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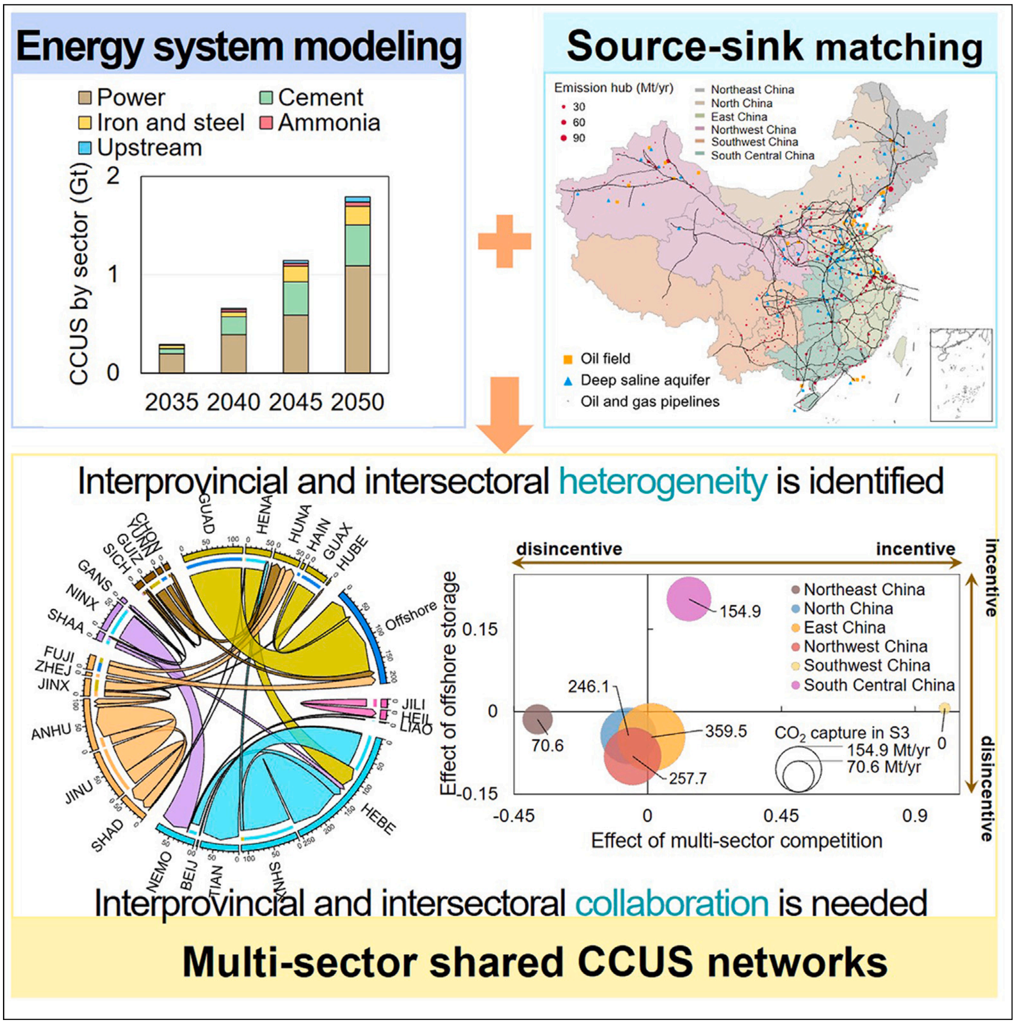

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Highlights

Sectoral CCUS mitigation potential is harmonized with plant-level CCUS deployment

Cross-region CO_2 transport patterns of typical network configurations are explored

Offshore reservoirs will store 11.5% of the total capture of 1.74 Gt/yr in 2050

19000-km trunk lines are expected to link major emission hubs with storage sites

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China's multi-sector-shared CCUS networks in a carbon-neutral vision

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SUMMARY

China's carbon-neutral vision necessitates carbon capture, utilization, and storage (CCUS), which is still in its infancy due to inadequate infrastructure and indeterminate technology diffusion. To address the concerns, this study links spatially explicit CO_2 source-sink matching with bottom-up energy-environment-economy planning to propose China's multi-sector-shared CCUS networks, with plant-level industrial transfer and infrastructure reuse considered. Nearly 19000-km trunk lines are needed by a capture of 1.74 Gt/yr in 2050, with 12-, 16-, 20-, and 24-inch pipelines enjoying the largest share of over 65%. Inspiringly, some CO_2 routes accounting for 50% of the total length match well with the rights-of-way for oil and gas pipeline corridors. Regional cost-competitiveness improvement is observed given available offshore storage, with 0.2 Gt/yr redirected to the northern South China Sea. Furthermore, the interprovincial heterogeneity and intersectoral externality of CCUS scaling-up are unveiled, requiring a rational allocation of benefits and costs inherent in the value chains.

INTRODUCTION

Committed emissions from existent and planned fossil energy-related infrastructures without additional abatement run counter to the international community's pursuit of limiting global warming to 1.5°C.[1–4] As home to the largest fleet of coal-fired power plants (CFPPs)[5] and some youngest industrial emission-intensive facilities including iron and steel plants, cement plants, and chemical plants,[6] China has to endeavor to implement switching from coal to renewables and rapid expansion of low-carbon technologies to realize a carbon-neutral vision before 2060.[7] Indicated by this national climate ambition which largely mirrors the 1.5°C limit,[8] carbon capture, utilization, and storage (CCUS) will be an indispensable part of the decarbonization portfolio of not only the power sector but also some hard-to-electrify industries,[6,7] thereby reducing the risk of stranded assets[9] and supporting the deployment of negative emission technologies (NETs)[10] like bioenergy with carbon capture and storage (BECCS) and direct air capture with storage.

From the sectoral perspective, CCUS-equipped thermal plants are expected to address the seasonality of renewables[11] and can perform together with other levers to achieve a carbon-neutral power system.[12] Besides, the pronounced role of CCUS in decarbonizing industrial process-related emissions (e.g., ironmaking and steelmaking,[13] cement manufacturing,[14] and chemical production[15]) is worthy of attention. Specifically, Sun et al. suggested that internal revenues generated by process optimization and integration can enhance the economic viability of CCUS in the iron and steel sector.[16] Cao et al. highlighted the urgency of CCUS deployment and material efficiency improvement for cement industry in emerging regions.[17] Although the coal-to-chemical industry produces much less emissions than the former two,[18] it provides low-cost opportunities for early CCUS demonstration particularly in China,[19] thus driving the cost reduction through learning-by-doing and paving the way for CCUS diffusion in other sectors. Currently, about 40 demonstration projects with a total capture capacity of 3 Mt/yr CO_2 are in operation or under construction in China;[20] however, CCUS still lags far behind the deployment level required for the carbon neutrality target, thus rendering it urgent to envisage a sector-specific CCUS roadmap to keep the door to net-zero emissions open.

The shared CCUS networks is of vital significance to massive deployment and application of CCUS and carbon dioxide removals (CDR),[21,22] which has received unprecedented attention around the world recently. For example, the long-run CCUS networks for the power sector and the near-term transport infrastructure

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layout aiming at low-cost CO_2 sources are both explored in the USA, with their economic viability influenced by different financial incentives also carefully discussed.[23,24] Regarding the connection patterns and dynamics of the shared CCUS infrastructures and CO_2 chains, the least-expensive and spatiotemporally explicit networks with multiple modes of transport are designed for Swiss waste-to-energy sector to meet the requirements of typical emission reduction pathways.[25] Besides, various degrees of coordination and cooperation among nations, embodied as a climate target for a mere country level or a wider scope, are of importance to planning the optimal CCUS layouts, as identified in other case studies of Europe.[26] Technological progress is also taken into account to better estimate the dynamic cost of a global CCUS layout complying with the 2°C goal.[27] Focusing on the potential contributions of CCUS to NETs and clean fuel supply,[28] comprehensive infrastructure blueprints complementary to BECCS deployment[29,30] and low-carbon production of energy carriers (including hydrogen,[31,32] methanol, and ammonia[33]) are also discussed in some countries and regions.

Renewed interest in China's CCUS deployment has also been largely triggered by the nation's increasingly strong climate ambitions, especially the carbon neutrality pledge.[34–36] Considering the uncertainty of mitigation technology competition, representative CCUS layouts for decarbonizing China's CFPPs are unveiled to satisfy diverse levels of CO_2 capture demand.[37] The impacts of CCUS deployment time and transport distance on the mitigation potential are also explored.[38] While the former two research studies only pay attention to the onshore storage, the opportunity of CCUS implementation in China's southeastern coastal region is assessed in another study with nearby offshore storage reservoirs considered solely.[39] Apart from the technology roadmap, insightful advice is made on improving plant-level cost-competitiveness of CCUS[40] and boosting policy incentives conducive to CCUS deployment and commercialization.[41,42] Although these research greatly enrich the knowledge about the CCUS layouts for CFPPs in China, the following key issues regarding all-round scaling-up of CCUS still remain unexamined yet: (i) the impacts of widespread CCUS deployment in industrial point sources (i.e., ironmaking and steelmaking, cement manufacturing, and chemical production) on the overall infrastructure layout; (ii) the significance of competition between onshore storage and offshore sequestration to mitigation portfolios of certain provinces; (iii) the opportunity of synergizing CO_2 pipeline infrastructure design with China's oil and gas pipeline network planning[43] in the future.

