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CCS Clusters Provide a Decarbonization Pathway for China's Small-Scale Coal-Fired Power Plants

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Abstract

Coal-fired power plants account for about half of China's energy-related CO₂ emissions, making their decarbonization critical for climate change mitigation. However, small-scale facilities have received limited attention in carbon capture and storage (CCS) deployment due to their limited economies of scale. CCS clusters provide a cost-effective pathway to mitigate emissions from these plants. Four CCS deployment scenarios are developed to examine the mitigation potential and economic implications of including small-scale facilities. Point-to-point and clustered source-sink matching are applied to 3983 facilities and national storage site data for oilfields and saline aquifers. Results show that small-scale facilities account for 3.2 Gt CO₂ of cumulative abatement over 2030–2060, reducing the contribution required from large facilities. CCS clusters further reduce average transport distances for small-scale facilities by 71.5% and limit system cost increases to 0.4%, compared with a 3.8% increase under point-to-point layouts. Compared with the large facility point-to-point scenario (36.1 \$/t), the average levelized cost of CCS is 12.7% lower when small-scale facilities are included and 15.5% lower under clustered deployment. These findings can support the sustainable transformation of China's coal power sector by informing CCS deployment and shared infrastructure planning.

Keywords: small-scale coal-fired power plant; CCS cluster; carbon neutrality; source-sink matching; climate change mitigation; energy sustainability



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1. Introduction

Human activities have increased global surface temperature by more than 1 °C above pre-industrial levels [1,2]. These changes have implications for power systems. Higher temperatures alter heating and cooling demand, while changes in wind speed and solar radiation affect electricity generation. Previous studies have examined these effects on generation capacity [3], supply reliability [4], and power system adequacy [5]. Power systems also affect the climate. Fossil-fuel power generation produces large amounts of CO₂ and contributes to global warming. Emissions from China's coal-fired power plants account for about one-seventh of global CO₂ emissions from fossil-fuel combustion and nearly half of China's CO₂ emissions from fossil-fuel combustion [6–8]. China has pledged to peak carbon emissions before 2030 and achieve carbon neutrality before 2060. It also submitted an updated Nationally Determined Contribution (NDC) in 2025 [9]. Meeting

these targets will require substantial emissions reductions from the power system. Against this background, achieving an orderly reduction in emissions from coal-fired power plants (CFPPs) is one of the issues facing China's low-carbon power transition.

As renewable generation expands, coal-power utilization rates and generation are expected to decline [10]. Under a transition scenario with lower coal-power demand and extensive CCS retrofitting, CO₂ emissions from CFPPs could fall to approximately 3% of national emissions by 2060 [11]. Existing plants may be retired, operated flexibly, co-fired with biomass, or retrofitted with carbon capture and storage (CCS) [12]. If these plants are compulsorily retired and replaced with zero-carbon power sources, their direct operating emissions can be avoided. However, most of China's CFPPs are less than 15 years old, compared with a typical design lifetime of 30 years [13]. Accelerated retirement could therefore increase the risk of stranded assets. Reducing operating hours can lower coal-fired generation, while flexibility retrofits can support the integration of renewable energy. However, neither measure eliminates the CO₂ emissions from plants that remain in operation. Although nature-based solutions can contribute to carbon removal, their potential is limited by land availability and ecological constraints [14]. CCS can reduce these remaining emissions through CO₂ capture, compression, transport, and geological storage.

Source-sink matching models are important tools for exploring CCS deployment pathways. They generally integrate spatial information with mathematical optimization to identify connections between emission sources and storage sites and to design transport networks under technical and economic constraints. Depending on the model formulation, linear, mixed-integer linear, or nonlinear programming may be used. Early models centered on source-sink connections and CO₂ pipeline network optimization. As datasets and optimization methods improved, the models expanded to include mitigation targets, storage injectivity, phased deployment, and multi-objective decision-making, and evolved from individual source-sink connections to cluster planning with multiple sources, multiple sinks, and shared pipeline networks. Representative models include SimCCS [15], SimCCS_TIME [16], InfraCCS [17], and C³IAM/GCOP [18]. These models have been applied at global, national, and regional scales to assess CCS layouts [19–21], mitigation potential [18,22–24], pipeline infrastructure [25], and economic performance [26,27].

However, small-scale coal-fired power facilities (hereafter referred to as small-scale facilities) have received limited attention in CCS assessment, largely due to limited economies of scale [21,28,29]. CCS retrofit candidates are coal-fired power facilities considered for retrofit in the optimization model. Previous studies generally consider only facilities above 300 MW with more than 15 years of remaining lifetime (Table S1). As a result, many small-scale facilities with capacities below 300 MW are excluded from CCS assessments. Although individual facilities have relatively small installed capacities, their aggregate CO₂ emissions at the national level are not negligible [30]. In addition, some small or older facilities normally given low priority may still offer low-cost CCS retrofit opportunities because of their favorable locations relative to storage sites [31]. Capture technologies tailored for small-scale facilities are increasingly being developed (Table S2) [30]. Modularization and standardization in equipment manufacturing reduce construction time and lower capture capital costs, including rotating packed beds and prefabricated absorber units [32]. Studies also show that unit capture costs in solvent-based post-combustion capture processes exhibit limited sensitivity to facility scale [33], and scale-related economic disadvantages may have been overstated.

In addition to capture costs, transport and storage (T&S) costs influence the economic feasibility of CCS for small-scale facilities. Under point-to-point deployment, each source is connected to a storage site through a dedicated pipeline. For geographically dispersed facilities, dedicated pipelines and injection infrastructure can impose substantial additional

costs, limiting economic viability. CCS clusters and hubs allow multiple facilities to share infrastructure [34]. This can reduce unit costs and improve network utilization, making CCS more affordable for small-scale facilities. While some countries have begun exploring the development of small-scale industrial facility clusters [35], the system-level implications of incorporating these facilities into national CCS deployment strategies warrant further assessment.

This study aims to explore the mitigation potential and economic feasibility of CCS retrofits for small-scale facilities and to assess whether clustered transport and storage networks improve their deployment conditions relative to point-to-point connections. The analysis includes 3983 coal-fired power facilities as emission sources, 24 main sedimentary basins and 1181 oilfields as storage sites ($40 \times 40 \text{ km}^2$). Based on these data, two source-sink matching models are developed for point-to-point and clustered transport networks. Each model is applied to two candidate sets, including large facilities only or both large and small facilities, producing four scenarios. The effects of candidate coverage and network configuration on mitigation contribution, transport distance, and deployment costs are subsequently evaluated. The results provide facility-level evidence on the role of small-scale facilities in China's power system decarbonization and support the coordinated planning of CCS deployment and regional cluster infrastructure.

