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Potential assessment of CO_2 source/sink and its matching research during CCS process of deep unworkable seam

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It is of great significance for the engineering popularization of CO_2-ECBM technology to evaluate the potential of CCUS source and sink and study the matching of pipeline network of deep unworkable seam. In this study, the deep unworkable seam was taken as the research object. Firstly, the evaluation method of CO_2 storage potential in deep unworkable seam was discussed. Secondly, the CO_2 storage potential was analyzed. Then, the matching research of CO_2 source and sink was carried out, and the pipe network design was optimized. Finally, suggestions for the design of pipe network are put forward from the perspective of time and space scale. The results show that the average annual CO_2 emissions of coal-fired power plants vary greatly, and the total emissions are 58.76 million tons. The CO_2 storage potential in deep unworkable seam is huge with a total amount of 762 million tons, which can store CO_2 for 12.97 years. During the 10-year period, the deep unworkable seam can store 587.6 million tons of CO_2, and the cumulative length of pipeline is 251.61 km with requiring a cumulative capital of \$ 4.26×10^{10}. In the process of CO_2 source-sink matching, the cumulative saving mileage of carbon sink is 98.75 km, and the cumulative saving cost is \$ 25.669 billion with accounting for 39.25% and 60.26% of the total mileage and cost, respectively. Based on the three-step approach, the whole line of CO_2 source and sink in Huainan coalfield can be completed by stages and regions, and all CO_2 transportation and storage can be realized. CO_2 pipelines include gas collection and distribution branch lines, intra-regional trunk lines, and interregional trunk lines. Based on the reasonable layout of CO_2 pipelines, a variety of CCS applications can be simultaneously carried out, intra-regional and inter-regional CO_2 transport network demonstrations can be built, and integrated business models of CO_2 transport and storage can be simultaneously built on land and sea. The research results can provide reference for the evaluation of CO_2 sequestration potential of China's coal bases, and lay a foundation for the deployment of CCUS clusters.

Keywords Carbon capture, utilization and storage (CCUS), Source-sink matching model, CO_2 geological storage, Mileage saving method, Deep unworkable seam, Huainan coalfield

CCUS stands for CO_2 Capture, Utilization and Storage[1]. On the one hand, CCUS technology can reduce CO_2 emissions in the atmosphere and reduce the concentration of greenhouse gases[2,3]. On the other hand, it can help industries with CO_2 high-emission achieve low-carbon development and promote economic transformation[4,5]. Therefore, CCUS technology has broad application prospects in the field of global energy and environment. CO_2 emissions from coal are the largest source of carbon emissions in China, and it will take a long time for China to transform its energy situation[6,7]. Therefore, based on CCUS technology, it is of profound significance to reduce CO_2 emissions from coal, and can promote the realization of China's dual-carbon strategy.

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CO_2 geological sequestration, a core component of CCUS, is an effective way to achieve large-scale de-carbonization[8,9]. Scientific evaluation of CO_2 storage potential in sedimentary basin and realization of source-sink matching are the basis of CCUS cluster deployment[10,11]. Major sedimentary basin in China have great potential for CO_2 storage, and the storage forms are diverse[12]. However, due to the lack of unified methods for CO_2 storage potential in sedimentary basin in China, the assessment of CO_2 storage potential greatly varies[13]. The CO_2 sequestration potential of geological body in China, such as oil and gas fields, deep unrecoverable seam, production and closed mines and goaf areas, is unclear and needs to be evaluated in detail.

Carbon emission sources in China's coal base are concentrated, and CO_2 emission sources and CO_2 storage sinks are highly overlapping[14], which provides favorable conditions for CCUS cluster deployment. CCUS technology is the only way for coal base to achieve near zero for CO_2 emission in the future, and the deployment of "Coal base + CCUS" cluster has scale and agglomeration effects[15]. The geographical proximity of CO_2 sources and sinks can save more costs for CO_2 transportation, and the geographical concentration of a large number of CO_2 sources and sinks is also conducive to large-scale and clustered layout engineering practices. Geological body, such as deep unrecoverable seam, is the most typical forms of CO_2 storage in coal bases[16,17]. However, its CO_2 geological storage is still in the exploration stage, and there are few studies on its CO_2 storage potential[18]. Therefore, it is necessary to establish potential assessment methods suitable for the characteristics of China's coal bases.

The CO_2 sequestration process can be simplified as the reverse process of the CBM extraction process, and its core mechanism is the dynamic process of CO_2 adsorption and displacement of CBM[19,20]. Therefore, the mechanism of CO_2 geological storage in unworkable seam is mainly about the mechanism of CO_2 adsorption and desorption in coal seam[21]. The coal resource in Huainan and Huaibei coalfields account for 97.7% of the total resources in the province, and the distribution is concentrated[22–24]. Therefore, the Huainan coalfield is determined as the estimation coalfield for CO_2 storage in this study. Due to the limitation of technical and geological conditions, the buried depth of coal mining in Anhui province is limited to less than 1000 m at present stage, and the coal seam with 1000–2000 m is the resource amount, which will be exploited in the next stage, and belongs to the deep unworkable seam at the present stage[16], that is, the geological reserves with burial depth of 1000–2000 m are used to estimate the CO_2 storage potential in Anhui province.

In this study, the deep unworkable seam in Huainan coalfield was taken as the research object. Firstly, the evaluation method of CO_2 storage potential in deep unworkable seam was discussed. Secondly, the CO_2 geological storage potential was analyzed. Then, based on the lowest cost objective function and improved mileage saving method, the matching research of CO_2 source and sink for CO_2 geological storage was carried out, and the pipe network design was optimized. Finally, from the perspective of time and space scale, suggestions on the design of network planning of CCS source and sink are put forward in Huainan coalfield. The research innovations are described as follows: (1) Evaluation method of CO_2 storage potential in deep unworkable seam is discussed; (2) Matching problem of CO_2 source and sink is studied, and its pipe network design is optimized; (3) Design idea of network planning of CCS source and sink is systematically proposed. The results can provide reference for the evaluation of CO_2 sequestration potential of coal bases in China, and lay a foundation for CCUS cluster deployment.

Geological setting and analysis method

Geological background of the study area

Based on regional structural analysis, the Huainan coalfield is located at the southern margin of North China Plate. In the west–east direction, the coal field boundary lies between the Kouziji-Nanzhaoji faults and the Xinchengkou-Changfeng faults. From north to south, the coalfield boundary lies between the Shangtangming-Longshan faults and Yingshang-Dingyuan faults (Fig. 1)[25,26]. The coalfield is a near east–west hedge tectonic basin with imbricate fan composed of nappe structures on both sides of the basin and simple synclinic structure in the interior (Fig. 1).

The coal-bearing strata are Taiyuan formation of upper Carboniferous series, Shanxi formation and Xiashihezi formation of lower Permian series, and Shangshihezi formation of upper Permian series, with a total thickness of about 900 m and about 40 layers of coal seams[27,28]. In the coal-bearing strata, there are 9–18 coal layers with a single layer thickness greater than 0.7 m on average, the maximum thickness is 12 m, and the total thickness is 23–36 m, which are distributed in Shanxi formation, Xiashihezi formation and lower part of Shangshihezi formation. In this study, the CO_2 emission sources were 10 coal-fired power plants in the coalfield with numbered D1-D10, respectively. Deep unworkable seams are CO_2 storage sinks, which are bounded by faults and numbered B1-B15, respectively (Fig. 1).

Evaluation method of CO_2 geological storage potential

In deep unworkable seam, CO_2 geological storage is mainly in adsorbed, dissolved and free states[29], and adsorption storage is the main storage form of coal seam[30]. Considering the storage differences of different phase of CO_2, the following potential assessment model of CO_2 storage can be adopted[16,31]:

$$M_{CO_2} = 0.001\rho_{CO_2}M_{Coal}(m_{ab} + m_d + m_f) \tag{1}$$

where M_{CO_2} is CO_2 storage capacity, t; ρ_{CO2} is the CO_2 density, kg/m^3; M_{coal} is proved coal reserves, t; m_{ab}, m_d and m_f are the stored quantity of CO_2 adsorbed, dissolved and free states in coal per unit mass, m^3/t.