To bridge the research gap listed above, this study develops a technology-rich and spatially explicit assessment framework based on the soft linkage between China CCUS DSS 2.0 and China TIMES (Figure 1) to analyze China's multi-sector-shared CCUS networks for the first time. Taking advantage of bottom-up energy system optimization, CCUS prospect is comprehensively evaluated under the constraints of supply-demand balance for energy system, with both technology competition and behavioral change carefully considered. Considering the potential interaction between industrial layout and CCUS deployment, a plant-level screening strategy dealing with CCUS retrofit suitability is proposed based on available techno-economic attributes and projected capacity expansion or phasing-out pathways, which collaborates with spatially explicit source-sink matching to explore shared CCUS networks in line with the carbon neutrality target. Furthermore, three scenarios differed by network configurations (Table 1) are established to investigate the spatial heterogeneity of provincial-level deployment and sector-specific diffusion. Distinguished from most existing research relying on every single source-sink pair to determine overall layouts, this study pursues a step forward in long-term CCUS decision-making by implementing the concept of emission hubs, storage hubs, and shared transport infrastructure to achieve economies of scale.[22] More details can be found in STAR Methods.

RESULTS

CCUS prospect in China's energy system transformation

The uncertainty of China's energy system decarbonization has been assessed by multi-scenario analysis[36,44] and inter-model comparison[8] in previous studies, focusing on the emission reduction pathways and pivotal technologies. Considering the trade-off between near-term mitigation pressure and long-term dependence on CDR, a moderate emission reduction pathway is preferable in this study. As shown in Figure 2A, the total annual energy-related CO_2 emissions is projected to peak at 10.37 Gt in 2025 and drop to 0.5 Gt in 2050, with the power emissions decreasing from 4.4 Gt to −0.6 Gt over 2025–2050 and achieving net-zero between 2040 and 2045. A significant emission reduction of 89% from 2020 to 2050 is also shown in industry sector. Behind the profound energy system transformation is a huge switching in primary energy structure, which is embodied in a plunge of 83% over 2025–2050 for fossil fuels (coal, oil, and natural gas) without CCUS. Apart from scaling-up of renewables, CCUS (by coal, oil, natural gas, and biomass) is going to experience promising diffusion, accounting for 19% of the total primary energy supply

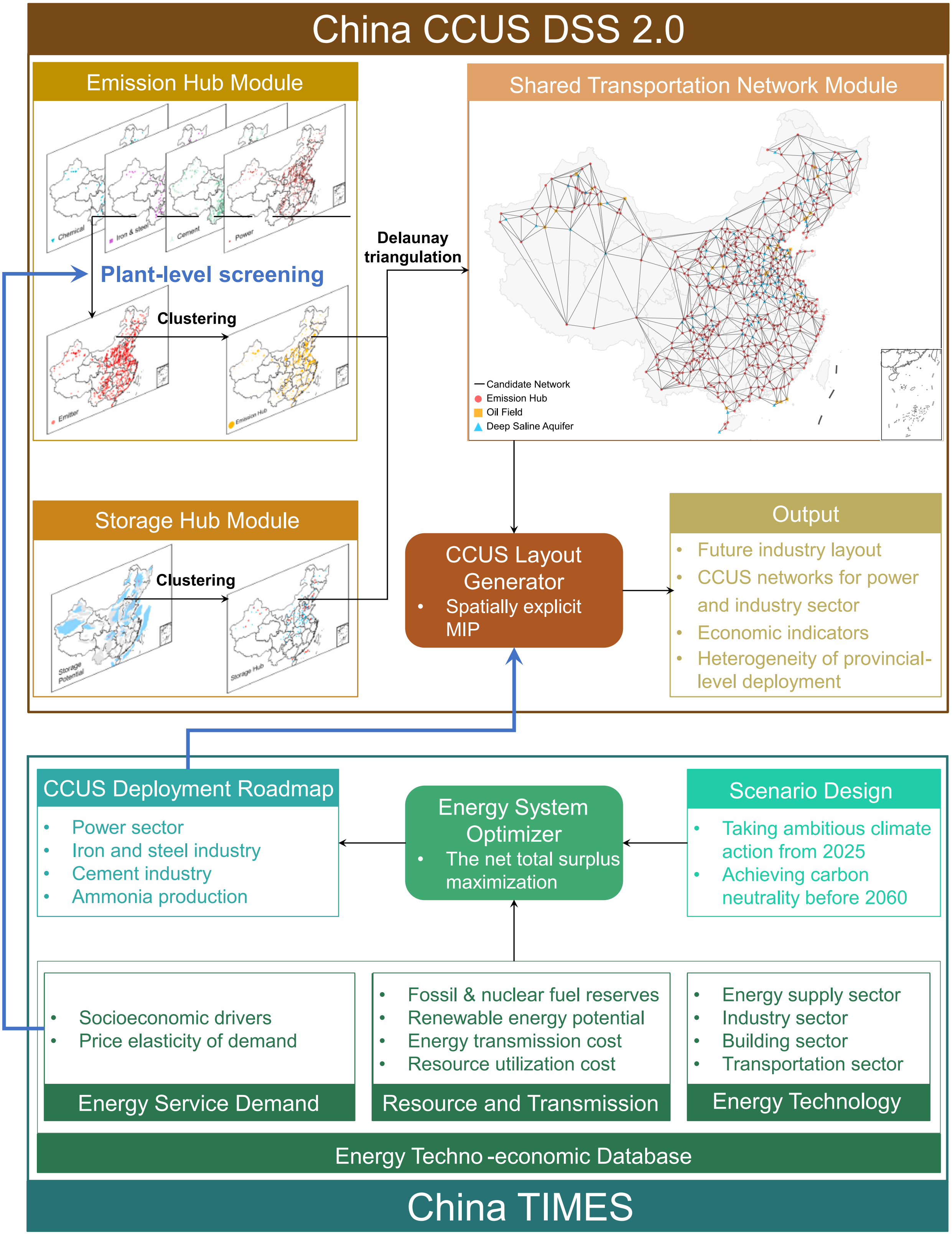

Figure 1. The soft linkage between China CCUS DSS 2.0 and the China TIMES model

Intra- and inter-model link are represented by black and blue lines, respectively.

Table 1. Scenario definition

Scenario	Source type: Power sector	Source type: Industry sector	Storage mode: Onshore storage	Storage mode: Offshore storage
S1	√	√	√	
S2	√	√	√	√
S3	√		√	

of 98.8 EJ in 2050 (Figure 2B). With the output of cement, crude steel, and synthetic ammonia decreasing by 64%, 57%, and 18% over 2020–2050 (Figure 2C), the decline in energy service demand derived from production mode and consumption pattern shifts also contributes to decarbonization in the demand sectors, thus acting as key clues to future layouts of industrial facilities and CCUS deployment. As shown in Figure 2D, CCUS will play an increasingly important role in deep decarbonization of power sector and other industrial facilities from 2035 and reach a total CO_2 capture of 1.79 Gt in 2050, with the power sector, cement production, iron and steelmaking, upstream sector, and ammonia synthesis contributing 1.09 Gt, 0.42 Gt, 0.19 Gt, 0.05 Gt, and 0.04 Gt, respectively. Due to considerable share of CCUS in industry sector, the impact of various kinds of industrial emission sources on the overall CCUS layout cannot be neglected.