2. Methods

This section describes the methodology used to assess whether CCS clusters can provide a decarbonization pathway for small-scale coal-fired power plants in China. The analysis uses models and scenario comparisons to examine different CCS deployment configurations. The following subsections present the overall research framework, data sources, source-sink matching models, and scenario settings.

2.1. Framework

This framework consists of four main components: data inputs, CCS deployment modeling, scenario design, and CCS retrofit opportunity assessment for small-scale facilities (Figure 1).

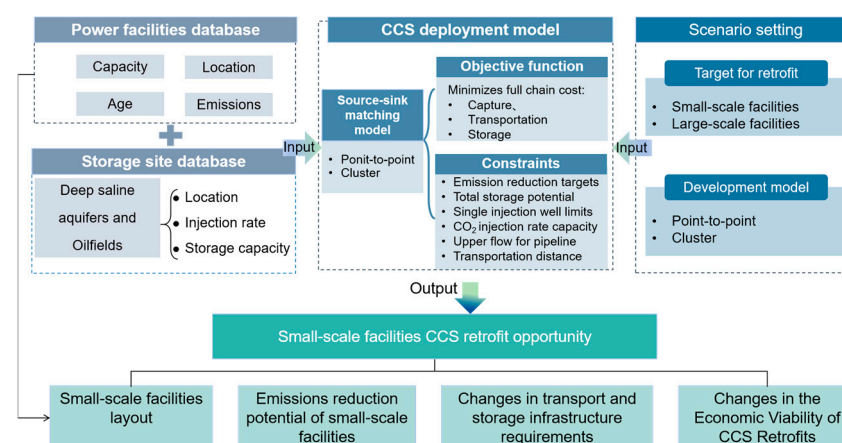


Figure 1. Model framework.

The data inputs include the power facility database and storage site data. The power facility database supports the characterization and spatial layout analysis of small-scale facilities. The storage site data provide geological storage capacity and injection rate capacity for candidate sites. Based on these inputs, CCS deployment is optimized using source-sink matching models under specified mitigation constraints. Both point-to-point and clustered configurations are considered to identify the spatial deployment patterns,

retrofit scale, and transport and storage (T&S) networks. Four scenarios are constructed by varying retrofit scope and network development model. The optimized results are used to evaluate CCS deployment opportunities for small-scale facilities, including emission reduction potential, T&S infrastructure requirements, and economic viability. Detailed descriptions of the data sources, model formulation, and scenario settings are provided in the following sections.

2.2. Data Sources

The power plant facility database is primarily sourced from the publicly available Global Coal Plant Tracker [36]. It is supplemented by World Electric Power Plant Database [37] and further augmented and cross-validated using several industrial databases [38,39]. The integrated database contains plant-level attributes including installed capacity, commissioning year, technology type, operational status, and geographic coordinates. These records represent the current status of existing facilities and reported planned projects rather than historical time-series data or model-generated future projections. The final database covers 3983 power facilities. Among them, 3199 facilities are currently operational with a combined installed capacity of 1175 GW, accounting for roughly 77.6% of the national total installed capacity in 2025 [40]. An additional 784 facilities, with a total planned capacity of about 434 GW, are in the announced, permitted, pre-permit, or under-construction stages.

The optimal spatial density of CO₂ injection wells lacks a widely accepted engineering benchmark. Based on engineering practice and existing studies [41], an existing national CO₂ storage site database was spatially aggregated from 5 × 5 km to 40 × 40 km grids using ArcGIS Desktop 10.8.2 to identify candidate storage sites [42]. This database includes geological storage capacity and injection rate for candidate storage sites.

2.3. CCS Source-Sink Matching Model

2.3.1. Point-to-Point Source-Sink Matching Model

The point-to-point source-sink matching approach is a streamlined pipeline deployment strategy in which each emission source is assigned to a single, most suitable storage site. The problem is formulated as a mixed-integer linear programming (MILP) model and solved using Gurobi Optimizer 13.0.3, with the objective of minimizing the total cost of the CCS system under a carbon-neutrality target. The objective function is presented below:

$$\min f_p = K_p + M_p + N_p \quad (1)$$

where f_p is the full-chain cost of the CCS projects over the planning period from 2030 to 2060 (\$); K_p , M_p and N_p denote the total costs associated with CO₂ capture, transport, and storage, respectively (\$). The system boundary includes only costs directly associated with CCS deployment: capture retrofits, transport, and storage. Construction costs for new power facilities and facility-specific incremental costs for additional flue-gas treatment are excluded. A uniform annual discount rate of 5% is applied to all discounted cost and revenue terms in the model [43]. Capture costs are calculated as follows:

The CO₂ capture cost is calculated using aggregate capital and operation and maintenance (O&M) costs as follows:

$$K_p = \sum_i (C_i^c + O_i^c) \times Z_i^c \quad (2)$$

where C_i^c denotes the capital costs of CO₂ capture at facilities i (\$), adjusted to reflect technology-driven cost reductions as described in Note S1 and discounted over the asset lifetime. O_i^c denotes the O&M costs of CO₂ capture at facilities i (\$); Z_i^c is a binary decision

variable indicating whether facility i is retrofitted (1 if retrofitted, otherwise 0). The capital cost of CO₂ capture is calculated as:

$$C_i^c = IT_i \times UC \quad (3)$$

where IT_i is the installed capacity of facility i (kW), and UC is the unit capital cost of CO₂ capture (\$/kW). The transport cost is calculated as:

$$M_p = \sum_{(i,j)d} T_{(i,j)} \times (C_d^t + O_d^t) \times Z_{(i,j)d}^t \quad (4)$$

where $T_{(i,j)}$ is the transport distance between facilities i and the storage site (km). C_d^t and O_d^t denote the discounted capital and O&M costs per unit transport distance for pipelines of size d (\$/km). d is the pipeline diameter, with candidate sizes of 6, 14, 22, 38, 54, and 70 inches. These sizes follow previous studies [39,44]. $Z_{(i,j)d}^t$ is a binary decision variable indicating whether source i is connected to storage site j via a pipeline of size d (1 if connected, otherwise 0). The storage cost is calculated as:

$$N_p = \sum_j [(C_j^s + O_j^s) \times Z_j^s - \text{EOR} \times s_j] \quad (5)$$

where C_j^s and O_j^s denote the discounted capital and O&M costs associated with well drilling at storage site j (\$). Z_j^s is a binary decision variable indicating whether storage site j is selected for CO₂ injection during the planning period (1 if selected, otherwise 0); s_j is the cumulative CO₂ storage at site j during the planning period (Mt). EOR is the discounted average revenue from CO₂-enhanced oil recovery over 2030–2060 (\$/Mt), calculated as:

$$\text{EOR} = \sum_{t=2030}^{2060} \frac{p_{\text{oil}} \times Btt \times \text{ratio}}{(1+r)^{t-2030}} \times 10^6 \quad (6)$$

where p_{oil} is the crude oil price (\$/barrel), ratio is the CO₂ displacement rate for oil (t oil/t CO₂), Btt is the number of barrels per tonne of oil (barrel/t oil) [31], and r is the discount rate. The factor 10^6 converts the revenue per tonne of CO₂ to the revenue per megatonne.

