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Assessing Representative CCUS Layouts for China's Power Sector toward Carbon Neutrality

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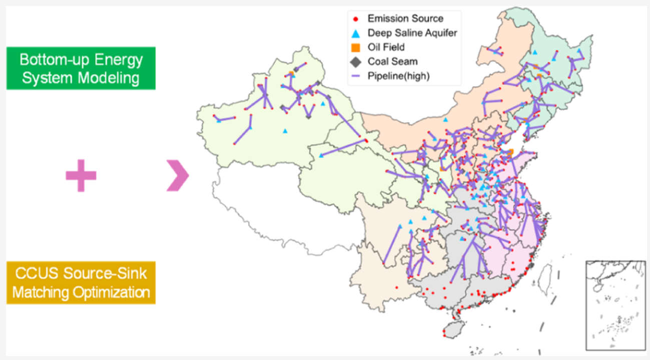

ABSTRACT: China's carbon neutrality target is building momentum for carbon capture, utilization, and storage (CCUS), by which the power sector may attain faster decarbonization in the short term. However, an overall CCUS pipeline network blueprint remains poorly understood. This study, for the first time, links the China TIMES model and ChinaCCUS Decision Support System 2.0 to assess representative CCUS layouts for the power sector toward carbon neutrality, with the level of deployment and the maximum transportation distance from emission sources to storage sites considered. The total length of the proposed layouts under the low, medium, and high levels of deployment are about 5100, 18,000, and 37,000 km, with the annum CO_2 captures of 0.4, 1.1, and 1.7 Gt, respectively, whereas pipes of medium diameters (12, 16, and 20 in) account for the majority in all three plans. As the deployment rate increases, the layouts generally spread from Northeast, North, and Northwest China to East, South Central, and Southwest China. However, some local exceptions take place considering terrain areas that the pipeline passes through. In addition to engineering guidance, this assessment also illuminates the opportunity for improving the efficiency of CCUS based on carbon pricing.

KEYWORDS: *CCUS, carbon neutrality, China TIMES, source-sink matching, climate change mitigation, pipeline network layouts, terrain areas*

1. INTRODUCTION

With the consensus of the 1.5- and 2-degree warming limits,[1] 29 economies have formally proposed carbon neutrality commitments by national legislation, submission agreements, or policy declarations.[2] As the world's largest CO_2 emitter, China announced the climate goal to achieve carbon neutrality before 2060, which is of great significance to promote net-zero emissions in the world. With total installed capacity exceeding 1020 GW and still growing,[3] China's coal-fired power generation contributed to about 45% of the total national emissions in 2019,[4] bearing much pressure for decarbonization.

Considering limited improvement in energy efficiency and the instability led by large-scale deployment of renewables in the near term, carbon capture, utilization, and storage (CCUS) is expected to play an important part in achieving net-zero emissions both in China and globally through two aspects: (i) realizing deep carbon reduction from energy assets including power plants and (ii) enabling wide applications of negative emission technologies through engineered systems, such as bioenergy with carbon capture and storage (BECCS) and direct air capture with storage (DACS).[4,5] Eight operational CCUS facilities currently exist in China with CO_2 capture of about 1 Mt per annum, covering industries such as power generation, chemical production, and cement production,[6] which is still inadequate for China's carbon neutrality target. However, CCUS is much likely to experience rapid development and wide implementation during the next decades, given its inclusion in the National 14-th Five-Year Plan.[7] Therefore, there is an urgent need for a comprehensive assessment on the national-scale CCUS layout backing up sustainable development for the long run.

CCUS prospect evaluation is a prerequisite for pipeline infrastructure design. Although formidable roles of CCUS are confirmed in many research studies, the level of deployment varies significantly. Regarding the ratios of CCUS capture to total CO_2, the maximum difference of about 25% is identified under the 1.5 °C warming limit by multi-model comparison.[8] The huge impacts of socioeconomic development and technology competition on CCUS deployment are also discussed.[9] Specifically, the uncertainty of China's decarbon-

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ization pathway can cause a maximum variation of 197 GW for the total CCUS capacity in 2050 under different scenarios,[10] thus calling for exploring roadmaps with diverse technology portfolios and assessing the role of CCUS to ensure more representative pipeline network layouts.[11]