Promising industrial layout and implicit leverage of fossil fuel infrastructure

Figure 3A depicts the current distribution of China's major emitters and potential CO_2 storage sites. To lay a solid foundation for envisaging the panorama of CCUS implementation, this research examines not only three major industries driving CCUS deployment (coal-fired power generation, blast furnace ironmaking, and cement production) but also some chemical industry point sources which produce high concentrated CO_2 stream and enjoy low-cost opportunities. As shown in Figure 3D, CFPPs ranks first in the total CO_2 emissions of most provinces. A more concentrated layout is discovered for the iron and steel industry, with the top five provinces (Hebei, Jiangsu, Shandong, Liaoning, and Shanxi) altogether providing more than 50% of the total output (Figure 3B). Specially, Hebei alone produces over 20% of the total products, with its iron and steel industry enjoying the largest share of the total provincial emissions. However, totally different characteristics are identified for the cement industry. Besides great dispersion of facility locations, obvious heterogeneity of the production level exists among provinces. As seen from Figure 3D, the cement industry is only second to the power sector for most southern provinces in terms of CO_2 emissions, while the counterpart in northern areas presents a much humbler proportion of the total emissions in corresponding provinces, which can be attributed to significant differences in capacity utilization and local demands. Although refineries and coal chemical industry contribute rather limited emissions compared with the former three industries on a national scale, they shoulder much more appreciable shares in Inner Mongolia, Shaanxi, Ningxia, and Xinjiang due to the coal-rich resource endowment in these provinces. Furthermore, these interprovincial heterogeneities of industrial structure may lead to various CCUS diffusion patterns and roadmaps.

Considering the decline of industrial capacity demands in the future, plant-level screening strategies especially for the cement industry and steel industry are employed to deepen the understanding of prospective arrangement of industrial clusters and lay a solid foundation for planning shared CCUS networks in advance. Figures 3B and 3C show the CO_2 emissions retained as candidates for CCUS source-sink matching in each province for the steel and cement industry, respectively. By filtering out the emission sources failing the plant-level screening of CCUS suitability, the proportion of CO_2 emissions from Hebei's iron and steel industry to that from this overall industry would decrease from about 24% to less than 20%. Furthermore, the share of the cement industry emissions in provinces of Northeast China, North China, and Northwest China would climb from about 20% up to 27%. These changes suggest the possibility of interprovincially relative transfer of industrial capacity driven by the combination of industrial upgrading and low-carbon transition.

This study identifies 484 emission hubs, 7 offshore sequestration sites, and 106 onshore storage sites[45,46] (Figure 3E) to further examine the CCUS layouts in line with China's carbon neutrality goal. In this research scope, a total storage potential of about 2469 Gt is regionalized and allocated to 113 potential storage sites, with onshore and offshore storage accounting for about 94% and 6%, respectively. Of the total annual emissions of 3.4 Gt produced by these 484 emission hubs, the CFPPs rank first with 2 Gt, followed by the

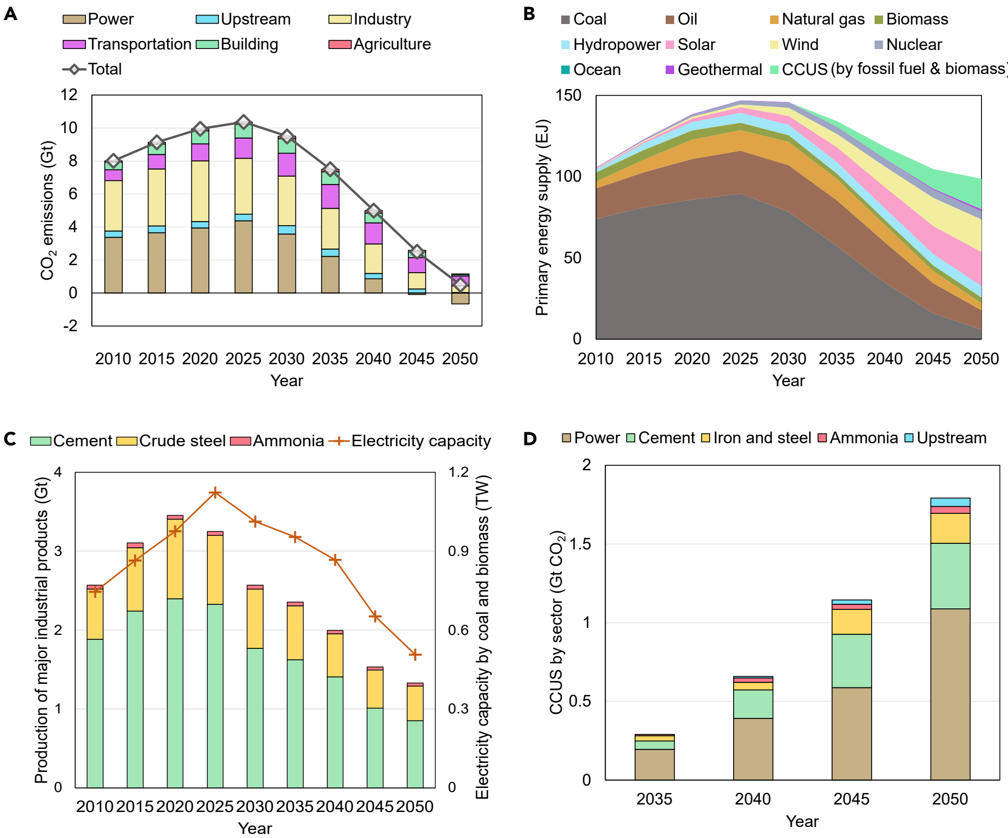

Figure 2. Bottom-up identification of the opportunities for extensive CCUS application

(A) Sectoral energy-related CO_2 emission pathway in line with China's carbon neutrality goal.

(B) The switching of primary energy supply indicates the phasing-out of unabated fossil fuel and the scaling-up of cleaner alternatives.

(C) Projection of major industrial products and electricity capacity by coal and biomass.

(D) CCUS deployment potential.

emissions from steelmaking and cement production, accounting for 0.8 Gt and 0.5 Gt, respectively. The emissions from ammonia synthesis comes the last with 0.1 Gt. Furthermore, the opportunity of synergizing shared CCUS networks with oil and gas pipeline planning is preliminarily implied by feature-based proximity analysis of the emission hubs and the rights-of-way for oil and gas pipelines. Specifically, 135 and 273 emission hubs are within the 10-km and 30-km buffer of oil and gas pipelines, with the annual CO_2 supply of 1.1 Gt and 2.3 Gt, respectively. Given the accessibility to the rights-of-way, China's multi-sector-shared CCUS networks may be fairly practicable and promising.

Multi-sector-shared CCUS layouts in typical network configurations

The impacts of the offshore storage on the overall CCUS layouts are unveiled by comparison between Figures 4A and 4B. In the absence of offshore sequestration, several large-scale and long-distance transport trunk lines are likely to be established across some southern provinces to satisfy the projected CCUS capture, owing to the lack of appropriate onshore storage sites there. Figures 4C and 4D shed light on more quantitative details about the different patterns of cross-region CO_2 transport. Sharp distinctions of flow direction lie in East China, Southwest China, and South-Central China. In S1 (see Figures 4A and 4C), Sichuan Basin and Jianghan-Dongting Basin serve as two main storage options for most emissions from Sichuan, Chongqing, Guizhou, Guangxi, Hunan, Jiangxi, Guangdong, and Fujian. If offshore reservoirs are reachable, however, only about 35% of the total capture from Fujian is still transported to onshore reservoirs and the remaining is redirected to offshore sites in Pearl River Mouth Basin in S2 (see Figures 4B and 4D). Notably, 99% of the total capture from Guangdong and 100% of that from Guangxi are most likely to be injected into offshore storage sites. Besides, Hainan and Yunnan are expected to witness an

