DOI 10.15302/J-SSCAE-2022.03.006

Potential Analysis and Technical Conception of Exploitation and Utilization of Tar-Rich Coal in Western China

Wang Shuangming [1, 2, 3], Wang Hong [4, 5], Ren Shihua [4, 6], Dong Shuning [7, 8], Zheng Dezhi [4], Tan Kelong [9], Hou Enke [3], Wang Shengquan [3], Qu Yang [10], Jiao Xiaomiao [4]

1. Geological Research Institute for Green Coal Mining, Xi'an University of Science and Technology, Xi'an 710054, China
2. Shaanxi Key Laboratory of Geological Support for Coal Green Exploitation, Xi'an 710054, China
3. College of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China
4. China Coal Research Institute, Beijing 100013, China
5. China Coal Technology and Engineering Group Corporation, Beijing 100013, China
6. School of Management, China University of Mining and Technology-Beijing, Beijing 100083, China
7. Xi'an Research Institute, China Coal Technology & Engineering Group Corporation, Xi'an 710054, China
8. Shaanxi Key Laboratory of Prevention and Control Technology for Coal Mine Water Hazard, Xi'an 710077, China
9. General Prospecting Institute of China National Administration of Coal Geology, Beijing 100039
10. CCTEG Coal Industry Planning Institute, Beijing 100120, China

Abstract: The resources of tar-rich coal in Western China are abundant and available for large-scale development. Understanding the oil and gas resource properties of tar-rich coal and promoting the development and transformation of tar-rich coal to produce oil and gas are crucial for increasing domestic oil and gas supply, relieving external dependence on oil and gas, and ensuring national energy security in China. This study estimated the potential of tar-rich coal resources in Western China based on the exploration of coal resources, reviewed the its current status and existing problems, and proposed basic concepts and technical conception for the development and utilization of tar-rich coal in Western China considering the new requirements for carbon reduction, intelligent green development, and compensation for oil and gas shortage. The development and utilization of tar-rich coal needs to focus on key technologies, including high-precision comprehensive exploration, high-recovery-rate mining, underground *in situ* pyrolysis, pyrolysis and gasification integration, and *in situ* pyrolysis char CO_2 storage. Furthermore, we suggest that the tar-rich coal should be included in the management of unconventional oil and gas resources, scientific and technological research on the development and utilization of tar-rich coal should be strengthened, a national demonstration area should be established, and development of new energy and tar-rich coal in Western China should be coordinated to maximize the special advantages of tar-rich coal as coal-based oil and gas resources and realize the low-carbon and high-value utilization of coal resources.
Keywords: tar-rich coal; western regions; coal-based oil and gas; potential of resources; development and utilization; technical system

Received date: May 06, 2022; **revised date:** June 01, 2022
Corresponding author: Ren Shihua, Researcher of Coal Research Institute Co., Ltd. Major research fields include coal-related technical and economic evaluation and energy strategies. E-mail: ren@cct.org.cn
Funding program: CAE Advisory Project "Research on Resource Guarantee for Planning and Layout of Coal-Based Oil and Gas Strategic Bases" (2022-XZ-36);CAE Advisory Project "Research on Development Strategy of Oil-rich Coal in West China" (2020-XZ-12)

Chinese version: Strategic Study of CAE 2022, 24 (3): 049–057

Cited item: Wang Shuangming et al. Potential Analysis and Technical Conception of Exploitation and Utilization of Tar-Rich Coal in Western China, Strategic Study of CAE, https://doi.org/10.15302/J-SSCAE-2022.03.006

1 Introduction

In China, the total amount of oil and natural gas resources is relatively small, especially in terms of per capita oil and natural gas resources, comprising only about 1/15th of the global average owing to its large population. Currently restricted by resource conditions, China's dependence on oil and natural gas is rising, reaching 73.5% and 43.2%, respectively, in 2020 [1]. In particular, its dependence on oil currently exceeds the historical highs of the United States. With advances in economic development and improved living standards, China's oil and gas demand is expected to continue increasing [2,3]. However, conventional oil and gas production is limited in China, and unconventional oil and gas production is difficult to increase and stabilize. In the context of increasing oil and gas import risks on the global stage, the development of new ways to produce oil and gas to enhance the independent supply capabilities is urgently needed to ensure national energy security. Oil-rich coal can be used to produce oil, gas, and semi-coke through medium- and low-temperature pyrolysis, which has the advantage of a high oil and gas conversion efficiency and a low production cost. As such, in China, oil-rich coal is rich in potential oil and gas resources. Thus, implementing the development and transformation of oil-rich coal, with oil and gas as the main product, and promoting the large-scale development of the industry is not only a reasonable path to realize the clean and low-carbon development of coal, but also to increase the oil and gas supply and alleviate the strategic choice of oil and gas dependence [4–6]. These are important for promoting both domestic circulation and dual international-domestic circulation.

