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Intelligent and ecological coal mining as well as clean utilization technology in China: Review and prospects

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A B S T R A C T

Coal is an essential fossil fuel in China; however, coal mining and its utilization are being under the increasing pressure from ecological and environmental protection. Therefore, the consulting project "*Technical Revolution in Ecological and Efficient Coal Mining and Utilization & Intelligence and Diverse Coordination of Coal-based Energy System*," initiated by Chinese Academy of Engineering, puts forward three stages (3.0, 4.0 and 5.0) of China's coal industry development strategy. Aimed at "reduced staff, ultra-low ecological damage, and emission level near to natural gas," breakthroughs should be achieved in the following three key technologies during the China Coal Industry 3.0 stage (2016–2025): including intelligent coal mining, ecological mining, ultra-low emission and environmental protection. This paper focuses on the development trends of the China Coal Industry 3.0 and its support for China Coal Industry 4.0 and 5.0 is analyzed and prospected as well, which may offer technical assistance and strategy orientation for realizing the transformation from traditional coal energy to clean energy.

1. Introduction

Coal is the most essential and fundamental fossil fuel in China. In 2014, the total production of primary energy sources in China was 3.60 billion tce (tons of standard coal equivalent), with the coal production accounting for 76.8%. On the other hand, the total consumption of primary energy sources in China was 4.26 billion tce, with the coal consumption accounting for 66.0% [1]. Since 2015, the rising trend in coal production and consumption has been changing with the world's economic slowdown and China's economic transition and adjustment.

As shown in Fig. 1, research predicts that the absolute total amount of coal consumption will keep relatively stable, and the proportion of coal consumption in primary energy source is gradually decreasing but remains above 50% [2]. Growth in global coal demand slows sharply relative to the past (0.2% p.a. versus 2.7% p.a. over the past 20 years); global coal consumption will peak in the mid-2020s [3]. Much of this slowdown is driven by China as its economy adjusts to a more sustainable pattern of growth and government policies prompt a shift away from coal towards cleaner, lower-carbon fuels. China's coal consumption is projected to broadly plateau over the next 20 years, in sharp contrast to the rapid, industrialization-fuelled growth of much of the past 20 years. Even so, China remains the world's largest market for coal, accounting for nearly half of global coal consumption in 2035, as shown in Fig. 2, where OECD is an acronym of Organization for Economic Co-operation and Development, and toe is an acronym of tonne of oil equivalent [3].

Research agrees well with the practical situation: the China's coal consumption decreases 2.9% in 2014, decreases 3.6% in 2015 and chain relative ratio flattens in 2016 [2]. Because of China's economic transition and adjustment as well as the increasing emphasis on ecological and environmental protection, the high-strength and low-level coal production and consumption have come to an end. China's coal production and consumption may have reached peak earlier than predicted, and China's economy is moving toward a green growth stage [4]. Like China's economy, China's coal industry is undergoing structure adjustment and meticulous production. Intelligent and ecological production as well as clean and low-carbon utilization has already become the new direction.

"*Technical Revolution in Ecological and Efficient Coal Mining and Utilization & Intelligence and Diverse Coordination of Coal-based Energy System*" initiated by the Chinese Academy of Engineering,

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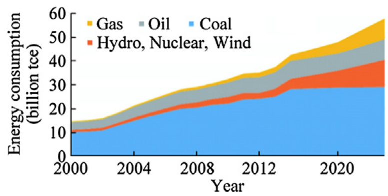

Fig. 1. China's energy consumption structure and prediction during 2000–2030.

puts forward three stages (3.0, 4.0 and 5.0) of China's coal industry development strategy [5,6]. The China Coal Industry 3.0, from now to 2025, strives to fulfill "reduced staff, ultra-low ecological damage, and emission level near to natural gas" through 10 years' technology progress and transition development. Furthermore, China Coal Industry 4.0 plans to realize "near-unmanned mining and near-zero emission" in 2035. Finally, China Coal Industry 5.0 may reach the objective "no coal above ground, no staff underground, zero emission and zero damage", completing the transformation from traditional energy towards clean energy [7–11].

Based on research trends in related fields, this paper analyzed the development of coal mining and utilization over the next ten years and put forward three key technologies during China Coal Industry 3.0 (2016–2025), including intelligent coal mining, ecological mining, ultra-low emission and environmental protection. The development trends of China Coal Industry 3.0 and its foundation laid for coal industry 4.0 and 5.0 are analyzed and prospected.

2. China Coal Industry 3.0 development goals and technology roadmap

The next decade will be the critical period for China's coal industry to upgrade technology and transit development patterns. On the one hand, coal mining will be more efficient and safer with less staff and less ecological damage; on the other hand, the coal conversion and utilization technologies will also be more efficient with lower energy consumption and less environmental pollution.