In the unit mass coal, the storage potential of CO_2 adsorbed state in deep unworkable seam can be characterized by the following formula[16,31]:

$$m_{ab} = m_{ex}/(1 - pT_c/8Zp_cT) \tag{2}$$

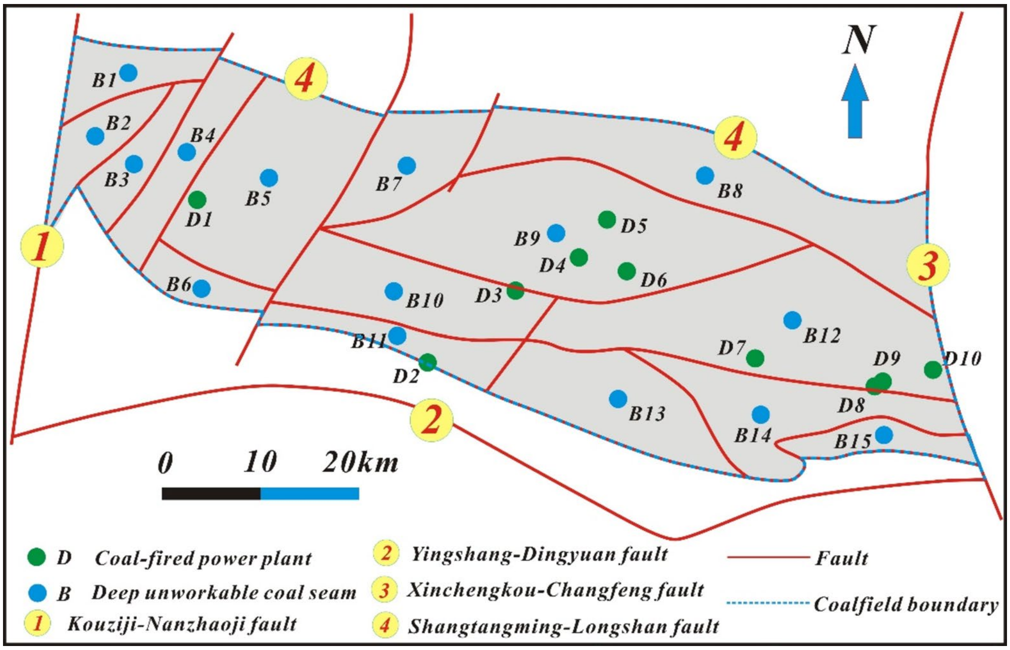

Figure 1. Geological background of Huainan coalfield and distribution of CO_2 source-sink geological points in deep unrecoverable coal seams.

where P is the reservoir pressure, which is also CO_2 adsorption pressure, MPa; T_c is CO_2 critical temperature, K; Z is the CO_2 compression coefficient; p_c is CO_2 critical pressure, MPa; T is the reservoir temperature, which also CO_2 adsorption temperature, K; and m_{ex} is the CO_2 excess adsorption amount per unit mass of coal, m^3/t, which can be calculated using the following D-R adsorption model[16,31]:

$$m_{ex} = m_0(1 - \rho_f/\rho_a)e^{-D\left[\ln(\rho_a/\rho_f)\right]^2} + k\rho_f \quad (3)$$

where m_0 is the maximum CO_2 adsorption capacity of coal per unit mass tested by adsorption experiment, m^3/t; ρ_f and ρ_a are the densities of free and adsorbed CO_2 under the real temperature and pressure conditions, kg/m^3; D is the adsorption constant, and k is the constant associated with Henry's Law.

In coal reservoir, CO_2 density is a function of pressure and temperature, which can be expressed as $\rho_f = f(p, T)$, and can be further characterized as follows[16,31,32]:

$$\rho_g = p/((1 + \delta\phi_\delta^\tau) \cdot RT) \quad (4)$$

where $\delta = \rho_c/\rho_f$ is the CO_2 reduced density; ρ_c is the CO_2 critical density, kg/m^3; $\tau = T_c/T$ is the reduced temperature; and $\phi(\delta,\tau)$ is the Helmholtz free energy, which can be controlled by temperature and density[16,31,32]:

$$\phi(\delta,\tau) = \phi^0(\delta,\tau) + \phi^r(\delta,\tau) \quad (5)$$

where $\phi^o(\delta, \tau)$ is the Helmholtz free energy of ideal fluid, and $\phi^r(\delta, \tau)$ is the Helmholtz free energy of the residual fluid.

In deep unworkable seam, the storage potential of dissolved CO_2 per unit mass of coal is a function of coal porosity, water saturation, coal density and CO_2 solubility, which can be characterized as follows[16,31]:

$$m_d = 1000 \cdot \varphi S_w S_{CO_2}/\rho_{Coal} \quad (6)$$

where φ is the coal porosity, %; S_w is the water saturation, %; S_{CO_2} is the CO_2 solubility, and ρ_{coal} is the coal density, kg/m^3.

According to Boyle-Mariotte law, the free CO_2 storage potential per unit mass of coal in deep unworkable seam can be characterized as follows[16,31]:

$$m_f = 1000 \cdot \varphi S_g p T_0/(\rho_{visual} Z p_0 T) \quad (7)$$

where S_g is the gas saturation, %; P_0 is the standard atmospheric pressure, MPa; T_0 is the temperature under the standard condition, K; and ρ_{visual} is the coal apparent density, kg/m^3.

Construction of matching model of CO_2 source-sink

CO_2 source and sink matching

CO_2 source-sink matching is the basis of CCUS cluster deployment and its pipe network design and construction, with the goal of minimizing CO_2 transportation cost and maximizing carbon removal. Its essence is the optimization planning of CCUS cluster system[33,34]. Based on CO_2 emission source, storage sink, storage geological process, transport network connecting source and sink and corresponding parameter data, the dynamic optimal matching between CO_2 source and sink can be achieved in terms of target quantity, continuity and economic efficiency (Fig. 2).

The matching of CO_2 source and sink is mainly based on the characteristics of large number, different types and scattered locations of CO_2 emission sources (i.e., thermal power, steel, cement, chemical industry, etc.) and storage sinks (i.e., saltwater layer, CO_2-ECBM, CO_2-EOR, MCO_2-ILU, CO_2-SDR, etc.). Based on the discussion of constraint conditions and determination of objective function, the influence of regional geographical conditions, traffic, population density, transportation cost and transportation mode on CO_2 transport between emission sources and storage sinks is fully considered in the CCUS system. The optimal matching of CO_2 emission sources, storage sinks and transportation parameters was realized, so as to determine scientific and reasonable CO_2 source and sink matching schemes (Fig. 2).

Objective functions

Based on the theory of network analysis in operations research, theoretical models of CO_2 source-sink matching within CCUS technology can be constructed in Huainan coalfield by using the minimum support tree method. The construction of theoretical models should meet the following basic assumptions: (1) Source and sink with the lowest cost should be firstly matched; (2) Allow the matching of one source with multi sinks or one sink with multi sources; (3) Sequestration sink must meet the requirement of CCUS planning period.

In this study, the lowest total cost of matching of CO_2 source-sink in CCS technology is taken as the objective function, namely:

$$COST_{\min} = \sum_{i=1}^{m}\sum_{j=1}^{n}(C_C + C_T + C_S) \tag{8}$$

where i refers to the ith CO_2 source; j means the jth CO_2 sink; m indicates the number of CO_2 sources and the value is 10, and n indicates the number of CO_2 sinks with the value of 15.

(1) CO_2 capture cost (i.e., C_C)

Based on the analysis of the industrial sources report published by the National Energy Technology Laboratory of the United States, the average capture cost of CO_2 source in coal-fired power plants is \$ 64.35 /t[30,35]. Therefore, the capture cost of CO_2 source in Huainan coalfield can be characterized as follows:

$$C_C = \sum_{i=1}^{m}\sum_{j=1}^{n}\omega_{ij}X_{ij} \tag{9}$$

whereω_{ij} represents the CO_2 capture cost in the i coal-fired power plant, \$/t; and X_{ij} represents CO_2 transport amount from the i coal-fired power plant to the j sequestration sink, t.

(2) CO_2 transportation cost (i.e., C_T)

CO_2 transport is most common by pipeline, ship and tanker, and pipeline transportation is suitable for directional transportation with large capacity, long distance and stable load, which mainly includes construction cost and operation and maintenance cost. The operation and maintenance cost accounts for about 1.5% of the construction cost[35], which can be calculated according to formula 10 and 11, respectively.

