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Cost curve of large-scale deployment of CO_2-enhanced water recovery technology in modern coal chemical industries in China

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ABSTRACT

China has emerged as a world leader in the coal chemical industry, which requires large amount of water and results in considerable CO_2 emissions. This situation has led to the challenge of the CO_2-Water nexus for China and particularly for the sustainable development of its coal chemical industry. CO_2-enhanced water recovery (CO_2-EWR) technology can provide large-scale CO_2 mitigation and additional water supply in an integrated manner, especially in arid areas. Meanwhile, CO_2 streams from industrial separation processes in the coal chemical industries are amenable to separation and can dramatically simplify or even dispense with the capture process. This study presents the first systematic assessment of a cost curve for onshore CO_2-EWR potential using CO_2 streams from industrial separation processes by an evaluation framework encompassing CO_2 emission inventory, site suitability evaluation, and source–sink matching with techno-economic models. Preliminary results focused on the full capacity of several coal chemical processes as of 2015 suggest that CO_2-EWR technology can mitigate 269 million tons of CO_2 from industrial separation processes at relatively low cost ranging from 12 to 30 USD/t CO_2 in China. Furthermore, 404 million tons of underground water could be produced for further desalination and utilization. When additional capacity under development could become fully operational, the emissions of 878 million tons of CO_2 could be mitigated and provide 1318 million tons of vital water resources. Therefore, CO_2-EWR technology can be essential to clean and sustainable development of the coal chemical industry and may provide low-cost opportunities to accelerate the deployment of large-scale CCUS projects in China.

1. Introduction

China's abundant coal reserves and urgent concerns about energy security and economic development have driven local governments in coal-rich regions to invest in coal chemical technology. China has emerged as a world leader in the coal chemical and coal conversion industry. However, the environmental impact resulting in huge CO_2 emissions and water consumption caused by this dramatic development of the coal chemical industry are concerns for stakeholders, such as governments, investors, enterprises, and the public in China. Carbon capture, utilization and storage (CCUS) technology is an essential component to reduce CO_2 emissions and produce value-added products on a meaningful scale. Among these options of CCUS technologies, CO_2 capture and CO_2 aquifer storage with CO_2-enhanced water recovery (CO_2-storage/CO_2-EWR, abbreviated as CO_2-EWR) are considered an effective approach to large-scale CO_2 mitigation and water production with relatively high technology readiness levels and low cost, especially in arid regions with high water stress and high water price (Davidson et al., 2009; Davies et al., 2013; Kobos et al., 2011; Ziemkiewicz et al., 2015).

The coal chemical industry in China uses coal as a raw material to produce gases, liquids, and solids of various chemicals and cleaner energy forms. The traditional coal chemical industry mainly includes calcium carbide, synthetic ammonia, and coke with mature technology. Newly emerging modern coal chemical industries encompass coal to methanol, coal to olefins, coal to oil, coal to synthetic gas, coal to ethylene glycol, and coal to other oil substitutes. The technologies used by the industry include coal gasification and coal liquefaction processes that emit high-purity CO_2 and pure CO_2 (> 80% or 98.5%, respectively) (Feng et al., 2013). These high purity streams of CO_2 represent a considerable portion of the total CO_2 resulting from the industry and can be more readily altered to produce pure CO_2 streams (even at a high

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pressure) (Feng et al., 2013; Meng et al., 2007; Zhao and Gallagher, 2007). This results in large quantities of high purity CO_2 streams available from the coal chemical industry, and when combined with CO_2-EWR offers an opportunity to address the energy-water-climate and economic challenges facing the coal chemical industry, large-scale deployment of CCUS technologies, and China's low-carbon future (ADB, 2015; Zhang et al., 2013).

Understanding the magnitude and cost range of CO_2-EWR technology to deploy across the modern coal chemical industry is the first step towards large-scale deployment and impact in addressing the nexus of CO_2 mitigation and water supply in China's coal chemical industry. This study aims to develop an evaluation framework to assess the CO_2 emission and potential of CO_2-EWR in several industrial separation processes of the coal chemical industry in China. This study also analyzes source–sink matching with a techno-economic model and examines the preliminary techno-economic feasibility of deploying CO_2-EWR projects at a sub-basin scale. Finally, the study defines the magnitude of matched capacity, distribution of potential sites, and cost ranges for matched CO_2 storage capacity in aquifers with pure CO_2 streams from coal chemical factories in China.

2. Evaluation framework

A number of studies have been conducted to examine the technical and economic feasibility of deploying CCUS at various levels including basin and regional levels by source–sink matching assessments (Dahowski et al., 2012; Middleton et al., 2012). Cost curves for full-chain CCUS systems based on optimized capacity constrained source–sink matching provide an informative framework to examine the potential for commercial-scale CCUS to deploy across the various industries and locations (Dahowski et al., 2012; Middleton et al., 2012). A framework of source–sink matching is shown in Fig. 1. The framework includes CO_2 emission evaluation, site suitability evaluation, source–sink matching evaluation that includes techno-economic modeling, and cost curve of potential integrated CCUS projects. Numerous improvements and updates are presented in this framework, such as CO_2 inventories, site suitability evaluation, geological characterization and site performance evaluation, and source–sink matching modeling. The details will be discussed in the subsequent chapters. The cost range, spatial distribution of potential CCUS projects, and matched CO_2 storage capacity with the set of modeled CO_2 sources and storage reservoirs can be obtained using this systematic evaluation framework (Dahowski et al., 2012; Middleton et al., 2012).

2.1. CO_2 emissions from the coal chemical industry in China

The modest amounts of CO_2 from industrial separation processes of the traditional coal chemical industry have commonly been utilized for such things as food additives and feedstock for fertilizer and other chemical products. The much larger modern coal chemical industry, which has been developing and growing in recent years, encompasses a broader set of processes that will swamp traditional markets for the resulting CO_2. The status of several typical coal conversion processes in the modern coal chemical industry in China has been investigated by using data from various sources, including enterprise databases from the Chinese Academy of Sciences, annual industry reports, websites, and enterprise interviews. The coal conversion processes analyzed in this study include coal to oil (direct and indirect liquification), coal to methanol, coal to natural gas, coal to olefins, coal to ethylene glycol, and coal to dimethyl ether. The calculation methodology of CO_2 emissions from these processes is mainly based on the emission factors (EFs) of various coal chemical plants as presented in the literature. The investigation results show that 297 coal chemical manufactories were in operation in 2015 and 399 manufactories at various stages (e.g., in operation, in construction, and verified by administrative organizations) at the end of 2016. The calculation methodology of CO_2 emissions is based on EFs and available plant capacities and productivities, as shown in following formula:

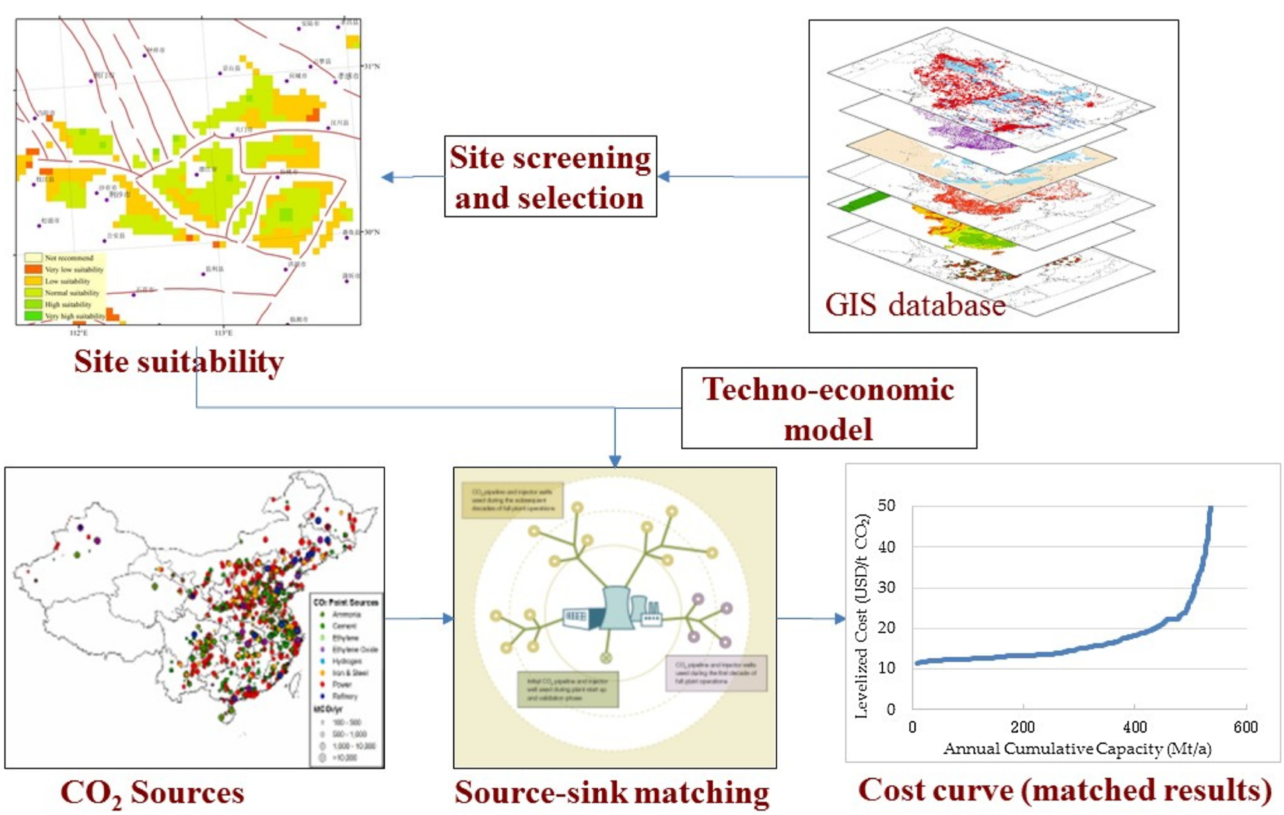

Fig. 1. Evaluation framework for cost curve analysis.

Table 1
EFs for CO_2 emission in various coal chemical processes (Zhang et al., 2016).

Coal chemicals	EFs of CO_2 from industrial separation (ton CO_2/ton product)	EFs of dilute CO_2 (ton CO_2/ton product)	EFs of total CO_2 (ton CO_2/ton product)
Coal to natural gas	2.70	2.10	4.80
Coal to methanol	2.06	1.79	3.85
Coal to dimethyl ether	2.80	2.20	5.00
Coal liquefaction (directly coal to oil)	3.33	2.23	5.56
Coal liquefaction (indirectly coal to oil)	5.10	1.76	6.86
Coal to olefins	6.41	4.11	10.52
Coal to ethylene glycol	3.50	2.10	5.60

$$ECO_2 = \sum_{j}^{N} \sum_{i}^{M} (ECO_2)_{ij} = \sum_{j}^{N} \sum_{i}^{M} (EF_{ij} \times P_{ij}) \tag{1}$$

where ECO_2 is the total annual CO_2 emissions of all coal chemical industry, $(ECO_2)_{ij}$ is the estimated annual CO_2 emissions of the i^{th} CO_2 emission source within j^{th} coal chemical process, EF_{ij} is the EF of the i^{th} CO_2 emission source within j^{th} coal chemical process, P_{ij} is the production yield of the i^{th} CO_2 emission source within j^{th} coal chemical process, N is the number of coal chemical processes in this inventory, and M is the number of factories with j^{th} coal chemical process.