The objective function is evaluated under the following constraints:

The cumulative CO₂ captured from all retrofitted facilities must satisfy the reduction target.

$$\sum_{i \in I} Cap_i \times Z_i^c \geq \text{Target} \quad (7)$$

where Cap_i is the cumulative CO₂ captured by facilities i (Mt), and Target is the required CO₂ reduction over 2030–2060 (Mt).

Mass balance constraints require that captured CO₂ is equal to the amount transported from sources and injected into storage sites.

$$\sum_j (x_{i,j} \times L_i) = Cap_i \times Z_i^c \quad (8)$$

$$\sum_i (x_{i,j} \times L_i) = s_j \quad (9)$$

where $x_{i,j}$ is the annual amount of CO₂ transported from emission sources i to storage sites j (Mt/a); L_i is the remaining service life of facilities i (a).

The realized storage volume must satisfy both the geological storage potential and the injection-rate limitations of each storage site.

$$s_j \leq Q_j^{\text{stor}} \times Z_j^s \quad (10)$$

$$s_j \leq Inj_j \times W_{max} \times H \quad (11)$$

$$w_j \leq W_{max} \quad \forall j \in J \quad (12)$$

where Q_j^{stor} is the maximum geological storage capacity of site j (Mt); Inj_j is the per-well injection capacity (Mt/(well·a)); H is the planning period (a). W_{max} is the maximum number of injection wells allowed at each storage site, set to 50 wells, following [39]. Where w_j is the number of injection wells developed at the storage site.

Source-sink connections are restricted to 250 km, consistent with the economic assumption that intermediate recompression is generally unnecessary for CO₂ pipelines within this distance [45,46].

$$0 \leq T_{(i,j)} \leq 250 \quad (13)$$

2.3.2. Cluster Source-Sink Matching Model

The clustered CCS source-sink matching follows the same MILP framework as the point-to-point model and was implemented in Python 3.14.2. They differ in how the CO₂ transport and storage network is represented. The objective function remains the minimization of the full-chain CCS cost:

$$\min f_c = K_c + M_c + N_c \quad (14)$$

where f_c is the full-chain cost of the clustered CCS projects over the planning period (\$); K_c , M_c , and N_c denote the total costs associated with CO₂ capture, transport, and storage under the clustered configuration, respectively (\$). The total capture cost is expressed as:

$$K_c = \sum_c Z_c^c \times \sum_{i \in c} (C_i^c + O_i^c) \quad (15)$$

where C_i^c and O_i^c denote the discounted capital and O&M costs of CO₂ capture for facility i within cluster c , respectively (\$). $i \in c$ indicates that facility i belongs to cluster c . Z_c^c is a binary decision variable indicating whether cluster c is selected for CCS retrofit (1 if retrofitted, otherwise 0).

In the clustered CCS deployment, multiple emission sources are connected to one or more shared storage sites through a common CO₂ transport network, with intra-cluster connectivity determined using Prim's minimum spanning tree algorithm described in [26]. A hub node aggregates CO₂ flows from individual sources before transport to storage sites [47,48]. Transport cost is calculated as the sum of three distance components:

$$M_c = \sum_{(c,j)d} (C_d^t + O_d^t) \times (T_{(c,h)} + T_{(h,j)} + T_{(j,j')}) \times Z_{(c,j)d}^t \quad (16)$$

where C_d^t and O_d^t denote the discounted capital and O&M costs per unit transport distance for pipelines of size d (\$/km). $T_{(c,h)}$, $T_{(h,j)}$ and $T_{(j,j')}$ denote the total minimum inter-source distance within a cluster, the distance from the hub to the storage site, and the distance between storage sites, respectively (km). $Z_{(c,j)d}^t$ is a binary decision variable indicating whether cluster c is connected to storage site j via a pipeline of size d (1 if connected, otherwise 0). The total storage cost is expressed as:

$$N_c = \sum_j [(C_j^s + O_j^s) \times Z_j^s - EOR \times s_j] \quad (17)$$

The objective function is evaluated under the following constraints.

The cumulative CO₂ captured from all retrofitted clusters must satisfy the reduction target:

$$\sum_{c \in C} Cap_c \times Z_c^c \geq Target \quad (18)$$

where Cap_c is the cumulative CO₂ captured by cluster c , calculated as the sum of CO₂ captured by all facilities within the cluster (Mt).

Mass balance constraints require that captured CO₂ is equal to the amount transported from sources and injected into storage sites:

$$\sum_j \sum_{i \in c} x_{i,j} \times L_i = \sum_{i \in c} Cap_i \times Z_c^c \quad (19)$$

$$\sum_c \sum_{i \in c} x_{i,j} \times L_i = s_j \quad (20)$$

where $x_{i,j}$ denotes the annual amount of CO₂ transported from facility i within cluster c to storage site j (Mt/a).

The realized storage volume must satisfy both the geological storage potential and the injection-rate limitations of each storage site:

$$s_j \leq Q_j^{stor} \times Z_j^s \quad (21)$$

$$s_j \leq Inj_j \times W_{max} \times H \quad (22)$$

$$w_j \leq W_{max}, \forall j \in J \quad (23)$$

where s_j denotes the realized CO₂ storage at site j (Mt); Q_j^{stor} is the maximum geological storage capacity of site j (Mt).