There is a need to accelerate the realization of the clean and low-carbon utilization of coal, as well as promote the transformation from fuel-based utilization to raw material-based and material-based utilization [7–10], to build a clean, low-carbon, safe and efficient energy system. Based on China's coal-dominated energy resource endowment and energy production and consumption characteristics, and combined with a large demand for substitute oil and gas supply, it is essential to reconstruct the development and utilization mode of oil-rich coal. Furthermore, giving full play to the special advantages of oil-rich coal as coal-based oil and gas resources, as well as realizing the low-carbon and high-value-added utilization of coal resources, will be an important measure to support the achievement of carbon peaking and carbon neutrality. At present, many studies have focused on the occurrence law and geochemical characteristics of oil-rich coal in China. For example, focusing on oil-rich coal in Yushenfu mining area, the multi-scale pore structure of oil-rich coal was analyzed in a previous study by means of low-temperature liquid nitrogen adsorption method, mercury intrusion method, nuclear magnetic resonance method, and gas permeation method. The results indicated that the oil-rich coal had a large pore specific surface area and low-temperature nitrogen adsorption capacity, as well as good physical properties for oil extraction and gas refining [11]. The occurrence characteristics of oil-rich coal in typical mining areas of the Carboniferous-Permian coalfield in northern Shaanxi have also been previously studied, in which the variation characteristics of tar yield in recoverable coal seams and the temporal and spatial distribution of oil-rich coal were analyzed, and the influencing factors of oil-rich coal occurrence were discussed [12]. In another study, the organic geochemical characteristics of oil-rich coal were analyzed by gas chromatography-mass spectrometry in six main coal seams of the Jurassic Yan'an Formation in northern Shaanxi [13]. Finally, according to the tar yield of the raw coal, researchers determined the occurrence characteristics of oil-rich coal and conducted classification research based on the No. 2-2 and 5-2 Coal of Yan'an Formation in Yushen Mining. In their study, the sedimentary environment of oil-rich coal seam 2-2 and 5-2 was discussed combined with parameters, such as ash composition index, sulfur content, and mirror idler ratio [14].

It is worth pointing out that, to date, existing research has mainly analyzed the occurrence characteristics of oil-rich coal based on specific mining areas or coal seams. By contrast, comprehensive research and analysis of the development and utilization technology system of oil-rich coal in China is currently lacking. In recent years, a series of studies on the resource attributes and development and utilization of oil-rich coal have been carried out [15–18], and the concept that "oil-rich coal is coal-based oil and gas resources" has been proposed. In the present study, the reserves and distribution characteristics of oil-rich coal resources in western China are analyzed, and the current development and utilization of oil-rich coal, including existing problems associated with its exploration, are analyzed. A fundamental concept and a technology system of oil-rich coal development and utilization in western China are proposed, and key technologies are identified to provide a reference for future research on the development and management of oil and gas resources.

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2 Analysis of oil-rich coal resources in Western China

2.1 Definition of oil-rich coal

According to the classification of the tar yield of coal, the oiliness of coal is divided into three grades, according to the *Mineral Resources Industry Requirements Manual* (2014 Revision), as listed in Table 1. Similarly, the coal industry standard "Classification of Tar Content in Coal" (MT/T 1179–2019) divides the tar content in coal into four grades, as listed in Table 2. Coal with a tar yield above 7% is denoted as "medium", "high", and "extra-high" oil yield coal, respectively. However, although it is of great significance to define oil-rich coal by its tar yield, the intrinsic characteristics of oil-rich coal were not described from the perspective of its resource attributes.

Table 1. Classification of tar yield of coal.

Grade	Tar yield (%)
High oil-rich coal	＞12
Oil-rich coal	7–12
Oily coal	≤7

Table 2. Classification of tar content in coal.

Grade	Name	Tar yield (%)
Low oil yield coal	Tard-1	≤7
Medium oil yield coal	Tard-2	7–12
High oil yield coal	Tard-3	12–15
Extra high oil yield coal	Tard-4	＞15

In this study, the resource attributes of oil-rich coal are defined from three perspectives: coal resources, oil and gas resources, and mineral resources. First, oil-rich coal is a coal resource with a medium and low degree of coalification, whose volatile yield is generally greater than 30%. Second, oil-rich coal is a medium-low maturity oil and gas resource, with a tar yield greater than 7% and a vitrinite reflectance of 0.5% –1%. Third, oil-rich coal is a layered sedimentary mineral resource that integrates the properties of coal, oil, and gas, with an organic matter content of over 60% (composed of carbon, hydrogen, oxygen, and other elements), and an inorganic matter content of generally less than 30% (composed of silicon aluminum oxide, etc.). Hydrogen and carbon atoms with a high energy density can be transformed into the occurrence form of oil and gas through pyrolysis.