CO_2 EFs vary with different coal conversion technologies. However, CO_2 EFs can be simplified to an average value of two types: high purity CO_2 from industrial separation processes and dilute CO_2 from other processes. The EFs are based on the national consultant report on coal chemical industry published by Zhang et al. (2016). The EFs for processes evaluated in this study are shown in Table 1.

Capacity, production, and CO_2 emission statistics for the modern coal chemical industry in China are shown in Tables 2 and 3. The total amounts of annual CO_2 emission from coal chemical industries are 258 Mt/a, 556 Mt, and 1551 Mt, as assessed based on actual production in 2015, full capacity in 2015, and total capacity in 2016 (including in operation, in construction, and verified by administrative organizations), respectively. Furthermore, the corresponding high-purity or pure CO_2 streams from industrial separation processes are 142 Mt, 304 Mt, and 907 Mt CO_2 annually, thereby providing early opportunities for large-scale deployment of CCUS technology. On the surface, the increase in capacity between 2015 and 2016 suggests strong growth and expansion of the industry. However, the inconsistencies in the total capacity for 2016, full capacity in 2015, and actual operating capacity in 2015 within several coal chemical processes also suggest differences in reporting between the central government and active investment partners (i.e., local government, enterprises, private entities, and other stakeholders), and the nature of technology development within the industry. Although China's abundant coal reserves and acute concerns about energy security and cheap materials help explain the country's considerable interest in coal chemical industry, the driving forces for this industry are complicated and policies have been inconsistent. The local governments and enterprises in coal-rich regions have strong incentives to invest in the coal chemical industry. However, the central government has attempted to slow down the development of the industry given their wariness about the huge impact of coal chemical technologies on the environment and resources such as water, land use, and minerals. The central government has required new strict health, safety, and environment (HSE) evaluations on all coal chemical factories at various stages, including early feasibility studies, during construction and operation, as well as verification of administrative organizations. The discrepancy of environmental policy between the central and local governments helps in partially explaining the dramatic development but extremely low operating rate of the coal chemical industry in China. The technology development status in the coal chemical industry in China is that the owners of coal chemical factories consistently use new technologies and new equipment to improve the production and conversion efficiency. These technologies still need more time to be improved and become fully operational, especially for this rapidly expanding coal conversion industry. These two reasons can mostly explain the great inconsistency among the total capacity, designed capacity, and actual operating capacity in the coal chemical industry in China. Given the progress of HSE evaluation and technology improvement, the operating rate of some coal chemical factories has reached approximately 100% by the end of 2017. Hence, most of the total capacities of several processes in the modern coal chemical industry from 2016 are expected to be fully operative before 2025.

The distribution of the 297 coal chemical factories in operation are shown in Fig. 2. The resulting CO_2 emissions are inventoried and mapped based on the 2015 full capacity evaluation. These CO_2 sources are primarily concentrated in North, Northwest, Northeast, and Southwest China.

2.2. Site suitability evaluation

The offshore aquifer storage of CO_2 requires offshore infrastructure including platforms and pipelines that result in significantly greater costs and challenges compared with onshore storage. Therefore, the site suitability of onshore aquifer sites is evaluated at the sub-basin scale for this macro-scale study in the evaluation framework.

Site suitability evaluation of CO_2 aquifer storage was performed using geographic information system (GIS) and a spatial analysis process based on multicriteria methods that considered the following three priority objectives: (A) technical optimization in terms of capacity and injectivity; (B) risk minimization; and (C) compliance with environmental restrictions regarding existing surface and subsurface use (Wei et al., 2013).

CO_2 aquifer storage sites must have favorable reservoir-seal

Table 2
CO_2 emission based on actual production in typical coal chemical processes in 2015.

Coal chemical industry	Actual production in 2015 (Mt/a)	CO_2 from industrial separation (Mt/a)	Total CO_2 (Mt/a)	No.	Operating rate	Full capacity in 2015 (Mt/a)	CO_2 from industrial separation (Mt/a)	Total CO_2 (Mt/a)
Coal to natural gas	3.5	9.4	16.7	4	3.4%	36.5	15.5	27.5
Coal to methanol	50.5	104.1	194.6	240	43.9%	115.0	236.3	441.6
Coal to dimethyl ether	3.2	12.8	22.9	14	30.9%	10.4	20.5	36.6
Coal liquefaction (directly coal to oil)	0.1	0.6	0.9	1	10.1%	0.2	0.8	1.3
Coal liquefaction (indirectly coal to oil)	0.7	3.5	4.7	7	3.5%	1.4	4.4	5.9
Coal to olefins	1.6	10.2	16.8	17	5.5%	9.5	20.8	34.1
Coal to ethylene glycol	0.1	0.5	0.8	13	0.7%	9.6	5.0	8.0
Total		142	259	297			304	556

Table 3
CO_2 emission based on total capacity in typical coal chemical processes in 2016.

Coal chemical industry	Total capacity (Mt/a)	CO_2 from industrial separation (Mt/a)	Normal CO_2 (Mt/a)	Total CO_2 (Mt/a)	No.
Coal to natural gas	103.0	278.1	216.3	494.4	35
Coal to methanol	115.0	236.9	205.9	442.8	242
Coal to dimethyl ether	10.4	29.1	22.9	52.1	16
Coal liquefaction (directly coal to oil)	1.1	4.7	2.5	7.2	1
Coal liquefaction (indirectly coal to oil)	19.5	99.2	34.2	133.4	12
Coal to olefins	28.9	185.4	118.9	304.3	41
Coal to ethylene glycol	20.9	73.0	43.8	116.9	52
Total		907	645	1551	399

conditions: reservoir properties (e.g., porosity, permeability, and heterogeneity), seal properties (e.g., capillary entry pressure, permeability, thickness, and fracturing pressure), and boundary conditions (e.g., open or closed hydraulic boundaries). The risk is largely characterized as a function of the properties of the primary seal (e.g., threshold pressure, thickness, permeability, lateral continuity, fracture network, and crossing major faults) and any secondary seals, the type and presence of potential leakage pathways (e.g., abandoned wells, faults, and other potential migration paths), and the potential for different hazards that can affect a storage area. These hazards include acidic water formations, seismic activity, landslides, large-scale surface deformation, or the presence of sensitive receptors (e.g., population density in urban areas, industrial zones, water resources, and noble natural resources (Grataloup et al., 2009). The site of CO_2 storage should be compliant with legislation, regulation, and environmental restrictions regarding existing surface and subsurface use (e.g., highly populated cities, natural preservation parks, water resources, and scare resource reservoirs).

The basin and sub-basin scale characterization and reservoir-seal classification are used to score and screen site suitability. The site suitability evaluation results of onshore aquifer sites are shown in Fig. 3. Most suitable sites are located in North, Northeast, and Northwest China. The distributions of suitable aquifer sites are in some parts inconsistent with the distributions of CO_2 sources from coal chemical factories. Note that the CO_2 sources in South China have limited nearby options for storing CO_2, and no options within the 250-km maximum transport distance considered in this analysis.

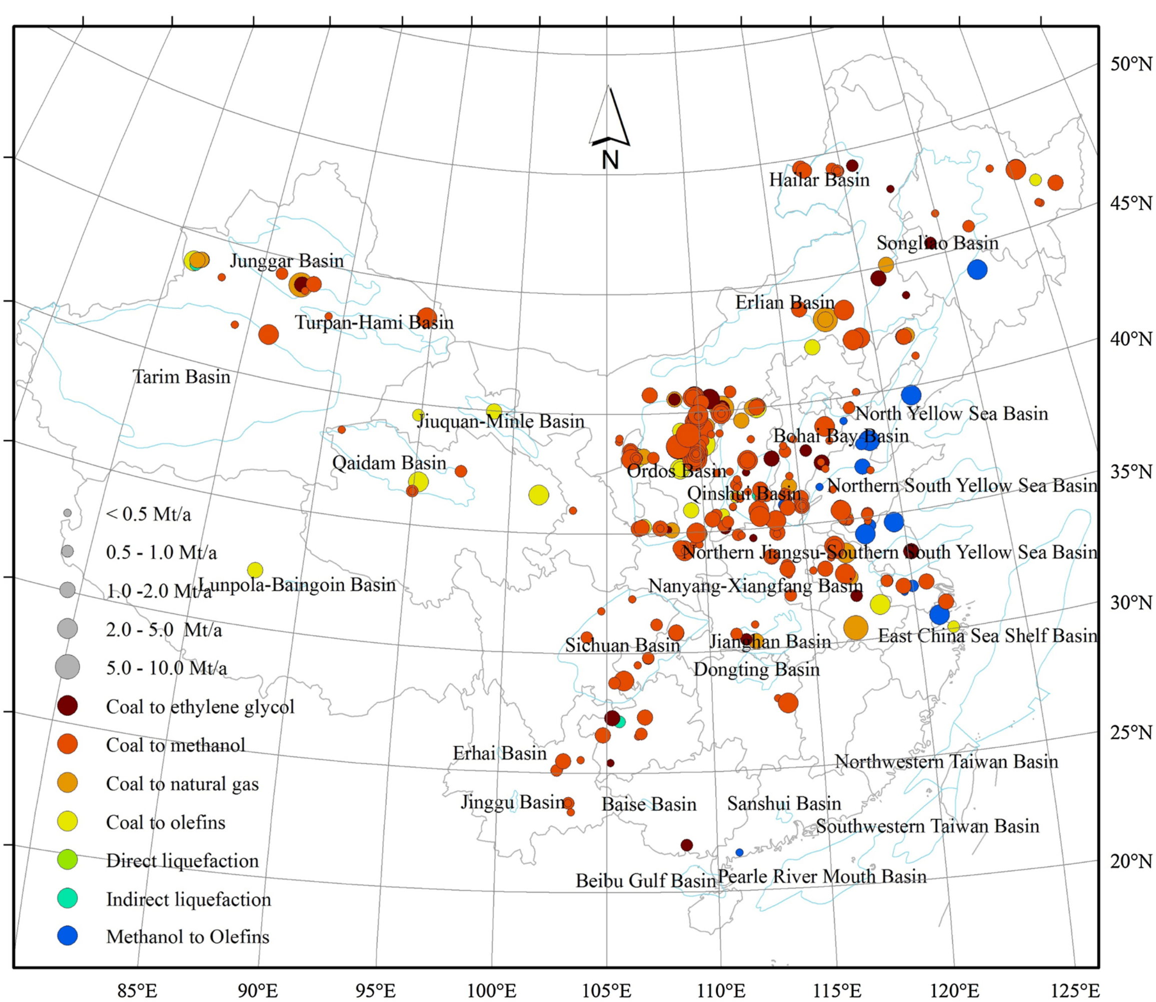

Fig. 2. Distribution of CO_2 stream from industrial separation processes in coal chemical factories in China (Full capacity in 2015).