CO_2 pipeline network design, which is typical of graph theory and can be solved by mixed integer linear programming (MILP) combined with geographic information system (GIS),[12−15] is another key part for CCUS implementation. Several CCUS source-sink matching (SSM) decision support systems (DSS) have been developed for pipeline infrastructure planning, such as GeoCapacity DSS[16,17] and InfraCCS[18] in Europe, Market Allocation Model (MARKAL)-NL-UU[19] in the Netherlands, WESTCARB[20] in the United States, ChinaCCUS DSS[12−15] in China, and C^{3}IAM/GCOP[21] on a global scale. In addition, SSM has also exerted its effectiveness on frontiers ranging from life cycle optimization of the CCUS supply chain[22−24] to low-carbon hydrogen production[25] and large-scale deployment of BECCS.[26] Recently, much progress has been made in CCUS layouts commensurate with China's low-carbon development. Zhou et al. proposed a plan of offshore CO_2 transport and storage for Guangdong Province.[27] Fan et al. demonstrated the necessity of cross-region CO_2 transportation based on a county-level SSM.[28] Wang et al. proposed optimal CCUS planning for China's power sector under the 2 °C constraint, with an average transportation distance of less than 115 km.[29] However, the following important factors may have been overlooked: (i) the uncertainty of deployment led by technology competition[30] (like CCUS vs renewables), public acceptance,[31,32] and employment impacts;[33,34] (ii) the differences in investment cost caused by spatial heterogeneity of emission sources and storage sites; (iii) the influences of terrain areas on transportation route selection.

To fill the research gaps, this research links the China TIMES (The Integrated MARKAL−Energy flow optimization model System) and ChinaCCUS DSS 2.0 to realize the integration of CCUS prospect evaluation and geospatial analysis. This is also the first study, to the best of our knowledge, to conduct a comprehensive assessment on overall CCUS blueprints aiming at China's carbon neutrality, which may provide insights into engineering construction and mechanism design in the coming decade.

2. METHODOLOGY

2.1. China TIMES Model. Taking advantage of both the MARKAL[35] and the EFOM,[36] TIMES, a bottom-up model developed by the Energy Technology System Analysis Program in the International Energy Agency,[37] provides insights into the development of multi-scale energy systems in various time spans. To characterize the national conditions more specifically, China TIMES was developed based on China MARKAL with 5-year intervals from now to 2050, which has proven to be effective and reliable in decision-making of climate mitigation solutions,[38,39] optimal planning for decarbonization pathways of energy systems (e.g., power sector,[40] industry sector,[41−44] building sector,[45] and transportation sector[46]) and co-benefits analysis.[43,47] Driven by the energy demand of several sectors including industry, building, transportation, and agriculture, China TIMES determines the most cost-effective mix of energy technologies and fuels under constraints of resource endowment and policies. Each module in this model represents certain energy processes and finally all modules are coupled through physical conservation and economic principles. Abundant with over 500 energy technologies in its database, this model assesses the role CCUS plays in achieving China's ambitious climate target from the perspective of the whole energy system, thus illuminating the impact of technology competition on the national-scale CCUS layout.

2.2. ChinaCCUS DSS 2.0. As the upgraded version of ChinaCCUS, ChinaCCUS DSS 2.0, whose computing platform is based on Python and ArcGIS, is devoted to exploring pipeline network layouts commensurate with the carbon neutrality target using the newest SSM database.

The workflow of ChinaCCUS DSS 2.0 is as follows. First, based on the emission source data set and storage site data set, source and sink layers containing location information and attribute information (emissions, life time, storage potential, shape, area, etc.) are generated. Furthermore, the *K*-means clustering algorithm is used to identify injection sites for storage reservoirs considering feasible implementation. Second, candidate routes are obtained by Delaunay triangulation algorithm and the connectivity matrix, distance matrix, and terrain penalty matrix are calculated through spatial analysis of candidate routes and terrain features, which are passed to the SSM module as inputs. Third, an MILP is established to explore the least expensive solution under different scenarios. Last, the national-scale CCUS layout is visualized in ArcGIS, allowing for further analysis.

Taking CO_2 capture, transportation, and storage as major decision variables, SSM optimizes the least expensive overall CCUS layouts while meeting engineering standards. A more detailed description about this typical MILP is given below.