Thus, while oil-rich coal is comprised of the attributes of coal, oil, and gas, the oil and gas resources in it exist in unconventional forms and cannot be obtained by conventional oil and gas exploitation methods. As a result, it is more accurate to describe oil-rich coal as a coal-based oil and gas resource. A scientific understanding of the properties of the oil and gas resources of oil-rich coal has both theoretical and practical significance for elucidating the causal relationship between coal, oil, and gas, enriching and developing the theory of oil and gas accumulation, and increasing oil and gas supply within the domestic market.

2.2 Quantity and distribution of oil-rich coal resources

In terms of the distribution of coal resources, a part of the low-to-medium-rank metamorphic coal in Shaanxi, Inner Mongolia, Xinjiang, Gansu, Ningxia, and other provinces is comprised of oil-rich coal, with significant differences in the proportion of oil-rich coal resources and tar yield. In Shaanxi Province, the size of these oil-rich coal resources can be as high as 1.5×10^{11} t, widely distributed in Jurassic coalfields, Triassic coalfields, and Carboniferous-Permian coalfields in northern Shaanxi, and Jurassic coalfields in Huanglong. The average tar yield of the Triassic coalfields in northern Shaanxi can reach 11.42%, while the average tar yields of the Jurassic coalfields and Huanglong coalfields in northern Shaanxi are 9.33% and 8.04%, respectively. The tar yields of the Carboniferous-Permian coalfield is known to fluctuate greatly, wherein the average tar yields of the Shanxi and Taiyuan Formations in the Gucheng mining area in the north are 9.12% and 9.58%, respectively, while those in the Weibei coalfield in the south are only about 1.7% [6].

Previous studies have shown that China's oil-rich coal resources are mainly distributed in five provinces: Shaanxi, Inner Mongolia, Ningxia, Gansu, and Xinjiang. Within these provinces, the preliminarily estimated resource amount of oil-rich coal is over 5.5×10^{11} t (Table 3) [6,18,19]. The potential oil resource is 5×10^{10} t, while the gas resource is about 7.5×10^{13} m^3 (mainly composed of H_2, CH_4, C_2H_6, and CO), which is higher than that of shale gas (recoverable resources are about 2.18×10^{13} m^3 [20]) and shale oil (recoverable resources are about 3.5 × 10^9 t [21]). Therefore, the large-scale development of China's oil-rich coal industry has a strong resource base.

Table 3. The amount of oil-rich coal resources in Western China.

Province	Accumulative proved resources (×10^8 t)	Retained resources (×10^8 t)	Oil-rich coal resources (×10^8 t)	Proportion of oil-rich coal resource (%)
Shaanxi	2511.03	1878.88	1500	80
Inner Mongolia	10 011.79	6588.86	2000–2600	30–40
Ningxia	479.35	410.6	80	20
Gansu	450.44	434.14	90	20
Xinjiang	4225.58	4102.77	2050	50
Total	17 678.19	13 415.25	5500–6100	—

3 Analysis of current exploitation and utilization of oil-rich coal in western China and existing problems

3.1 Exploration status and existing problems

3.1.1 Insufficient understanding of oil-rich coal resources

Oil-rich coal is a coal-based oil and gas resource with the properties of coal, oil, and gas that has not yet been scientifically recognized or utilized. The formation of oil-rich coal is accompanied by a specific geological historical evolution process and geological conditions, and there are significant differences in the resource status of coal seams in different eras and regions (even the same era and different coal seams). At present, research on the corresponding geological scientific issues, including the metamorphic evolution law of oil-rich coal and geological driving conditions, is scarce. The resulting poor understanding of oil-rich coal, both in terms of its distribution and as a resource itself, makes it difficult to support the clean and efficient utilization of oil-rich coal.

3.1.2 Lack of normative documents for oil-rich coal exploration

The exploration and evaluation of oil-rich coal resources is currently in its infancy. There are no special provisions for the exploration of oil-rich coal in neither previous nor current industry standards for solid mineral exploration or coal geological exploration. According to the *Regulations for Coal and Peat Geological Exploration* and *Coal Quality Evaluation Standards for Coal Resources Exploration*, when the yield of basic volatiles from air drying of raw coal is greater than 28%, 50% of coal seeing points are selected for low temperature dry distillation test of raw coal, and the tar yield of raw coal is determined accordingly. However, at present, the exploration, processing, and utilization of oil-rich coal lacks standard specifications for coal rock, coal quality, sampling, testing, and evaluation. This lack of relevant standard systems is not conducive to the orderly development of oil-rich coal exploration.