These are a process shifting away from quantitative changes to qualitative changes. Technological systems of production that focused on mechanized and intelligent mining, as well as low-carbon and clean utilization, should be pushed forward to realize the following strategic objectives of China Coal Industry 3.0:

(1) Reduced underground staff

Staff working underground should decrease by 70%; coal mining should be fully-mechanized; and the percentage of automation and informatization should reach 80%.

(2) Ultra-low ecological damage

The protection and utilization rates of associated underground resources (methane gas, water, heat) should be above 50%; the surface subsidence damage reduces by 50%; and the ground surface ecological recovery rate should be above 80%.

(3) Extra-low emission

Emission level near to natural gas and the total emission amount almost peak; more than 50% coal resource could be utilized cleanly and emitted super-cleanly. Fig. 3 shows the overall technology roadmap.

3. Intelligent and ecological coal mining technology

As one of primary energy sources, ecological coal mining not only copes with the physical environmental change to ensure the resource mining activities completed smoothly but also focuses on reduction of the adverse impact on the ecological environment. Over a dozen years high-intensity mining, China's energy demand has been greatly satisfied, and the pursuing objective has been transferred gradually from the pure quantity of resources to the following: (1) equipment self-adaption to the changes of complex technical and geological environment encountered in the mining process; (2) mitigation of negative environmental impacts caused by mining activities; and (3) the recovery of ecological environment. Breakthroughs in intelligent and ecological mining technology should be made and vigorously promoted, including:

(1) Digital mining technology of internet-based multi-information fusion

At present, most large-scale coal mines have built the digital mine models, which digitizes the early information acquired from the drilling, seismic prospecting, radar scanning and so on, forming the initial coal mine geological data model. Later, the information, such as mining development, roadway layout, ventilation, and safety monitoring and control, is fused. Foundation platforms are structured for the overall production scheduling, safety assurance, transportation, personnel monitoring, shown in Fig. 4. However, most of the platforms are only a simple collection and unified managed at present, lacking practical information fusion. Therefore, decisions from each level are primarily made by personnel. Meanwhile, because the production control system has no association with the foundation platform, the geological data model can't be dynamically corrected according to production status, and the geological information can't get involved in decision-making either.

China Coal Industry 3.0 emphasizes on solving the above problems. For one thing, information acquisition and fusion technology should be strengthened by making full use of the existing technology, such as internet of things, automation, intelligence, big data,

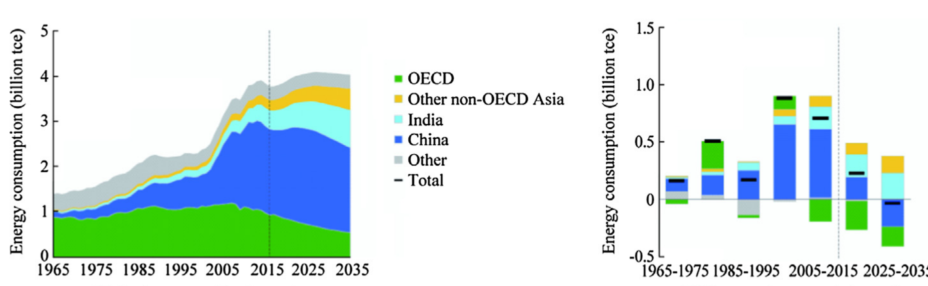

Fig. 2. Global coal consumption and demand growth.

