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Coal measure energy production and the reservoir space utilization in China under carbon neutral target

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Coal measure energy production and reservoir space utilization are both important for energy security and can assist in achieving carbon neutrality. Coal measure energy production and reservoir utilization are therefore of scientific significance. This study focuses on the security of coal supply by discussing the possible technical approaches of combining low-carbon mining of coal measure resources and coal reservoir space utilization. Our study found that 1) the integration of underground coal gasification and carbon capture and sequestration (UCG-CCS) is an effective technology to improve energy efficiency and achieve the carbon neutral target in China; 2) CO₂-enhanced coalbed methane (CO₂-ECBM) recovery is an important way to reduce CO₂ emissions during coalbed methane recovery; and 3) the integrated technology of solid waste filling (WF), coal bioconversion (CB), gas production (GP), and CO₂ capture and sequestration (CCS) in coal goafs and abandoned coal mines can improve the energy production efficiency and reservoir space utilization and reduce geological disasters due to surface subsidence. These integrated technologies will become increasingly important for coal measure energy production and efficient reservoir space utilization as they will provide scientific theory and technical support to achieve carbon neutrality.

KEYWORDS

carbon neutral target, CO₂ sequestration, reservoir space utilization, UCG-CCS, WF-CB-GP-CCS

1 Introduction

China is richly endowed with coal but has fewer oil and gas resources. Coal production and consumption account for a high proportion of China's energy production and consumption (Zou et al., 2021a; Chen et al., 2021; Xie et al., 2021). The total primary energy production in China increased from 628 million tons of standard coal in 1980 to 4.08 billion tons of standard coal in 2020, and the total energy consumption increased from 517 million tons of standard coal to 4.98 billion tons of standard coal over the same period (Figure 1). The Chinese gross domestic product (GDP) rapidly increased from 367.87 billion yuan to 101,598.62 billion yuan (National Bureau of Statistics of China, 2021; Zou et al., 2021b). The rapid development of China's economy has been supported by the increased consumption of energy. The increased energy output also caused a large increase in greenhouse gas emissions, such as CO₂ (Dong et al., 2014; Yang et al., 2020). In 2020 alone, China's energy-related CO₂ emissions were about 9.9 billion tons, accounting for 30.9% of the global total carbon emissions and ranking first in the world

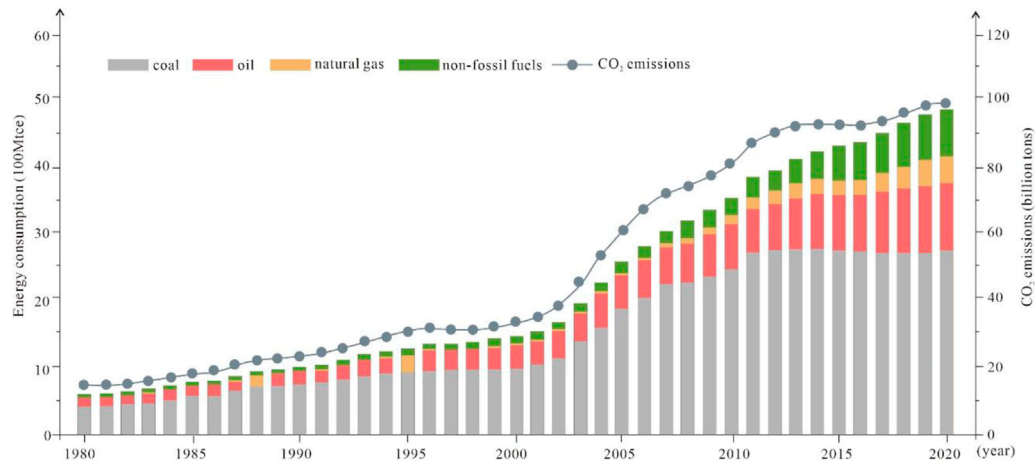


FIGURE 1
Trends of energy consumption and CO₂ emissions in China from 1980 to 2020.

(Zhang et al., 2021). Against this background, even if the proportions of natural gas and renewable energy could be increased to reduce the carbon-intensive power supply, the development of renewable energy will not outpace the price and security advantages of coal-fired power (Hecking, 2016; Fan & Chen, 2018; Zhang et al., 2018). China's 14th Five-Year Plan (2021–2025) and the Outline of Long-term Goals for 2035 specifically stated the following: “We will formulate an action plan to peak carbon emissions by 2030, improve the system of controlling both the total amount and intensity of energy consumption, and promote the clean, efficient and safe use of fossil energy such as coal.”