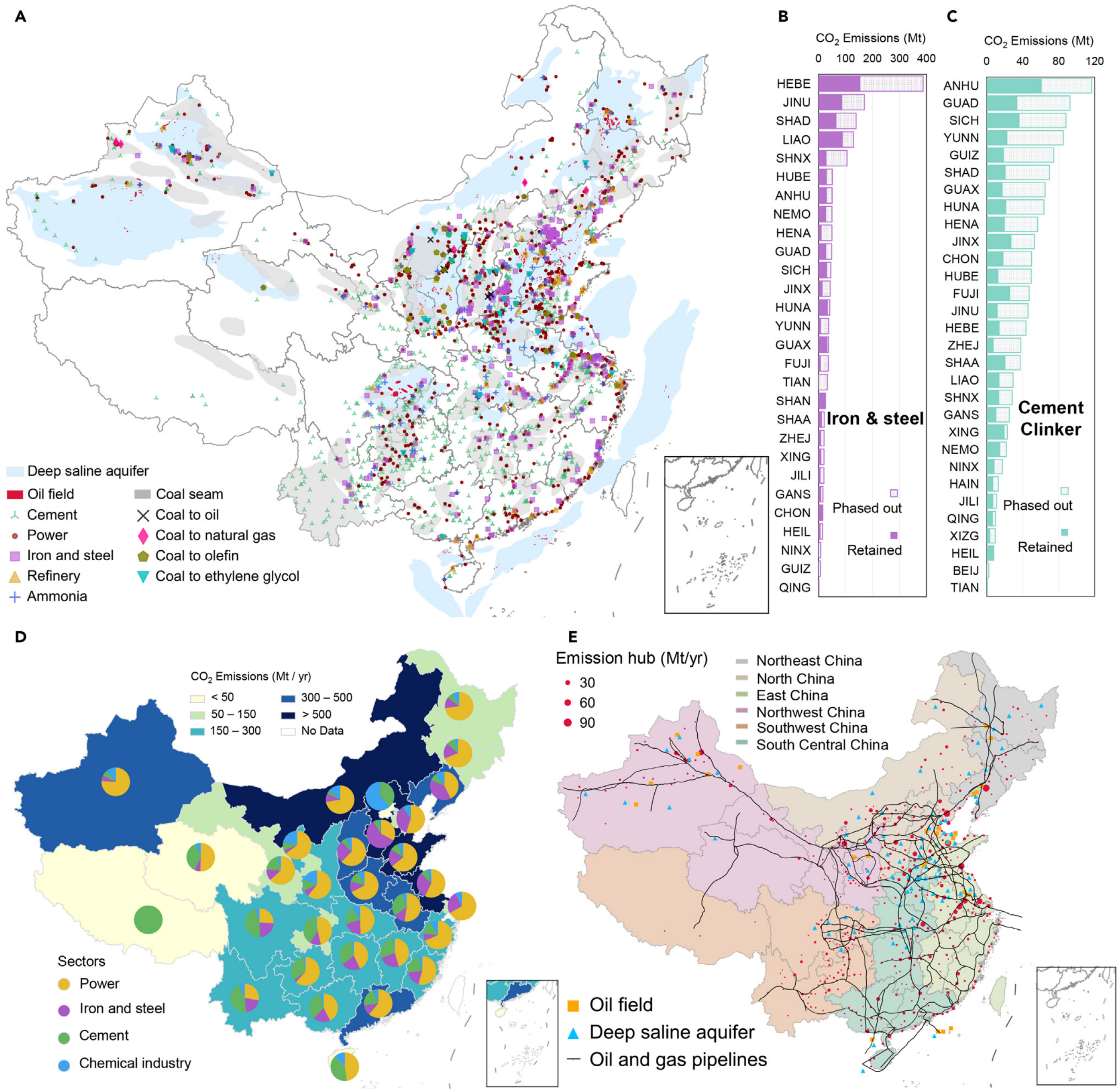

Figure 3. China's major emission sources and potential storage sites

(A) Distribution of China's current energy-intensive industrial clusters and main storage reservoirs.

(B and C) – Projections of the layouts of future iron and steel industry, and cement industry based upon the combination of energy service demand decline and current plant-level suitability for CCUS. More details of the abbreviations of the provinces are listed in Table S1.

(D) CO_2 emissions at the present level, included and examined within the scope of this research by sector and by province.

(E) The opportunity of leveraging existing rights-of-way and repurposing oil and gas pipeline networks for CO_2 transport. The location of existing and future oil and gas pipelines is based on Medium- and Long-term Oil and Gas Pipeline Network Planning.[43]

improvement in regional CCUS cost-competitiveness resulting from the participation of offshore sites in proposed layout, while Qinghai may exhibit the opposite.

The opportunity of leveraging existing and planned rights-of-way is preliminarily assessed through comparison of CO_2 trunk lines (Figures 4A and 4B) with oil and gas delivery channels (Figure 3E). Take the layout

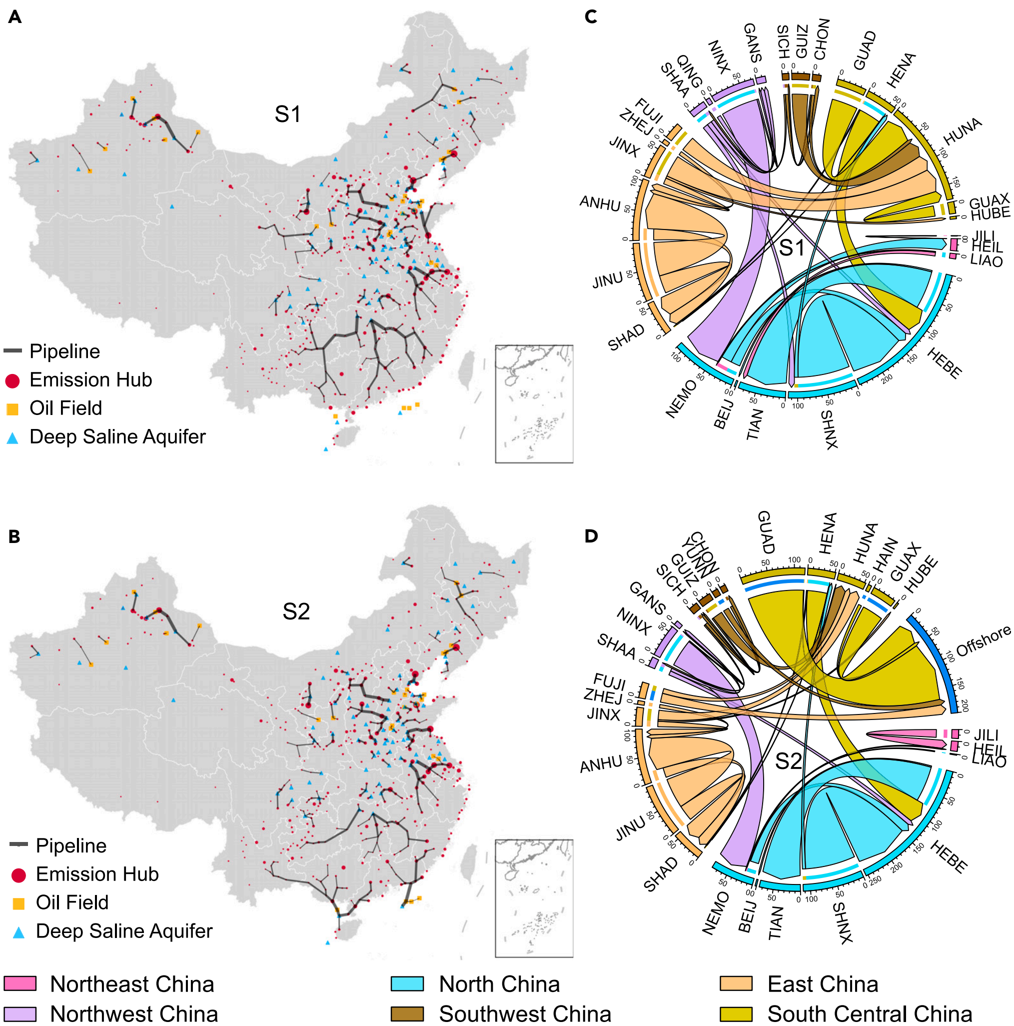

Figure 4. Proposed layouts and corresponding interprovincial CO_2 transport patterns

(A and B) Shared CCUS networks under S1 and S2, respectively. Please see layouts under S3 in Figure S3.

(C and D) Cross-region CO_2 flow in different CCUS networks. The arrows point from the provinces where the emission sources are located to the provinces where the storage sites lie. The transportation volume of the source-sink pairs within a single province is excluded. More details about the abbreviations of the provinces can be found in Table S1.

in S2 as an example. The most pivotal matching is displayed in the provinces relevant to the offshore transport and storage plan, where the rights-of-way for oil and gas transport may be hopefully shared with CO_2 pipelines there. Specifically, the proposed CCUS networks transporting CO_2 in Yunnan, Guangxi, Hainan, and western Guangdong largely mirror the product oil channel planned in southern China (Figure 3E), which is on the bottom-left side of South-Central China. The same opportunities are also identified for the trunk routes linking emission hubs in eastern Guangdong and Fujian, which is consistent with the connecting lines of natural gas purposed there. In view of the fall of fossil fuel's demand in the long run (Figure 2B), more attention is recommended to pay to synergizing shared CCUS network construction with oil and gas network planning, which can boost the economic viability of large-scale CCUS projects.