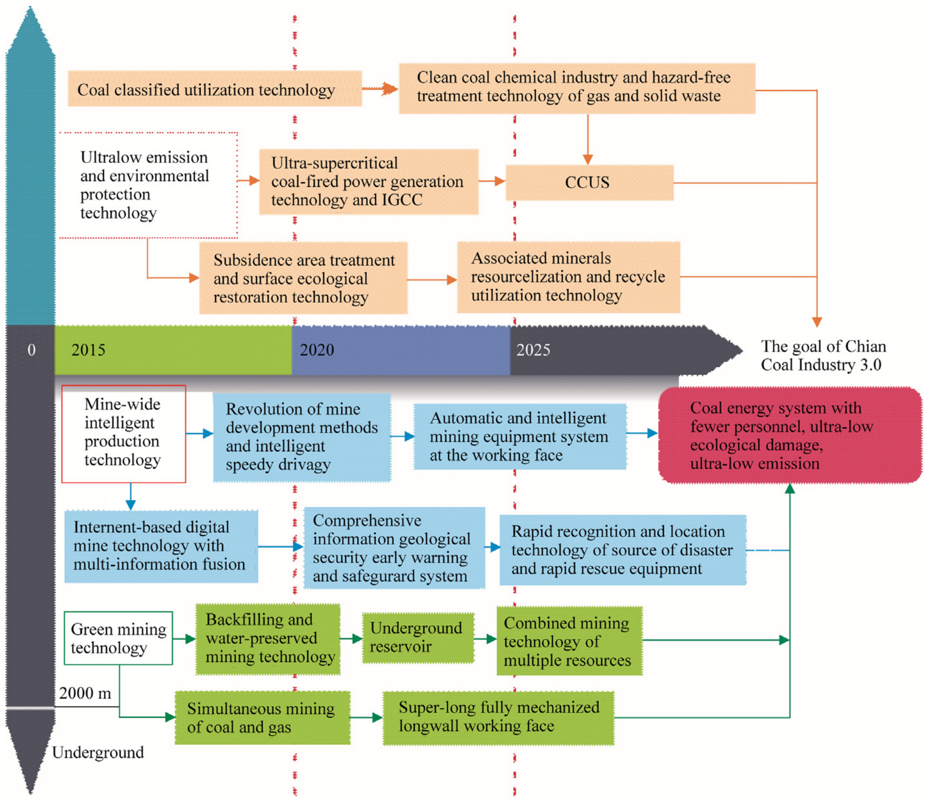

Fig. 3. China Coal Industry 3.0 objectives.

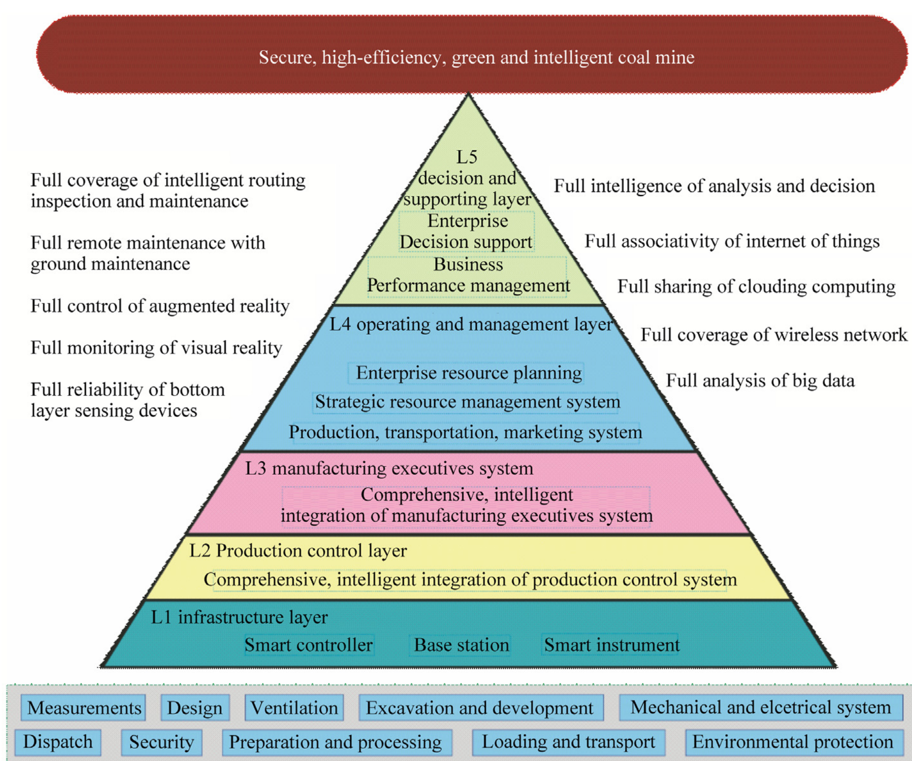

Fig. 4. Internet-based multi-information fusion digital mining technology.

and cloud computing [12]. For another thing, for the purpose of providing necessary information for intelligent mining and safety assurance, breakthroughs need to be made in the construction and dynamic correction of high accuracy three-dimensional dynamic geological model to build the high accuracy four-dimensional GIS platform [13].

(2) Technological change in mining development method and intelligent rapid excavation

At present, mining development is developing towards large-scale and centralization. It is being promoted that only one longwall face for each mine with less chain pillar. Because the gate road development rates generally lags behind those needed to meet longwall capabilities, the conflict between longwall face advance and gate road development has been a prevalent problem, and how to resolve such an issue has been a significant research direction. For the purpose of solving the problem, non-chain-pillar mining method, like "N00 construction method" and gob-side entry retaining, has been studied and developed [14,15]. Furthermore, improving the intelligence and collaboration ability of gate road development system is also an important research area, such as developing integrated equipment that combines driving, bolting, support, transportation, and prospection. Therefore, breakthroughs should be made in the following key technologies: intelligent cutting, fast support, fast transportation, intelligent ventilation, and safety assurance, shown in Fig. 5.