Source-sink connections are restricted to distances no greater than 250 km, reflecting common economic assumptions that CO₂ pipelines within this range typically do not require intermediate recompression:

$$0 \leq T_{(c,j)} \leq 250 \quad (24)$$

2.4. Description of Scenarios

Four scenarios are set up, differing in the range of facilities eligible for CCS retrofit and in the way emission sources are linked to storage sites. As shown in Figure 2, L includes only large-scale facilities, whereas LS includes both large- and small-scale facilities. The letters P and C refer to the transport and storage configuration. P represents dedicated point-to-point connections, whereas C allows multiple sources to share T&S infrastructure within a cluster.

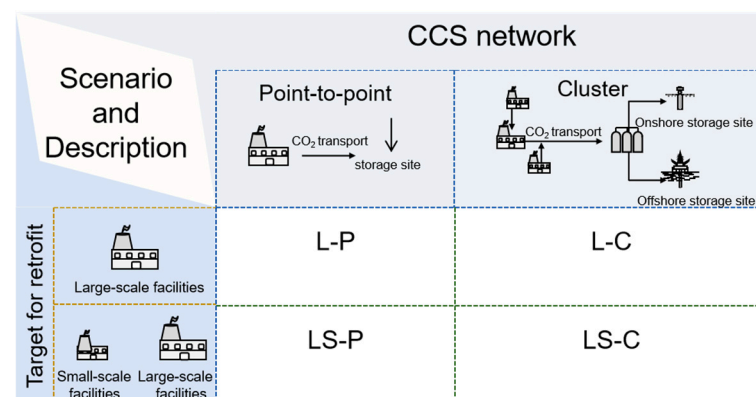


Figure 2. Overview of the model scenarios.

The four scenarios serve different comparison purposes. The L-P scenario serves as the reference case because it broadly follows previous source-sink matching studies. In these studies, large-scale coal-fired power facilities were directly connected to storage sites [41,49]. LS-P retains this connection pattern but extends the analysis to smaller facilities, making it possible to examine how their inclusion changes the results. L-C keeps the focus on large facilities but replaces individual connections with shared infrastructure. LS-C combines broader facility coverage with a clustered network. It examines whether shared infrastructure improves the feasibility of CCS deployment for smaller facilities. The effect of facility coverage can therefore be assessed by comparing scenarios with the same network type, while the effect of clustering can be examined among scenarios with the same facility coverage. Emission-reduction targets and cost assumptions remain unchanged across the four cases.

3. Results

3.1. Characteristics and Layout of Small-Scale Coal-Fired Power Facilities

Approximately 30.1% of China's power facilities have installed capacities below 300 MW and are classified in this study as small-scale facilities, collectively accounting for 7.6% (561.6 Mt/a) of total CO₂ emissions from the national power system (Figure 3a). These facilities are concentrated in Northeast China, which hosts 11.3% of all facilities nationwide and contributes 2.1% of total national CO₂ emissions. At the provincial level, the proportion of small-scale facilities varies widely (Figure 3b). The three provinces with the highest shares are Jilin, Shandong and Liaoning, where small-scale facilities account for 50.6%, 50.5%, and 46.5% of their respective power facilities, respectively. These provinces are emblematic of China's traditional industrial base. By contrast, provinces dominated by hydropower and emerging low-carbon resources show much lower shares of small-scale facilities. For example, Yunnan and Hunan report shares of 4.7% and 5.3%. This spatial pattern reflects long-standing regional differences in energy structure and industrial development pathways.

Small-scale power facilities in China are one year older than the sector-wide mean operating age of 12 years (Figure 3c). Large and young facilities (Q4) account for the majority of power facilities nationwide, with 1418 facilities, reflecting the prevailing emphasis of CCS retrofit strategies on scale and asset age. Small-scale facilities are mainly concentrated in the young category (Q3), accounting for 474 facilities in total. East China alone hosts 203 of these facilities, representing 42.8% of the national total. By comparison, North China and Central China contain only 47 and 30 facilities in this quadrant, respectively. This uneven spatial distribution suggests that CCS screening approaches focused primarily on facility scale may overlook a substantial pool of small-scale power assets with viable abatement potential in regions critical to China's decarbonization trajectory.

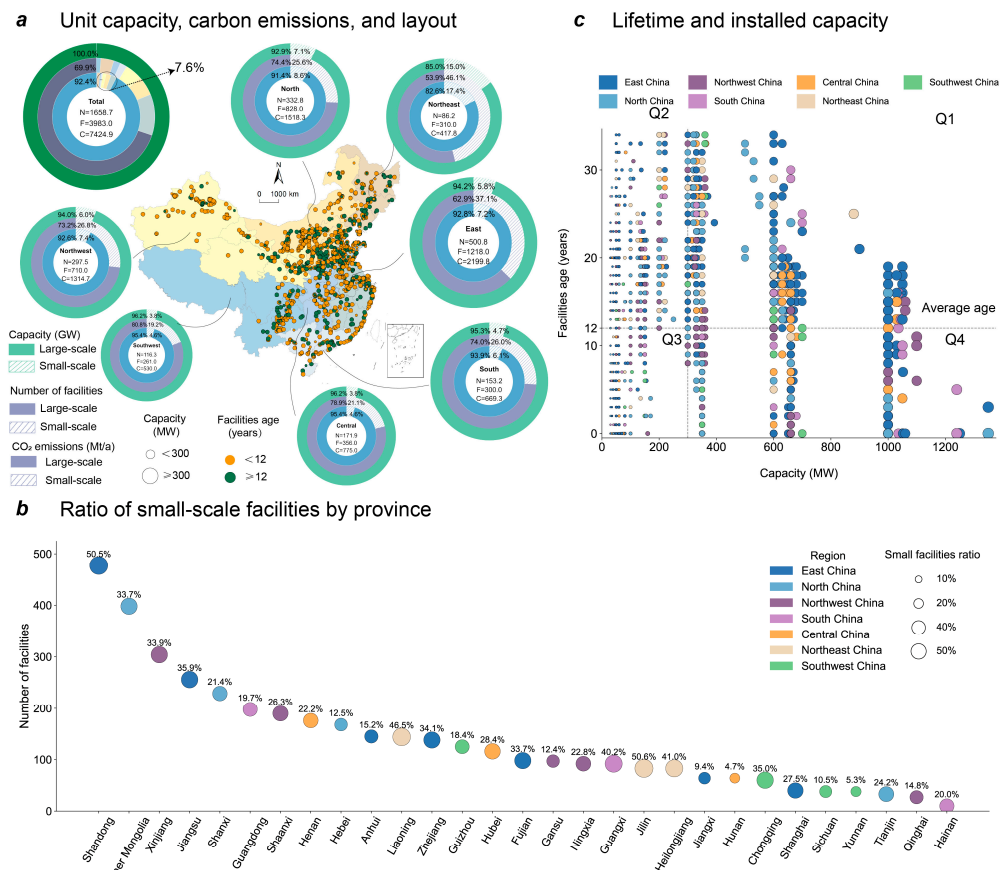


Figure 3. Location, capacity, and operating age of small-scale facilities in China. Note: (a) shows 3983 power facilities aggregated into 1365 geographically distinct power plants. Multiple facilities located at the same plant appear as a single point. In (b), the percentages indicate the shares of small-scale facilities in each region. (c) Scatter plot of facility age versus capacity colored by region, with the dashed line representing the average facility age.