Comparison of transport scale and economic performance of the layouts

Figure 5 provides statistical characteristics of pipeline networks proposed in two scenarios. In terms of the total number and length of pipelines (Figures 5A and 5B), slight differences are found between two scenarios. Over 270 routes will be selected to construct the shared CO_2 transportation trunk lines in S1 and S2, with the total length of 18629 and 18577 km, respectively. More specifically, medium-sized pipelines with the diameter of 12-inch, 16-inch, 20-inch, and 24-inch will play the most significant roles, amounting

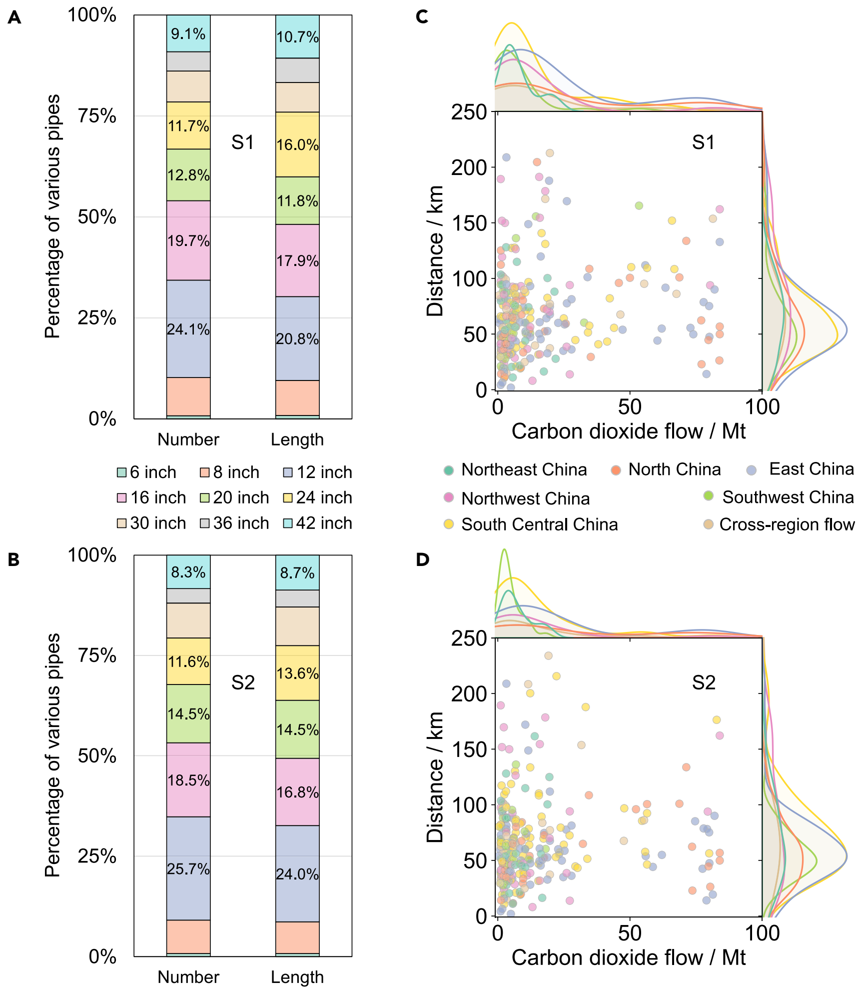

Figure 5. Statistical characteristics of two different configurations of CCUS pipeline networks

(A and B) – Proportions of different pipelines regarding the number and the laying mileage.

(C and D) Two-dimensional comparison of the trunk routes in each region.

to about 68% and 70% of the total number in S1 and S2. Similar pattern is also identified in the lying mileage by various pipes, with the share of medium-sized pipelines reaching 66% and 69% of the total length in S1 and S2, respectively. In addition, more large-sized 42-inch pipelines will be chosen in S1, with a gap of 0.8% and 2% for the number and the length compared with those in S2. Apart from the overall pipeline network properties, distinctions obviously show in regional transport scale (Figures 5C and 5D). Generally, there is a greater probability of establishing large-scale CO_2 transport networks in East China, North China, Northwest China, and South-Central China than in the other two regions. For instance, the total laying mileage of trunk lines in East China is expected to reach over 4000 km in S1, with the maximum length and flow of a single transportation route exceeding 200 km and 80 Mt/yr, respectively. However, the laying mileage in Southwest China is less than 40% of that in East China, with the maximum single flow of just over 50 Mt/yr. Given offshore storage, a noticeable reduction of 8.6% is indicated in the nationwide annual transport equivalent. Nonetheless, regions exhibit significant disparities, with the most remarkable decrease of 22 Gt km and increase of 23 Gt km in East China and South-Central China, respectively.

Figure 6 describes the offshore storage competitiveness and cost component varying with ascending CCUS deployment levels. Although onshore deep saline aquifers (DSAs) dominate the total CO_2 storage from a nationwide perspective, sequestering CO_2 into offshore oil fields or DSAs does exhibit superiority particularly in southern coastal regions to a certain degree, thus making it worthy of a decarbonization portfolio there. As seen from Figure 6A, offshore sequestration sites will contribute a total annual CO_2 storage

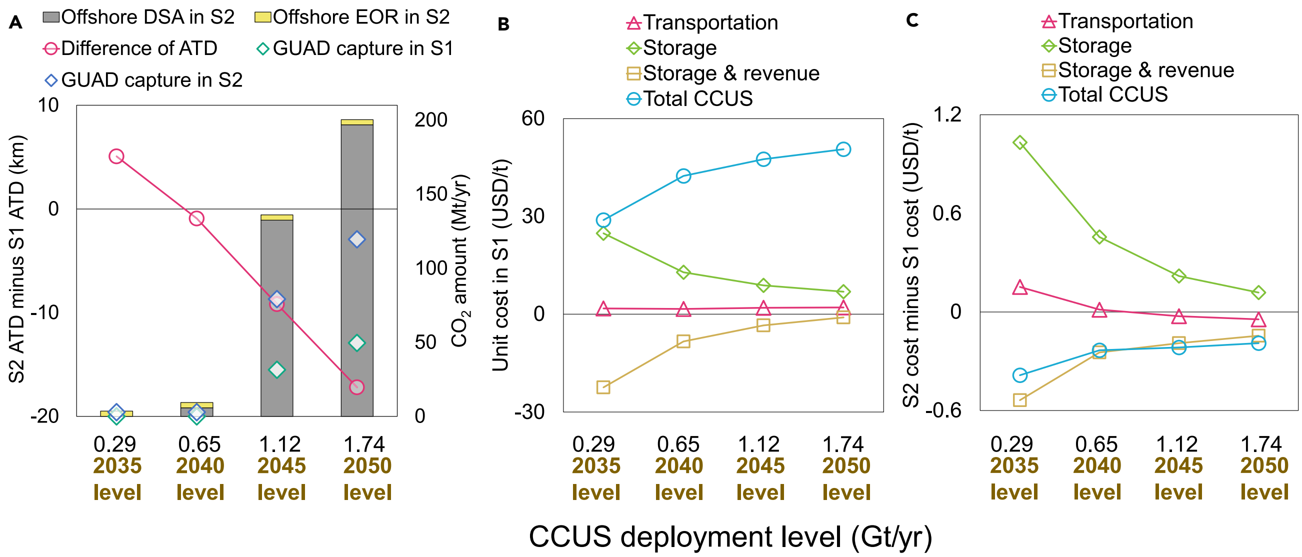

Figure 6. Comparison of physical and economic indicators for two different CCUS schemes

(A) Offshore storage deployment pathways and its impacts on CO_2 transport networks. Note: DSA – deep saline aquifers; EOR – enhanced oil recovery; ATD – average transport distance; GUAD – Guangdong Province.

(B) The estimation of cost components varying with CCUS deployment levels.

(C) Unit cost differences between S1 and S2. Note: The cost of CCUS shown in the figures includes the revenues from EOR.

of around 0.2 Gt in 2050, of which offshore oil fields and DSAs register 3.5 Mt and 196.8 Mt, respectively. The shift of CO_2 storage mode in southern provinces is also accompanied by gradual change of the average transport distance for the overall CCUS layouts, which indicates that emission hubs in some southern provinces witness a relative enhancement in the priority of CCUS deployment. For example, when CCUS deployment only reaches 0.65 Gt/yr in S1, there is still no motivation for Guangdong to join the shared CCUS networks. However, Guangdong would donate a capture of 2.8 Mt/yr in S2 and end up with a potential of about 119 Mt/yr in 2050, which is 2.4 times the capture in S1. It should be highlighted that the prospect of 119 Mt/yr indicated by this research is close to a suggested capacity of 110 Mt/yr in 2050 from a hypothetic proposal of offshore transport and storage for Guangdong Province,[47] which demonstrates the credibility and validity of the shared CCUS networks proposed in this study to a certain extent.

According to CCUS deployment pathways obtained from China TIMES (Figure 2D), this research further explores economic viability of proposed CCUS layouts with different scale. The unit cost of CCUS is about 50.6 \$/t when the deployment reaches the 2050-level in S1 (Figure 6B), with the unit cost of transportation and storage being about 2.1 \$/t and 6.9 \$/t, respectively. This assessment is consistent with the cost range reported in previous study[48] and largely mirrors the cost level for cases of shared CCUS networks examined in recent research.[49] Furthermore, different features are expected in unit cost differences (Figure 6C). Although the unit cost of storage in S2 may be higher than that in S1, the unit cost of CCUS in S2 can still be lower if considerable revenues brought by additional offshore CO_2-enhanced oil recovery (CO_2-EOR) are available. Therefore, the oil price and CO_2-EOR potential may serve as key uncertainties indicating the economic viability of proposed CCUS layouts. However, a critical deployment level may exist for the break-even point of the unit transportation cost difference between S1 and S2. These cost variations mimic the combination of the economies of scale and technology competition between onshore and offshore storage to a certain degree, which indicates a trade-off between the globally and locally optimum solution is needed for the policymaker.