(3) Automatic and intelligent mining equipment system at the working face

At present, the development trend of fully-mechanized coal mining is automatic and intelligent mining. Automatic technology has been applied to mining engineering around the world since the 1990s, such as tele-mining/remote control mining technology in Canada and automatic mining "Grountecknik 2000" strategy in Sweden [16,17]. The electro-hydraulic control system of hydraulic roof supports, the automatic control system of the shearer, and other control systems for other equipment have been gradually studied in China since 2000. These systems significantly improve the efficiency and safety of longwall face by the collaborative operation of the shearer, the armored face conveyor (AFC), hydraulic roof supports, visualization of longwall face, and the communication and remote control of longwall face.

With the increasing complexity of coal mining, the traditional mechanized and automatic mining technology cannot meet the requirements of further improvement of the mining efficiency and safety level. Therefore, intelligent mining becomes inevitable. LASC straightness monitoring and control system in Australia, as well as new mechanization and automation of longwall and drivage equipment (NEMAEQ) project in Europe, has made significant achievements in the intellectualization of coal mining equipment [18–20]. Some universities and institutes in China are conducting researches in many fields, such as underground inertial navigation and precise location, straightness intelligent control, intelligent adjustment of cutting height, the achieved results are in the process of perfection and promotion.

As shown in Fig. 6, the intelligent control technology for one single machine has been resolved, but the control of complete sets of equipment is still centralized control mode based on Industrial Ethernet, which is hard to satisfy the control requirement of rapid increasing fully-mechanized coal mining equipment group. The new control method and architecture innovation on the system level are also gradually developed, including of self-organized cooperative control method of hydraulic roof supports group, dynamic decision-making based on the feedback of sensory perceptual system, longwall face control system and application platform based on distributed decision-making [21]. Once these

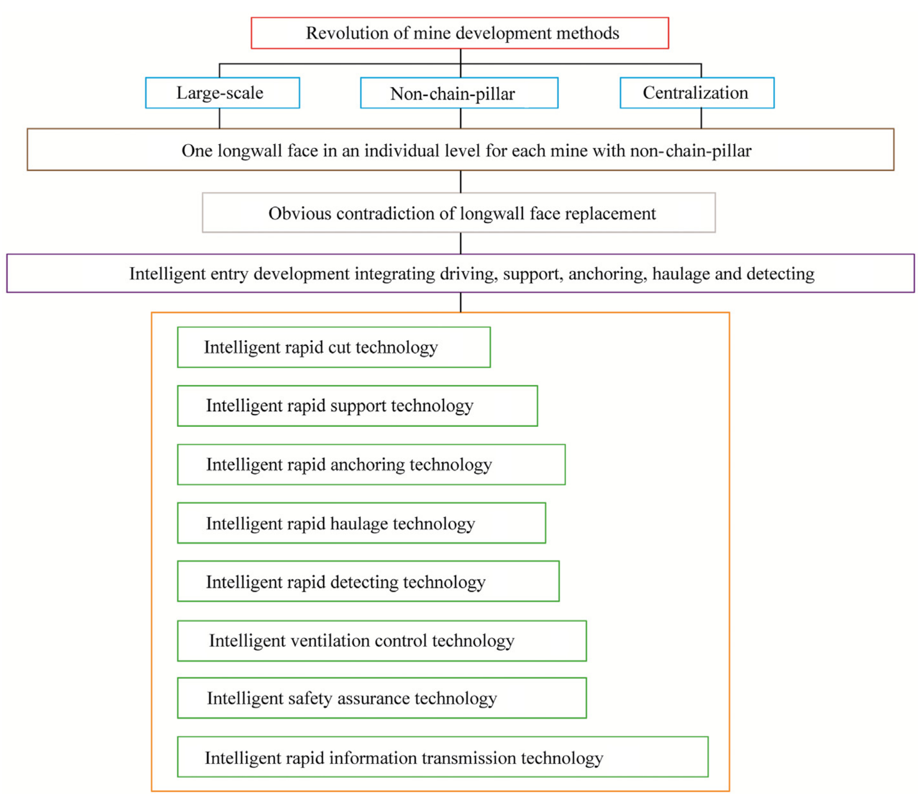

Fig. 5. Technological change in mining development and intelligent rapid excavation.