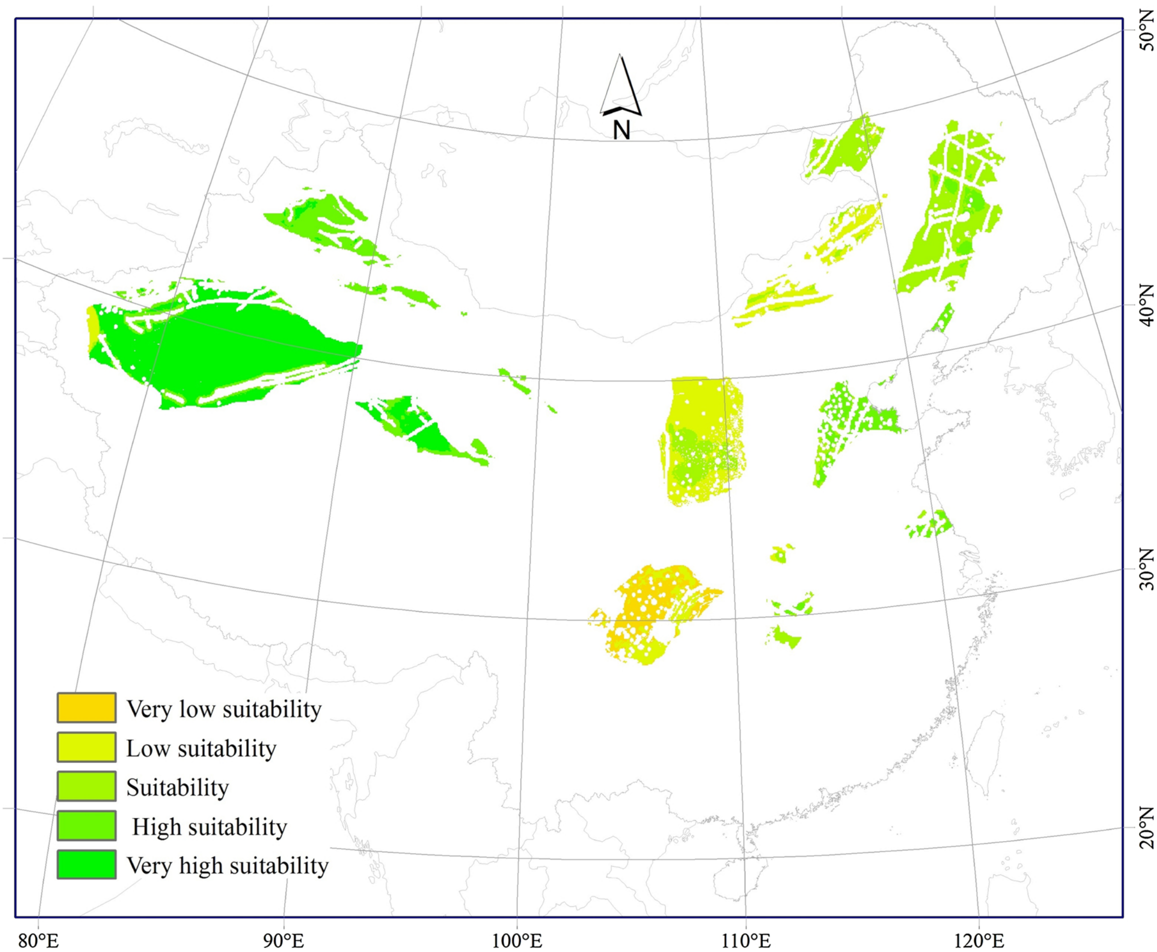

Fig. 3. Site suitability distribution of onshore aquifer sites in China.

2.3. Techno-economic evaluation

Techno-economic evaluation is a crucial step for the feasibility study of CCUS projects. Many techno-economic models are available for integrated CCUS systems, such as the International Energy Agency model, Battelle Pacific Northwest National Laboratory model, Los Alamos National Laboratory's carbon capture (CCS) simulation model, National Energy Modeling System – CCUS model, and integrated environmental control model (Berkenpas et al., 2009; Dahowski et al., 2012; Fukai et al., 2016; Middleton and Bielicki, 2009; Rubin et al., 2015, 2013; Van Alphen et al., 2010; Zelek et al., 2012). Various techno-economic models are used for each part of a CCUS system, including CO_2 capture, compression, pipeline, geological utilization, and storage (Dutcher et al., 2015; EIA, 1994; Ettehadtavakkol et al., 2014; Faltinson and Gunter, 2009; Fukai et al., 2016; McCoy, 2008a, b; McCoy and Rubin, 2006, 2008, 2009; Rubin et al., 2013; Sun and Smith, 2013; Tola and Pettinau, 2014). Previous studies have been widely reviewed and accepted for estimating the costs of different components of an integrated CCUS system.

The techno-economic evaluation for CCUS project consists of the technical aspect (technical design and technical performance evaluation) and economic evaluation. The techno-economic model can be classified based on the order of increasing complexity and precision from empirical, semi-analysis, numerical simulation, and field specifics. The techno-economic evaluation depends highly on the precision and type of available data and corresponding models. Given more types and higher precision of available data, more detailed technical design, and corresponding economic models, cost evaluation can be performed with increased reliability and reduced uncertainties. In this macro-scale evaluation techno-economic models using empirical and budgetary models are employed. The technical features of integrated CCUS projects are described as follows.

2.4. Technical feature of integrated CCUS project

The technical design and performance evaluation of an integrated CCUS project includes CO_2 capture, compression, transportation, geological utilization (CO_2-EWR), and storage.

2.4.1. CO_2 capture in the process of coal gasification or coal conversion

CO_2 capture technologies are not new, and amine-stripping systems and industrial separation system have been used in commercial applications for nearly 80 years (Abass, 2010; Chen et al., 2013; Rubin et al., 2015; Sun and Smith, 2013). However, significant variability and uncertainty remain in the expected commercial costs of CO_2 capture from various types and scales of candidate sources. The literature on CO_2 capture presents a wide range of cost estimates based on varying combinations of base plant configuration and capture system designs, operating parameters, energy costs, and new build versus retrofit application (IPCC, 2005). Various mature capture technologies are used to separate dilute or low-purity CO_2 streams, such as amine-based CO_2 capture system. Typical low-purity post-combustion capture costs at a scale of a million tons annually range from 45 USD/t CO_2 to 90 USD/t CO_2 (Porter et al., 2017; Zhao et al., 2013). Therefore, the capture of typical dilute CO_2 streams is not considered for this evaluation of early or low-cost deployment opportunities.

The typical separation methods for high partial pressure acid gas in the coal conversion industry are mainly physical absorption processes (e.g., rectisol or selexol) or similar processes (Abass, 2010; Chen et al., 2013; Sun and Smith, 2013). The rectisol process is widely used worldwide, especially for syngas separation in the coal chemical industry in China. If the impurities of the CO_2 stream from the industrial separation are within the permissable range of CO_2 pipeline standards, then the pure CO_2 from the rectisol process can be directly compressed after simple purification (methanol removal) and dehydration, and then transported to suitable sites for CO_2 geological utilization and storage. The capture costs of CO_2 streams from industrial separation processes can be avoided with technical alteration on the industrial separation processes.

2.4.2. CO_2 compression

Supercritical or liquid CO_2 must be boosted to maintain effective CO_2 transport. This compression process consists of two steps. CO_2 is initially compressed by a multistage compressor from 0.1–0.2 MPa ($P_{initial}$) to its supercritical state of 7.38 MPa ($P_{cut-off}$) and then boosted by a one-stage booster pump to designated inlet pressure of 12–15 MPa. The compression process dramatically increases the temperature of the CO_2, and must be cooled. The techno-economic model of CO_2 compression follows the model by McCollum and Ogden (2006). In this model, a five-stage compressor and one-stage pump are assumed. The following expression represents the optimum compression ratio for each of these stages:

$$CR = (P_{cut-off}/P_{initial})^{(1/N_{Stage})}(N_{Stage} = 5) \quad (2)$$

The compression power ($W_{s,i}$) of each stage is calculated as follows (McCollum and Ogden, 2006):

$$W_{s,i} = \left(\frac{1000}{24 \times 3600}\right) \times \left[\frac{m \times Zs \times R \times T_{in}}{M \times \eta_p}\right] \times \left(\frac{Ks}{Ks - 1}\right) \times \left(CR^{\frac{Ks}{Ks-1}} - 1\right) \quad (3)$$

As such, the compression power should be calculated for each stage, and the total compression power is as follows:

$$Ws_{total} = Ws_1 + Ws_2 + Ws_3 + Ws_4 + Ws_5 \quad (4)$$

where m is the CO_2 mass flow [t/d]; $P_{initial}$ is the initial pressure that can vary depending on the CO_2 stream but is atmospheric pressure (0.1–0.15 MPa) for most scenarios without technical alteration; $N_{stage} = 5$; $R = 8.314$ kJ/(kmol K); $M = 44.01$ kg/kmol; $T_{in} = 313.15$ K (i.e., 40 °C); $\eta_p = 0.75$ (efficiency factor); 1000 = kg/t ; 24 = h/day; 3600 = s/h; Zs is the average CO_2 compressibility for each individual stage, that is, $Zs = 0.995$ (Stage 1), 0.985 (Stage 2), 0.970 (Stage 3), 0.935 (Stage 4), and 0.845 (Stage 5); Ws_I is the power requirement for each individual stage; and k_s is the average ratio of the specific heats of CO_2 for each individual stage, that is, $k_s = 1.277$ (Stage 1), 1.286 (Stage 2), 1.309 (Stage 3), 1.379 (Stage 4), and 1.704 (Stage 5). Power needs for boosting the pressure of the cut off pressure ($P_{cut-off}$) to the final outlet pressure (P_{final}) are estimated as follows:

$$W_p = \left(\frac{1000 \times 10}{24 \times 36}\right) \times \left[\frac{m \times (P_{final} - P_{cut-off})}{\rho \times \eta_p}\right] \quad (5)$$

The following equations are assumed: $\rho = 630$ kg/m^3, $\eta_p = 0.75$ (efficiency factor), (1000 = 1000 kg/t, 24 = 24 h/d, 10 = 10 bar/MPa, 36 = 36 m^3·Bar/kW). These equations presented by (McCollum and Ogden, 2006) form the basis for estimating the performance and costs of CO_2 compression.

2.4.3. CO_2 pipeline transportation

Pipeline transportation with supercritical CO_2 ($SC-CO_2$) and dense phase are recommended as cost-effective methods and are being used widely for long-distance CO_2 transportation. The physical properties of the CO_2 stream significantly affect the technical design and cost assessment of CO_2 pipeline projects.

Dense-phase CO_2 transport is flexible for unstable velocity during operation and maintenance and is suitable for low-temperature regions. The disadvantage is that CO_2 state and physical properties vary with temperature, and work efficiency of a dense CO_2 pipeline is considerably lower than that of a Supercritical $-CO_2$ pipeline. For the demonstration project, the dense-phase CO_2 is suitable for unstable work efficiency and unpredictable situations during the integration of a full-chain CCUS project.

The performance model for pipeline transportation follows the performance model by Wei et al. (2016). These technical parameters for performance evaluation mainly include pressure drop, flow velocity, operating pressure, temperature, roughness, inlet/outlet pressure, and CO_2 density, among others (Knoope et al., 2013). Among these parameters, pipe diameter plays a key role in existing techno-economic models. The diameter of the pipe segment in this study is calculated using the given parameters, namely, segment spacing, velocity, and pressure drop, and the following iterative method presented by McCoy and Rubin (2008):

$$d = 1000 \cdot \left[\frac{64 \cdot Z_{ave}^2 \cdot R^2 \cdot T_{ave}^2 \cdot F_f \cdot \dot{m}^2 \cdot F_f \cdot l}{\pi^2 \cdot [M \cdot Z_{ave} \cdot R \cdot T_{ave} \cdot (p_{in}^2 - p_{out}^2) + 2 \cdot g \cdot p_{ave}^2 \cdot M^2 \cdot (h_{in} - h_{out})]}\right]^{0.2} \quad (6)$$

where $\dot{m}$ is the design mass flow [kg/s]; P_{in} and P_{out} are the inlet and outlet pressures [Pa], respectively; d is the inner diameter of the pipe [mm]; F_f is the friction coefficient; M is the molecular weight of CO_2 [g/mol]; h_{out} and h_{in} are the pipeline outlet and inlet altitudes [m], respectively; Z_{ave} is the average CO_2 compression factor; R is the universal gas constant; T_{ave} is the average temperature [K]; p_{ave} is the average pressure [Pa]; and l is the length of a pipe segment [m].