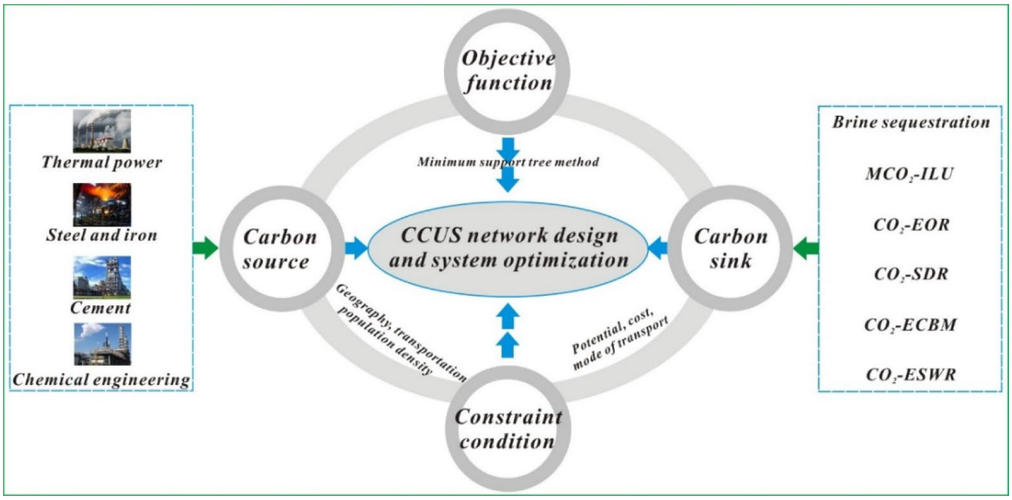

Figure 2. Schematic diagram of connotation of CO_2 source and sink matching.

$$C_{T-j} = 9970 \times \sum_{i=1}^{m}\sum_{j=1}^{n} L^{1.13}X_{ij}^{0.35} \tag{10}$$

where L is the distance of pipeline transportation, km.

$$C_{T-y} = 0.015N \times 9970 \times \sum_{i=1}^{m}\sum_{j=1}^{n} L^{1.13}X_{ij}^{0.35} \tag{11}$$

where N represents the transportation cycle of the pipeline, year.

Therefore, CO_2 transport cost can be characterized as follows:

$$C_T = (1 + 0.015N) \times 9970 \times \sum_{i=1}^{m}\sum_{j=1}^{n} L^{1.13}X_{ij}^{0.35} \tag{12}$$

(3) CO_2 sequestration cost (i.e., C_S)

The cost of CO_2 geological storage is closely related to the amount of CO_2 storage and the type of storage site, and the average storage cost coefficient is \$ 5.59 /t[30,35]. Therefore, the cost of CO_2 geological storage in coal reservoir can be characterized as follows:

$$C_S = \sum_{i=1}^{m}\sum_{j=1}^{n} \varepsilon_{ij}X_{ij} \tag{13}$$

whereε_{ij} is the sequestration cost factor of transporting CO_2 from coal-fired power plant i to sequestration sink j, \$/t.

In summary, by substituting formulas (9), (12) and (13) into formula (8), the minimum objective function of total cost of CO_2 source-sink matching in CCS technology can be obtained:

$$MinZ = \sum_{i=1}^{m}\sum_{j=1}^{n} (\omega_{ij}X_{ij} + (1 + 0.015N) \times 9970 \times L^{1.13}X_{ij}^{0.35} + \varepsilon_{ij}X_{ij}) \tag{14}$$

Constraint conditions

Based on the basic assumptions of theoretical model, in the planning process of matching pipe network of CO_2 source-sink with CCS technology, the constraint conditions of the lowest total cost objective function are as follows:

(1) The total amount of CO_2 captured from all CO_2 emission sources is equal to the total amount of pipeline transport, that is:

$$a_i = \sum_{j=1}^{n} X_{ij} \tag{15}$$

where a_i is the CO_2 capture amount of the ${}^{i}th$ coal-fired power plant.

(2) The CO_2 content transported by the pipeline to the storage site shall not exceed the storage capacity of the storage sink, that is:

$$b_j \geq \sum_{i=1}^{m} X_{ij} \tag{16}$$

where b_j is the storage capacity of the j^{th} storage sink.

(3) The amount of CO_2 captured in all coal-fired power plants must not exceed the total capacity of all potential sequestration sinks, that is:

$$\sum_{i=1}^{m} a_i \leq \sum_{j=1}^{n} b_j \tag{17}$$

(4) Non-negative constraint: the pipeline of CO_2 transport content is non-negative, that is:

$$X_{ij} > 0 \tag{18}$$

Optimization of matching pipe network of CO_2 source-sink

The core idea of the mileage saving algorithm is to merge two transportation loops into one loop to reduce the transportation distance in the merging process, and keep cycling until the limit condition is reached, thus reducing the transportation cost. Specifically, three points, A, B and C, transport goods from A to B and C, where the distance from A to B is L_{AB} (unit: km), the distance from A to C is L_{AC} (unit: km), and the distance from B to C is L_{BC} (unit: km), if the transportation from A to B and A to C is separately completed, the transportation distance is $2 \times (L_{AB} + L_{AC})$ with including the round trip process (Fig. 3a). If from A to B, then from B to C, and finally from C back to A, then the transport distance is $L_{AB} + L_{AC} + L_{BC}$ (Fig. 3a), then the distance saved is $2 \times (L_{AB} + L_{AC}) - (L_{AB} + L_{AC} + L_{BC}) = L_{AB} + L_{AC} - L_{BC} > 0$.

In CO_2 source-sink matching, each sink is taken as the distribution center and distributed with the connected source points. The basic principle is similar to the mileage saving method, except that there is only a transportation network from the source to the sink, and there is no return pipeline. Based on this, the idea of mileage saving method is introduced in this study, and it is improved to meet the needs of CO_2 source-sink matching and transportation network optimization. As shown in Fig. 3b, the CO_2 emitted from points B and C is transported to the storage sink A for storage. The most direct way is from B to A, and then from C to A, with a transport distance of $L_{AB} + L_{AC}$ (Fig. 3b). If it is transported from B to C and then from C to A or from C to B and then from B to A (Fig. 3b), the transport distance is $L_{AC} + L_{BC}$ or $L_{AB} + L_{BC}$. L_{AB} and L_{AC} need to be compared to choose a route with a smaller distance for connection. If $L_{BC} < L_{AB}/L_{AC}$, then L_{AB} (L_{AC}) − L_{BC} is the savings; if $L_{BC} > L_{AB}/L_{AC}$, then $L_{AB}/L_{AC} - L_{BC}$ is negative, which means no savings (Fig. 3b).

Results

CO_2 source and sink characteristics

Characteristics of CO_2 sources

In Huainan coalfield, CO_2 emission sources are 10 coal-fired power plants within the coalfield, of which 9 have been put into operation, 1 has finished commissioning and plans to put into operation. According to the "Greenhouse Gas Emission Accounting Methods and Reporting Guidelines for Chinese Power Generation Enterprises (Trial)" and related methods, the carbon emission intensity of the coal-fired power plants was calculated, and on this basis, the average annual CO_2 emissions of each coal-fired power plant were estimated. The installed capacity of China's coal-fired power plants is mainly 300 WM, 600 WM and 1000 WM, and the CO_2 emission intensity of which is 0.845 t/MW/h, 0.807 t/MW/h and 0.768 t/MW/h, respectively, and in this study, the mean value is taken as the basis for estimation[36,37]. Based on the average annual power generation statistics of each power plant, the average annual CO_2 emissions of each coal-fired power plant can be analyzed (Table 1).

As can be seen from Table 1, the average annual CO_2 emissions of coal-fired power plants vary greatly with ranging from 0.36 million tons to 17.12 million tons. Among them, the average annual CO_2 emissions of D7 power plant reach 17.12 million tons, accounting for about 30% of the total annual CO_2 emissions. The total annual CO_2 emissions of all coal-fired power plants are 58.76 million tons, which includes 5.28 million tons of emissions from the proposed D6 power plant (Table 1).