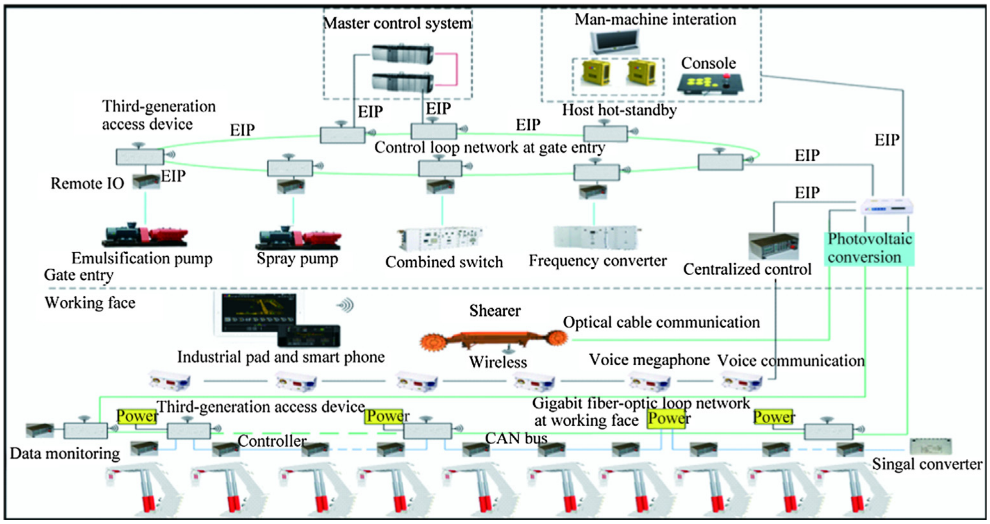

Fig. 6. Intelligent equipment and control system of a longwall face.

technologies are successfully applied, the equipment could make correct response to the changes of surrounding rock, significantly improving the level of intelligence of equipment.

(4) Simultaneous exploitation of coal and gas, ecological protection mining and treatment of coal mining subsidence areas

Ecological mining (or green mining) mainly includes three aspects: (1) simultaneous exploitation of coal and gas; (2) resources comprehensive utilization with low ecological damage; (3) ecological restoration of the damaged ecological environment. The following gives a further discussion about them.

China has made a significant advance in the simultaneous exploitation of coal and gas [22]. However, there still exist some problems in practice: (1) technical measures and drill hole patterns of gas drainage are lack of effectiveness, pertinence, and stability, leading to low economic benefits; and (2) low time-efficiency, weak cooperation, low gas drainage rate and mining with inadequate drainage caused by a tight schedule of extraction and development. These problems cause many potential safety risks. Therefore, aimed at substantially improving the efficiency and safety of the simultaneous exploitation of coal and gas, the China Coal Industry 3.0 needs to conduct further research on the following aspects: (1) broken structure evolution laws and spatial and temporal distribution characteristics of coal-rock mass containing gas under the condition of mining; (2) gas adsorption and desorption and material flow rules in coal-rock mass; (3) formation mechanism and control technology of gas directional flow in coal-rock mass; (4) spatial and temporal synergetic theory and control technology of simultaneous exploitation of coal and gas; and (5) exploitation and stepwise utilization of gas resource in coal mining area.

On the other hand, the following four aspects are the main parts to be developed to make comprehensive utilization of resources with low ecological damage:

(1) Super-long fully-mechanized longwall face and non-chain-pillar mining

At present, the length of most longwall faces is less than 300 m, and the conventional mining development and layout causes the uneven subsidence of the ground, which is hard to control and severely damage the surface eco-environment. However, super-long longwall face and non-chain-pillar mining can enhance the consistency of strata collapse and movement, resulting in surface even subsidence and reducing the surface fractures, and finally improve the surface eco-environment.

(2) Backfill coal mining

In the current practice of backfill coal mining, China's coal industry should base on the local geological characteristics of different coal mine areas developing new backfill materials that are suitable for safety and high-efficiency backfill mining [23]. It also needs to work on low-cost backfill transport system and corresponding equipment to make the backfill mining play a more significant role in breaking the technical bottleneck of inadequate backfill capacity, optimizing mining and backfill processes, and further enhancing the scale of backfill coal mining. The main technologies to be developed comprise the control ability and strategy of backfill coal mining on the surface subsidence, new backfill materials and corresponding equipment of transport system, and the selection and design of backfill equipment, etc.

(3) Coal mine distributed underground reservoir

A coal mine underground reservoir is formed by reconstructing the gobs where the coal is extracted, connecting the same mining level, different mining levels, and even many different coal mines by artificial channels. According to the production succession planning, mine water is stored according to time and location, forming the distributed underground reservoir, namely, coal mine distributed underground reservoir. The coal mine distributed underground reservoir has an effect on convergence and storage of mine water generated during the mining process by its migration law or under the human intervention. The water in the reservoir can be diverted to the surface to be utilized if needed. In this way, a coal mine can reach zero discharge of mining water and the protection of underground water and surface ecosystem.

The coal mine distributed underground reservoir technology is complex system engineering, including reservoir planning, design, construction, operation, monitoring, and management, which involves coal mining, water conservancy, and hydropower engineering. Shenhua Group, China's biggest coal company, has already constructed the largest coal mine distributed underground reservoir that can recycle mine water. In the China Coal Industry 3.0

stage, this technology will be further popularized to protect and utilize water resource feasibly and effectively.