Interprovincial heterogeneity of sectoral CCUS development

As shown in Figures 7A and 7B, the deployment potential of CCUS varies greatly among provinces. Among all the provinces embracing the opportunities of CCUS application, the expected deployment levels of Shandong, Henan, Hebei, Anhui, Xinjiang, Shanxi, Jiangsu, and Inner Mongolia rank in the top nine in both scenarios, with the sum of them reaching over 60% of the total annual capture in 2050. Generally, various degrees of difference are shown in mitigation contributions of CCUS to some provinces in this study. However, more apparent distinctions in the layout configurations are identified in Guangdong,

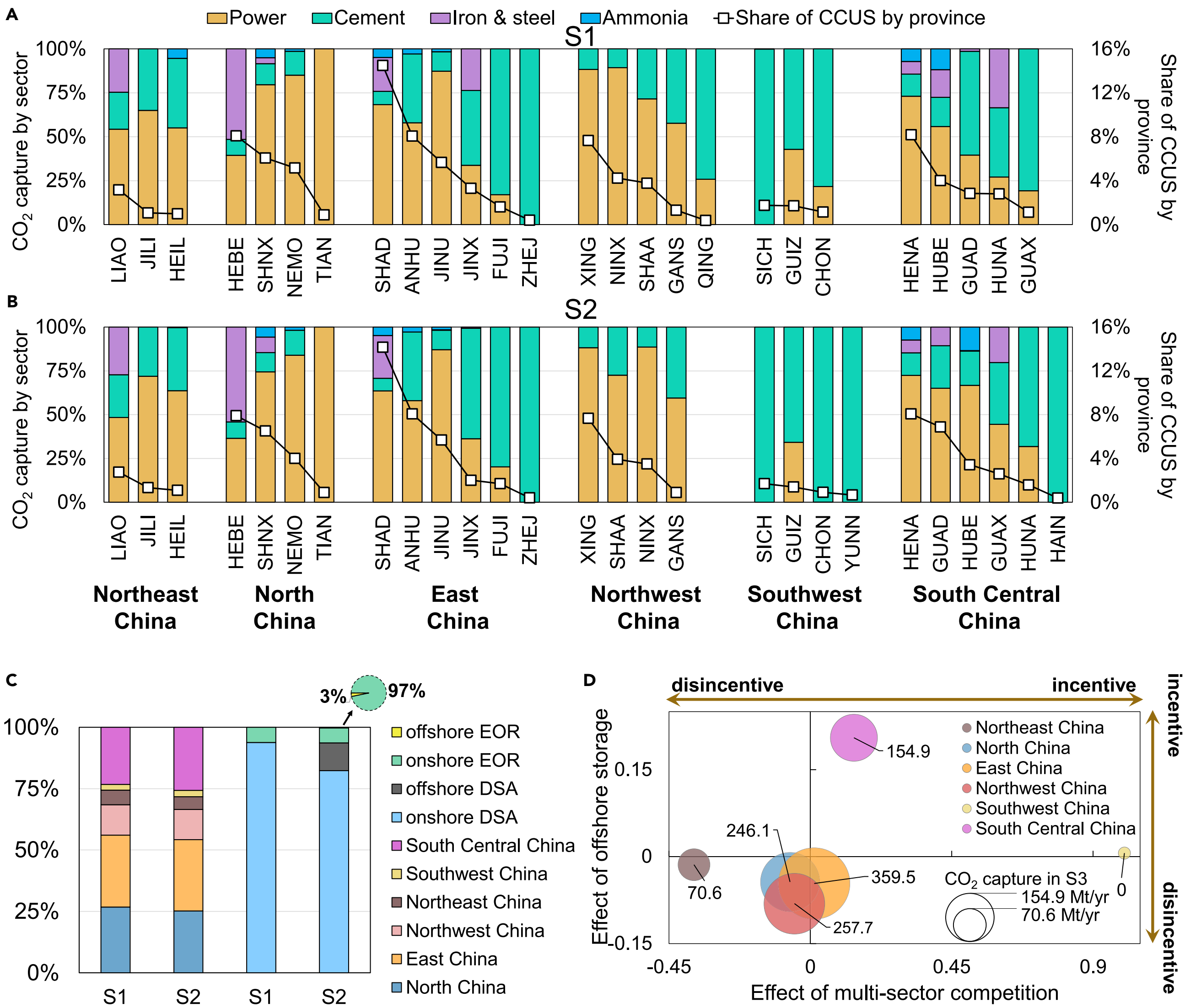

Figure 7. Comparison of provincial and sectoral CCUS deployment

(A and B) – CCUS diffusion patterns distinguished for different industries at the provincial level in S1 and S2, respectively. For China's 34 provincial administrative regions, Hong Kong, Macao, and Taiwan are not included in the assessment due to the limit of data availability. Beijing, Shanghai, and Tibet show lower CCUS cost-competitiveness than the other provinces in both two scenarios. More details about the provinces are shown in Figure S1 and Table S1.

(C) Differences of CO_2 storage between regions and the contribution of offshore storage in overall CCUS layouts.

(D) Incentives/disincentives of offshore storage (or industrial emission sources) to CCUS deployment with only onshore storage (or power sector) considered.

Guangxi, Yunnan, Hainan, and Fujian, with the former four provinces observing a noticeable increase in CCUS deployment and the last one witnessing the adjustment of transport routes (see Figure 4), thus emphasizing the impacts of offshore sequestration on regional CCUS roadmaps.

The diffusion of CCUS also displays remarkable dissimilarities among various industries of different regions in 2050. Take the layout under S1 as an example. For the total capture of 1.09 Gt/yr from overall power sector, the capture in Northeast China, North China, and Northwest China altogether accounts for 48.5%, which is 2.7 times the capture in Southwest China and South-Central China. However, different pattern is found for the cement industry, with 28.7% of the total sectoral capture in the former three regions and 37.8% in the latter two regions. CCUS deployment in iron and steel industry is more concentrated in certain areas, with the top two provinces (i.e., Hebei and Shandong) totaling about 63.7% of the total sectoral capture. Similar features are reflected in ammonia production, with the top four provinces (i.e., Shandong, Henan, Hubei, and Shanxi) accounting for 82% of the total sectoral capture.

Besides CO_2 capture, the whole picture of CO_2 storage also alters when offshore sequestration becomes a mitigation option. As shown in Figure 7C, South-Central China witnesses an increase of over 40 Mt/yr in CO_2 storage given the availability to offshore sequestration sites. However, Northeast China and North China are expected to experience a reduction of 12 Mt/yr and 27 Mt/yr in 2050, respectively. Further insights conducive to high-level decision-making of CCUS deployment could be obtained from the comparison of different CCUS layouts among S1, S2, and S3 (see scenario definitions in Table 1). As seen from Figure 7D, the engagement of multi-sector industrial point sources is most likely to be a strong incentive for emission hubs in Southwest China to deploy CCUS. However, it may act as a disincentive for the counterparts in Northeast China. This can be explained by regionally sector-specific imbalance between emission supply and CCUS demand, resulting from huge differences in industrial structure among provinces. From the perspective of storage modes, offshore sequestration may attract emission hubs in South-Central China to join the networks but discourage the counterparts in some other regions. More details about the two metrics shown in Figure 7D are in STAR Methods. The recognition of such heterogeneities of provincial-level deployment and industrial-specific diffusion is of vital significance for provincial governments to identify the exact role CCUS may play in the spectrum of various mitigation efforts. Only in this way is the most suitable CCUS roadmap for each province able to be conceived and decided.

DISCUSSION

Conclusion

Making the most of the relative merits of China TIMES and China CCUS DSS 2.0, multi-sector-shared CCUS networks commensurate with China's carbon-neutral vision are proposed for the first time, with the intention of achieving a harmonization between industry-wide CCUS development and plant-level CCUS deployment. From the perspective of infrastructure capacity-building and layout, about 19000-km CO_2 trunk lines are required by a total annual capture of 1.74 Gt in 2050, with the power sector, cement industry, iron and steel industry, and ammonia industry registering 1.09 Gt, 0.42 Gt, 0.19 Gt, and 0.04 Gt, respectively. The impact of offshore storage on CCUS deployment is revealed especially in southern provinces, which is accompanied by an obvious shift in cross-region CO_2 transport pattern, with 0.2 Gt/yr CO_2 redirected to Pearl River Mouth Basin and Beibuwan Basin in 2050. Regarding interprovincial and intersectoral heterogeneity, the economic viability of CCUS is expected to be noticeably improved in several southern provinces with reachable offshore reservoirs considered, albeit a much slighter enhancement for the nationwide layout. While the emissions from power generation and cement production is captured in almost all regions, CO_2 capture from the steelmaking and ammonia industries tends to be concentrated in several provinces, which indicates various carbon capture routes and different timing of CCUS promotion for each province.