Long-distance and large-diameter pipelines are considered smooth tubes for mature welding technologies. The Colebrook–White equation is used to calculate the hydraulic friction coefficient (McCollum, 2006), as shown as follows:

$$F_f = 0.25/\left[log_{10}\left(\frac{5.74}{Re^{0.9}} + \frac{\varepsilon}{3.7d}\right)\right]^2 \text{ and } Re = 4 \cdot \dot{m}/(\pi \cdot \mu \cdot d) \quad (7)$$

where Re is the Reynolds number, μ is the dynamic viscosity of the CO_2 [Pa·s], and ε is the roughness of the internal pipeline (e.g., 0.05 mm).

Applying these diameter-based techno-economic models and parameters to a given pipeline project will result in high variations in pipeline diameters and costs. These variations are based on different assumptions on the optimized technical characteristics in different models, such as pressure drop, booster station spacing, and efficient flow velocity (Knoope et al., 2013). If cost, material consumption, energy consumption, and other optimization processes are used, then using these equations with the same inputs may provide similar results.

The technical aspects of constructing the CO_2 booster station are similar to those of the natural gas booster station, from which the existing guidelines and standards of the CO_2 pipeline are referred. A booster station is essential to maintain the CO_2 state (pressure and temperature above supercritical or liquid state) and avoid an extremely high pressure drop (or choking condition), especially for long-distance pipeline transportation. A single-stage centrifugal pump is commonly used to counter the pressure drop (Mohitpour et al., 2000). The pressure increased by each booster station depends on the operating characteristics of the CO_2 pump and the high compressor efficiency zone. The number of booster stations ($N_{booster}$) can be expressed as

$$N_{booster} = INT\ [P_{drop}/(P_c - p_c)] \quad (8)$$

where P_{drop} is the total pressure loss in the entire pipeline, which represents the sum of frictional pressure head and height difference along the pipe [Pa]; INT function returns the integer part of the value; $P_{drop} = P_{friction} + (h_{out} - h_{in}) \times g \times \rho_{CO2}$; $P_{friction}$ is the frictional pressure drop [Pa]; P_c is the incremental pressure by a single booster station [Pa]; and p_c is the pressure loss in a single booster station, which includes the flow line and pump [Pa]. P_c and p_c are key coefficients provided by equipment suppliers. Pressure drop depends on flow velocity, pressure, temperature, elevation changes, pipeline, among others. The drop should be calculated for each pipeline segment by a detailed theoretical method or numerical simulation. However, simplifying the frictional pressure drop as linear with pipeline length within the choking limitation is reasonable. The number of booster stations can be determined by this simplified equation. The number of booster stations can also be designed via average spacing, which ranges from 150 km to 250 km based on pipeline calculation or the values recommended by pipeline guidelines or standards. $P_c - p_c$ can then be selected according to $P_{drop}/N_{booster}$. The total energy consumption of booster stations is the sum of each booster station, as shown as follows:

$$E_{station} = \sum m/24\bullet(P_{final} - P_{cut-off})/(\rho_{CO2} \times \eta_{booster}) \quad (9)$$

where $E_{station}$ is the energy consumption of booster stations [kW·h]; m is the CO_2 mass flow in the pipeline [t/d]; $P_{cut-off}$ and P_{final} are the inlet and outlet pressures of the CO_2 pump, respectively [Pa]; and $\eta_{booster}$ is the compression efficiency of pumps. Other power consumptions in the booster station are related to the supplementary equipment and daily requirements. These consumptions are assumed to be 5–10% of the power consumption of the pump.

The major technical components of booster stations include factory buildings, working yards, power supply systems, CO_2 pumps, automatic controls, heating and ventilating parts, flow lines and connections, valve systems, and other apparatuses. In addition to these, the first and last booster stations require pigging and receiving devices for a "pig run "monitoring technology, respectively.

2.4.4. Co_2-ewr

CO_2-EWR uses water production wells (i.e., pressure mitigation wells) to avoid high pressure buildup during high-volume CO_2 injection processes. The number and well pattern of CO_2 injection wells and water production wells depends on site-specific conditions, including spatial distribution of lithology, porosity, permeability, relative permeability, minerals, in situ pressure, thickness and depth of reservoir-seal, fracturing pressure, and boundary conditions, among other properties. The Workflow for techno-economic evaluation of CO_2-EWR patterns is shown Fig. 4.

2.4.4.1. Site characterization and monitoring. The complex geological model that includes reservoir structure, fluid model, rock model, boundary condition, and other properties are based on the systematic site characterization and monitoring, verification, and accounting (MVA) technologies. These technologies include well logging, seismic investigation (2D/3D/4D), well-based sampling, down-hole monitoring, wellhead monitoring, core testing, surface CO_2 concentration monitoring, atmosphere monitoring, satellite-based monitoring, and other site characterization and monitoring tools. The cost of site characterization and MVA highly varies with technology types, and related geological volume to be monitored. The technologies used in this evaluation is the minimum requirement of MVA technologies concluded by expert panel, such as a small amount of 3D seismic investigation, periodical 2D seismic investigation crossing entire sites, well logging, periodical well-based monitoring, and shallow underground/surface CO_2 concentration monitoring for possible CO_2 leakage (Wang, 2010).

2.4.4.2. Site performance evaluation. The methodology to be applied in site performance evaluation and the types and level of detail of the necessary data vary depending on the scale and resolution of the assessment (Bachu, 2007). The basin-scaled capacity assessment methodology and empirical method of well injectivity are used in this site performance evaluation based on data availability and evaluation stage. The well pattern design is mainly based on the maximum injectivity of single vertical well and volumetric capacity method recommended by Goodman et al. (2011); the site performance model mainly follows the model used by Claridge (1972) and McCoy (2008b).

The CO_2-EWR model is similar to the CO_2-enhanced oil recovery (EOR) model. The enhanced water recovery is expressed in terms of the production of underground water volume (*OWIP*) and overall recovery efficiency (Claridge, 1972; Goodman et al., 2011; McCoy and Rubin, 2008). The recovery efficiency of water can also be obtained by empirical method, analysis method, or numerical simulation.

$$EWR = OWIP\bullet E_r \quad (10)$$

$$\text{the CO2 storage capacity: } M_{CO2} = \rho_{CO2res}\cdot OWIP\bullet E_r \quad (11)$$

$$OWIP = A_n\bullet h_n\bullet \varphi_e\bullet S_{wi} \quad (12)$$

$$E_r = E_m\bullet E_a\bullet E_v\bullet E_d \quad (13)$$

When no CO_2 recycling is assumed, the maximum CO_2 capacity of the storage site is the amount of injected CO_2 when CO_2 breakthrough occurs in the production wells; and in the sweep efficiency form, $E_r \le (F_i)_{BT}$. $(F_i)_{BT}$ can be obtained by

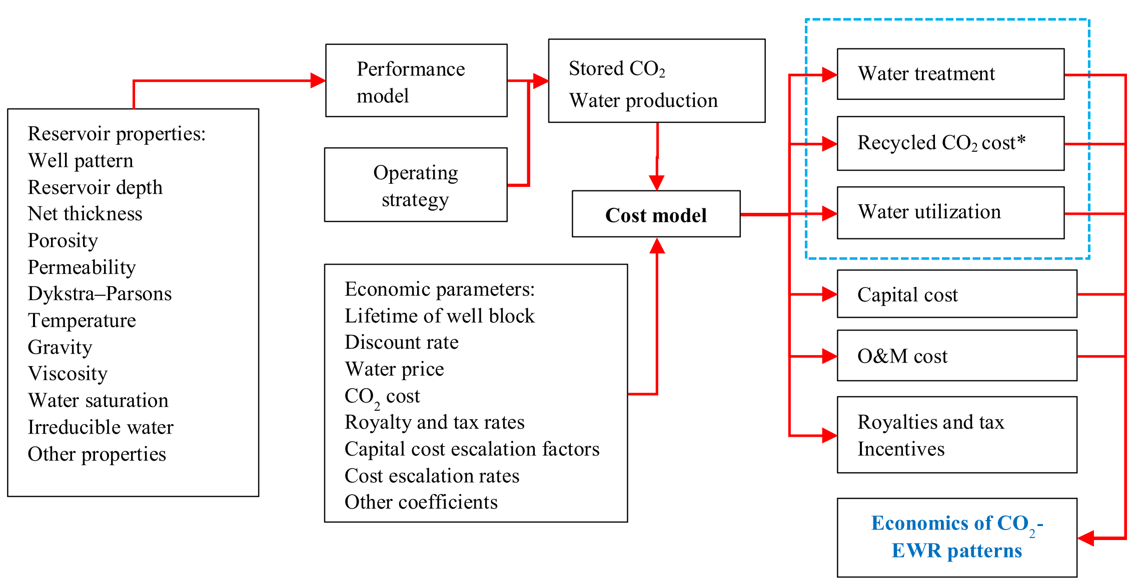

Fig. 4. Workflow for techno-economic evaluation of CO_2-EWR patterns.
*Possible scenario for CO_2-EWR technology when the re-injection of recycled CO_2 is economic.

$$\log(F_i)_{BT} = 0.2232\log(K)^2 - 1.3847\log(K) - 0.1809 \quad (14)$$

where K is the Koval factor and is the production of Koval mobility [-], $(F_i)_{BT}$ is the fraction of CO_2 amount in the formation to total water pore volume when CO_2 breakthrough occurs in the production wells [-]; EWR is the recoverable water [m^3]; $OWIP$ is the original water in place [m^3]; ρ_{CO2res} is the CO_2 density under reservoir condition [t/m^3]; E_r is the overall sweep coefficient [-]. The displacement efficiency components, such as mobilization efficiency (E_m), areal (horizontal) (E_a), vertical (E_v), and (linear) microscopic displacement efficiency (E_d), reflect different physical barriers that inhibit CO_2 from contacting the entire pore volume of a given basin or region. The detailed parameters and approaches are based on the paper by Claridge (1972) and McCoy (2008b).

The production of net area (A_n) [m^2], net thickness of geological formation (h_n) [m], average effective porosity (φ_e) [-], and water saturation (S_{wi}) [-] accounts for the total bulk volume containing the water to be assessed. and ρ_{CO2res} is the CO_2 density under reservoir conditions [t/m^3]. The sweep coefficients can also be obtained by the method recommended by Goodman et al. (2011).

$$E_r = E_a \bullet E_L \bullet E_v \bullet E_g \bullet E_d \quad (15)$$

The displacement efficiency components, such as areal (E_a) [-], vertical (E_L) [-], gravity (E_g) [-], and microscopic (E_d) [-], reflect different physical barriers that inhibit CO_2 from contacting the entire pore volume of a given basin or region. The percentage of net volume ($A_n \bullet h_n \bullet \varphi_e$) to the total geological volume ($A_{tot} \bullet h_{tot} \bullet \varphi_{tot}$) is a function of geologic parameters. Without site-specific geological conditions, E_r can also be obtained by other empirical models, analytical models, and numerical modeling, such as TOUGH2, CMG, or ECLIPSE.