Assessment of CO_2 sink

The core parameters of potential assessment of CO_2 geological storage are mainly derived from engineering data, test data, experimental data and scientific research papers (Table 2)[16,31,38,39]. In this study, for deep unworkable seam in Huainan coalfield, the proved reserves with burial depth ≤ 1500 m are obtained from coal exploration,

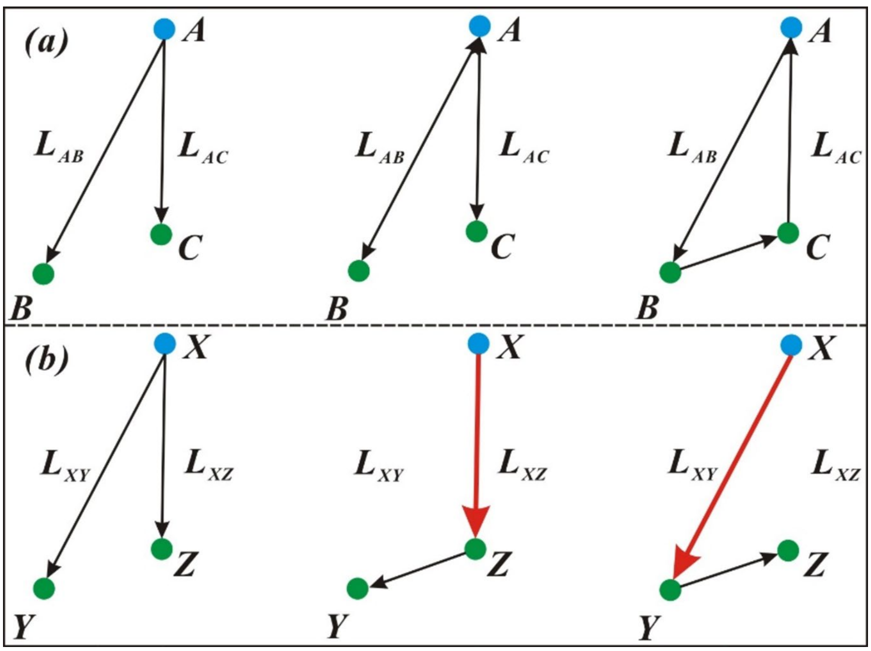

Figure 3. Optimization of CCUS source-sink matching pipe network. (**a**) Traditional mileage saving methods; (**b**) Improvement of the mileage saving method.

Number	Coal-fired power plant	Annual power generation (10^8 kwh)	Average annual CO_2 emissions (10^6 t)
1	D1	102	8.16
2	D2	4.45	0.36
3	D3	96	7.68
4	D4	28.94	2.32
5	D5	73.57	5.89
6	D6	66	5.28
7	D7	214	17.12
8	D8	19.32	1.55
9	D9	60.23	4.82
10	D10	70	5.6
Total		734.51	58.76

Table 1. Estimated average annual CO_2 emissions from 10 coal-fired power plants in Huainan coalfield.

Meaning	Value	Unit	References
Proven reserves with burial depth ≤ 1500 m	1.99×10^9	t	[16,31,38,39]
Proven reserves of coal buried 1500–2000 m	4.03×10^9	t	[16,31,38,39]
Pressure gradient	1.08	MPa/100 m	[16,31,38,39]
Geothermal gradient	3.10	℃/100 m	[16,31,38,39]
Constant temperature zone depth	30.00	m	[16,31,38,39]
Constant temperature zone temperature	298.95	K	[16,31,38,39]
CO_2 critical pressure	7.38	MPa	[16,31,38,39]
CO_2 critical temperature	304.21	K	[16,31,38,39]
Critical density of CO_2	0.45×10^3	kg/m^3	[16,31,38,39]
Maximum adsorption capacity of CO_2 with burial depth ≤ 1500 m	26.36	m^3/t	[16,31,38,39]
Maximum adsorption capacity of CO_2 at the depth of 1500-2000m	21.98	m^3/t	[16,31,38,39]
Coal seam porosity	3.89	%	[16,31,38,39]
Water phase saturation	70.00	%	[16,31,38,39]
Gas phase saturation	60.00	%	[16,31,38,39]
True density of coal seam	1.45	kg/m^3	[16,31,38,39]
Apparent density of coal seam	1.62	kg/m^3	[16,31,38,39]

Table 2. Core parameters of CO_2 geological storage potential assessment.

and the proved reserves with burial depth > 1500 m are predicted reserves by the resource management department. The geothermal gradient is 3.10 °C/100 m. When the depth of coal seam is less than 1000 m, the pressure gradient is 0.95 MPa/100 m. When the depth of coal seam is more than 1000 m, the pressure gradient is 1.08 MPa/100 m[16,31]. The core parameters of CO_2 geological storage potential assessment can be detailed in Table 2[16,31,38,39].

The CO_2 geological storage potential of deep unworkable seam in Huainan coalfield is huge, and the total amount is 762 million tons. The adsorbed, free and dissolved CO_2 can be stored 685 million tons, 53 million tons and 24 million tons, respectively. The CO_2 geological storage with adsorbed state in deep unworkable seam is the most dominant, accounting for 89.895% of the total storage. When the buried depth of coal seam is ≤ 1500 m and > 1500 m, the total CO_2 geological storage is 253 million tons and 510 million tons, with accounting for 33.17% and 66.83% of the total storage, respectively. Regardless of the state in which CO_2 is stored, the total amount of CO_2 stored when the buried depth is greater than 1500 m is greater than that under the same state when the buried depth is less than 1500 m (Table 3).

Burial depth/m	Adsorbed state/10^8 t	Free state/10^8 t	Dissolved state/10^8 t	Storage capacity/10^8 t
1000–1500	2.29	0.16	0.08	2.53
1500–2000	4.57	0.37	0.16	5.10
Total	6.85	0.53	0.24	7.62

Table 3. Evaluation results of CO_2 storage potential in deep unworkable coal seams.

When the buried depth of coal seam is > 1500 m and ≤ 1500 m, the proved coal reserves are 4.03 billion tons and 1.99 billion tons, respectively, with a ratio of 2.025. For the total amount of CO_2 geologic storage and its adsorption, free and dissolved state, the ratio of coal seam buried depth > 1500 m and ≤ 1500 m is 2.016, 1.996, 2.312 and 2.000, respectively. The main reason why the ratio of total CO_2 geological storage and total adsorption state is lower than 2.025 is that although the CO_2 geological storage potential of deep unworkable seam is positively correlated with the proved coal reserves, the maximum CO_2 adsorption capacity at the depth ≤ 1500 m is much higher than that at the depth > 1500 m. With the increase of burial depth, the reservoir pressure gradually increases, and the CO_2 storage potential in free state in pore structure gradually increases, which will make the free CO_2 ratio far greater than 2.025.

Matching characteristics of CO_2 source-sink

Plane distribution characteristics of CO_2 sinks

The total CO_2 storage potential of deep unworkable seam in Huainan coalfield is 762 million tons (Table 3). For the average annual CO_2 emissions of the 10 coal-fired power plants, it can be stored for 12.97 years. The deep unworkable seam is the most potential body for CO_2 storage in Huainan coalfield. The unrecoverable coal seam with buried depth ≤ 1500 m can meet the CO_2 geological storage requirements of coal-fired power plants for 4.31 years. Considering the technical challenges and implementation costs of CO_2 storage in coal seam with different burial depths, the unworkable coal seam with burial depths ≤ 1500 m should be the main target reservoir for the implementation of CO_2-ECBM technology in the next five years.

With fault structure as the boundary, the deep unworkable seam can be divided into 15 CO_2 storage blocks, and the comparative analysis of the plane distribution of CO_2 storage sinks can be carried out according to the plane area size (Fig. 4). The main blocks of CO_2 geological storage are B9, B12, B8 and B5, and their sealable stocks are 124 million tons, 114 million tons, 97 million tons and 85 million tons, respectively, among which the largest two blocks, B9 and B12, can store the CO_2 emissions of 10 coal-fired power plants for nearly four years. The four blocks with larger area are also the main blocks of the CO_2 source-sink matching.