Policy implications

As the world's largest emission producer, China faces the challenging problems of carbon locked-in due to its many youngest energy-intensive facilities. Therefore, China urgently needs to accelerate the progress of CCUS to pursue a balance between climate change mitigation and the risk of large-scale stranded assets. This study opportunely offers high-level policy considerations for CCUS deployment and popularization in the power sector and industry sector. Firstly, governments and industries should collaborate to facilitate more research, development, and demonstration of CCUS projects according to local industrial hubs, sector-specific technology diffusion level, and geological storage potential. Notably, provinces including Shandong, Shaanxi, Ningxia, Inner Mongolia, and Xinjiang may enjoy the deployment priorities for low-cost CCUS applications by virtue of quantities of high-purity CO_2 sources and rich storage potential there, thereby providing engineering references for other regions and supporting the maturity of shared CCUS networks. Moreover, emission sources enjoying highest priority of source-sink matching could be viewed as "capture-ready", which should conduct CCUS retrofits as early as possible. Those emitters exhibiting much lower CCUS cost-competitiveness ought to look for other mitigation solutions. For example, hydrogen-based routes and scrap-based secondary steelmaking may serve as promising alternatives for the iron and steel plants that are absent from the proposed CCUS layouts. Secondly, interprovincial and intersectoral cooperation need to be strengthened to coordinate the evolution of shared CCUS networks composed of emission hubs, storage hubs, and the most importantly, CO_2 transport layouts. Some CO_2 trunk routes with the length of about 50% of the total are most likely to share the rights-of-way with oil and gas pipeline corridors. This proportion may be even higher with feeder pipelines considered. Given the decline of oil and gas demand in the long term, great importance should be attached to investigating the technical feasibility of repurposing oil and gas pipeline networks for CO_2 transport. In addition, effective market instrument design based on interprovincial heterogeneity and intersectoral externality can also nourish a sustainable CCUS system. Thirdly, unlock the potential of offshore sequestration reasonably to diversify the profiles of mitigation options for massive emissions in southern coastal areas. Based upon the differences of CO_2 transport pattern identified in this research, the degree to which offshore storage is employed should be further examined with socioeconomic factors fully considered.

Limitations of the study

Uncertainties exist in CCUS deployment prospect, which have been explored in the previous research and is constrained by more moderate low-carbon transition pathways utilized in this study.[37,44] Admittedly, the secondary modes of CO_2 transport within individual emission hubs and the evolution of CCUS layouts have not been fully taken into account, which need to be further explored. In addition, the nomination of potential storage sites can make a difference to the layout of shared CCUS networks. Apart from CO_2-EOR and CO_2-DSA included in this research, other possible sequestration reservoirs and burgeoning ways of CO_2 utilization can be considered in this modeling framework in the future. Limitations also reside in inadequate techno-economic data from large-scale CCUS projects currently, which can be updated to provide more reliable insights into the shared CCUS networks in further research.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106347.

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AUTHOR CONTRIBUTIONS

Conceptualization, H.T. and W.C.; methodology, software, validation, formal analysis, H.T. and S.Z.; data curation, H.T., S.Z., and Q.Z.; writing – original draft, visualization, H.T.; writing – review & editing, H.T., W.C., S.Z., and Q.Z.; supervision, W.C.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
The Integrated MARKAL–Energy flow optimization model System (TIMES)	Energy Technology Systems Analysis Program-International Energy Agency	https://github.com/etsap-TIMES/TIMES_model
GAMS 39	GAMS Development Corp	https://www.gams.com/39/docs/index.html
Gurobi 9.5.1	GUROBI OPTIMIZATION, LLC	https://www.gurobi.com/
Python 3.7	Python Software Foundation	https://www.python.org/
ArcGIS Desktop 10.7	Environmental Systems Research Institute, Inc.	https://www.esri.com/en-us/home

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Wenying Chen (chenwy@tsinghua.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

- Data: The data reported in this study are available from the lead contact on reasonable request.
- Code: This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon reasonable request.

METHOD DETAILS

Spatially explicit analysis of CCUS layouts

China CCUS Decision Support System 2.0 (China CCUS DSS 2.0), the core of which is a spatially explicit mixed-integer programming (MIP) based on CO_2 source-sink matching (SSM),[50,51] was developed to support nation-scale CCUS layouts in line with China's climate ambitions.[37,45,52,53] The main workflow of China CCUS DSS 2.0 is shown in Figure 1. First, point sources are resampled by $0.25° \times 0.25°$ grids to generate multiple emission-related connected domains, which consists of contiguous grids containing different types of CO_2 emitters. Subsequently, a virtual center, namely an emission hub, is assigned to each connected domain to represent all the physical sources within it. The longitude and latitude of an emission hub are equal to the average of those for physical sources belonging to the corresponding domain. Second, storage hubs are regionalized by applying K-means clustering algorithm to the centroids of multiple polygons stemming from overlay analysis of the storage potential layer and administrative division layer. Third, Delaunay triangulation algorithm is employed to generate candidate CO_2 transportation routes based on the geographic coordinates of the emission hubs and storage hubs. Connectivity matrix and distance matrix, which are obtained according to the candidate transportation network, are passed to the SSM-based MIP together with the attribute parameters of emission and storage hubs as inputs to explore the least expensive CCUS layouts.

The objective function of CCUS SSM is to minimize the total cost of CCUS (denoted as Z), resulting from the process of CO_2 capture (Z^{cap}), transportation (Z^{tra}), storage (Z^{sto}), and revenues generated by CO_2-enhanced oil recovery (Z^{rev}):

$$Z = \min_{\substack{i \in S \\ p,q \in U \\ j \in R}} \left[\sum_{i \in S} Z_i^{cap}(a_i) + \sum_{\substack{p \in U \\ p \neq q}} \sum_{q \in U} Z_{pq}^{tra}(t_{pq}) + \sum_{j \in R} Z_j^{sto}(b_j) - \sum_{j \in R} Z_j^{rev}(b_j) \right] \quad \text{(Equation 1)}$$

$$Z_i^{cap}(a_i) = \sum_{g \in G} \left(CAPEX_{cap}^g(a_i^g) \cdot CRF + OPEX_{cap}^g(a_i^g) \right) \quad \text{(Equation 2)}$$

$$Z_{pq}^{tra}(t_{pq}) = CAPEX_{tra}(t_{pq}) \cdot CRF + OPEX_{tra}(t_{pq}) \quad \text{(Equation 3)}$$

$$Z_j^{sto}(b_j) = CAPEX_{sto}(b_j) \cdot CRF + OPEX_{sto}(b_j) \quad \text{(Equation 4)}$$

$$Z_j^{rev}(b_j) = l_{oil} \cdot \frac{b_j}{t_{oil}} \cdot k_{oil} \quad \text{(Equation 5)}$$

$$CRF = \frac{(1+r)^n \cdot r}{(1+r)^n - 1} \quad \text{(Equation 6)}$$

where a_i^g is the annual CO_2 capture from the sector g of the emission hub i; a_i is the annual CO_2 capture from all the sectors of the emission hub i; b_j is the annual CO_2 sequestered in the storage site j; t_{pq} is the annual CO_2 flow transported from the node p to the node q. $CAPEX_{cap}^g(a_i^g)$, and $OPEX_{cap}^g(a_i^g)$ are the cost of capital construction, and operation and maintenance related to a CO_2 capture of a_i^g, respectively. $CAPEX_{tra}(t_{pq})$, and $OPEX_{tra}(t_{pq})$ are the cost of capital construction, and operation and maintenance related to a CO_2 transport of t_{pq}, respectively. $CAPEX_{sto}(b_j)$, and $OPEX_{sto}(b_j)$ are cost of capital construction, and operation and maintenance related to a CO_2 storage of b_j, respectively. *CRF* is the capital recovery factor derived from the discount rate r and project lifetime n. l_{oil} is the wellhead price of oil; t_{oil} is the CO_2 replacement rates for oil; and k_{oil} is the tonne to barrel conversion ratio. The main constraints of this MIP are listed below.

