional mining methods will eventually develop into safe and reliable methods. The premise is a new mode and method of intelligent and precise mining using few (or no) people. Key technologies for precise risk identification and monitoring and early warning for typical dynamic disasters in coal mines can be proposed and can change from depending on experience and relying on the roughness of qualitative analysis to realizing quantitative analysis and precise intelligent mining in time and space.90,91 With the development of the country, the risk of typical dynamic disasters in coal mines can be accurately identified, monitored, and addressed (e.g., via early warnings). The transformation of energy utilization orientation and the improvement of the utilization rate of resources can be analyzed. The current situation regarding the utilization of closed/abandoned mine resources at home and abroad can also be analyzed. The scientific problems faced regarding the resources can be described. The research direction and content for precise development and utilization can be suggested, in view of China’s response to this problem. Coal resources are not single and independent. There are always co-associated resources in the process of coal mining. Faced with the problems and challenges of coal and co-associated resources mining, the scientific connotation and key scientific problems of precision mining can be put forward, and the main research direction can be determined.

With the advancement of science and technology, the deep integration of advanced technology in the coal industry, and the unremitting efforts of a large number of researchers, new theories, technologies, and equipment are constantly emerging. The proposal of precision mining technology provides direction for solving the most urgent problems. To promote the development of precision mining and realize the transformation of coal mining from traditional high-risk labor-intensive mining to high-precision technology-intensive mining, research on coal precision mining will be an indispensable link.

4.4  Green development of abandoned mines

After long-term development and utilization of coal resources in China, the mining depth has increased year by year, and coal mining has entered the deep mining stage. At the same time, a large number of shallow mines have been abandoned due to resource exhaustion. Due to the limitation of previous mining mode and mining methods, the coal resource recovery rate is low, leaving a large amount of coal and coalbed methane in abandoned mines. The leakage of gas from abandoned mines not only causes waste of resources, but also pollutes the environment; the effective use of coalbed methane in abandoned mines can effectively solve environmental pollution problems and can also be used as an important resource to supplement China’s energy structure. The existing energy shortage problem has played a certain mitigating effect. Therefore, through the evaluation and calculation of coalbed methane resources in abandoned mines, as well as the development and utilization, it can provide new ideas and directions for the co-mining mode of coal and gas in China.

Based on the deformation law of overburden in the process of coal mining, Meng et al.92 took Jinsheng coal mine as an example, analyzed the pore volume and gas saturation distribution in the goaf through theoretical analysis and mathematical derivation, and established the evaluation mode and method of coalbed methane resources in the goaf of abandoned mines. Han et al.93 theoretically determined the calculation range of CBM Resources in abandoned mines based on the theoretical analysis of coal rock mechanics, the theory of rock movement affected by coal mining, and the theory of coal adsorption/desorption, combined with relevant data at home and abroad. Yuan et al.94 pointed out that intelligent and precise development is the only way for the utilization of abandoned mine resources through in-depth analysis of the development and utilization of abandoned mine resources at home and abroad, put forward the scientific problems faced by the development and utilization of abandoned mine resources in China, and systematically expounded the development and utilization direction and research content of abandoned mine resources in China. Liu et al.95 introduced the current situation of the development and utilization of China’s transformation coal mines by analyzing the types of transformation coal resources. They pointed out that there are some problems in the utilization of China’s waste coal resources, such as insufficient development and utilization, high operation cost,
and the low utilization rate of underground space resources occupies an important part in many problems.

Through the establishment of the evaluation method of abandoned mine gas resources, the design of key technologies and safety measures for drainage and utilization, in-depth investigation and analysis of the mining potential, and development prospects of China's abandoned mine gas resources, the development of China's abandoned mine resources will move toward three directions of energy utilization, resource utilization, and functional utilization. The green development of abandoned mines plays an important role in the development and utilization of mine resources. It is of great significance to improve the level of coal mine safety, promote the adjustment of energy structure, and ensure the national energy security and sustainable and healthy economic development.

5 CONCLUSION

The development of China's coal industry has a long history and has provided an important motivation for the rapid development of China's economy. At the same time, in the process of coal mining, mine disasters have emerged constantly, causing a large number of casualties and massive property losses. Therefore, scientists and technicians have overcome difficulties to create important theories and practical technical equipment for solving mine disasters (especially gas disasters).

At present, through the theoretical development and engineering applications of the coal and gas co-mining mode approach in China, three typical modes have gradually formed: the Huainan mode, based on protective layer unloading mining; the Jincheng mode, based on directional long drilling technology; and the Songzao/Yangquan mode, based on perforating drilling technology. These modes provide a strong impetus and motivation for solving the difficulties and challenges of coal mining in China. However, these mining modes have their own merits and demerits, and they are not ideal green, environmentally protective, efficient, and energy-saving extraction modes and methods. Experts and scholars in the coal industry are also exploring the future development trends of coal and have suggested ideal mining methods, mainly including fluidized mining technology, intelligent unmanned mining technology, precision mining technology, green development of abandoned mines technology, and other technical means, so as to replace traditional mining methods.

ACKNOWLEDGMENTS

The authors want to thank the anonymous reviewers for their valuable suggestions. The authors also express their appreciation of the funding provided by the National Natural Science Foundation of China (No. 51874122, No. 51704100), Key R & D and Extension Projects of Henan Province (202102310223, 202102310545), Program for innovative research team of Henan Polytechnic University (T2019-4), the Fundamental Research Funds for the Universities of Henan Province (NSRF180426), Program for Innovative Research Team of Henan Polytechnic University, and the Key Research Projects of Henan Higher Education Institutions (19B440004).

CONFLICT OF INTEREST

None declared.

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How to cite this article: Liu J, Yang T, Wang L, Chen X. Research progress in coal and gas co-mining modes in China. Energy Sci Eng. 2020;8:3365–3376. https://doi.org/10.1002/ese3.739