3.1.3 Insufficient investment in oil-rich coal exploration

China's coal geological exploration is mainly funded by central or provincial governments and coal enterprises. Central or provincial governments entrust geological exploration units to complete the pre-survey and general survey mainly in the form of geological exploration funds. In contrast, coal geological exploration funded by coal enterprises is mostly autonomous and managed by the exploration right holder. Generally, detailed and precise investigations are carried out after the mining area and mine field are divided, aiming at providing a geological basis for mine design and construction. At the national level, there is no special fund for oil-rich coal resource exploration, and it is difficult to support the large-scale development and utilization of oil-rich coal.

3.1.4 Low exploration accuracy in oil-rich coal

Previous research has revealed the distribution characteristics of oil-rich coal fields and tar resources, providing a foundation for the management and large-scale development of oil-rich coal resources. At the national level, no detailed exploration of oil-rich coal resources has been carried out nationwide, and no state-level scientific and technological projects have been set up to support the development and utilization of oil-rich coal. At present, the understanding of index parameters, such as plane distribution, thickness change, and tar yield of oil-rich coal, is far from meeting the needs of oil-rich coal resource evaluation. As a result, the data supporting the corresponding evaluation is based on previous coal resource exploration results. Within the scope of the delineated exploration area (pre-mining area), the tar yield of 50% of the raw coal is determined according to the requirements of the specification, which cannot meet the precision requirements of the degree of detailed investigation of special coals.

DOI 10.15302/J-SSCAE-2022.03.006

The organic maceral, mineral composition, volatile matter, elemental component content, and harmful element distribution of oil-rich coal directly affect the pyrolysis products and efficiency of coal, such that the resulting exploration accuracy is lower. Therefore, the exploration degree and precision cannot currently support the demand for the high quality exploitation and utilization of oil-rich coal.

3.2 Development status and existing problems

3.2.1 High intensity of coal exploitation in oil-rich coal distribution area

In the five western provinces where oil-rich coal is concentrated, the total coal production capacity was about 2.6×10^9 t/a. In 2019, the coal output was 2.074×10^9 t, exceeding 50% of the national coal output. Large-scale and high-intensity exploration has led to insufficient subsequent reserves in some provinces and regions, affecting resource continuity.

3.2.2 Unbalanced development of mine intelligence level

Furthermore, in the five western provinces where oil-rich coal is concentrated, advanced and efficient large-scale modern coal mines coexist with outdated coal mines with a low production efficiency, while large-scale coal enterprises with strong funding, advanced management, and international competitiveness coexist with small- and medium-sized coal enterprises with poor management and operating difficulties. In general, the level of automation, informatization, and reliability of coal mining technology and equipment in small- and medium-sized coal mines is low.

3.2.3 Disturbances in coal mining environment

The aforementioned five western provinces are arid and have fragile ecological environments. Damage to underground and surface water systems and surface subsidence caused by coal exploitation have a large impact on the local ecological environment. In fact, many old mining areas in Shaanxi Province and Ningxia Hui Autonomous Region are failing to meet the requirements for environmental protection. Furthermore, the green development level of coal in Inner Mongolia Autonomous Region needs to be improved, and pressures associated with ecological environment restoration and governance are growing. In addition, coal-rich areas are currently experiencing a serious shortage of water resources, including Hami City and Changji Prefecture in Xinjiang Uygur Autonomous Region.

3.2.4 Insufficient evaluation of the ecological impact of exploration

Mining (exploration) units are required to prepare technical reports related to ecological environment restoration and governance, such as the *Environmental Impact Assessment Report*, the *Water Resources Demonstration Report*, and the *Soil and Water Conservation Plan*. Despite this, at the stage of mine design and construction, secondary geological disasters caused by coal mining, the degree of impact to the ecological environment, water resources, and land resources, and the implementation of effective restoration and management measures continue to be a weaknesses of coal geological exploration.

3.3 Utilization status and existing problems

3.3.1 Unreasonable utilization

In the five western provinces, 75% of the oil-rich coal is consumed for thermal coal combustion, while 20% is used for chemical engineering. In Shaanxi Province, coal consumption in 2019 was 2.186×10^8 t. Coal is mainly used for power generation and by the metallurgy and chemical industries: 6.48×10^7 t for thermal power generation (accounting for 29.64%), 5.745×10^7 t for metallurgy (accounting for 26.28%), 5.725×10^7 t for chemical use (accounting for 26.19%), 1.252×10^7 t for building materials (accounting for 5.73%), and 2.657×10^7 t for civil and other uses (accounting for 12.16%). In this context, the proportion of pyrolysis utilization for the production of oil and gas is very low, and the oil and gas components are not exploited to their full potential.