(4) Surface ecological and environmental restoration and improvement

The research focus will be the mechanism of effect of the ecological environment as well as the evolution law of earth and ecosystem under various technical and environmental mining conditions. It is necessary to establish the following two system: the early warning and forecasting system of eco-environmental disasters; the decision support system of environmental protection and rehabilitation. For the purpose of gradually rehabilitating the surface landform and vegetation damaged by mining subsidence, the following researches should be conducted: mining design method of relieving surface eco-environmental damage, treatment of acidic gangue pile, ecological engineering reclamation, bio-microbics eco-environmental rehabilitation, the development and industrialization of equipment and materials of surface eco-environment treatment, water and soil conservation, etc.

4. Clean and efficient coal utilization and environmental protection technology

Environmental pollution and carbon emission have been being an evitable problem in the process of coal utilization, and some scholars and institutions proposed the concepts like "coal elimination in China." However, these ideas don't take into account the actual situation of China's economic and social development, and they can't resolve the issue of clean utilization of fossil fuel either.

China has so far solved a batch of the main technical issues on coal clean and efficient utilization, including coal-fired power generation with ultra-low pollutant emissions, high-efficiency green conversion using coal as the raw material, low-cost carbon capture, utilization, and storage (CCUS). In the future, coal resources should be burnt and converted intensively, shifting from primary energy to secondary energy supply and making the coal resource play equal role in being both raw material and fuel. In the China Coal Industry 3.0 stage, the critical factor to achieve the above objectives is the large-scale development and application of coal clean and efficient utilization technology as well as environmental protection technology.

(1) Coal-fired power generation with ultra-low pollutant emissions

Through years of effort, breakthroughs in clean and efficient coal utilization have been achieved. The high-efficiency industrial pulverized coal-fired boiler is independently researched and developed, with thermal efficiency above 90% and its pollutant emission level near to the standard of the natural gas boiler. In terms of coal-fired power generation, the average coal consumption of power plants with a capacity above 600 MW decreased from 10841 kJ/kWh in 2005 to 9229.5 kJ/kWh in 2015, and the emissions declined more than 15% [24]. For some power plants, such as Shanghai Waigaoqiao and Huaneng Shidongkou, the coal consumption can be reduced to 270 gce/kWh, and the emissions meet, even exceed, the standard of natural gas. Meanwhile, the CCUS technology has begun promotion and application.

In the China Coal Industry 3.0 stage, there are still some key technical problems to be tackled besides vigorously promoting the existing advanced technology, including: (1) core technology and critical materials for 600 MW ultra-supercritical high-efficiency power generation, deep purification technology for pollutant in fuel gas, (2) key equipment of coal chemical industry with low power consumption, (3) conversion techniques and devices with low sensitivity to coal quality, (I4) high efficiency water conversation and wastewater treatment technology in coal chemical industry. For example, Fig. 7 shows the high-efficiency technology of desulfurization and denitrification that is one of the key technologies of ultra-low pollutant emissions.

(2) High-efficiency green raw coal conversion and utilization

Raw coal conversion and utilization technology mainly include coal liquefaction, coal gasification, coal-based synthetic natural gas (Coal-to-SNG), coal to olefin (CTO), etc. The international development of coal conversion technology is centralized in the 1970s and 1980s or may be earlier. After that, the oil and gas production increases rapidly, and the global focus shifts to oil, gas, and chemical industry, resulting in slowing down or stagnation of development for coal deep processing and conversion technology. With China's increasing requirement for coal deep processing and conversion technology, advanced international technologies have been applied in China's coal industry, while there is no new project built in where they are developed. Furthermore, China's energy resource conditions that "rich coal, meager oil and little gas" requires developing raw coal conversion and utilization technology.

In recent years, the coal conversion technologies, such as coal gasification, coal-to-liquid (CTL), and coal-to-olefin (CTO), have been developing quickly in China. Seven sets of coal-to-olefin (CTO) apparatus with a production capacity of 4.08 million t/a and nine sets of coal-to-ethanol apparatus with a production capacity of 1.95 million t/a have been constructed [25]. The Shenhua Group associates with the China Coal Research Institute (CCRI) and other institutes in developing the direct coal liquefaction (DCL) process that owns the independent intellectual property and building the world's first DCL facility with the capacity to convert a million tons of coal into oil. In the area of indirect coal liquefaction (ICL), China has successfully developed the ICL techniques that possess independent intellectual property. The industry demonstration has already been completed, building four engineering projects: Shenhua (180 thousand tons/year), Yitai (160 thousand tons/year), Lu'an (160 thousand tons/year), and Yankuang (100 thousand tons/year) [26]. As shown in Fig. 8, a 4 Mt/a coal-to-liquids demonstration project in Shenhua Ningxia coal industry group was completed and put into operation in December 2016.