3.2. Impact of Small-Scale Power Facilities on CCS Deployment

Achieving the carbon neutrality target requires a cumulative CO₂ reduction of 32.4 Gt in the power system between 2030 and 2060 [50], with model constraints allowing reductions to meet or exceed this target. As shown in Figure 4a, when only large-scale facilities are eligible (L-P and L-C), cumulative reductions exceed the target by 0.58 Gt due to the discrete scale of large units. After small-scale facilities are included (LS-P and LS-C), the system can more precisely meet the reduction requirement, limiting the excess to 0.09 Gt. Small-scale power facilities contribute 3.2 Gt CO₂, accounting for 9.9% of total abatement. Expanding CCS eligibility to small-scale power facilities increases the number of retrofitted units by 26.8%, including 243 small-scale power facilities (Figure 4b).

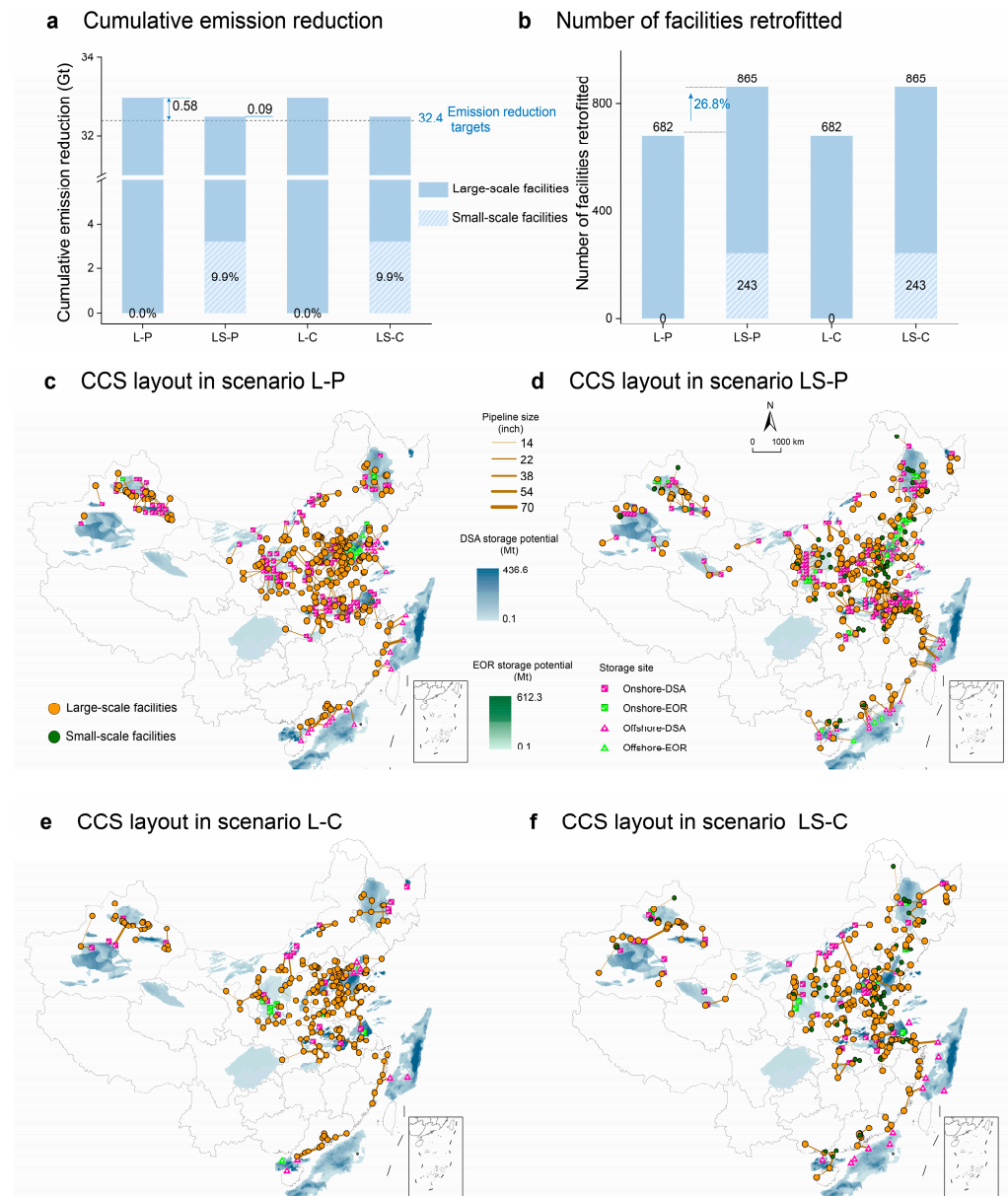


Figure 4. CCS layouts and CO₂ emission reductions under different scenarios. Panels (a,b) show cumulative CO₂ emission reductions and the number of CCS retrofitted facilities, while panels (c–f) illustrate the spatial deployment of CCS projects across scenarios. *Note:* a common legend is used for (c–f).

Incorporating small-scale power facilities shifts regional CCS mitigation toward East China due to its concentration of small emitters. Figure 4c–f show the spatial distribution of CCS deployment across scenarios. Under the L-P and L-C scenarios, CO₂ reductions are concentrated in East and North China, with cumulative reductions of 9.7 and 8.1 Gt CO₂, respectively (Table S4). With small-scale power facilities retrofitted (LS-P and LS-C), cumulative reductions increase by 23.7% in East China. By contrast, reductions in North China and Central China decline by 1.6 and 1.4 Gt CO₂, respectively. CCS deployment in Southwest China is no longer selected (Figure S1). When only large-scale facilities are retrofitted (L-P and L-C), CCS deployment is concentrated in Shandong, Hebei, and Xinjiang, with cumulative reductions of 4.5, 4.1, and 4.0 Gt CO₂, respectively (Figure S2). With small-scale power facilities retrofitted (LS-P and LS-C), Shandong and Xinjiang remain the largest contributors, with small-scale power facilities accounting for 0.8 and 0.5 Gt CO₂,

respectively. Small-scale power facilities do not change the leading provinces but alter abatement composition within them.