Matching characteristics of CO_2 source-sink

According to the preliminary potential assessment analysis, for the average annual CO_2 emissions of the 10 coal-fired power plants in Huainan coalfield, the deep unworkable seam can be stored for 12.97 years. Therefore, in this study, the matching study of CO_2 source-sink was conducted based on the cumulative CO_2 emissions of 10 coal-fired power plants in Huainan coalfield in 10 years for deep unworkable seam (Fig. 5).

Based on the matching results of CO_2 source and sink during the 10-year cycle in Huainan coalfield, it can be seen that the coal-fired power plant of D1 can be mainly stored in blocks of B2, B3, B4 and B7, with the stored stocks of 20.2 million tons, 19.7 million tons, 30.9 million tons and 10.8 million tons, respectively. Coal-power plant of D2 is mainly stored in block of B5, and the stored stock is 3.6 million tons. The coal-power plant of D3 is mainly stored in blocks of B7 and B10, with a stored stock of 25.8 million tons and 51 million tons, respectively. Coal-fired power plant of D4 is mainly stored in blocks of B8 and B9, with a storage capacity of 10.9 million tons and 12.3 million tons, respectively. Coal-fired power plant of D5 is mainly stored in block of B9, with a stored stock of 58.9 million tons. Coal-fired power plant of D6 is mainly stored in block of B9, and the stored stock is 52.8 million tons. Coal-fired power plant of D7 is mainly stored in blocks of B8, B12 and B14, with stored stocks of 61.1 million tons, 58.3 million tons and 51.8 million tons, respectively. Coal-fired power plant of D8 is mainly stored in block B8, with a stored stock of 15.5 million tons. Coal-fired power plant of D9 is mainly stored in block of B13, and the stored stock is 48.2 million tons. The coal-fired power plant of D10 is mainly stored in block of B12, with a stored stock of 56.0 million tons (Fig. 5). During the 10-year cycle, the CO_2 in deep unworkable seam

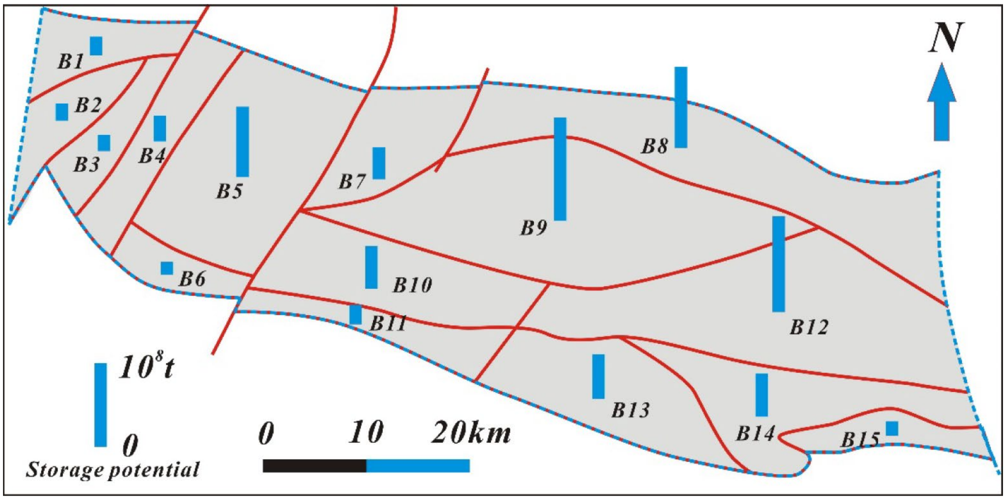

Figure 4. Plane distribution of CO_2 storage sink in unrecoverable coal seams of Huainan coalfield.

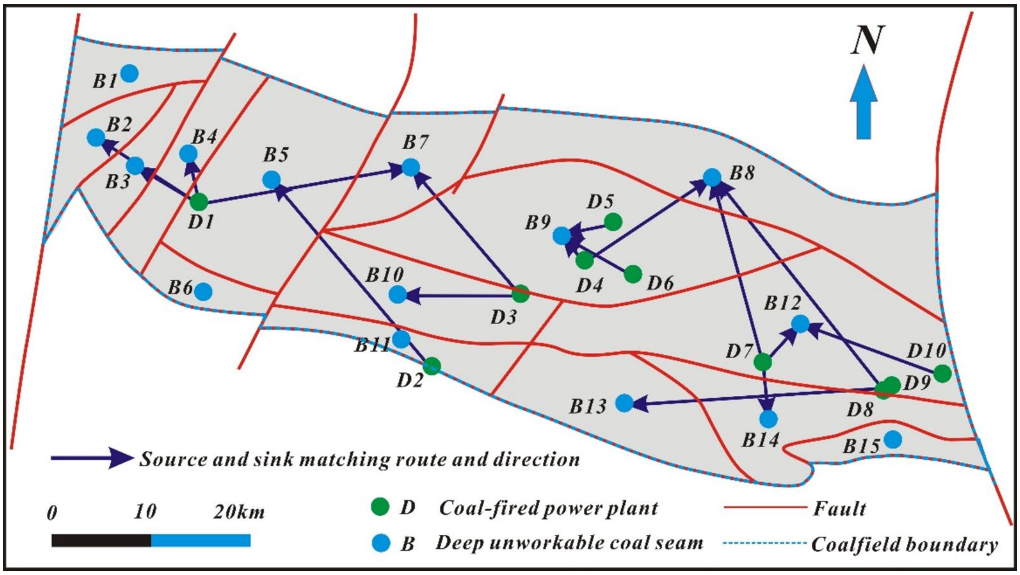

Figure 5. CCS source and sink matching of cumulative CO_2 emissions from 10 coal-fired power plants in Huainan coalfield during the 10-year cycle.

can be stored up to 587.6 million tons, and the cumulative planned pipeline is 251.61 km, which will require a cumulative capital of \$ 4.26×10^{10}.

Discussions

Optimization of matching pipe network of CO_2 source-sink

Analysis of matching pipe network of CO_2 source-sink

Based on the analysis of matching pipe network of CO_2 source-sink in deep unworkable seam, it can be seen that the transportation routes of pipelines of 9, 4, 16, 5 and 8 are relatively long, which accounts for 53.65% of the total transportation route length (Fig. 6). Because the transportation cost is proportional to the route, it is important to optimize the line length of pipelines of 9, 4, 16, 5 and 8 to reduce the total cost.

Based on the analysis of CO_2 storage and transport costs and their proportion in deep unworkable seam, it can be seen that the transport costs of blocks of 8, 7, 12 and 13 are the highest, which accounts for 36.96%,

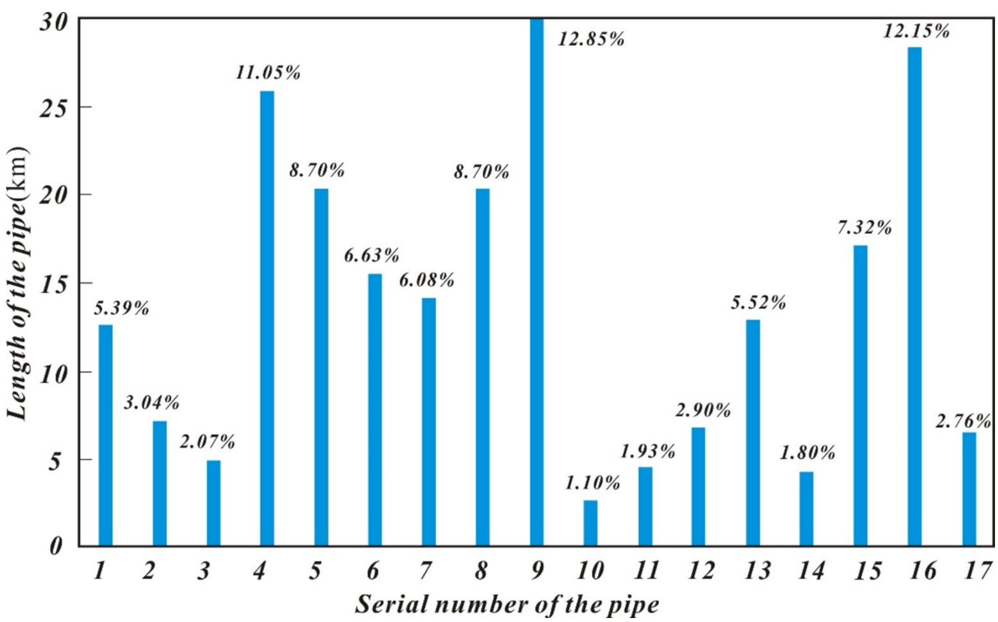

Figure 6. Analysis of the number, length and proportion of CO_2 source-sink matching pipe network in deep unrecoverable coal seams.