3.3.2 Lack of a deep processing industry chain for oil-rich coal pyrolysis products

The product structure of oil-rich coal utilization is not oil-first, and the ability of pyrolysis tar and pyrolysis gas to produce fine chemical products and special oil products is currently insufficient. The upstream and downstream industrial chains of semi-coke for gasification, power generation, blast furnace injection, ferroalloy production, and high-end carbon material preparation have not yet been formed, as shown in Fig. 1.

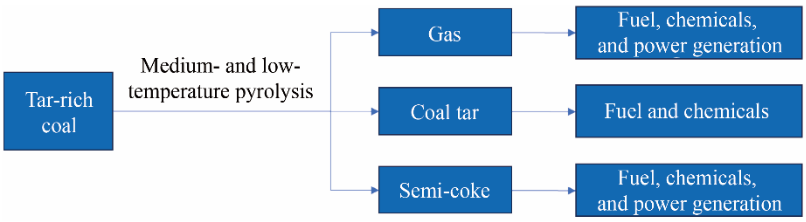

Fig. 1. Schematic of the industrial chain of oil-rich coal pyrolysis and utilization.

3.3.3 Immature large-scale utilization technology

After years of development, low-rank coal pyrolysis and modern coal chemical technologies are gradually maturing. However, several technical problems remain to be solved. In terms of low-rank coal pyrolysis, key technologies, such as pulverized coal pyrolysis, catalytic pyrolysis, and oil and dust separation, are still found in the demonstration and optimization stages. The oil yield and the scale of single unit are relatively small, and the comprehensive utilization of semi-coke is lagging behind.

4 Concepts and technical systems for the exploitation and utilization of oil-rich coal in Western China

4.1 Exploitation and utilization

4.1.1 Establishing the concept that oil-rich coal is a resource of coal-based oil and gas and optimizing their development layout

The fact that oil-rich coal is a rich source of oil and gas needs to be highlighted. Since oil-rich coal is a coal-based oil and gas resource, the development and utilization mode of this type of coal is intrinsically different from that of ordinary coal. As such, specific measures need to be established to maximize the development of oil-rich coal resources and give full play to the value of oil and gas contained in oil-rich coal. To this end, existing oil-rich coal resources needs to be evaluated and a supplementary method for the exploration of oil-rich coal based on the existing geological exploration data needs to be developed. Considering the ecological red lines set by environmental authorities, the ecological protection of the Yellow River Basin, coal occurrence, and other influencing factors, the oil-rich coal resources and their recoverable scale need to be objectively evaluated. Then, a specific development sequence based on the scale and area of oil-rich coal needs to be developed, which differs to that of ordinary coal.

The integration of oil-rich coal pyrolysis has great potential for improving efficiency and reducing carbon emissions. In 2019, the amount of oil-rich coal used for combustion power generation and heating in Western China was about 5.2×10^8 t. By integrating pyrolysis and power generation, nearly 5×10^8 t of oil can be produced, energy efficiency can be improved by 6%, and carbon emissions can be reduced by 2.8×10^8 t.

4.1.2 Exploiting oil-rich coal resources efficiently to meet requirements of economic and social development

There is an urgent need to promote the green development and exploitation of coal resources to protect the ecological environment. In accordance with the green development concept proposed by General Secretary Xi Jinping, that “lucid waters and lush mountains are invaluable assets”, a systematic planning before mining, precise control during mining, and effective recovery after mining are needed to develop oil-rich coal green mining technologies, promote the collaborative development, and build a new integrated development model. By improving the oil-rich coal recovery rate and fully exploiting oil-rich coal resources, the coordinated development of resource exploitation and environmental protection can be achieved, thereby actively protecting the environment. In this context, the coordinated development of coal and coalbed methane will improve the development efficiency of resources and achieve the goal of transforming coal resource mining into the co-production of coal, oil, and gas, among other resources.

4.1.3 Exploiting the oil and gas resources of oil-rich coal to increase domestic oil and gas supply

The cascade utilization of oil can be used to maximize the use of oil and gas components in oil-rich coal and produce light gasoline, special oil products, high-end coal-based oxygenate products, high-quality gas, and other oil and gas products and their substitutes, thereby increasing domestic oil and gas supply. Furthermore, coupling and integration processes can be implemented to improve the added-value of the resulting products. Through the coupling and integration of various single technologies, multiple products, and different grades of energy, the

DOI 10.15302/J-SSCAE-2022.03.006

investment and cost associated with these processes can be reduced, the utilization efficiency can be improved, and the added-value of product utilization can be increased. Ultimately, this results in the transformation of coal from fuel to both raw materials and fuels.