To keep the global temperature rise within 1.5°C, as proposed in the Paris Agreement, net-zero global CO₂ emissions, where there is a balance between man-made removal and man-made emissions, must be achieved by 2050. This is known as “carbon neutrality” (Chen et al., 2021). Global climate catastrophes are becoming more and more severe. Achieving this goal is regarded as the key to climate security and the survival of humanity (Zhang et al., 2021). By the end of 2020, 127 countries and regions had put forward their carbon neutrality targets, with some having set timetables for restricting or banning the use of fossil energy (Chen et al., 2021). At the General Debate of the 75th Session of the United Nations General Assembly, President Xi Jinping of the People's Republic of China promised that the CO₂ emissions will achieve peak before 2030, and carbon neutrality will be achieved before 2060.

Coal measure energies, which include coal, coalbed methane, coal measure gas, and shale gas, are the main current sources of energy in China. The production of coal measure energies and the utilization of their reservoir spaces are important for achieving the carbon peak and carbon neutrality targets in China. Over the past few decades, significant progress has been made in the exploration and production of coal measure energies.

For a long time, coal mining rates were low in China, being affected by the resource conditions, the state of mining technologies, and resource management. The resource recovery rate of a state-owned coal mine was generally about 50%, while the resource recovery rate of locally administered state and township-individual coal mines with relatively poor conditions was only about 20%–30% (State

Administration of Coal Mine Safety, 2002). From 1949 to 2014, the total amount of residual coal in China was 126.644 billion tons. These included state-owned, local state-owned, and township-individual coal mines at 26.93 billion tons, 20.198 billion tons, and 78.87 billion tons, respectively (Huang et al., 2014). The main obstacle was how to improve the coal mining rate.

In contrast, the volumes of coal goafs totaled 13.836 billion m³ in China by the end of 2016. These coal goafs led to frequent mining disasters such as land subsidence, and it is estimated that the volume of coal goafs in China will reach 23.452 billion m³ by 2030 (Xie, 2018). Challenges that must be addressed in coal goaf mining are how to efficiently use the underground space and reduce coal goaf mining disasters.

Coal measure gas in China has the characteristics of “three low and one high” (low pressure, low permeability, low saturation, and high content) due to the complex geological conditions that often complicate coal measure gas production (Lv et al., 2011). Improving the recovery of coal measure gas is a key problem to overcome. Only a few technologies can simultaneously exploit coal measure energy and optimally use coal reservoir space. Coal measure energy production must be increased to reach China's carbon neutral target, and the reservoir space utilization must be optimized. To meet the demand for clean and green mining against the background of future carbon neutrality, this study considers these two technologies comprehensively by focusing on coal measure energy production and reservoir space utilization from theory and practice.

2 Theoretical basics

2.1 Principle of underground coal gasification (UCG)

Underground coal gasification, which involves *in situ* coal gasification, is the controlled burning of coal under *in situ* conditions (Figure 2). The thermal and chemical reaction of the solid organic matter in the coal generates mixed gases during controlled burning. These gases can be converted into various fuels

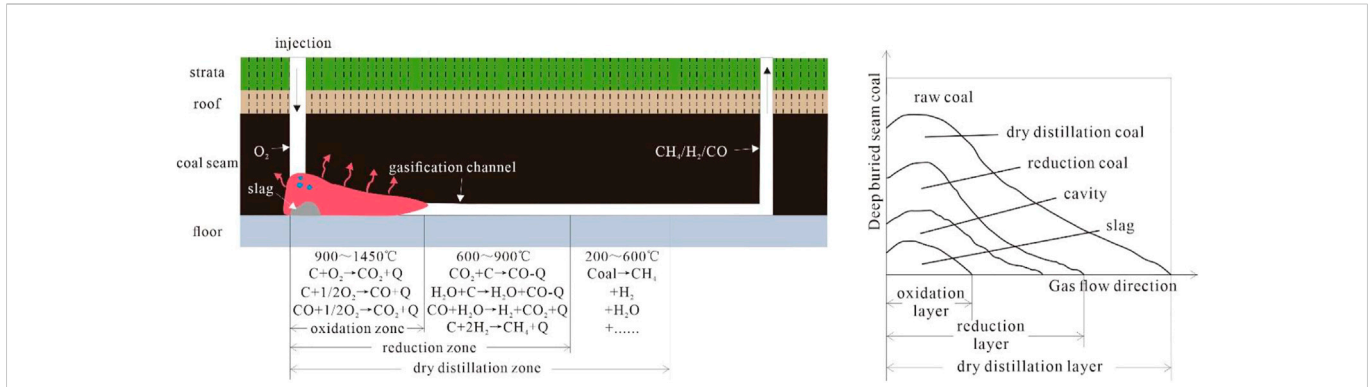


FIGURE 2
Principles of UCG and the gasification reaction zone diagram.