14.01%, 11.60% and 11.86% of the total CO_2 storage and transport costs, respectively. The transportation cost of four CO_2 storage sinks accounted for 74.43% of the total cost. Therefore, blocks of 8, 7, 12 and 13 of deep unworkable seam will be the focus of optimization of matching pipe network of CO_2 source-sink. Blocks of 1, 6, 11 and 15 do not need to bear CO_2 geological storage for the time being, which can be used as alternative blocks for CO_2 storage (Figs. 5 and 7).

Optimization of matching pipe network of CO_2 source-sink

Based on the improved mileage saving method, the optimization results of matching pipe network of CO_2 source-sink in deep unworkable seam can be obtained (Fig. 8).The unchanged pipe network paths are D1–B4, D1–B7, D3–B10, D4–B8, D4–B9 and D7–B13 (Fig. 8), and the routes among other source-sink take the minimum total transportation cost as the objective function, and the pipe network optimization is carried out according to the constraints of the emission source and the storage capacity (Fig. 8).

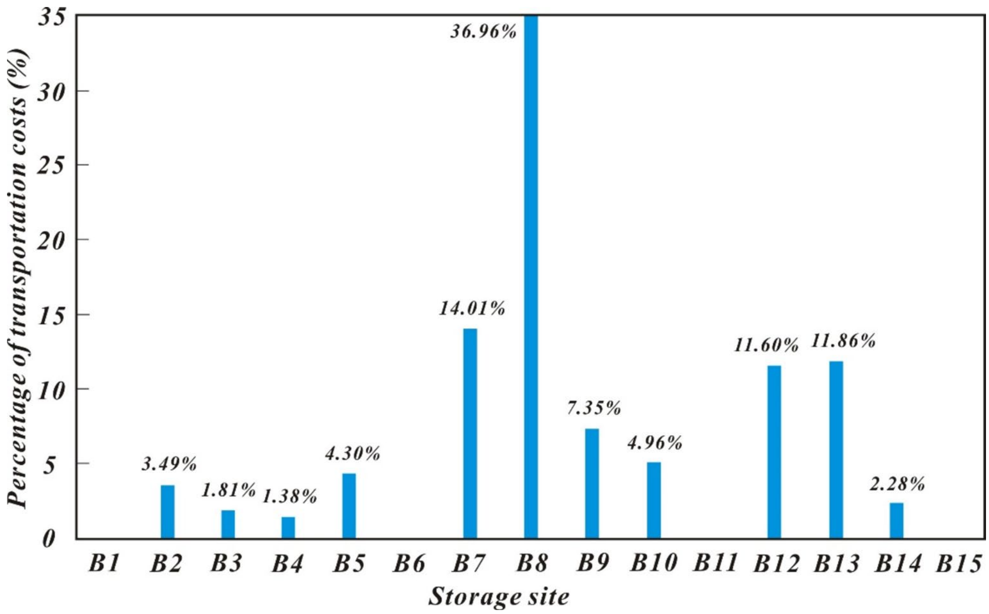

Figure 7. Transportation cost and proportion of CO_2 storage sinks matched by CO_2 source and sink in deep unrecoverable coal seams.

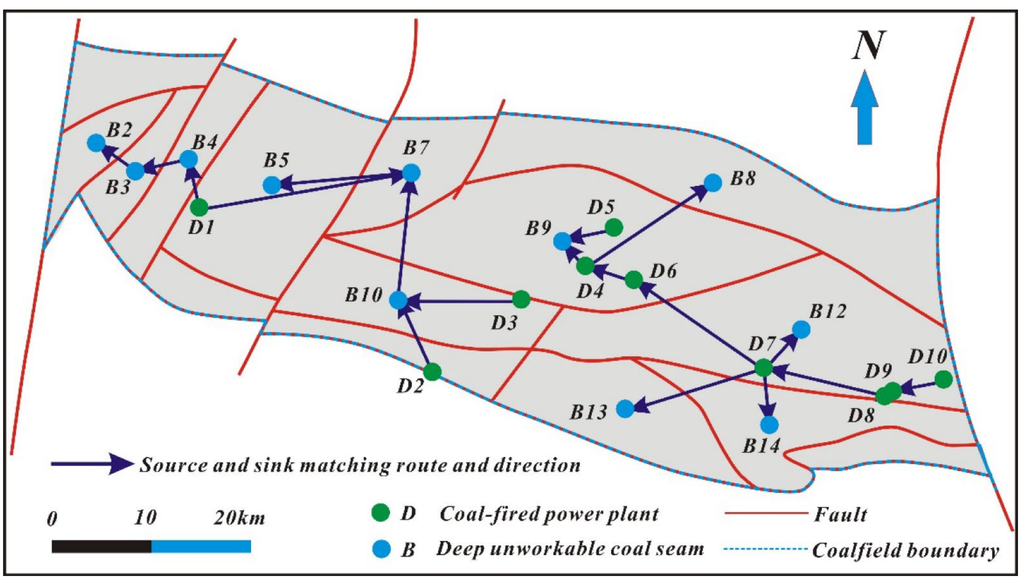

Figure 8. Optimization results of CO_2 source-sink matching pipe network in Huainan coalfield.

Based on the optimization results of matching pipe network of CO_2 source-sink in Huainan coalfield, it can be seen that the accumulated mileage saved is 98.75 km, and the accumulated cost saved is $ 25.669 billion, which accounts for 39.25% and 60.26% of the total mileage and cost of pipeline, respectively (Table 4). Among them, the mileage and cost savings of 13 and 14 blocks in deep unworkable seam are more obvious, which accounts for 10.43% and 10.10% of the total mileage and 16.20% and 16.01% of the total cost, respectively (Table 4).

Planning and design of matching pipe network of CO_2 source-sink

Pipeline network planning on a time scale

By analyzing the optimization results of matching pipe network of CO_2 source-sink in Huainan coalfield and the amount of CO_2 transported by each pipe network line, it can be seen that the entire pipe network is centrally distributed in the east and west regions, and it is obvious that the transport amount of the eastern pipe network is significantly greater than that of the western one (Fig. 9). The thicker the lines of the route, the greater the traffic amount (Fig. 9). The planning and design of matching pipe network of CO_2 source-sink should refer to the thickness of the transportation line, that is, the amount of CO_2 transported (Figs. 10, 11, 12). The planning and design of matching pipe network of CO_2 source-sink in Huainan coalfield is proposed in accordance with three steps:

First step: It is recommended to preferentially plan the pipeline route of D9–D8–D7–B12–D6–D4–B8 in the eastern region, and the D3–B10 and D1–B4 in the western region. This planned pipeline can effectively connect the coal-fired power plants of D9, D8, D7, D6 and D4, and unworkable blocks of B12, B8, B10 and B4 of Huainan coalfield (Fig. 10). At this step, the total amount of CO_2 that can be transported by the pipeline network is 6.65 billion tons, and the total amount of CO_2 that can be stored is 2.27 billion tons, which accounts for 56.99% and 38.74% of the total transportation and storage stock of CO_2, respectively.

Second step: It is recommended to further plan the pipeline lines of D10–D9, D7–B13, D7–B14, D4–B9, D5–B9, B10–B7, and B4–B3–B2, which can further effectively connect the deep unworkable seam in the east,

CO_2 sink	Mileage saving/km	Cost saving/$ billion	Proportion of total distance transported/%	Proportion of total transportation cost/%
B2	7.50	12.40	2.98	2.91
B3	2.08	2.88	0.83	0.68
B5	2.50	1.95	0.99	0.46
B7	4.17	7.83	1.66	1.84
B8	18.33	56.70	7.29	13.31
B9	3.33	9.33	1.32	2.19
B12	9.17	28.40	3.64	6.67
B13	26.25	69.00	10.43	16.20
B14	25.47	68.20	10.10	16.01
Total	98.75	256.69	39.25	60.26

Table 4. Cumulative mileage and cost savings of CO_2 source and sink matching each geological storage sink.