The well pattern type and well injectivity depend on site-specific geological conditions, including the properties of reservoir, seal, and boundary conditions. The spatial distribution of reservoir-seal properties, such as porosity, permeability, top depth, net thickness of reservoir, fluid saturation, in situ pressure, threshold pressure, fracturing pressure, boundary conditions, and other properties, have great impact on well injectivity. Without site-specific geological conditions, the well pattern can be determined by maximum injectivity of a single well. The injectivity of a single vertical well is assessed by the following empirical model by Law and Bachu (1996):

$$Q_{CO2/well} = \alpha_{inject} \times \lambda_c \times h \times (P_{max} - P_{res}) \quad (16)$$

where $Q_{CO2/well}$ is the maximum CO_2 injection rate of a single well [t/d]; h is the reservoir thickness [m]; and P_{max} is the maximum pressure allowed for CO_2 injection, which is determined by the synthesis results of fracturing pressure, capillary pressure of caprock, and other properties [MPa]. The maximum injection pressure is also administrated by the legislation and regulation systems. P_{res} is the initial reservoir pressure [MPa]. α_{inject} is the injectivity coefficient, that is, $\alpha_{inject} = 0.0208\ [t/m^3]$ for vertical well based on field data, which includes the effect of perforation, casing, and maximum pressure of injection. The number of injection wells can then be obtained as follows:

$$N_{inject} = Ceil\ (\eta_{inject} \times m/Q_{CO2/well}) \quad (17)$$

where N_{inject} is the number of injection wells; m is the flow rate [t/d]; and η_{inject} is the injection coefficients that reflect the well pattern type, that is, five- or seven-spot well pattern, and pressure buildup effect. *Ceil* function returns the smallest integer greater than or equal to the value. Then, the total well number is the sum of injection, production, and additional wells for monitoring or engineering purpose. Maintaining sufficient well spacing d_{well} and distance between injection well and sensitive objects (e.g., abandoned wells, leakage faults, nearby reservoirs) can avoid possible leakage pathways, the boundary issued by administrative approvals, and contamination of energy and mineral resources. The five-spot well pattern is assumed in this evaluation; the ratio of injection well to production well is 1:1. The well spacing of well patterns and projected area of affected geological volume on the surface can be calculated as follows:

$$A = (365 \bullet Q_{CO2/well} \bullet CF \bullet N)/(\rho_{CO2res} \bullet h_n \bullet \varphi_e \bullet E_r) \quad (18)$$

$$d_{well} = \eta_{area} \bullet \sqrt{A/N_{inject}} \quad (19)$$

where A is the projected surface area of reservoir [m^2], which is the maximum migration radius of the CO_2 plume by single injection well over its lifetime; and η_{area} is the coefficient of the surface area caused by reservoir heterogeneity and variation of injection strategies, that is, 1.0–3.0. N is the lifetime of CCUS project [year]; CF is the capacity factor [-]. Water recovery rate E_r by analytical model can refer to the iterative method by Claridge (1972) or other methods. The maximum plume radius at the end of injection, which determines the minimum well spacing, can also be refined by the analytical expression of Nordbotten et al. (2005). This analytic solution provides a quick estimate of the spread of the CO_2 plume during the lifetime of the operation.

2.4.5. Water Utilization belongs to the technical feature of integrated CCUS projects

The goals of water utilization will dictate the treatment processes, technical design, and costs for creating a useable water stream. The water treatment methods and water quality will affect capital investment and infrastructure decisions for water treatment. The water treatment methods include membrane method, thermal method, evaporation, and underground reinjection. Among these methods, the membrane methods (reverse osmosis (RO) and nano-filtration (NF)) and thermal methods (multiple-effect distillation (MED) and multiple-stage flash (MSF)) are the most applicable for CO_2-EWR. The treatment method selection depends highly on the total dissolved solid (TDS) of water. For legislation requirements of no evaporation pool and no waste disposal into natural water systems in China, a hybrid water treatment method for industrial utilization is used in this evaluation. The schematic of the treatment method is shown in Fig. 5. In this method, the pretreated water is desalinated by the membrane process. The concentrated water is then desalinated by thermal method. Afterward, highly concentrated water, which is not economic for further treatment, is re-injected underground to satisfy the zero-waste policy in China. The desalinated water is ready for industrial utilization. This schematic can be adjusted based on site-specific situations. The performance model of water treatment follows that by Sullivan et al. (2013) and the DEEP model (Desalination Economic Evaluation Program).

During a preliminary system design phase, site-specific information is unavailable. Thus, literature data must be used to assess the entire processes and costs. The goal in this analysis is to provide and evaluate reasonable cost ranges at appropriate levels, and not to provide specific technical design and budgetary costs, given the uncertainties in underground water quality, site parameters, energy supply, and final system design considerations that will be determined in the future. The cost range estimates can help evaluate future risks of investment and system design (Ziemkiewicz et al., 2015).

2.4.6. Summary of key technical characterization for full-chain CCUS project

The CO_2 stream from industrial separation process in the coal chemical plant is suitable for CO_2 geological utilization and storage. The technical characteristics are as follows. CO_2 is collected from an industrial separation process with some technical alterations for pure CO_2 stream in the coal chemical factory. The process adjustments include altering N_2 stripping gas to CO_2 or large-volume vacuum pumps in the last flash regeneration towers in the rectisol process, which is commonly used in China. CO_2 is then compressed and transported to selected suitable aquifer sites for CO_2-EWR. The CO_2 is injected into the deep saline aquifer and the produced water is desalinated for water sale. The major technical characteristics of full-chain CCUS projects are

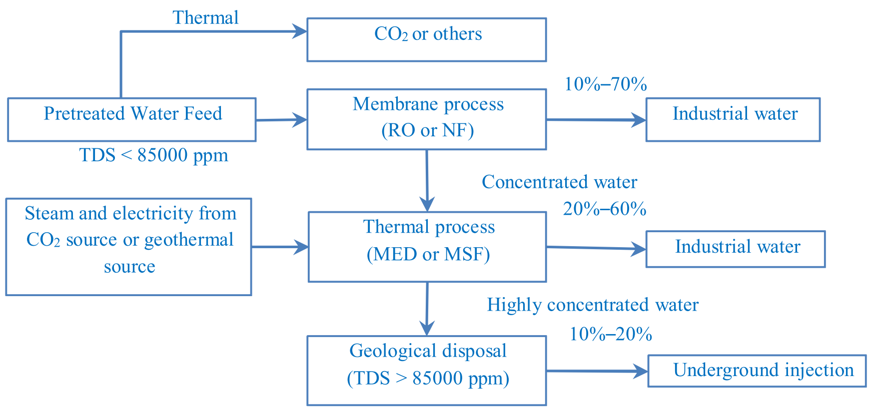

Fig. 5. Schematic of hybrid water treatment method.

Table 4
Major technical characteristics of full-chain CCUS projects.

Lifetime	CO_2 capture	CO_2 compression	CO_2 transport	CO_2 utilization and storage options
20 years for the entire project	Gaseous CO_2 (0.10 MPa and 30 °C)	0.10 MPa to pipe inlet pressure (12 MPa)	Dense CO_2 pipeline	CO_2-EWR and water desalination for sale

shown in Table 4. A basic assumption is that the technical alteration of industrial separation processes and related costs is not included in the techno-economic evaluation of the CCUS project and that 100% of the pure CO_2 stream can be used for the CCUS project.

The compression process uses a five-stage compressor from 0.15 MPa to cut-off pressure (e.g., 7.38 MPa) and the one-stage pump continues to allow inlet pressure of pipeline (12.0 MPa in this evaluation). The technical parameters and economic evaluation follow the parameters and methods by McCollum and Ogden (2006) and Dahowski et al. (2012). The major technical parameters for the CO_2 compression are shown in Table 5.

Route selection of pipeline is essential for the safety and cost of pipeline projects. However, while actual route selection will occur during early project development, the pipeline distance estimated for costing purposes in this evaluation is based on 1.17 times the straight line distance between the source and sink (center of storage sites), which is similar with the method used by Dahowski et al. (2012). The major technical parameters for the pipeline project are shown in Table 6.

The operating strategy of multiple injection wells with pressure control wells (or water production wells) are selected for this large-scale CO_2 injection process, which is similar with that of the CO_2-EOR process. The five-spot well pattern is selected in this techno-economic evaluation. The produced saline water is transported to nearby cities for water desalination and industrial utilization. The site performance follows the analytical method described above. The CO_2-EWR can provide water resource for industrial utilization, which is vital in arid and highly water-constrained regions in the north, northwest, and northeast regions of China. In these regions, the price of industrial water is diverse and ranges from 1.0 to 3.0 USD/t. An average price of 2.0 USD/t desalinated water is assumed for all regions for the water treatment in the CO_2-EWR process. The major technical parameters for the CO_2-EWR project are shown in Tables 7 and 8.

Table 5
Major technical parameters for CO_2 compression.

Parameter	Definition [Unit]	Deterministic parameter
P_{in}	Inlet pressure [MPa]	0.15
P_{out}	Outlet pressure [MPa]	12
T	Average CO_2 temperature [°C]	30 °C

Table 6
Major technical parameters for pipeline project.

Parameter	Definition and Unit	Deterministic parameter
L	Source-sink Distance [km]	Given by source–sink matching model
P_{in}	Inlet pressure [MPa]	12
P_{out}	Outlet pressure [MPa]	9
T	Average CO_2 temperature [°C]	Average surface temp
T_g	Average ground temperature [°C]	10
Z_{CO2}	CO_2 compression factor	PVT data by Peng-Robinson method
ρ_{CO2}	CO_2 density [kg/m^3]	PVT data by Peng-Robinson method
D	Pipeline diameter [mm]	Calculated by equation
	Pipe steel grade	X70 steel
σ_s	Steel yield stress [MPa]	483

2.5. Economic feature of integrated CCUS project

The economic evaluation includes the economic model and economic parameters of the integrated CCUS project and can be conducted based on the technical feature or technical design.

2.5.1. Economic model

The cost of a full-chain CCUS project for each identified case includes cost components of CO_2 compression, CO_2 pipeline transportation, and CO_2-EWR. The cost evaluation for each technical component includes Capital Expenditures (CAPEX), and Operation and Maintenance (O&M) costs (Rubin et al., 2015). For CO_2-EWR, additional revenue from water sale is considered in the model. The schematic diagraph of techno-economic evaluation on a full-chain CCUS project is shown in Fig. 6. The alteration or improvement cost of CO_2 stream from industrial separation processes is not considered here.

This budget-type techno-economic model includes costs of major technical components used in various techno-economic models. The economic model of CO_2 compression is mainly based on the economic model by McCollum (2006). The CAPEX of CO_2 compression mainly considers the cost of five-stage CO_2 compressors and one-stage pumps, and supplementary facilities. By contrast, O&M cost consists of equipment maintenance and energy consumption. The economic model of the pipeline also includes the CAPEX and OPEX. The total pipeline

Table 7
Major technical parameters for CO_2-EWR project.