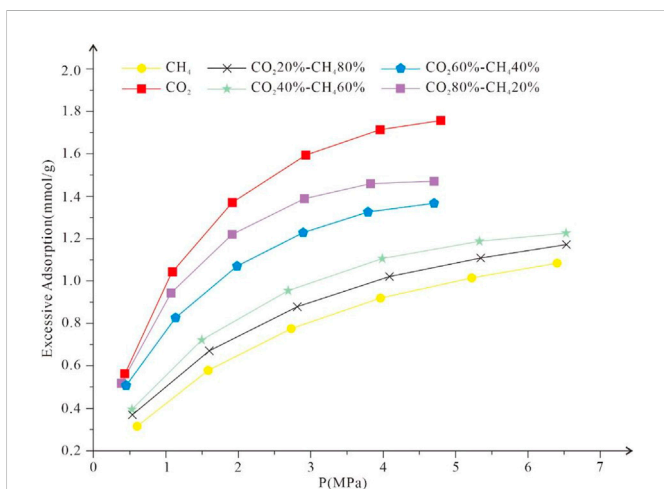


FIGURE 3
Curves of gas isothermal adsorption on coal.

or raw materials after ground classification, such as natural gas for power generation, carbon monoxide, and hydrogen for synthetic ethanol. UCG is a relatively new technology for the clean utilization of coal and the production of chemical raw materials (Blinderman, 2017; Perkins, 2018). UCG has a high coal recovery rate (up to 85%) and can be generated at a low economic cost. It also has a limited environmental impact with almost no groundwater pollution risk. Since it is an unstuffed form of underground coal mining, it has a higher worker safety performance, especially for some thin coal seams, deep high gas coal seams, abandoned coal seams, and marginal unminable coal seams. However, its application can be restricted by the coal quality, hydrogeology, and other limitations (Qin et al., 2019).

The ash content of the slag in the oxidation zone is 94.9%, with a small amount of unburned carbon after UCG (Ma, et al., 2019). The volatile content of the residue in the reduction zone is lower than that of the residue in the dry distillation zone, and the fixed carbon content is slightly higher than that in the dry distillation zone. From the temperature and the reaction of the coal seam, the coal seam first undergoes drying and distillation and then undergoes gasification at a

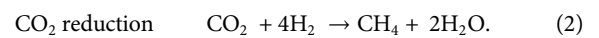
higher temperature, making the volatile content of the residual in the reduction zone lower and the fixed carbon content higher. The results show that the residues in the reduction zone and the dry distillation zone contain a small amount of O and S atoms.

Principle of CO₂ sequestration and enhanced coalbed methane (CO₂-ECBM) recovery

Decades ago, researchers found significant differences in the adsorption capacities of gases in coal and shale (Figure 3). Generally, CO₂ absorbs better on coal and shale than methane under the same conditions (Liu et al., 2010). Therefore, scientists proposed simultaneous CO₂ sequestration and enhanced CBM and shale gas recovery in the same geological formation. Later, due to the demand for greenhouse gas emission reduction, CO₂ sequestration in coal measure strata and enhanced coal measure gas recovery were favored.

Principles of biogas and coal bioconversion (CB)

Biogas is generated by microbial fermentation of organic substances under anaerobic conditions. Biogas is generally generated in marshy areas. People often see marshes, sewage ditches, or cesspools emitting biogas bubbles. During biogas generation, human and livestock manure, straw, sewage, and other organic substances are fermented under anaerobic (oxygen-free) conditions in a closed biogas tank, where biogas fermentation microorganisms decompose and transform the organic material to biogas. Methanation of the organic substrates under anaerobic conditions is thought to occur in four generally accepted stages (Figure 4). The pathways of biogas are acetic acid fermentation and CO₂ reduction:



Coal measure gas is an unconventional natural gas. There are two types of coal measure gas: thermal and biological. Biogenic coal measure gas, similar to biogas, is formed through the synergic degradation of organic matter by microbial communities in a coal

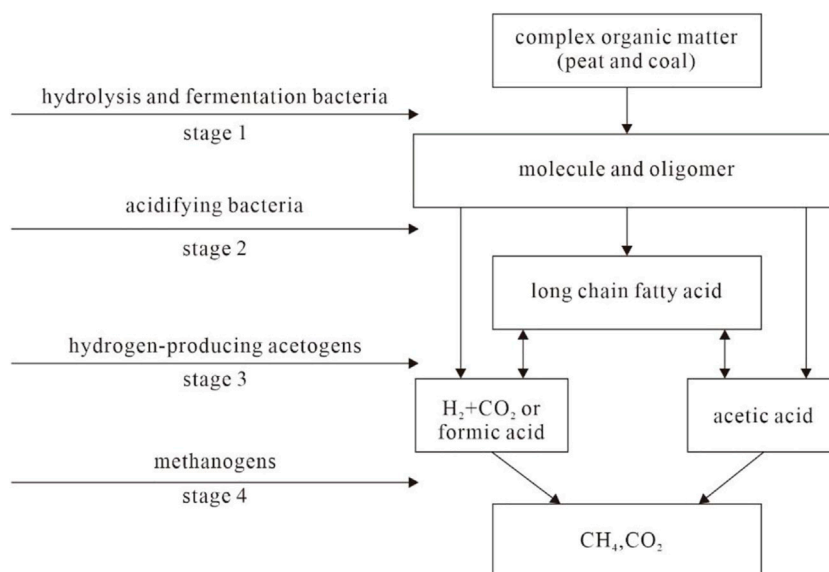


FIGURE 4
Four stages of organic substrate methanation under anaerobic conditions.

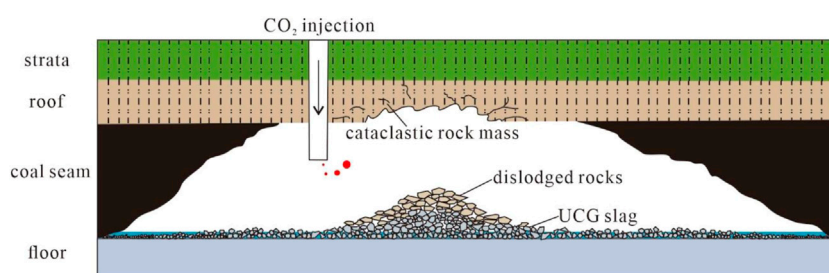


FIGURE 5
Schematic diagram of CO₂ sequestration in the UCG space.

seam. Due to the theory of biogenesis, coal bioconversion has been receiving more attention as a clean coal utilization technology (Zhang et al., 2017; Zhao et al., 2022).

3 Integration of technologies and their applications

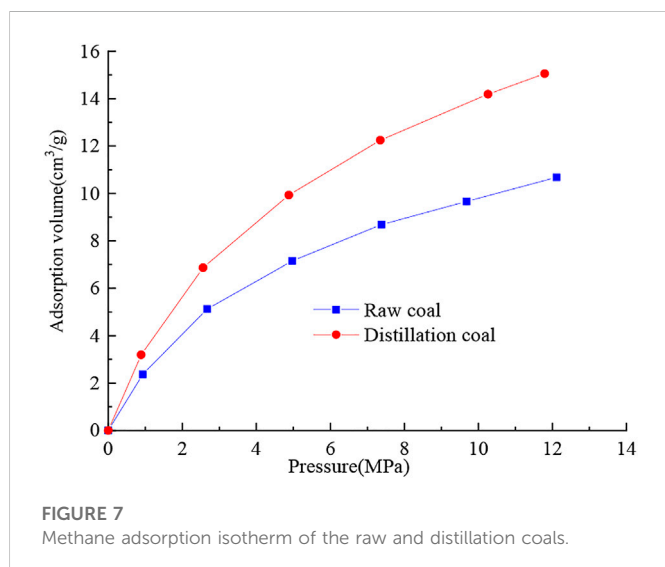
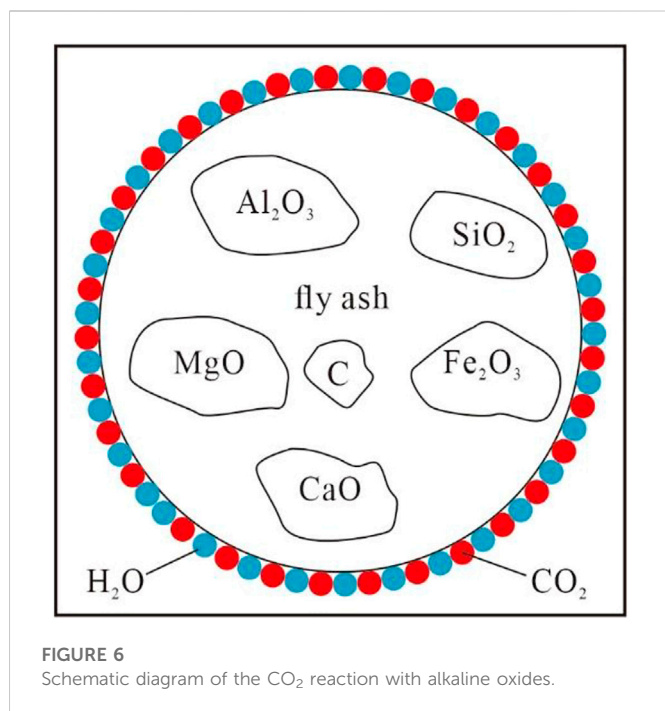
The energy composition and carbon neutralization target in China requires that coal measure energy should be produced effectively, with low carbon emissions, and that the reservoir space should be utilized effectively. Therefore, several integrated technologies were proposed to exploit coal measure energy and efficiently use the reservoir space.