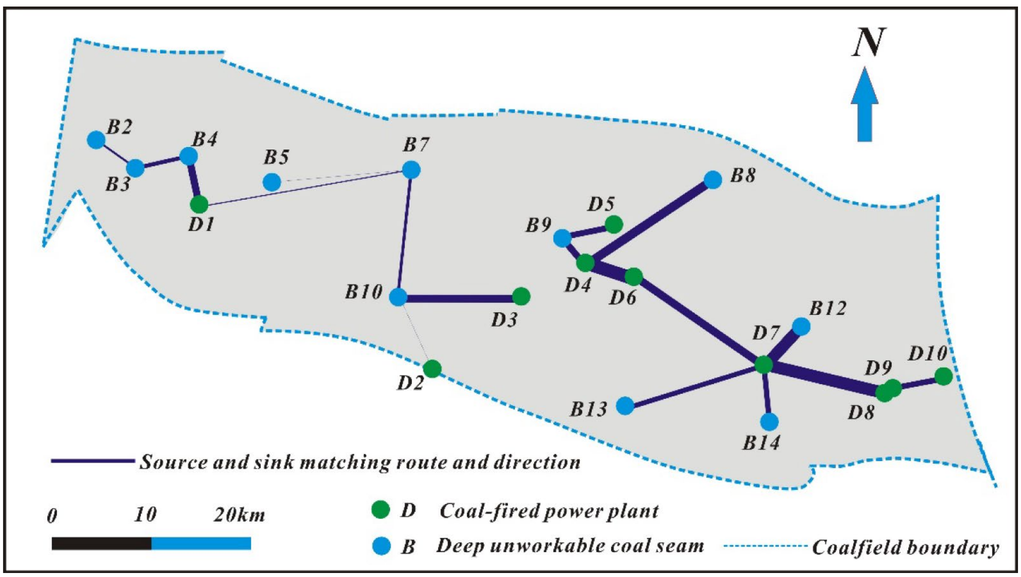

Figure 9. CO_2 transport statistics of CCS source-sink matching pipe networks in Huainan coalfield.

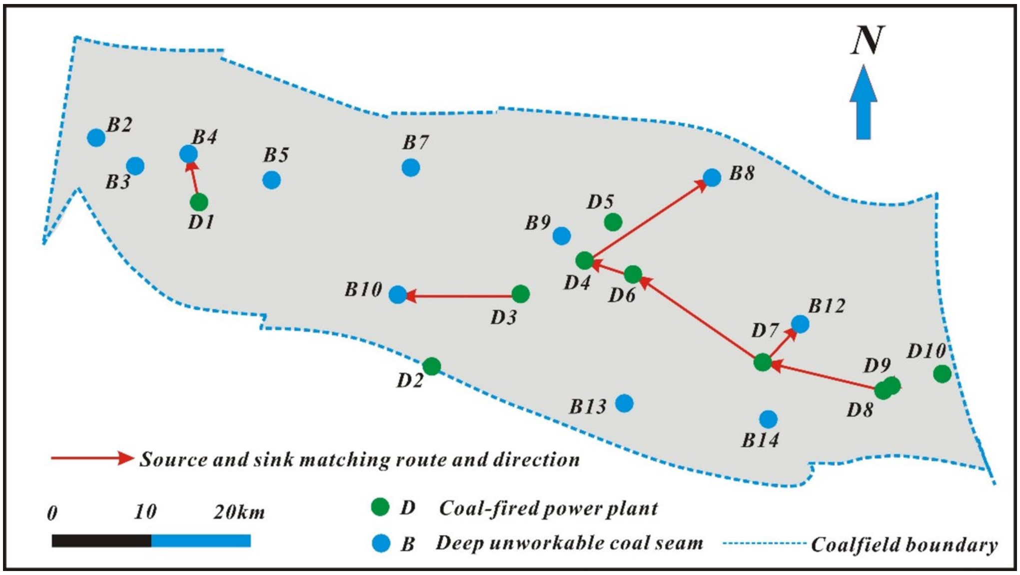

Figure 10. Three-step planning and design of CO_2 source-sink matching pipe network in Huainan coalfield (First step).

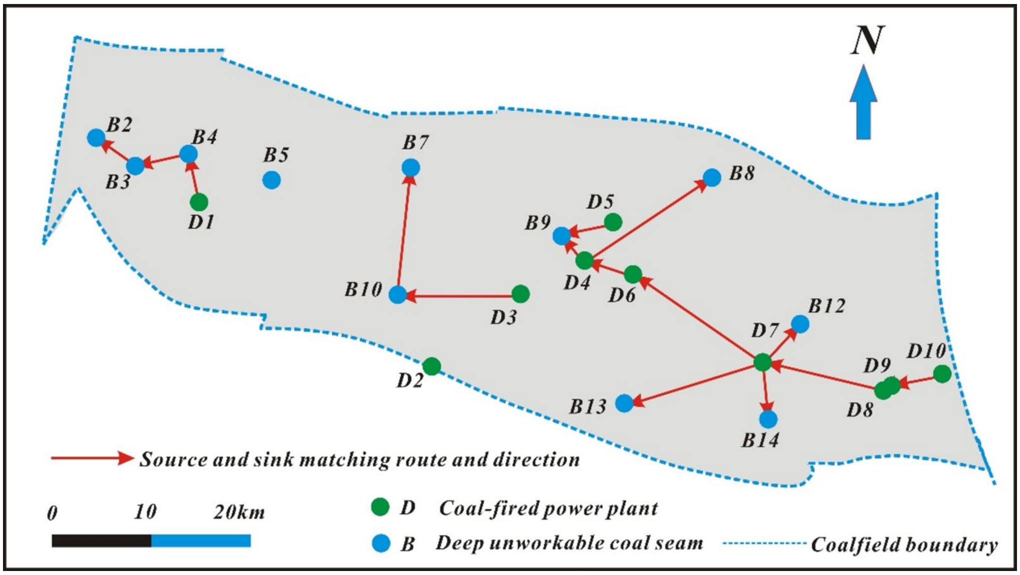

Figure 11. Three-step planning and design of CO_2 source-sink matching pipe network in Huainan coalfield (Second step).

middle and west areas (Fig. 11). After the pipeline network planning at this step, the total amount of CO_2 transported can be 10.345 billion tons, and the total amount of CO_2 stored can be 5.84 billion tons, which accounts for 88.66% and 99.39% of the total CO_2 transport and storage, respectively.

Third step: Complete the design of all remaining pipelines to connect the deep unworkable seam in the east and west of the study area. It is suggested to add the design of B3 and B4 pipelines, so as to run through all CO_2 emission sources and CO_2 storage sinks in Huainan coalfield, so as to realize all CO_2 transportation and geological storage (Fig. 12).

Pipeline network planning at the spatial scale

In this study, the location of each point in deep unworkable seam is determined by taking the center location of each region (Fig. 1), but in the actual well location layout, the regional center location is often not the only consideration. Therefore, the analysis of the type of CCS pipeline within each region and the planning of CCS pipeline network between each region are very important (Fig. 13).

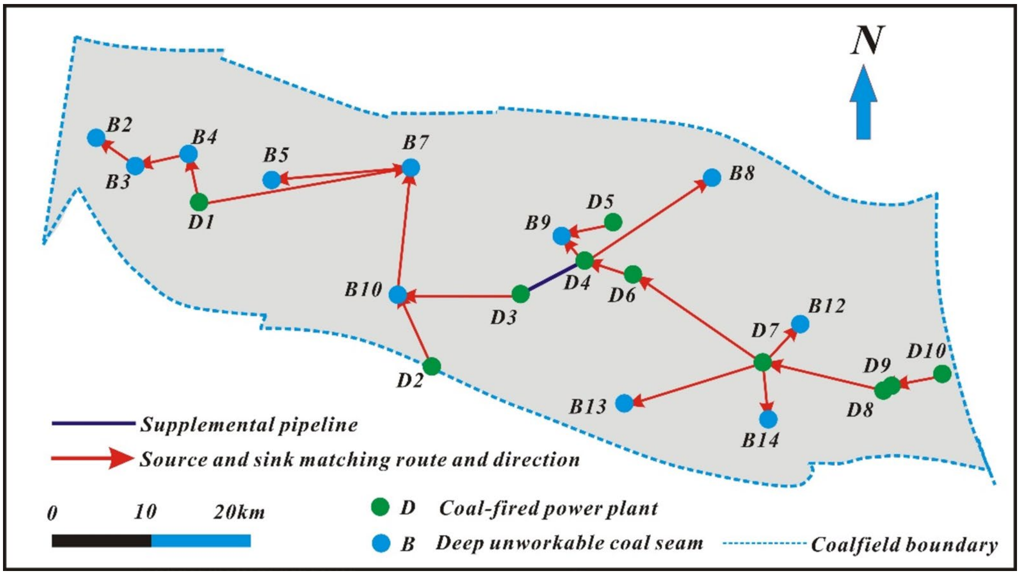

Figure 12. Three-step planning and design of CO_2 source-sink matching pipe network in Huainan coalfield (Third step).