(3) Low-cost carbon capture, utilization, and storage (CCUS)

CO_2 is a major factor that affects global climate change, and coal combustion is the primary source of CO_2 emissions. 45% of the total amount of CO_2 emission will stay in the atmosphere, and 30% is absorbed by the marine ecosystem as well as 25% by the terrestrial ecosystem [27]. On these grounds, CO_2 growth can be stopped if human being reduces around 50% of the total amount of CO_2 emission by means of emission reduction, replacement, conversion, offset, and carbon sequestration. Moreover, CO_2 negative growth can

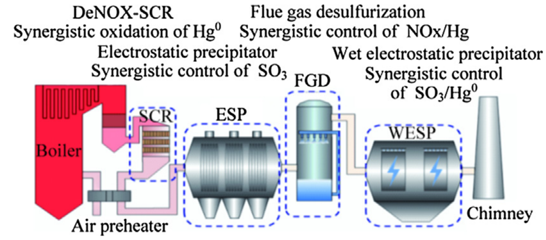

Fig. 7. High-efficiency desulfurization and denitrification technology in coal-fired power plant.

Fig. 8. A 4 Mt/a indirect coal liquefaction demonstration project in Shenhua Ningxia coal industry group.

also be achieved by properly increasing the carbon sequestration. The Chinese government has made a commitment that the carbon emissions should begin to decline by 2030. To comply with this, China should greatly promote the development and application of carbon reduction technology in the China Coal Industry 3.0 stage.

At present, coal capture, utilization and sequestration (CCUS) technology is still at the start-up stage in China. Fig. 9 shows the technology principles and roadmap of CCUS. Associated research has been conducting actively by Chinese universities and institutes as well as many other industries related to fossil fuel, such as petroleum exploitation, coal-fired power, and coal-to-liquids. Research and industrial demonstrations have been conducted in many aspects, such as CO_2 capture and utilization, oxygen-enriched combustion, high-purity CO_2 geological sequestration, enhanced oil recovery (EOR) and enhanced coal bed methane recovery [28]. Huaneng Group took Beijing thermal power plant as a demonstration project of CO_2 capture. Completed and put into operation in 2008, it successfully captured the CO_2 with a purity of 98% and achieved over 85% recovery rate and 3000 t/a recovery amount. The CO_2 captured can be refined to the food-grade purity, which can be used in beverage and food industries. Huaneng Group also pushed forward the implementation of a CO_2 capture demonstration project with a capacity of 100 thousands t/a at Shidongkou second power plant in Shanghai. Furthermore, Huaneng Group's Tianjin IGCC power plant demonstration project is under construction where the CO_2 captured is used for EOR.

In terms of EOR, China started on CO_2-EOR/CO_2-EGR in 2005, which is relatively late. China National Petroleum Corporation (CNPC) conducted the filed trail of CO_2-EOR in Daqing oil field in 2008 and Sinopec built a 30 thousand t/a CO_2-EOR demonstration project in Shengli oil field. China cooperated with Canada on the first research project about CO_2-EGR applied in deep coal seams, and its current test results show that injecting CO_2 into the coal bed methane well will increase the methane recovery rate. Furthermore, the research data shows 1 million tons of CO_2 can be sequestrated into one square kilometer coal seam, and the recovery rate of coal-bed methane well can be improved by 80%.

The CCUS technologies mentioned above and their application laid a solid foundation for the carbon reduction during the stage of China Coal Industry 3.0 stage.

5. Technological development prospect of China Coal Industry 3.0 and its technical support for 4.0 and 5.0 stages

Through the summary and analysis of aforementioned critical technologies, the great anticipations for the China Coal Industry 3.0 could be concluded as follows:

(1) Digital mining, intellectual mining and safety monitoring technology will have an accelerated development, and address technical problems, such as safety situation, mining area environment, working conditions, and labor intensity;
(2) Continuously improved efficiency of comprehensive utilization of resources, consistently developed ecological mining technology and equipment, and substantially reduced the environmental damage;
(3) Making an obvious progression in the energy transition from traditional energy to clean energy and making breakthroughs in clean burning coal, high-efficiency conversion, and utilization.

(1) "Transparent Earth"—3D visualization of geological information

Accurate and comprehensive 3D visualization of the geological model is the foundation for exact coal mine planning and development. The China Coal Industry 4.0 and 5.0 need to make breakthroughs in high-precision geological modeling to accurately describe a broader scope of Earth's tectonics and reveal the fundamental laws and dynamic changing characteristics of deep strata deposition. These breakthroughs can provide essential data support for the exploitation of underground mineral resources and deep ground scientific research. Fig. 10 shows the visualization model of geological information and its application in mining area division.