Parameter	Definition [Unit]	Range of value
h_n	Net thickness of aquifer formation [m]	[50–300] depending on the sedimentary basin
φ_e	Average effective porosity of reservoir	[0.125–0.25] depending on the sedimentary basin
K_h	Vertical and horizontal permeability [mD]	[1–50] depending on the sedimentary basin
TDS	Total dissolved solid [ppm]	25000
$Type_{pattern}$	Type of well pattern (e.g. five- or seven-spot)	5-spot well pattern
DP	Dykstra–Parsons, heterogeneity coefficient (e.g., 0.7–0.9)	[0.7–0.9] depending on the sedimentary basin
d_{well}	Well spacing [m]	Calculated by model
$Depth$	Average well depth in reservoir [m]	[1000–3000] depending on the sedimentary basin
T	Reservoir temperature [°C] (e.g., 70 °C)	[40–70] depending on the sedimentary basin
P_{water}	Price of industrial water nearby the storage site [USD/t]	2.0

Table 8
Major economic parameters for full-chain CCUS project.

Parameter	Definition [Unit]	Deterministic parameter
CF	Capacity factor	0.8
N	Lifespan of CO_2-EWR project [a]	20
r	Discount rate [%]	10%
P_{ele}	Electricity price [RMB/kW·h]	0.509
P_{water}	Price of industrial water nearby the storage site [USD/t]	2.0

investment cost is affected by the location and landform factors, in addition to the transportation scale and length of the pipeline. The cost model of the pipeline follows the budget-type pipeline model by Wei et al. (2016). The cost model of CO_2-EWR follows the CO_2-EOR model by Wei et al. (2016) and CO_2-EWR model by McCoy (2008a). The CAPEX of CO_2-EWR includes the costs of site characterization and evaluation, well drilling and completion, CO_2 flow line and connections, injection equipment, water production equipment, water treatment plant, and MVA.

CCUS costs are highly sensitive to the techno-economic parameters and market conditions. Technical parameters (e.g., system service lifetime; project scale; and reservoir properties, including reservoir and fracture pressure, thickness and depth, and permeability) are highly site-specific. Economic parameters are discount rate, tax policy, electricity prices, pipeline length, geographic features, reservoir properties, and so on. Among these parameters, reservoir properties have significant effects on the geological utilization and storage cost via the design of well pattern and site performance.

Economic parameters mainly originate from different sources, including 1) economic parameters used by petroleum industries (e.g., PetroChina and Sinopec (Zhou et al., 2012)) and 2) consultations from experts from related enterprises and design institutes. All the costs and revenues are escalated to 2012. Then, the levelized cost is shown in net present value, as follows:

$$C_{levelized} = Cost^{annual}/Q_{CO2} \tag{20}$$

The net present value of levelized cost is

$$C_{levelized} = NPV/M_{CO2} \tag{21}$$

No specific transfer of carbon value is found among the different components of an integrated CCUS project. Therefore, the tax related carbon transfer is not considered in this evaluation. Meanwhile, the policy related to CO_2 mitigation is unclear; thus, the tax ratio and incentives of the integrated CCUS project is assumed as 0% in this evaluation.

2.5.2. Economic parameters

The cost parameters of integrated CCUS projects vary because of the diverse conditions across various regions, such as differences in topography, vegetation, economy, population, and industry policy. Cost parameters differ for each region. The main material charge can be simplified as material price multiplied by the domestic material freight rate in different regions by statistical data (CNPC, 2010; Sinopec, 2010a). The regional difference does not show significant difference (± 30% variation) in levelized costs of CO_2 capture, transportation, and storage. However, detailed evaluation of the cost of potential CCUS projects crossing different regions is difficult. The cost components for this macro-scale economic evaluation use the cost parameters of Central China as a reference. The economic parameters, such as main material, transportation, installation, land requisition, verification, energy, labor, and evaluation fee, can refer to the economic parameters presented in

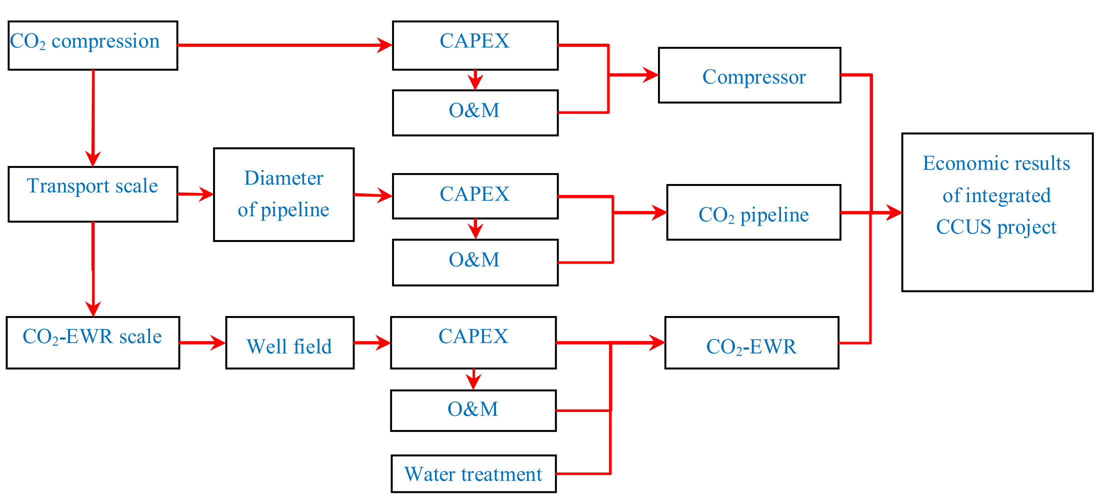

Fig. 6. Schematic of techno-economic evaluation on full-chain CCUS project.

the "China National Petroleum Construction Project Economic Evaluation Parameters" (Sinopec, 2010b; Zhou et al., 2012).

2.6. Cost curve development

The development of a cost curve for CCUS necessitates quantifying full end-to-end costs for the set of all feasible source–sink pairs to conduct optimized source–sink matching, which is similar to the analysis by Dahowski et al. (2012) but with numerous updates and refinements.

The source–sink matching model considers the preliminary technology design and economic evaluation of full-chain CCUS project, such as source location, capture technology, size, compression technology, pipeline routing, reservoir capacity, injection strategy, injectivity, and potential for enhanced resource recovery for each prospective reservoir. As described in the paper by Dahowski et al. (2012), this source–sink matching evaluation effectively assumes that all modeled CO2 sources immediately seek to begin CCUS operations at the beginning of the analysis. Although this assumption is unrealistic, this assumption is useful and necessary from the standpoint of evaluating the potential and costs for large-scale CCUS to deploy across a nation's geographic and industrial landscape, which is what the resulting cost curve depicts. This assumption focuses purely on defining the magnitude and range of costs for matched CCUS capacity over the set of modeled CO_2 sources and storage reservoirs to better understand the potential for CCUS and in this case CO_2-EWR.

The cost of each source–sink pair can be evaluated with GIS data of reservoir properties of suitable sites, CO_2 sources, and spatial analysis tools with techno-economic model in GIS software. Resulting costs, including CO_2 capture (not included in this evaluation), compression, transport, storage, and offsetting revenue, are evaluated in the pairing process. The matching process is performed by a competitive, site-constrained, least-cost optimization algorithm as described by Dahowski et al. (2012).

Based on the source–sink matching results, the cost curves are obtained as annual cumulative CO_2 storage capacity (x-axis) against the levelized cost of each source–sink pairs (y-axis) sorted by increasing order of levelized cost. As a result, a cost curve generated from a 20-year analysis period represents the maximum CO_2-EWR deployment capability of modeled CO_2 sources and evaluated storage reservoirs over that timeframe, and presumably a more realistic deployment capability over a much longer period.

3. Evaluation results and discussion

The objective of this evaluation is to determine the magnitude of annual cumulative matched CO_2 capture and storage capacity, enhanced water production potential, distribution of potential project sites, and cost ranges for CCUS with CO_2-EWR deployed in onshore aquifer sites using CO_2 from industrial separation processes in the coal chemical industry in China. The evaluation results include cost curve results and mapping of source–sink pairs.

3.1. Cost curve results

The resulting cost curve for the first 20 years of full-scale CCUS deployment in coal chemical factories based on 2015 full capacity is presented in Fig. 7. This curve indicates that potential CCUS projects can realize 269 Mt CO_2 emissions mitigation with levelized cost ranging from 11 USD/t to 30 USD/t CO_2 stored. This is the set of lowest-cost CCUS options available to couple CO_2 sources with storage reservoirs, subject to the stated capacity and distance constraints. The individual points on this curve represent viable combinations of specific source–reservoir pairs. Selected points from the cost curve results are highlighted and examined more closely in Table 9. Cost curves for complete end-to-end CCUS systems, which are based on optimized source–sink matching, provide an informative framework to examine the potential for commercial-scale CCUS to deploy across the coal chemical industry and locations in China.

The resulting curve comprises 297 pairs emitting between 0.08 Mt and 9.6 Mt CO_2 annually with an average of 1.02 Mt/a. The longest part of the cost curve stretches from approximately 11 Mt/a to 269 Mt/a of matched CCUS capacity with accompanying costs that range from 11 USD/t to 30 USD/t CO_2. Key points include 103, 211, 245, 269, 283, and 287 Mt/a at levelized costs of 15, 20, 25, 30, 40, and 50 USD/t, respectively. Every point in the cost curve represents a potential CCS project with a specific CO_2 source and the low-cost aquifer site within the modeling framework described above. The low-cost portion of the curve consists of approximately 211 Mt/a of matched CO_2 storage capacity at a levelized cost less than 20 USD/t and extends up to approximately 269 Mt/a at cost of 30 USD/t CO_2, before the slope turns steeper, indicating less potential at higher costs. The rapid increases of the cost above 269 Mt/a mainly result from small sizes of CO_2 sources and long transport distances. These preliminary results suggest that CO_2-EWR technology in the full capacity of coal chemical factories in 2015 in China can store 269 million tons of CO_2 annually from several typical modern coal chemical processes at relatively low cost that ranges from 11 USD/t to 30 USD/t CO_2. Furthermore, approximately 404 million tons of underground water for further desalination and industrial utilization could be produced.

3.1.1. Low-cost portion of the cost curve: possible early opportunities

This part of the curve contains 110 source–sink pairs with costs less than 20 USD/t and 91 source–sink pairs with between 20 USD/t and 30 USD/t, thereby representing approximately 37% and 17% of the total factories, respectively. Annual pure CO_2 emission rates from the sources range from 0.2 Mt/a to 9.7 Mt/a with an average of 1.34 Mt/a. Many of the resulting pairs require short pipelines to reach suitable storage reservoirs, although some sources end up building longer pipelines to reach more attractive sites. The resulting average transport distance for the entire group of potential projects is 68.9 km. Thus, the potential CCS project pairings identified in this low-cost portion of the cost curve may effectively represent promising early deployment opportunities. However, significant uncertainties remain and require additional techno-economic parameters and more detailed evaluation.