4.2 Technical systems

By focusing on the process of oil-rich coal exploration/development/utilization as a whole, with the aim of resolving existing problems, and building from the existing technical foundation, new technologies can be developed to create a better system for oil-rich coal development and utilization. In this context, traditional modes for the development and utilization of oil-rich coal will be reformed to enable the realization of the fine exploration of oil-rich coal resources, integrated mining, and the three-dimensional pyrolysis utilization of oil-rich coal resources.

4.2.1 Supplementary exploration of the distribution and variation of oil-rich coal resources using fine exploration technologies

Using coring analysis and intelligent logging, the space–sky–Earth integrated exploration technology can be constructed via the comprehensive use of high-resolution three-dimensional seismic exploration, high-precision electromagnetic detection, fast and accurate drilling technology, and remote sensing technology, among other means. In combination with geological big data technology, technology could be used to mutually validate and comprehensively analyze oil-rich coal resources to accurately detect their amount and distribution in Western China.

4.2.2 Addressing high recovery rates and fine sorting to minimize the waste of resources

In oil-rich coal, a coal-based oil and gas resource, the oil is utilized first, followed by the gas and the coal. In response to demand for economic development and the cascade utilization of oil-rich coal resources, one strategy involves planning the development of oil-rich coal resources separately using technologies, such as underground coal pillar-free mining, to improve recovery rates. The second strategy involves improving existing raw coal separation technologies to improve the level of oil-rich coal washing to provide sufficient raw coal for the pyrolysis of oil-rich coal.

4.2.3 Improving the pyrolysis technology system to address bottlenecks to large-scale development

Existing bottlenecks to the large-scale development of oil-rich coal cannot be fully resolved using current pyrolysis technologies as they are at the initial stages of research and development (R&D) and industrialization. The bottlenecks include difficulty in high-temperature gas-solid separation, high tar dust contents, and immaturity of the existing semi-coke high value-added utilization technology. Based on the demonstration of pyrolysis technology, the R&D of new technologies, such as catalytic pyrolysis, pressure pyrolysis, and polygeneration, will need to be carried out in depth to provide sufficient technical support for optimizing the pyrolysis of million-ton pulverized coal.

4.2.4 *In situ* pyrolysis technology for downhole extraction and conversion

To improve the efficiency and yield of pyrolysis, as well as evaluate the application of oil-rich coal underground *in situ* pyrolysis for the extraction of oil and gas resources, it is necessary to solve the problems of the poor thermal conductivity of coal, the low pyrolysis yield of coal tar, and the production of pollutants during pyrolysis. To address these issues, the technology of high-power electric heating and superheated steam heating can be applied to establish a thermal reaction field for underground oil-rich coal. As a result, the stability and conductivity of heat transfer in the *in situ* pyrolysis process of oil-rich coal can be increased, such that the heat generated by superheated steam is evenly dispersed into the coal seam, thereby improving pyrolysis efficiency.

5 Key technologies for the development and utilization of oil-rich coal

5.1 High-precision comprehensive exploration technology

The establishment of ecological red lines by environmental authorities combined with the development of intelligent coal mining, as well as safe and green mining, within the context of the precise exploration of oil-rich coal resources and their occurrence conditions provide direct support for the construction of modern coal mines and the coordinated development of coal resource development and ecological environment protection in mining areas. At present, different regions in Western China have significant differences in the proportion of oil-rich coal resources and tar yield [6]. In terms of spatial characteristics, oil-rich coal and the overall coal seam are coenriched. As such, the key to the development of high-precision exploration technologies is to find oil-rich coal seams with high hydrogen-rich components and a low coalification degree from the exploration coal seams. Therefore, a high-precision comprehensive exploration technology adapted to the occurrence characteristics of oil-rich coal in the Western China should be established, which focuses on breakthroughs in horizontal directional drilling, directional branch drilling, 3D seismic exploration, and high-precision electromagnetic exploration. The occurrence state and dynamics of geological bodies should be comprehensively characterized to address the shortcomings of traditional comprehensive exploration technology, in terms of both accuracy and depth detection.

After years of technical research, with seismic technology as the mainstay, and the cooperation of various technical means, breakthroughs have been made in the multi-dimensional comprehensive exploration technology that combines uphole and downhole techniques. Coal mine geological exploration using a technology system with 3D high-resolution seismic detection as the core, combining pre-mining and in-mining with the integration of uphole and downhole techniques, has gradually been established [22]. Horizontal directional drilling and directional branch drilling are key technologies for the accurate detection of oil-rich coal seams. Finally, this process is supplemented with coring analysis, targeting the process of extraction to oil-rich coal seam.