3.3. Economic Implications of Retrofitting Small-Scale Power Facilities

Including small-scale power facilities affects total system costs differently under the two network configurations (Figure 5a). Under the point-to-point deployment scenario (L-P), the total system cost is \$754.2 billion over the 2030–2060 planning horizon. Including small-scale power facilities (LS-P) raises this cost by 3.8%, mainly because of lower EOR revenue and higher capture costs. Compared with point-to-point deployment (L-P), clustered deployment (L-C) lowers transport and storage costs but matches fewer facilities to oilfields, resulting in lower EOR revenue and higher net T&S and total system costs. Compared with L-C, including small-scale facilities in LS-C increases the total system cost by only 0.4%, while net T&S cost decreases from \$78.0 billion to \$75.3 billion.

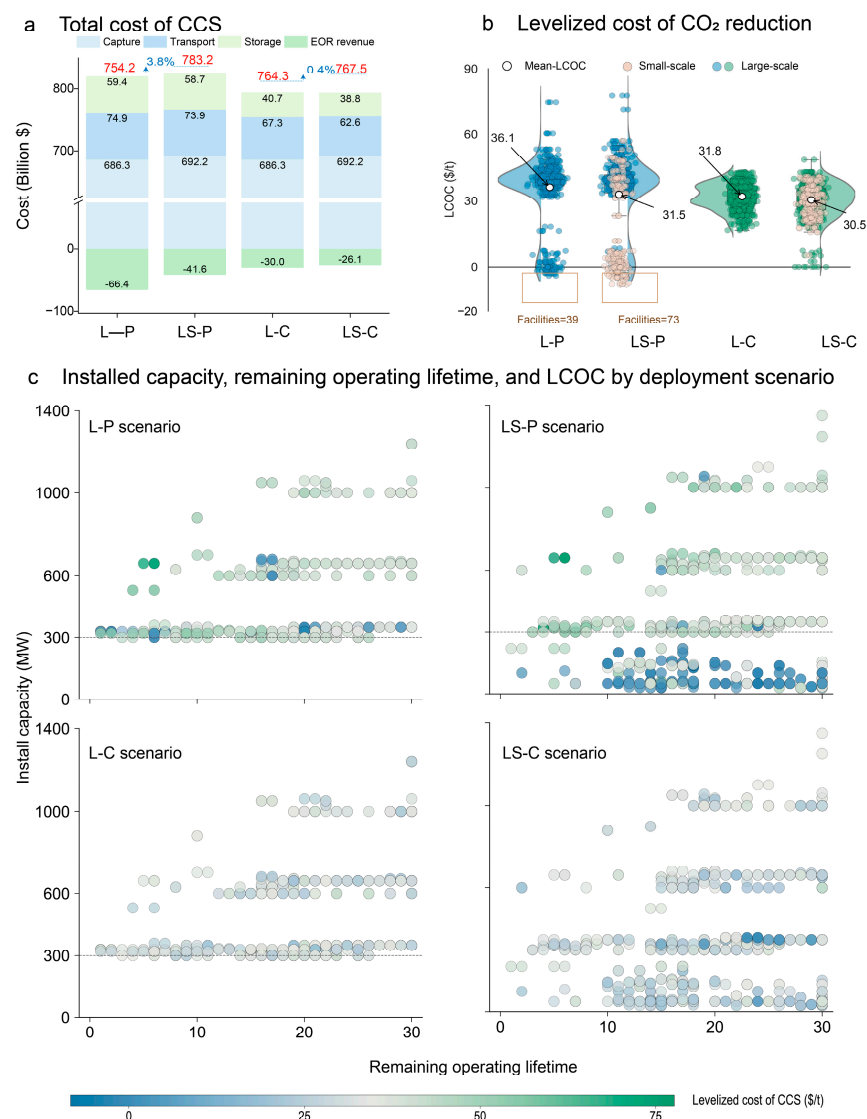


Figure 5. Economic analysis under different scenarios. (a) shows the total system cost and its components under each scenario between 2030 and 2060. The red values indicate the total system cost, calculated as capture, transport, and storage costs minus EOR revenues. (b) illustrates the distribution of levelized cost of CCS (LCOC) at the facility level. (c) shows the installed capacity and remaining operating lifetime of selected facilities, with color indicating facility-level LCOC, under point-to-point and clustered deployment.

The participation of small-scale power facilities in CCS retrofitting lowers the levelized cost of CCS (LCOC) (Figure 5b). Under the point-to-point configuration, retrofitting large-scale facilities only (L-P) shows an average facility LCOC of 36.1 \$/t, with 39 oilfield-linked facilities exhibiting negative values (from −4.1 to −0.3 \$/t). Including small-scale facilities (LS-P) reduces the average to 31.5 \$/t and increases the number of negative-LCOC facilities to 73, of which 65 are small-scale power facilities. Under clustered deployment, retrofitting large-scale facilities only (L-C) shows an average facility LCOC of 31.8 \$/t, which decreases by 4.1% and becomes more concentrated when small-scale power facilities are included (LS-C). This shows that clustered configurations incorporate low-cost abatement options from small-scale power facilities while limiting cost dispersion across facilities.

The relationship between LCOC and facility characteristics differs markedly between point-to-point and clustered CCS deployment (Figures 5c and S3). In the L-P scenario, LCOC is weakly correlated with installed capacity and remaining operating lifetime ($r = 0.12$ and 0.17 , respectively). Its association with transport distance is more pronounced ($r = 0.35$, $p < 0.001$). In the LS-P scenario, some small-scale facilities are matched with oilfield storage sites, generating EOR revenues that offset part of their CCS costs, as reflected in their low or negative LCOC values. For these facilities, LCOC remains positively correlated with transport distance ($r = 0.31$, $p < 0.001$). Under clustered deployment, LCOC values are more concentrated across facilities with different capacities and remaining operating lifetimes, and their correlations with all three facility characteristics are generally weak.