3.1.2. High-cost tail of the cost curve: Small, un-economic CCUS potential

The tail of the resulting cost curve (with resulting costs over 30 USD/t) is a short and steep section characterized by small projects with rapidly increasing costs (increasingly so for the projects with costs exceeding 50 USD/t). The pairs in this part of the curve, which provide only approximately 30 Mt/a of matched storage capacity, represent the types of CCUS projects that are unlikely to be considered viable options given their higher costs (ranging from 30 USD /tCO_2 to over 100 USD/tCO_2). The 58 source–sink pairs in this part of the curve represent sources ranging from 0.08 Mt/a to 1.24 Mt/a with an average of 0.33 Mt CO_2/a. Many of the resulting pairs require long pipelines. The resulting average transport distance for the entire group of potential projects is 134 km. These long transport distances, combined with higher-cost storage reservoirs and small sources sizes, lead to above average costs for this tail of the curve.

A total of 26 stranded CO_2 sources cannot match with suitable sites within 250-km searching range. These sources range in size from 0.12 Mt/a to 1.28 Mt/a with an average of 0.54 Mt CO_2/a. While accessing CO_2 storage via long pipelines may be an option, the reality is that longer pipelines add significant cost to these projects and make them less likely, particularly for early deployment without sufficient technology reserves and established pipeline network. Thus, these stranded CO_2 sources are not analyzed in this study.

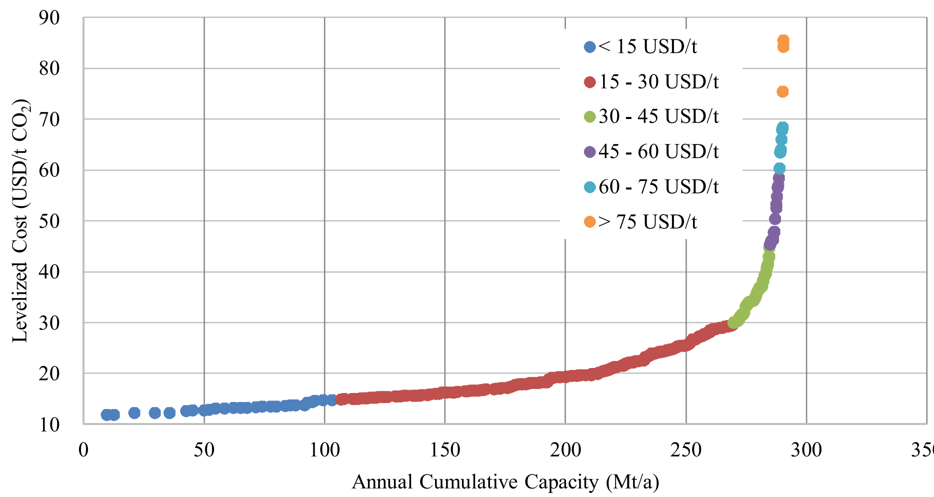

Fig. 7. Cost curve of possible full-chain CCUS project versus annual cumulative capacity based on full capacity of coal chemical industry in 2015 (250-km searching range).

Table 9
Selected points in the cost curve results for full capacity in 2015.

Source number	Levelized cost (USD/t)	Annual CO2 capacity (Mt/a)	Annual water supply (Mt/a)	Percentage of total number
27	≤ 15 USD/t	103	155	9%
110	≤20 USD/t	211	317	37%
160	≤25 USD/t	245	367	54%
201	≤30 USD/t	269	404	68%
239	≤40 USD/t	283	425	80%
252	≤50 USD/t	287	430	85%
259	≤60 USD/t	288	433	87%
271	≤100 USD/t	291	436	91%

3.2. Mapping the cost curve results

An examination of these regions of the resulting cost curve is useful to provide better insight into the general or typical characteristics of the source–sink pairings. However, over-generalization should be avoided because many combinations of features contribute to the cost and potential viability of a given pair.

Fig. 8 presents another useful way to examine the results of this optimized, capacity-constrained, source–sink matching procedure that is used to develop the cost curve. The 297 modern coal chemical factories are mapped and colored to indicate their position and levelized CCUS cost. The map highlights the range of estimated matched CCUS costs by source color across China and validates the broad applicability of CCUS for a large majority of China's coal chemical factories. The majority of promising lowest-cost CCUS project opportunities are located across North, Northeast, and Northwest China. The highest-cost projects typically coincide with extremely small CO_2 sources located either a long distance from suitable storage reservoirs or in areas with significant with reservoirs having lower injectivity or where there is strong competition for reservoirs from other sources. This result suggests that early opportunity siting can have better access to desirable sites and be relatively flexible geographically, thereby allowing for other factors to be considered in siting decisions.

The resulting possible full-chain CO_2 capture and CO_2-EWR project site distribution for the modern coal chemical industry in China is shown in Fig. 9. Most of these source–sink pairs are located in arid areas, such as Northwest and North China. These locations are crucial for CO_2 mitigation and the industrial and economic development in these regions. Thus, the CO_2-EWR projects associated with pure CO_2 from coal chemical industries can mitigate 269 million metric tons of CO_2 with a levelized cost less than 30 USD/t. The projects can provide vital water resources for industrial utilization in arid areas. The combination of CO_2-EWR from pure CO_2 streams in coal chemical factories might be an early opportunity to scale-up and demonstrate large-scale CCUS technology in China. The figure also shows the 26 excluded CO_2 sources (empty circles, as the stranded sources were identified to be in Southwest, East, and Northeast regions) for which no storage options are reachable within the 250-km maximum search radius employed in the study. Together, the stranded sources represent nearly 14 Mt/a and less than 5% of total CO_2 emissions from industrial separation processes in modern coal chemical factories that are unable to be stored because of limited regional supplies of CO_2 storage capacity. The largest concentrations of excluded and stranded CO_2 sources occur in the southwest, east, and northeast regions of China. Developing backbone pipeline network connecting nearby storage options might provide a viable option for CO_2 geological storage to such areas and help to alleviate a potentially growing mismatch between supply and demand for storage further north.

3.3. Scenario analysis

The CO_2 stream from industrial separation processes are approximately 142, 304, and 907 Mt annually for actual operating capacity in 2015, designed full capacity in 2015, and total capacity in 2016, respectively (including capacity in operation and verified factories). Due to the significant inconsistences in the CO_2 emissions under different production capacities, various scenarios analyses are conducted for further understanding.

The relationship between levelized cost of possible full-chain CCUS projects and annual cumulative CO_2 capacity in the coal chemical industry under various scenarios is shown in Fig. 10. The key results from the various scenarios are highlighted in Table 10. The CO_2 storage capacity with levelized cost less than 30 USD/t can reach 106, 269, 507, 690, 878 Mt/a under various scenarios of actual production in 2015, full capacity in 2015, 60% of total capacity, 80% of total capacity, and total capacity in 2016, respectively. The produced underground water can reach 160, 404, 761, 1035, and 1318 Mt/a for further water desalinization and industrial utilization. When the total capacity in 2016 for the coal chemical industry becomes fully operational, the CO_2-EWR projects with CO_2 streams from industrial separation processes in modern coal chemical industry will be able to mitigate huge CO_2 emissions and provide notable water resources. Therefore, these typical processes in the modern coal chemical industry in China may provide low-cost and attractive early opportunities to deploy and accelerate large-scale CCUS projects within China in the near future.

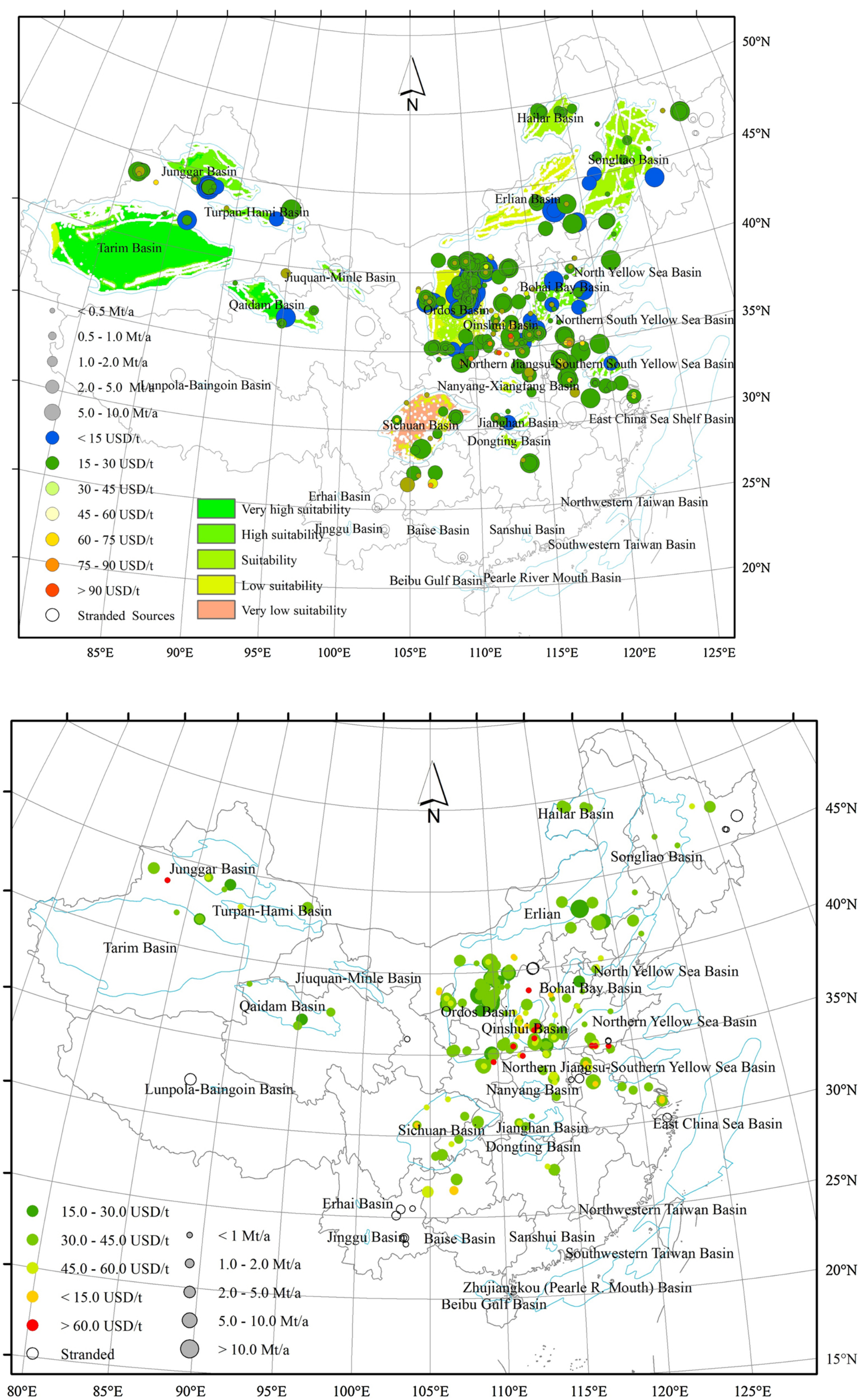

Fig. 8. CO_2 stream from industrial separation process with potential CCUS cost (250-km searching range).

The capacity of onshore aquifer sites has sufficiently high levels such that the supplied CCUS capacity remains relatively unchanged over several 20-year capacity-constrained full-scale deployment periods. The sensitivity study on several 20-year scenarios is not conducted in this cost curve study.