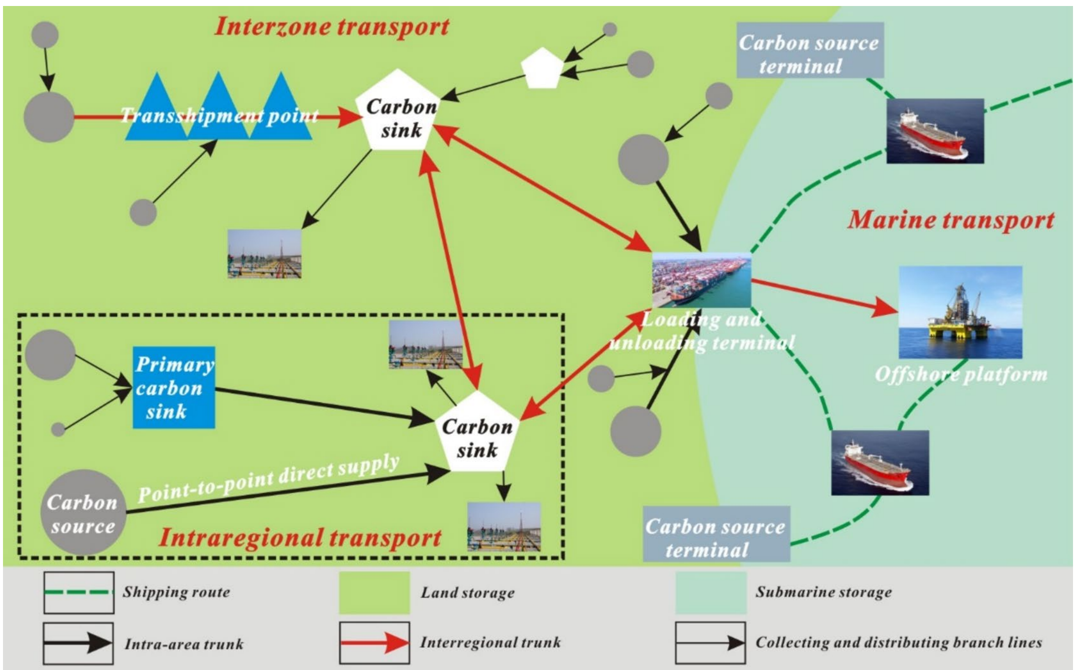

Figure 13. Schematic diagram of four types of CO_2 pipelines connecting carbon sources and carbon sinks.

According to the location and use of CO_2 pipelines in the pipe network, CO_2 pipelines can be defined as the following four types (Fig. 13): (1) Gas collection branch, that is, the pipeline that communicates CO_2 source and transfer point, and the transport phase is determined according to its economy; (2) Distribution branch, that is, the pipeline from the end of the communication pipeline to the carbon sequestration point; (3) Intra-regional trunk lines, that is, trunk pipelines from the transfer point to the carbon sequestration point in the region; (4) Interregional trunk lines, that is, shared pipelines connecting regions. As far as Huainan coalfield is concerned, in terms of spatial scale, priority should be given to planning intra-regional pipe networks in various regions within unworkable seam bounded by faults, that is, the pipe networks in various regions within B1–B15 (Fig. 13).

Whether it is a small area of Huainan coalfield or the whole large area of China, the CCS pipe network layout should follow the following ideas. First of all, small-scale carbon sources in the region should be transferred to main pipelines through gas collection branch lines, and commercial CO_2 pipeline demonstration projects can be built. Secondly, the collection and distribution pipelines of regional carbon sources can be planned within the basin to form a backbone sharing pipeline, and a variety of CCS carbon sequestration applications can be simultaneously carried out to build an interregional transport network demonstration. Then, for areas that do not have the conditions for storage, inter-regional trunk pipelines should be built to gradually form a cross-regional carbon network on land to fully meet the matching transport of source and sink. Offshore CO_2 storage resources should be developed, suitable coastal injection points should be selected, marine transport pipelines and ship transport should be simultaneously carried out, and integrated business models of transport and storage based on land and sea should be built (Fig. 13).

Conclusions

In this study, the deep unworkable seam in Huainan coalfield was taken as the research object. Firstly, the evaluation method of CO_2 storage potential in deep unworkable seam was discussed. Secondly, the CO_2 geological storage potential was analyzed. Then, the matching research of CO_2 source and sink for CO_2 geological storage was carried out, and the pipe network design was optimized. Finally, suggestions on the design of network planning of CCS source and sink are put forward in Huainan coalfield. The main conclusions are as follows:

(1) The total annual CO_2 emissions of each coal-fired power plant are 58.76 million tons, and the average annual CO_2 emissions of each coal-fired power plant vary greatly with ranging from 0.356 million tons to 17.12 million tons. The CO_2 geological storage potential of deep unworkable seam is huge, and the total amount is 762 million tons. It can store 685 million tons, 53 million tons and 24 million tons of CO_2 in adsorbed, free and dissolved states, respectively. For the average annual CO_2 emissions of coal-fired power plants, deep unworkable seam can be stored for 12.97 years. During the 10-year period, the deep unworkable coal seam can store 587.6 million tons, and the cumulative planning pipeline is 251.61 km, requiring a cumulative capital of \$ 4.26×10^{10}.

(2) The main blocks of CO_2 geological storage are B9, B12, B8 and B5, with stored stocks of 124 million tons, 114 million tons, 97 million tons and 85 million tons, respectively. The matching of CO_2 source and sink saved 98.75 km, and saved \$ 25.67 billion, accounting for 39.25% and 60.26% of the total mileage and cost, respectively. The mileage and cost savings in 13 and 14 blocks are more obvious, which accounts for 10.43%, 10.10% and 16.20% and 16.01% of the total mileage and cost, respectively.

(3) Based on the three-step approach, the whole line of CO_2 emission sources and CO_2 storage sinks in Huainan coalfield can be completed by stages and regions, and all CO_2 transportation and storage can be realized. CO_2 pipelines include gas collection branch lines, gas distribution branch lines, intra-regional trunk lines, and interregional trunk lines. Based on the reasonable layout of various types of CO_2 pipelines, a variety of CCS carbon sequestration applications can be simultaneously carried out, the intra-regional and interregional network demonstration for CO_2 transport can be built, and integrated business models of CO_2 transport and storage can be built simultaneously on land and sea.

Data availability

All data generated or analysed during this study are included in this published article (Please refer to the manuscript that has been uploaded).

Received: 29 April 2024; Accepted: 18 July 2024
Published online: 26 July 2024

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Acknowledgements
We would like to express our gratitude to the anonymous reviewers for offering their constructive suggestions and comments which improved this manuscript in many aspects. This work was financially supported by the Natural Science Research Project of Anhui Educational Committee (2023AH040154), the Anhui Provincial Natural Science Foundation (2308085Y30), the Anhui Provincial Key Research and Development Project (2023z04020001), the National Natural Science Foundation of China (No. 42102217; 42277483), and the University Synergy Innovation Program of Anhui Province (No. GXXT-2021-018).

Author contributions
H.F. and S.S.: The conception and design of the study, revising it critically for important intellectual content, final approval of the version to be submitted. H.F. and Y.W.: Drafting the article. J.G. and H.L.: Drawing of all figures. H.F. and Z.W.: Collection and analysis of the field data. S.Y.: Derivation of mathematical models.

Competing interests
The authors declare no competing interests.

Additional information
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