Using multi-dimensional three-dimensional exploration technologies, the utilization rate of exploration drilling data and the accuracy of seismic exploration can be improved further. With the help of computer simulation technology and spatial geographic information system platforms, current processes for conventional coal geological exploration should be transformed into digital exploration and information-based exploration models. Information on the distribution of oil-rich coal, changes in thickness, and tar yield, among other indicators, will improve the overall exploration of oil-rich coal resources and provide a foundation for further scientific developments.

5.2 High-recovery-rate mining technology

In China, the average recovery rate of coal resources is currently 40%, which is significantly lower than the global level at 80%; in particular, the recovery rate of small coal mines is lower [23]. At present, oil-rich coal is not exploited to its full potential and has a low recovery rate, which does not reflect to the high value of the corresponding oil and gas resources found in this type of coal.

High recovery rate mining requires the unified planning of oil-rich coal resources in mining areas, the design of development sequence and methods, and the adoption of special mining techniques to improve the coal recovery rate, as shown in Fig. 2. An appropriate design for a mining plan should be selected to reduce losses, which includes deciding on the number of coal pillars and waterproof coal pillars in the industrial square, in addition to optimizing the design plan of the mining area and arranging the layout of the roads therein. Under the conditions allowed by the geological conditions of the coal seam in the mining area, the inclination length of the panel should be increased to reduce the stage coal pillars in the mining area, and the panel should be arranged in a way that minimizes the losses caused by triangular coal and faults [23].

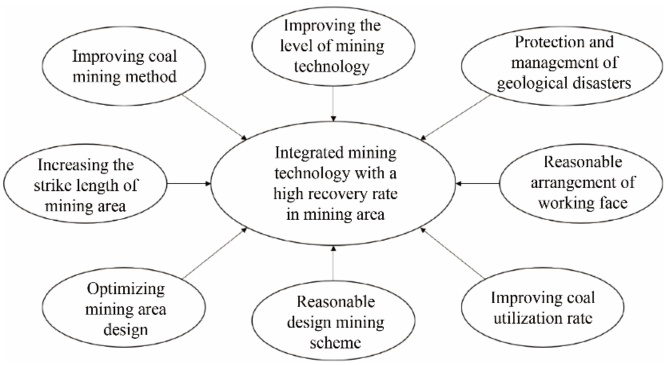

Fig. 2. Technology composition of high-recovery-rate mining.

5.3 *In situ* underground pyrolysis technology

In situ underground pyrolysis refers to the process in which heat is introduced into underground coal seam, and the resulting liquid and gaseous organic matter is extracted to the surface for processing after the solid organic matter of the coal is thermally cracked [24,25]. Through the *in situ* pyrolysis of oil-rich coal, the oil and gas

DOI 10.15302/J-SSCAE-2022.03.006

components are directly extracted, and most of the carbon in the coal is left in the underground residual coke, thereby realizing hydrogen extraction and carbon retention. The system corresponding to this deep coal *in situ* pyrolysis technology [26] requires an electromagnetic induction heating tube and a microwave heating tube in horizontal well for heating, and uses high temperatures to promote underground coal pyrolysis reaction. Then, the liquid and gaseous organic matter formed via pyrolysis are pumped to the surface via a vertical extraction well. Recent research on *in situ* fluidized coal mining [27] the theory of mining rock mechanics for deep *in situ* fluidized mining, and the development route of deep *in situ* fluidized coal mining, which provides a reference for the development of oil-rich coal underground *in situ* pyrolysis.

At present, there is a need to study technologies further, including high-power electric heating, superheated steam heating, and underground small nuclear reactor heating, for the development of an underground oil-rich coal thermal reaction field. This can then be coupled with renewable energy in the mining area to further reduce the use of fossil energy.

5.4 Pyrolysis and gasification integrated technology

With the goal of carbon neutrality in mind, integrating the technologies of oil-rich coal surface pyrolysis and gasification is an important step to achieving the conversion and utilization of coal classification and improving its quality, as well as improving energy utilization efficiency, and is quickly becoming a promising direction for the development and efficient utilization of clean oil-rich coal.

The integration of pyrolysis and gasification technologies can be divided into pyrolysis–gasification integration, pyrolysis–power generation–chemistry integration [6]. In Shaanxi province, the integration of pyrolysis and gasification technologies has been applied to thousands of tons of pulverized coal, creatively combining pulverized coal pyrolysis and semi-coke gasification in the same reactor to produce coal tar and syngas, resulting in a coal tar yield exceeding 15%. This demonstrates that these techniques can be applied to effectively solve the practical problems associated with traditional coal processing and utilization processes, namely low tar yields, the complex utilization of pyrolytic semi-coke, and environmental pollution. This integration has the technical advantages of a high tar yield, a high energy conversion efficiency, and advanced equipment, providing new perspectives for the integrated application of the ground pyrolysis and gasification of oil-rich coal.