3.1 Coal mining and reservoir space utilization

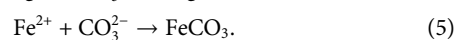
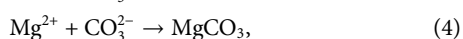
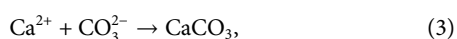
With continuous economic development, China's demand for energy is on the rise. Most of the easily exploitable shallow coal

seams have already been mined out. Traditional deep coal seam mining methods not only increase energy consumption and pollute the environment but also have a low recovery rate. After mining, it is difficult to use the residual coal reservoir space. Efficient technology is urgently needed to mine underground coal and ensure the rational utilization of the mined reservoir space to reduce disasters caused by surface subsidence. Therefore, we propose a technology that integrates UCG and CCS. In this integrated technology, combustible gas is provided by UCG, after which CO₂ is captured and sequestered in the residual UCG reservoir space.

Previous studies show that the coal reservoir space consists of UCG slag, the cavity, reduction coal, dry distillation coal, and raw coal after UCG, distributed outward along the gasification channel after UCG was implemented (Figure 5). There are significant differences in the material composition of the gasification slag in the three zones (Akbarzadeh & Chalatrnyk, 2014; Bhaskaran et al., 2015; Howaniec, 2016; Liu et al., 2018). As shown in Figure 2, Oxidation zone, reduction zone and dry distillation zone. These factors cause significant differences in the CO₂ sequestration paths of the three zones of the



UCG space. Slag is mainly composed of alkaline oxides, silica, and a small amount of residue carbon. This means that CO₂ sequestration on the slag surface occurs mainly *via* chemical reactions and/or CO₂ adsorption on residual carbon (Figure 6). The chemical reactions that sequester CO₂ are as follows:



The substances in dry distillation coal are dominated by organic matter and a small amount of morphologically transformed minerals. After high-temperature baking during coal gasification, dry distillation coal has a stronger gas adsorption capacity than raw coal and can, therefore, sequester more CO₂ (Figure 7). The composition of

reduced coal is between that of slag and dry distillation coal. CO₂ sequestration in dry distillation coal mainly occurs *via* adsorption and mineralization.

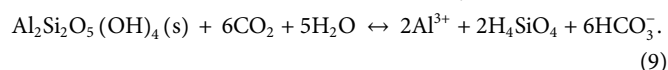
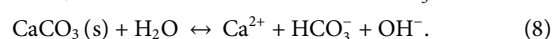
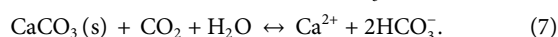
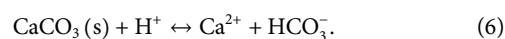
The integrated technology of UCG and CCS is efficient for mining coal resources, and the UCG space can also be used effectively while at the same time providing a new pathway for geological CO₂ sequestration.