(2) Unmanned mining

The ultimate objective of automatic and intellectual mining development is the unmanned mining of the entire mining processes. On the basis of artificial intelligence and distributed control, the existing mining and extraction patterns should be completely

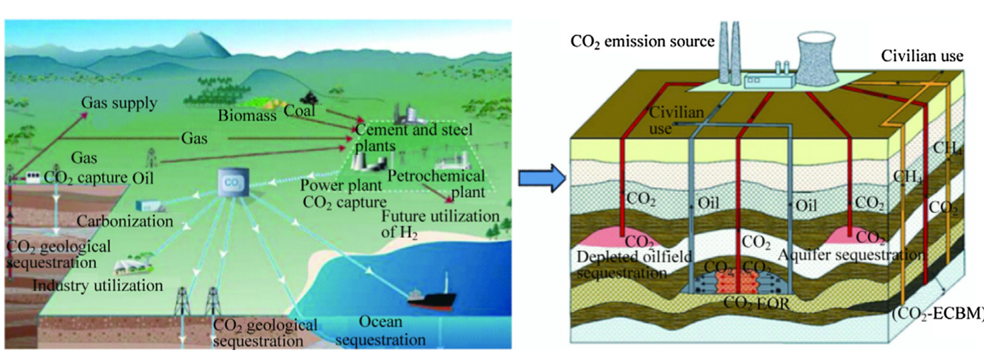

Fig. 9. CO_2 capture and geological sequestration.

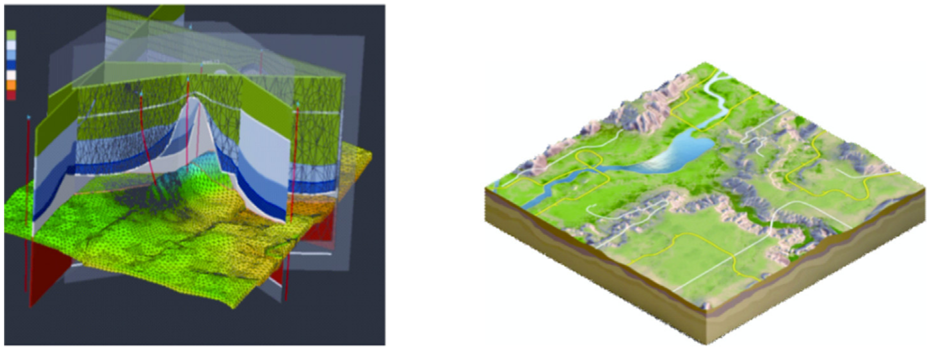

Fig. 10. Visualization model of geological information and mining area division.

changed to create a more reliable and intelligent equipment system. This system should possess the functions of self-decision-making, self-control, self-adaptive, and self-maintaining and should integrate deep resource mining, processing, back-filling, gasification, power generation, and other subsystems, which will actually realize "No personnel underground and No coal above ground" unmanned mining.

(3) Control technology of underground integrated conversion

In the stages of China Coal Industry 4.0 and 5.0, the clean coal utilization will, hopefully, be able to be completed underground (integrated coal-to-gas, coal-to-liquids, coal-to-power). In other words, the useful energy needed will be transported to the surface while the waste can be dealt with underground. Exact reaction processes and facility parameters are indispensable for the coal conversion. However, the existing technologies can't satisfy the high-efficiency and large-scale conversion processes underground. Therefore, it is evitable to supersede the current technology and dramatically improve the energy intensity to realize high-efficiency and intensive conversion in the limited underground space. Fig. 11 is a conceptual model of control technology of precise coal conversion and power transmission.

6. Conclusions

Coal, China's most primary and significant fossil fuel, safeguards the energy stability of national economic development and modernization. Through several decades of development, China's coal industry has been to the crucial crossroad. The breakthrough and practice of advanced ecological coal mining and high-efficiency conversion technology demonstrate: coal can be clean energy and "coal elimination in China," on the grounds of ecology and environment, is not reasonable.

The China Coal Industry 3.0 stage is the critical juncture of clean and ecological coal exploitation, in which remarkable achievements will be made, and a firm technical foundation should also be laid for the development of the China Coal Industry 4.0 and 5.0. It is a fundamental transformation stage and a transition period from "functional form" to "quality form." Strict management and regulation should be formulated to reverse the old pattern of production & operations management, guaranteeing the smooth and successful implementation of new technology. The investment in research and development should be increased to construct some major projects, including intelligent mining bases, circular economic park (CEP) with comprehensive utilization of resources, water resource conservation zone, surface ecological restoration demonstration base, coal-to-gas and coal-to-liquids demonstration base. Regulatory system of safe, high-efficient and green indexes should be strengthened, and the application of advanced technology should be spread in China Coal Industry 3.0 stage to realize the transformation of coal resource from traditional energy to ecological energy, from fuel to raw materials.

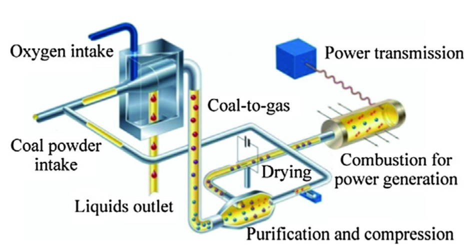

Fig. 11. Schematic of precise control technology and process of underground integrated conversion.

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