3.4. Limitations of this study

This techno-economic evaluation can provide a first-look and first-order evaluation of CO_2 storage options and costs of CO_2-EWR in the modern coal chemical industry within onshore China and provide a

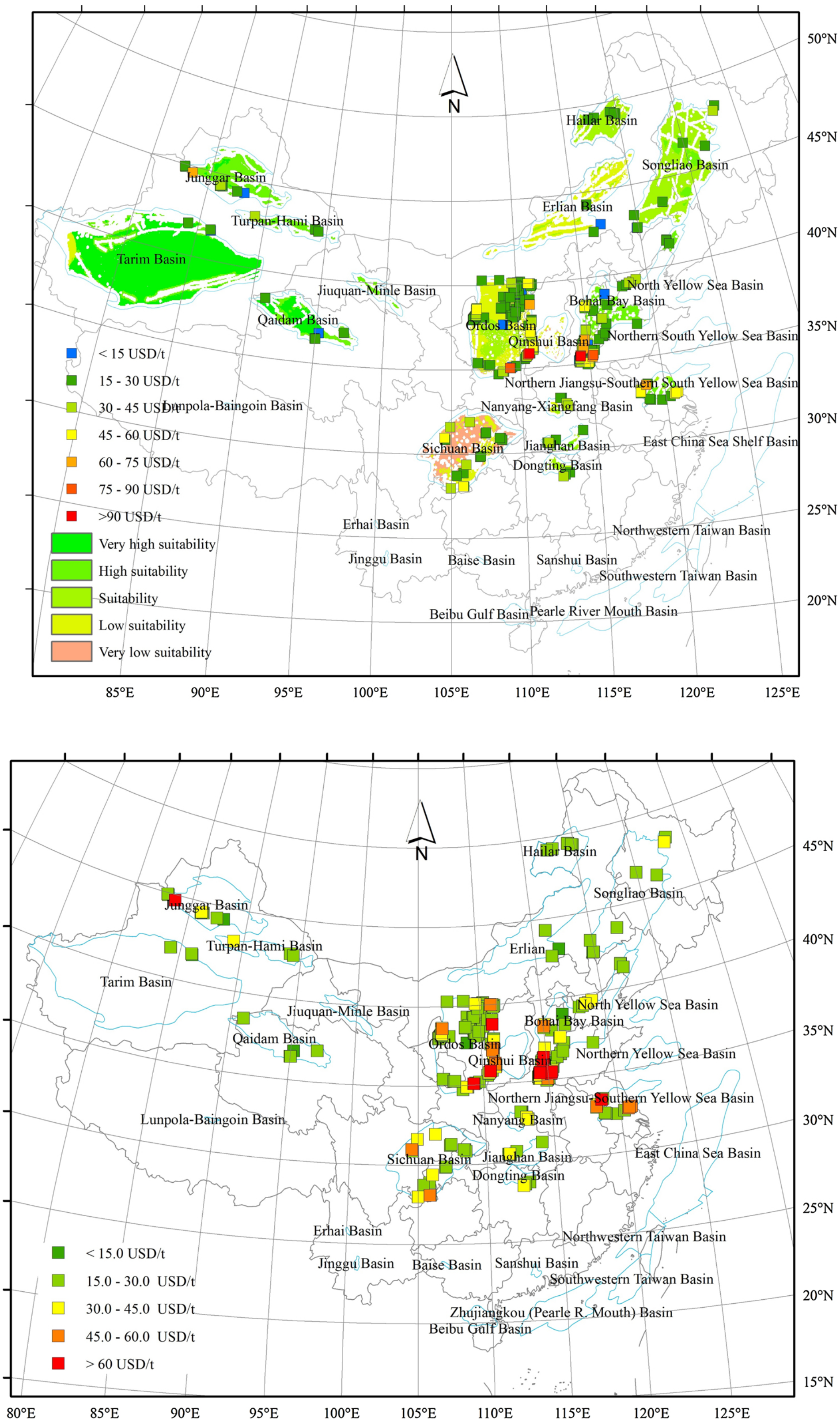

Fig. 9. Possible CO_2-EWR project site distribution of with site suitability in China (250-km searching range).

foundation for further project screening and selection via more detailed feasibility study. However, numerous additional areas are available for future research on the potential for CO_2-EWR technologies to deploy in the modern coal chemical industry within China. These areas include improved inventory methodology of CO_2 emission, geological characterization and site performance evaluation, and source–sink matching modeling. Continuous effort to update CO_2 stream characterization from various coal chemical processes and stages is important, especially for these CO_2 sources under development with high uncertainty. Continuous development of core data and understanding

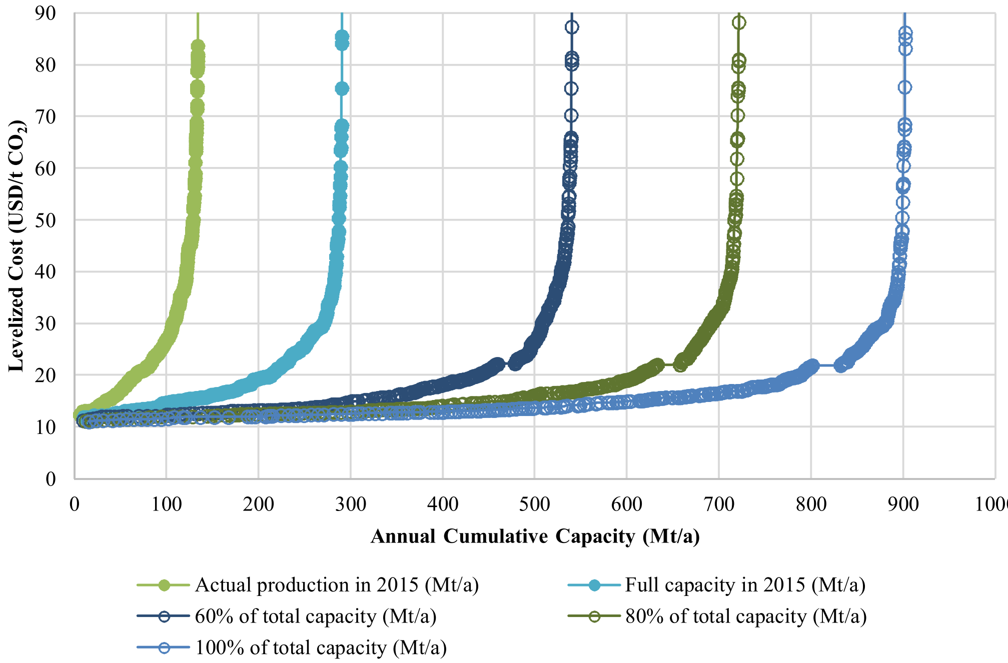

Fig. 10. Levelized cost of possible full-chain CCUS project versus annual cumulative CO_2 capacity in the coal chemical industry under various industry production scenarios.

of components of full-chain CO_2-EWR projects is also important. By using storage as an example, the sub-basin scale geology and injection strategy pertaining to the capacity, injectivity, suitability, timing of availability, geographic condition, and economic parameters have considerable effects on the techno-economic results of CO_2 storage. Though the model used in this study has been significantly updated, improved understanding of technical features, component costs, specific Chinese market conditions, and other factors that affect the costs of deployment in China will be important to consider. This and subsequent research will be critical in helping define carbon-dioxide mitigation and energy-related policy agendas in China, and understanding benefits, as well as potential challenges for both pilot and commercial-scale CCUS and CO_2-EWR projects.

The source–sink matching result is highly sensitive to technical and economic parameters. The source–sink evaluation in this study use representative data to evaluate the site suitability, techno-economic feasibility, and source–sink matching results of potential CO_2-EWR projects rather than using statistical data to provide a cost range for a specific source–sink pair. Therefore, these parameters should be studied carefully and evaluated with higher data resolution and more data types, as efforts move close to project development and practical application.

4. Conclusions

This analysis of the deployment potential for CCUS within the coal chemical industry in China evaluates the opportunities for supporting carbon mitigation and alternative water development via large-scale deployment of CO_2-EWR technologies within this growing industry. The results, while preliminary, offer useful insights into the potential application of the technologies within China and can help identify opportunities for additional early demonstration projects. An evaluation framework of source–sink matching for integrated CCUS project is developed in this study, which mainly includes CO_2 emission assessment, site suitability evaluation, and source–sink matching with techno-economic model. Then, the framework is applied to the several typical coal chemical processes in the proposed integrated CCUS demonstration projects in onshore aquifer sites in China. Through this systematic analysis, the key findings of this study are as follows:

1) The large CO_2 sources in several typical processes in the coal chemical industry (including coal to oil (direct and indirect liquefaction), coal to natural gas, coal to olefins, coal to ethylene glycol, and coal to dimethyl ether) are inventoried and mapped. Total CO_2 emissions are 258 Mt/a, 556 Mt, and 1551 Mt annually for actual operating capacity in 2015, full capacity in 2015, and total capacity in 2016, respectively (including capacity in operation, in construction, and verified by administrative organizations). The CO_2 streams from industrial separation processes alone are estimated at 142, 304, and 907 Mt CO_2 annually. Most of the plants are located in North, Northwest, and Northeast China. The CO_2 emissions from the coal chemical industry will significantly influence the strategy of CO_2 mitigation in China.
2) Source–reservoir matching with techno-economic model is analyzed. The preliminary study shows that the cost of commercial scale integrated CCUS (CO_2-EWR/storage) projects with the pure source

Table 10
Selected points in the cost curves under various industry production scenarios.

Scenarios	Number of sources	Maximum levelized cost	Annual CO_2 capacity (Mt/a)	Annual water supply (Mt/a)	Percentage of total CO_2 resource
Actual production in 2015	124	30 USD/t	106.4	159.6	30%
Full capacity in 2015	201	30 USD/t	269.0	403.5	68%
60% of total capacity in 2016	253	30 USD/t	507.3	761.0	60%
80% of total capacity in 2016	284	30 USD/t	689.7	1034.6	68%
Total capacity in 2016	309	30 USD/t	878.3	1317.5	74%

of CO_2 from a coal chemical plant can realize 106, 269, 507, 690, 878 Mt/a based on various capacity scenarios. These results are attained at costs ranging from 11 USD/t to 30 USD/t CO_2 under scenarios of actual production in 2015, full capacity in 2015, 60% of total capacity, 80% of total capacity, and total capacity for coal chemical industry in 2016, respectively. The corresponding produced underground water can reach 160, 404, 761, 1034, and 1318 Mt/a for further desalinization and industrial utilization. CO_2-EWR technology can help the coal chemical industry in China to control CO_2 emissions while enhancing water supply and enable this industry to be cleaner and more sustainable.

Results from this study reveal that the significant potential for CO_2-EWR technology to offer deep and sustained CO_2 emission reductions for China's coal chemical industry at a levelized cost of less than 30 USD/t. Therefore, CO_2-EWR technology can be essential to clean and sustainable development of the coal chemical industry in China, especially in arid areas. Meanwhile, the coal chemical industry may provide low-cost and attractive opportunities to accelerate the deployment of large-scale CCUS projects in China.

This national-scale assessment of large-scale deployment of CO_2 capture, pipeline transportation, and CO_2-EWR projects in modern coal chemical industry in China is based on available data and limited field experience. However, this preliminary assessment represents a first step in understanding the potential of CO_2-EWR technology to the coal chemical industry in China, and the degree to which the approach may be applicable to coal chemical facilities based on the scale, proximity, and characteristics of CO_2 emissions and available storage resources. Numerous additional areas are found for future research on the potential for CO_2-EWR technologies to be deployed in the modern coal chemical industry in China, for supporting low-carbon economic growth while addressing water scarcity challenges.

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