3.2 Coal measure gas production and its reservoir space utilization

Coal measure gas recovery is limited because the coal measure reservoirs have the “three low” (low pressure, low permeability, and low saturation) characteristics. Many researchers have suggested CO₂-enhanced coalbed methane recovery to make up for the defect of the reservoir and to reduce CO₂ atmospheric emissions during peak CO₂ emissions (Clarkson & Bustin, 2000; Mukherjee & Misra, 2018). The integrated technology that we suggest is simultaneous coal measure gas production and CO₂ sequestration. A schematic of this integrated technology is shown in Figure 8.

Thermodynamic calculations indicate that the maximum density of CO₂ is 500–700 kg/m³ under the reservoir temperature and pressures characteristic of a depth of 800–1000 m (Orr, 2009). Supercritical carbon dioxide (SC-CO₂) has both acidic and supercritical solvent characteristics. Therefore, it is both easy to have a series of complex interactions between SC-CO₂ and some inorganic minerals and to extract small organic molecular substances from the coal, which changes its pore structure, adsorption, and permeability.

A weak acidic system is formed after CO₂ has been injected into the coal measure strata. Under these conditions, carbonate minerals (such as calcite, siderite, and dolomite) in coal are prone to dissolution, precipitation, and carbonation, while clay minerals may undergo carbonation (Chen & Qin, 2012; Harvey et al., 2013; Du et al., 2018). The chemical reactions for the carbonate mineral dissolution are as follows:



The interaction between the CO₂ and the carbonate and clay minerals affects the pore structure, adsorption capacity, and permeability of coal measure reservoirs, which in turn affects the CO₂ injectability, sequestration capacity, and stability during the processing of enhanced coal measure gas recovery and CO₂ sequestration (Chen & Qin, 2012). The interaction between the CO₂ and carbonate minerals and/or clay minerals enlarges the pore size and increases the number of pores, which increases the pores' special surface and increases the methane adsorption ability (Chen et al., 2017a). Carbonate minerals (calcite, dolomite, etc.) dissolved after the reaction of CO₂-H₂O increase the permeability of the coal seam (Zhang et al., 2015).

Previous studies have shown that supercritical CO₂ extracted small and medium molecular substances that change the physical properties of coal, especially its adsorption and permeability characteristics. The

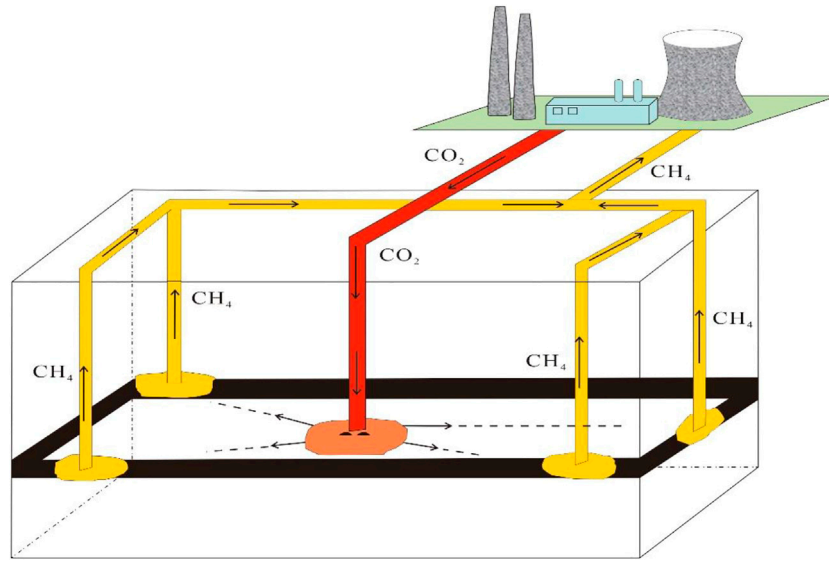


FIGURE 8
Schematic diagram of CO₂ sequestration and enhanced coal measure gas recovery.