3.4. CCS Transport and Storage Network of Small-Scale Power Facilities

Expanding CCS eligibility to small-scale power facilities increases total CO₂ transport distances, but the increase is limited under the clustered deployment model. As shown in Figure 6a, under the point-to-point configuration, retrofitting large-scale facilities (L-P) results in a total transport distance of 4.1×10^4 km. Retrofitting small-scale power facilities for CCS (LS-P) increases the total distance by 0.7×10^4 km. Under clustered deployment, total transportation distances are substantially lower. Retrofitting only large-scale facilities (L-C) reduces the total distance by 61.0% compared with the L-P scenario. When small-scale power facilities are also retrofitted (LS-C), the total distance increases by 0.5×10^4 km compared with the L-C scenario. This indicates that clustered deployment effectively limits the expansion of pipeline networks while accommodating the dispersed small-scale emission sources. At the facility level (Figure 6b), under the LS-P scenario, the average CO₂ transport distance for small-scale power facilities is 171.1 km. Under clustered deployment, this distance is reduced to 48.8 km, representing a 71.5% decrease, showing that clustered networks can significantly shorten transport routes for small-scale power facilities.

Retrofitting small-scale power facilities affects the pipeline diameter distribution (Figure 6b,c). Under the point-to-point configuration, retrofitting only large-scale facilities (L-P) relies mainly on 14-inch pipelines, which account for 69.4% of total pipeline length. Including small-scale power facilities (LS-P) reduces this share to 50.9%, while 6-inch pipelines rise to 24.3%. Under clustered deployment, retrofitting only large-scale facilities (L-C) primarily uses trunk pipelines larger than 30 inches, with 38-, 54-, and 70-inch pipelines accounting for 33.2%, 27.1%, and 3.0%, respectively. When small-scale power facilities are also retrofitted (LS-C), trunk pipelines remain dominant, accounting for 50.5%, while 6-inch pipelines increase to 4.7%.

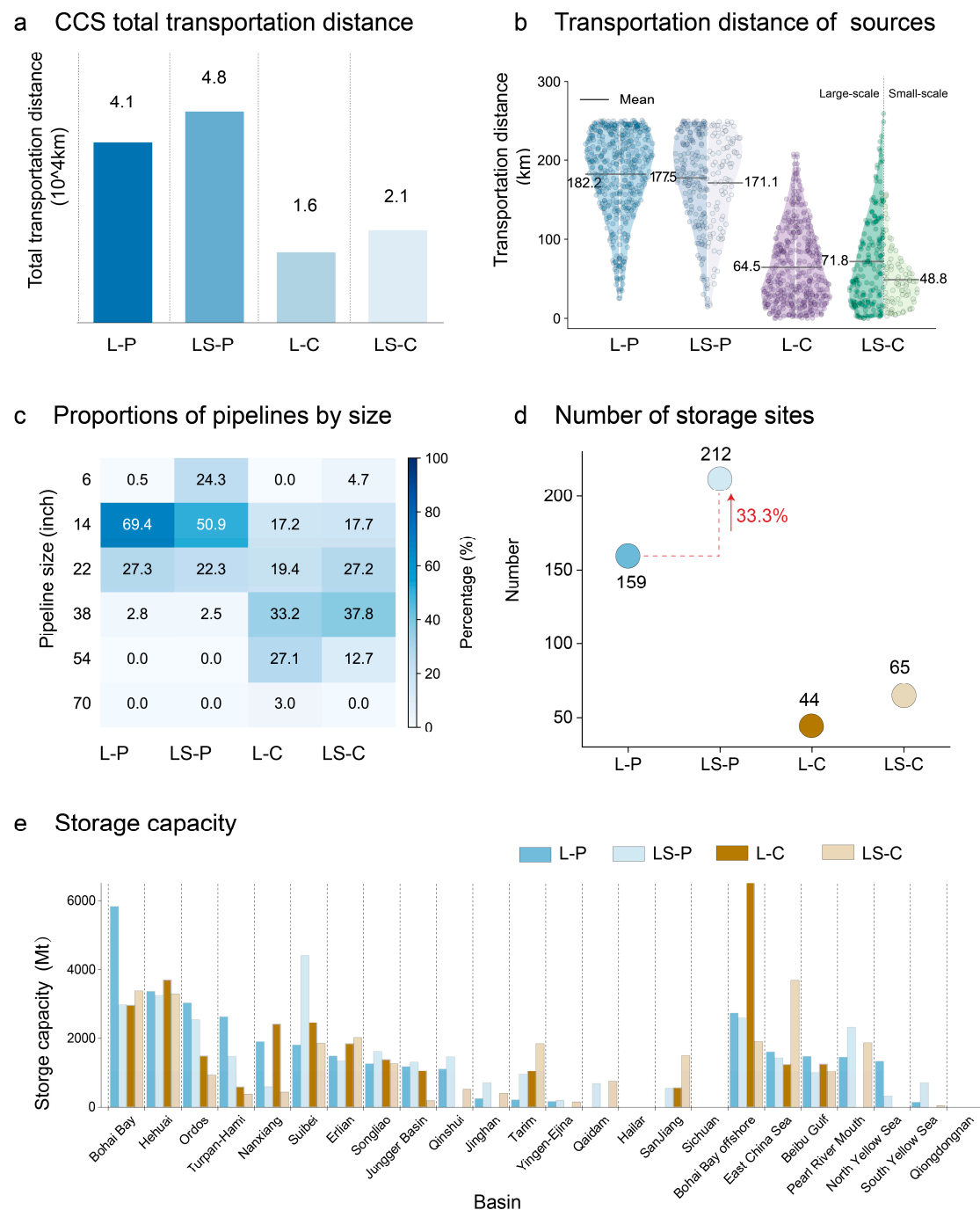


Figure 6. Transportation and storage facility requirements under different scenarios. (a) compares total CO₂ pipeline transport distances across scenarios. (b) presents the distribution of transport distances at the source level. (c) shows the proportion of pipeline lengths by diameter size. Panel (d) shows the number of storage sites utilized; the red upward arrow denotes a 33.3% increase from L-P to LS-P scenario. (e) illustrates the cumulative CO₂ storage amount by basin.

Retrofitting small-scale power facilities substantially increases the demand for storage sites, whereas clustered deployment effectively alleviates this constraint (Figure 6d). Under the point-to-point configuration, retrofitting only large-scale facilities requires 159 storage sites, which rises to 212 when small-scale power facilities are included (LS-P). Under clustered deployment, retrofitting only large-scale facilities requires 44 storage sites, and the inclusion of small-scale power facilities (LS-C) raises the number to 65, with the absolute increase remaining markedly lower than in the point-to-point scenario.