$$\sum_{\substack{p \in U \\ p \neq i}} t_{ip} - \sum_{\substack{q \in U \\ q \neq i}} t_{qi} - a_i = 0, \forall i \in S \quad \text{(Equation 7)}$$

$$\sum_{\substack{p \in U \\ p \neq j}} t_{jp} - \sum_{\substack{q \in U \\ q \neq j}} t_{qj} + b_j = 0, \forall j \in R \quad \text{(Equation 8)}$$

$$a_i^g - E_i^g \cdot \delta \leq 0, \forall i \in S \text{ and} \forall g \in G \quad \text{(Equation 9)}$$

$$a_i = \sum_{g \in G} a_i^g, \forall i \in S \quad \text{(Equation 10)}$$

$$b_j \cdot \tau - Q_j \leq 0, \forall j \in R \quad \text{(Equation 11)}$$

$$b_j - W_j \cdot l_j \leq 0, \forall j \in R \quad \text{(Equation 12)}$$

$$\sum_{d \in D} v_{max}^d \cdot N_{pq}^d \geq t_{pq}, \forall p, q \in U \text{ and } p \neq q \quad \text{(Equation 13)}$$

$$\sum_{i \in S} a_i^g \geq T^g, \forall g \in G \quad \text{(Equation 14)}$$

$$a_i^g \geq 0, \forall i \in S \text{ and} \forall g \in G \quad \text{(Equation 15)}$$

$$b_j \geq 0, \forall j \in R \quad \text{(Equation 16)}$$

$$0 \leq t_{pq} \leq 100, \forall p, q \in U \text{ and } p \neq q \quad \text{(Equation 17)}$$

$$0 \leq l_{pq} \leq l_{max}, \forall p, q \in U \text{ and } p \neq q \quad \text{(Equation 18)}$$

where Equations 7 and 8 describe the conservation of CO_2 flow in shared CCUS networks. Equations 9, 10, 11, and 12 ensure that the amount of CO_2 capture/storage does not exceed the maximum capacity of each emission hub/storage site. E_i^g and Q_j represent the CO_2 emissions from the sector g of the emission hub i and the storage capacity of the storage site j, respectively. δ and τ denote the capture rate and lifetime for storage, respectively. W_j and I_j represent the number of injection wells and the injectivity for one injection well at the storage site j, respectively. Equation 13 determines the pipe size for each CO_2 transportation route. v_{max}^d and N_{pq}^d denote the maximum flowrate of the pipeline with a diameter of d and the number of the pipelines with the same diameter. Equation 14 requires the total CO_2 capture from each sector meet the CCUS demand projected for each sector by China TIMES, which is represented by T^g. Equations 15, 16, 17, and 18 are constraints on the value range of some variables. l_{pq} and l_{max} represent the length of transportation route from the node p to the node q and the maximum transportation distance allowed. More details about the variables, parameters and sets are summarized in Table S2.

Bottom-up energy system modeling

As an energy system optimization model presented in the mathematical form of dynamic linear programming, China TIMES was developed based upon China MARKAL[54–56] with a time horizon spanning from 2010 to 2050 at 5-year time steps, which has effectively provided tailor-made solutions for China's energy transition and low-carbon development in aspects ranging from sectoral decarbonization pathways (i.e., power sector,[57,58] iron and steel industry,[59–61] cement industry,[62] transport sector[63] and building sector[64]) to mitigation co-benefits assessment (i.e., air quality improvement[65] and energy-water nexus[66]) and techno-economic uncertainty analysis.[44] By virtue of its technology-rich database, sector-specific portrayal and process-level modeling, China TIMES identifies the most economically viable portfolios of energy technologies and fuels to meet the projected energy service demand of end-use sectors under given carbon budget constraints (see Table S3). A simplified diagram of reference energy system embodied in China TIMES is given in Supplemental Information (see Figure S2).

To assess CCUS deployment potential, CCUS diffusion in the power sector and the industry sector (like ironmaking and steelmaking, cement manufacturing and ammonia production) is fully considered, with other mitigation solutions (fuel switching, renewables scaling-up, technology performance advancement and clean hydrogen popularization, etc.) also introduced into the modeling framework. It is also through the competition between various technology options that the role CCUS plays in decarbonizing China's power sector and other hard-to-abate industries is comprehensively evaluated.

Notably, in contrast to most bottom-up energy system models whose energy service demand are exogenous, China TIMES introduces price elasticity of demand, thus considering the changes in demand led by price variations and reflecting the behavioral shift during energy transition.[44] To achieve decarbonization, emission-intensive industries like steel, cement and ammonia bear severe pressure due to soaring production costs, making the output lower than that without climate targets. More details about the model structure and mathematical formulation of the TIMES paradigm can be found in tailored documentations for TIMES.[67,68]

Plant-level screening based on the model linkage framework

A soft-linkage framework is established to analyze national-scale CCUS layouts and simultaneously project CO_2 emission distribution (Figure 1). As a key input of China CCUS DSS 2.0, the amount of CO_2 capture relies on the CCUS deployment potential determined by China TIMES. In addition to CCUS prospects evaluation, identifying the candidates for CCUS deployment is also critical. This research takes plant-level techno-economic attributes as the criteria to filter out the unsuitable emission sources while the others would remain to be further examined by the final demand in 2050 projected by China TIMES. Specifically, unabated thermal power plants, cement production and blast furnace ironmaking processes are given the opportunity to retire early in China TIMES, thus making way for the expansion of cleaner production capacities with advanced technologies. Subject to the supply-demand balance, China TIMES maximizes the net total surplus and optimally derives the demand (equivalent to production) for different industrial products. The industrial product yields of cement and crude steel in 2050 are passed into China CCUS DSS 2.0 to support the plant-level screening of CCUS retrofits suitability.

Take the cement industry as an example. Considering appropriate scale of CO_2 capture and retrofit suitability depending upon the remaining lifetime, only those cement plants built after 2010 and with a daily capacity of over 5000-tonne cement clinker would be considered for further examination. If the total current cement output of those factories satisfies the projected demand of the cement products in 2050, these cement plants would be viewed as the candidates for CCUS source-sink matching. To address the regional heterogeneity of activity level, an adjusted average capacity factor is reassigned to all selected cement works according to the ratio of the total actual production to the total capacity in the current year. In other words, the facilities with the largest production capacity are retained as candidates for CCUS application, which mimics China's air pollutant control measure—supporting large projects with advanced technologies but phasing out small units with low efficiency.[69]

Effects of offshore storage and multi-sector competition

To grasp the potential effect of offshore storage and multi-sector participation on overall CCUS networks, three scenarios distinguished by storage modes and source types are set up, as shown in Table 1. This study innovatively constructs two metrics (i.e., M and N) based on the results of CCUS source-sink matching in these three scenarios to quantify the effects of offshore storage and multi-sector competition on the layout in S3, i.e., the most elementary CCUS layouts that only aims at the power sector and onshore sequestration (see Figure S3). The effect of multi-sector competition for region j shown in Figure 7D, denoted as M_j, is obtained from the comparison between S1 and S3, aiming to suggest the impacts of industrial sources on CCUS deployment in the power sector, which is defined as

$$M_j = \left(C_{1,j}^{power} - C_{3,j}^{power}\right) \Big/ C_{1,j}^{power} \qquad \text{(Equation 19)}$$

where $C_{1,j}^{power}$ and $C_{3,j}^{power}$ are the total CO_2 capture from the power sector of the region j in S1 and S3, respectively. With a larger M_j, the power sector of the region j will receive greater incentives brought by industrial sources' engagement in CCUS deployment, which reflects somewhat the positive externality embodied in the concept of shared CCUS networks.

The effect of offshore storage for region j shown in Figure 7D, denoted as N_j, is derived from the comparison between S1 and S2, which is formulated as

$$N_j = \left(C_{2,j}^{all} - C_{1,j}^{all}\right) \Big/ C_{1,j}^{all} \qquad \text{(Equation 20)}$$

where $C_{1,j}^{all}$ and $C_{2,j}^{all}$ are the total CO_2 capture from all types of sources of the region j in S1 and S2, respectively. With a larger N_j, the region j will observe greater CCUS cost-competitiveness due to the involvement of offshore sequestration in shared CCUS networks.

Data for emission sources and storage sites

This study collects and updates the latest information about China's major emission sources and storage sites.[37,45,50–53] As two carbon storage options receiving the widest attention, DSAs and oil fields in this study are regionalized and represented by 113 storage sites using clustering method, with a total storage potential of about 2465.6 Gt and 3.3 Gt, respectively. The emission sources collected and examined in this research covers nearly 3000 coal-fired power units and 1693 industry plants (cement manufacturing, iron-making and steelmaking, ammonia production, petroleum refining and modern coal chemical industries). After plant-level screening of CCUS suitability, 531 coal-fired power plants, 258 cement plants, 49 steelworks and 60 synthetic ammonia plants are retained as candidates for CCUS source-sink matching, with a total annual CO_2 emission of about 3.4 Gt. These 898 large CO_2 point sources are spatially aggregated and further represented by 484 emission hubs. More information about the parameters related to estimation of CO_2 emissions is listed in Table S4.