There is a clearly a need to harness the advances being made in the high-temperature gas-solid separation and oil-dust separation of medium- and low-temperature pyrolysis oil and gas and the pyrolysis of residual coke to achieve the large-scale development and industrialization of oil-rich coal pyrolysis and gasification.

5.5 *In situ* pyrolysis semi-coke CO_2 storage technologies

In situ pyrolysis can maximize the extraction of oil and gas resources from oil-rich coal and retain semi-coke underground, directly supporting the development goals of carbon peaking and carbon neutrality. After the *in situ* pyrolysis of oil-rich coal, a well-developed pore-fracture structure space is formed, and a large number of pyrolysis products are produced to form a pore structure dominated by mesopores and macropores. Then, CO_2 can be injected into the pyrolysis semi-coke layer for permanent storage. This technology provides an efficient space for the storage and adsorption of CO_2 with less disturbance to the caprock and a higher storage stability and safety compared with the conventional coal CO_2 storage methods. Thus, it represents a new method for carbon sequestration and reduction.

The *in situ* pyrolysis and CO_2 storage of oil-rich coal are currently in the early stages of exploration, with many existing bottlenecks and technical challenges. Basic issues, including the formation and regulation of CO_2 storage spaces, the evaluation of storage potential, the selection of geological conditions for storage, the evaluation of airtightness, and the detection of geological risks, need to be studied further. Sealing and thermal insulation materials can be used to fill coal seams underground to effectively implement oil and gas pyrolysis extraction and CO_2 adsorption space to achieve CO_2 physical adsorption storage in the semi-coke layer, which will expand the potential scale of CO_2 storage, as well as improving the long-term stability of CO_2 storage[28].

6 Measures to promote the development and utilization of oil-rich coal in Western China

6.1 Incorporating oil-rich coal into unconventional oil and gas resource management

Oil-rich coal is a coal-based oil and gas resource that integrates the attributes of coal, oil, and gas. Thus, it is recommended that oil-rich coal be included in the category of strategic mineral resources, as an unconventional oil and gas resource. The comprehensive evaluation of the development potential of oil-rich coal should be carried out according to the properties of this resource. The relevant requirements for oil-rich coal exploration should be included in the revision of the *Mineral Resources Law of the People's Republic of China* to provide a high-level basis and guarantee for promoting the development and utilization of oil-rich coal. In accordance with the principle of prioritizing the production of oil and gas, the scale of the exploitation of oil-rich coal resources should not be restricted by coal production capacity, and the scale of utilization should not be included in the total amount of coal fired.

6.2 Increasing the scientific and technological efforts in the development and utilization of oil-rich coal

Those key technologies required for the exploration, development, and transformation of oil-rich coal resources should be developed and a system with independent intellectual property rights for the entire industry chain should be established, thereby providing scientific and technological support for the large-scale development and utilization of oil-rich coal. First, the construction of national-level R&D centers and test platforms for the development and utilization of oil-rich coal should be prioritized to promote the development of relevant theories and technologies, including the mechanism underlying the formation of oil-rich coal, pyrolysis temperature field control, improving of the tar recovery rate, and underground *in situ* pyrolysis high-power heating. Second, a technology innovation platform in collaboration with enterprises should be established for the development and utilization of oil-rich coal in Western China.

6.3 Setting up a national demonstration zone for the development and utilization of oil-rich coal

Since the Yulin mining area of Shaanxi Province is abundant in oil-rich coal resources and has relatively simple mining geological conditions, it is recommended for the establishment of a national-level oil-rich coal industry development demonstration area for use in major national projects. The construction of oil-rich coal *in situ* mining and pyrolysis in large-scale oil and gas production projects should be supported to enable breakthroughs in oil-rich coal *in situ* pyrolysis, including high-power heating devices, coal seam cracking and infiltration enhancement devices, and a single one-million-ton pyrolysis device, to promote the technological progress of the large-scale and high-efficiency production of oil and gas from oil-rich coal.

6.4 Promoting the coordinated development of new energies and oil-rich coal in Western China

Western China is rich in wind and light resources, combined with a wide network of oil-rich coal distribution. As such, it has unique conditions for the coordinated development of new energies and oil-rich coal. To harness this large amount of resources, several technologies will need to be developed, including high-power electric heating based on wind energy/photovoltaic, coal seam permeability enhancement and thermal conduction, pyrolysis oil and gas thermal insulation, and anti-blocking transportation. To achieve this, *in situ* pyrolysis engineering tests of oil-rich coal in Western China will need to be conducted. Furthermore, corresponding tax incentive policies and subsidy policies should be implemented to promote the development and utilization of unconventional oil and gas resources.

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