Figure 6e shows the cumulative CO₂ storage by basin under different scenarios. Under point-to-point deployment with only large-scale facilities retrofitted (L-P), the top three storage basins are Bohai Bay, Hehuai, and Ordos, accounting for 17.7%, 10.2%, and 9.2%, respectively. With small-scale power facilities retrofitted (LS-P), CO₂ storage in the South Yellow Sea and Tarim Basin rises by 422.1% and 361.9%. Under clustered deployment, storage is more concentrated. With only large-scale facilities (L-C), the Bohai Bay offshore basin alone stores 7164.1 Mt. With small-scale power facilities retrofitted (LS-C), roughly 60% of the additional storage is taken up by Bohai Bay, the East China Sea, and the Pearl River Mouth, while each of Erlian, Sanjiang, and Tarim contributes less than 10%.

4. Discussion

4.1. Main Findings

In this study, small-scale facilities contribute 3.2 Gt of cumulative CO₂ reductions, accounting for 9.9% of the total. Including these facilities expands the range of options available for meeting the mitigation target and reduces reliance on a limited number of large emitters. Screening CCS candidates based only on installed capacity may therefore underestimate the mitigation potential of small-scale facilities.

In economic terms, expanding CCS eligibility to small-scale power facilities does not materially increase total system costs; in clustered scenarios, system costs rise by only 0.4%, while the average LCOC declines from 31.8 to 30.5 \$/t. The facility-level cost distribution also becomes tighter, suggesting that the limitations of scale may have been overstated in previous assessments [32,33]. Previous studies have found that some small facilities normally considered low-priority candidates can offer low-cost CCS retrofit opportunities when their locations and access to storage are considered [31]. In this study, under the LS-P scenario, 65 of the 73 facilities with negative LCOC are small-scale facilities. These facilities mainly benefit from short transport distances to oilfields and revenues from EOR. Therefore, small-scale facilities should not be excluded solely because of their relatively low installed capacity; their spatial location and available storage conditions should also be considered in CCS candidate screening.

Clustered networks further change the transport economics of small-scale facilities. In the point-to-point scenario, the average transport distance for small-scale facilities is 171.1 km, which is of a similar magnitude to that reported by Tang et al. [51]. In the clustered scenario, however, this distance decreases to 48.8 km, representing a reduction of 71.5%. Meanwhile, the number of required storage sites decreases from 212 to 65. These results indicate that clustered deployment does not simply expand facility coverage but substantially reduces the access costs of dispersed facilities through shared pipeline networks and centralized storage. The pipeline diameter distribution further supports this mechanism: large-diameter trunk pipelines carry the main CO₂ flows, while small-diameter branches connect dispersed small-scale facilities, forming a network structure that is more favorable for their participation.

Sensitivity analysis shows that clustered deployment offers more favorable conditions for incorporating small-scale facilities into CCS (Note S3). Changing the capacity threshold from the baseline value of 300 MW to 100 and 600 MW changes their share of cumulative CO₂ reductions from 9.9% to 3.8% and 44.8%, respectively. This share remains between 7.7% and 10.9% when the maximum transport distance and learning rate are varied. The technology learning rate has the greatest influence on total system cost and facility-level LCOC. Across the parameter settings examined, including small-scale facilities results in a smaller cost increase under clustered deployment than under point-to-point deployment.

From a policy perspective, screening CCS candidates should be combined with regional cluster planning rather than based only on the capacity of individual facilities. The

participation of small-scale power facilities optimizes regional emission reduction patterns, enhances system spatial flexibility, and reduces dependence on a limited set of large emitters. Turning CCS plans into actual projects will require coordination among government agencies, coal-fired power companies, T&S operators, storage-site owners, and financial institutions. Given the regional spillover effects of green finance identified in China [52], financial institutions could assess CCS clusters as integrated regional projects, considering facility-level capture costs, spatial location, and access to shared infrastructure rather than evaluating each small facility in isolation.

4.2. Limitations

These results can support CCS deployment and regional cluster planning in China, although several limitations remain. First, storage options are limited to enhanced oil recovery and deep saline aquifers, CO₂ transport is modeled solely via pipelines, and emission sources are limited to coal-fired power facilities. Other CO₂ sources, utilization pathways, and transport modes remain to be examined. Second, the model uses aggregate cost parameters and a static spatial optimization framework. It does not distinguish facility-specific costs, such as additional flue-gas treatment [53] and solvent use, or capture changes in facility operation. The omission of efficiency losses and replacement-generation costs may underestimate retrofit costs for less-efficient small subcritical units. It considers CCS retrofits rather than coal-power phase-down or plant retirement and therefore does not compare cumulative emission reductions across these pathways. Financing structures are also outside the cost model. Other factors, including cross-administrative network coordination or storage ownership, are not considered. Despite these uncertainties and limitations, its results provide important insights for CCS deployment in the power system.

5. Conclusions

This study compares four scenarios to separate the effects of facility coverage and network configuration on CCS deployment. Small-scale facilities below 300 MW contribute 3.2 Gt of cumulative CO₂ mitigation. Compared with point-to-point deployment, clustering reduces their average transport distance by 71.5% and limits the increase in total system cost from 3.8% to 0.4%. The average LCOC under clustered deployment decreases to 30.5 \$/t CO₂.

The results show that facility size alone does not determine the feasibility of CCS retrofits. Small-scale facilities with favorable locations and access to shared transport and storage networks may also provide low-cost mitigation opportunities. These results can inform CCS retrofit candidate screening and regional cluster planning as China pursues a more sustainable transformation of its coal power system.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18199692/s1>, Figure S1: CO₂ flow from regions to basins under different scenarios; Figure S2: CO₂ reductions by province; Figure S3: Correlation between key power facility parameters and the levelized cost of CCS; Figure S4: Spatial distribution of CCS clusters under the L-C and LS-C scenarios; Figure S5: Sensitivity analysis of the share of cumulative abatement from small-scale coal-fired power facilities; Figure S6: Sensitivity analysis of total system cost; Figure S7: Sensitivity analysis of LCOC; Table S1: Characteristics of power facilities eligible for CCS retrofitting in the existing literature; Table S2: Projects related to modular design and process intensification technologies; Table S3: Parameters related to the CCS model; Table S4: Cumulative CO₂ emission reductions under different scenarios; Table S5: Initial CAPEX for CCS retrofitting units and cost curve calculation results; Note S1: CCS unit investment learning curve model; Note S2: CCS cluster formation mechanism and characteristics; Note S3: Sensitivity analysis. References [11,26,31,33,35,39,54–87] are cited in the Supplementary Materials.

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