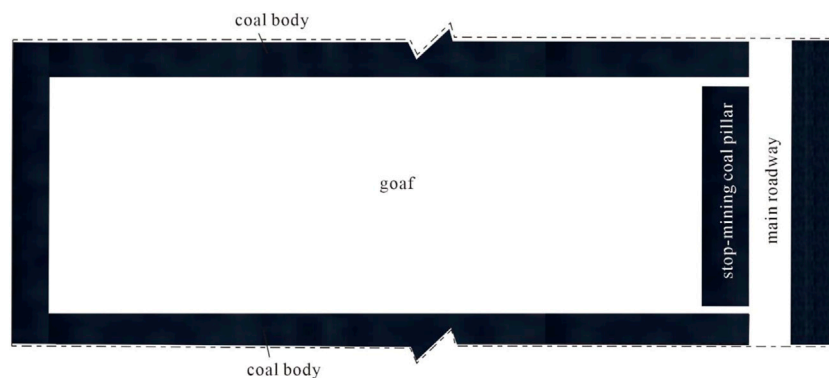


FIGURE 9
Schematic diagram of the coal goaf.

adsorption of coal was enhanced at the low-rank stage and weakened at the high-rank stage, which generally enhanced the recovery of coal measure gas and improved CO₂ geological sequestration (Chen et al., 2017b; Chen et al., 2018).

These studies have proved that CO₂-ECBM is an important extraction method to improve coal measure gas production, reduce CO₂ atmospheric emissions, and effectively utilize the coal measure reservoir space.

3.3 Gas production and the utilization of the coal goaf space and abandoned coal mine space

Previous studies have identified the presence of large volumes of coal measure gas in coal goafs and abandoned coal mines (Han, 2003; Meng et al., 2016). Coal mining in these strata can easily crack and collapse the

overlying strata (Wang et al., 2022). Random stacking of coal gangue and disposal of domestic garbage cause land waste and environmental pollution (Wang, 2006; Jin et al., 2014). An integrated technology of gas production (GP), waste filling (WF), coal bioconversion (CB), and CO₂ sequestration, based on the principles of biogas and biogenic coal measure gas, is proposed for the coal goafs and abandoned coal mines.

This paper uses the coal goaf as an example to illustrate the coal measure energy production and its reservoir space utilization. First, pipes are laid in the roof strata of the coal goaf for grouting and gas extraction after mining the coal. Figure 9 shows a schematic diagram of the coal goaf. Second, the coal goaf is infilled with solid wastes such as coal, gangue, and domestic garbage. Third, the coal goaf is closed to inject a solution of microorganisms and nutrients into the goaf. Fourth, CO₂ is injected into the coal goaf after a period of gas extraction to sequester the CO₂.

The feasibility of the integrated technology has been confirmed by research studies. After mining the coal seam, coal measure gas

accumulates in the coal goaf through the micro-fissures due to induced pressure differences caused by the mining disturbance (Liu, 2011; Sun, 2014; Yin et al., 2014; Wang et al., 2022). After filling the goaf with domestic garbage and gangue, the coal goaf space is used effectively with WF, and the organic matter in the domestic garbage, the gangue, and the coal is bioconverted to gas by the microorganisms under the anerobic conditions in the goaf (Lin et al., 2006; Rathi et al., 2015; Ritter et al., 2015). Accumulated and bio-converted gases provide sufficient gas resources for extraction. Meanwhile, the mesopore-specific surface area and the pore volume are decreased after coal-gangue-domestic garbage bioconversion, while the micropore-specific surface area increases as the pore volume decreases. After bioconversion, the gas adsorption capacities are increased (Zhang et al., 2017; Wang et al., 2021), which means that the residues can sequester more CO₂ in the goaf. The changes in the pore structure and gas adsorption enhance both CO₂ sequestration in the coal measure strata and coal measure gas recovery. Therefore, the WF-CB-GP-CCS technology is suitable for energy production and reservoir space utilization in coal goafs and abandoned coal mines.

4 Conclusion

The principles of UCG, CO₂-ECBM, biogas generation and CO₂ sequestration are used against the background of carbon neutrality that integrates the concepts of coal measure energy production and reservoir space utilization. This study found that 1) the integrated UCG-CCS technology can ensure better energy exploitation and reservoir space utilization in minable coal seams. 2) The integrated CO₂-ECBM is especially appropriate for coal measure gas exploitation and reservoir space utilization in unminable coal seams. 3) The integrated WF-CB-GP-CCS technology can be adopted for both energy production and effective reservoir space utilization in coal goafs and abandoned coal mines. These integrated technologies will become an important tool for coal measure energy production and reservoir space utilization and provide scientific theory and technical support for achieving the carbon neutrality target.

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Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

RC and FC designed the facilities; YB, FL, KH, and YZ compiled the data and plotted the graphs; RC and FC wrote original draft and reviewed; RC provided feedback to the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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