2.2.1. Objective Functions. The objective of SSM is to minimize the total cost (denoted as Z) of CCUS

$$Z = \min\left(\sum_{i\in S} C_i^{\text{cap}}\cdot a_i + \sum_{i\in S}\sum_{j\in R} c_{ij}^{\text{tra}}\cdot x_{ij} + \sum_{j\in R} c_j^{\text{sto}}\cdot b_j - \text{revenue}\right) \quad (1)$$

where C_i^{cap} is the unit cost of capture for node i; c_j^{sto} is the unit cost of storage for node j; c_{ij}^{tra} is the unit cost of transportation from node i to node j; and c_j^{sto} and c_{ij}^{tra} are endogenous variables, which depend on specific engineering processes including pipeline construction and well drilling. a_i, x_{ij}, and b_j are the amount of CO_2 capture, transportation, and sequestration, respectively; revenue is the income resulting from CO_2-enhanced oil recovery and CO_2-enhanced coal bed methane, which means this value is set to 0 when deep saline aquifers (DSAs) are selected

$$\text{revenue} = \sum_{j\in R}\left(p_{\text{oil}}\cdot\frac{b_j}{t}\cdot k_{\text{oil}} + p_{\text{gas}}\cdot\frac{b_j\cdot V_m}{M\cdot q}\right) \quad (2)$$

where p_{oil} and p_{gas} are the oil price and gas price in each site; t and q are the CO_2 replacement rates for oil and gas, respectively; k_{oil} is the ton to barrel conversion ratio; M is the molar mass of CO_2, 44 g/mol; and V_{m} is the molar volume of ideal gas, 0.0224 m^3/mol.

2.2.2. Constraints. 2.2.2.1. Conservation of Mass. For each node in the candidate route network, the CO_2 inflow is equal to the CO_2 outflow.

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$$\sum_{\substack{n \in U \\ n \neq i}} x_{in} - \sum_{\substack{n \in U \\ n \neq i}} x_{ni} - a_i = 0, \qquad \forall\ i \in S \tag{3}$$

$$\sum_{\substack{n \in U \\ n \neq j}} x_{jn} - \sum_{\substack{n \in U \\ n \neq j}} x_{nj} + b_j = 0, \qquad \forall\ j \in R \tag{4}$$

It should be noted that node n can be either a source or sink node. The realistic considerations embodied in this ingenious mathematical improvement, which differ from most existing research, realize the respective clustering of sources and sinks.

2.2.2.2. Capture and Storage Capacity. The optimal amount of CO_2 capture (sequestration) at each node depends on the corresponding capture (storage) capacity

$$a_i - E_i \cdot \eta \leq 0, \qquad \forall\ i \in S \tag{5}$$

$$b_j \cdot \tau - Q_j \leq 0, \qquad \forall\ j \in R \tag{6}$$

$$b_j - N_j \cdot I_j \leq 0, \qquad \forall\ j \in R \tag{7}$$

where E_i and Q_j represent the annual CO_2 emissions and storage capacity at the corresponding node; η is the capture efficiency, 95%; τ is the timeframe for storage, 30 years; N_j is the number of injection wells at node j; and I_j represents the injectivity for one well at node j, which depends on the category of CO_2 storage.

2.2.2.3. Pipeline Selection. Considering engineering construction standards, we have a pipeline flow limit

$$\sum_{d \in D} v_{\max}{}^{d} \cdot N_{ij}{}^{d} \geq x_{ij} \tag{8}$$

where $v_{\max}{}^{d}$ refers to the maximum flow rate of the pipeline with a diameter of d and $N_{ij}{}^{d}$ is the number of pipelines (of the same diameter) on the same route.

2.2.2.4. Driving Mechanism. The CCUS layout is expected to reach a CO_2 reduction target T

$$\sum_{i \in S} a_i \geq T \tag{9}$$

This can also be achieved by introducing carbon pricing (denoted as p_c) on CO_2 emissions without setting the amount target. In this case, eq 1 is changed into the following

$$Z = \min\left(\sum_{i \in S} C_i^{\text{cap}} \cdot a_i + \sum_{i \in S} \sum_{j \in R} c_{ij}^{\text{tra}} \cdot x_{ij} + \sum_{j \in R} c_j^{\text{sto}} \cdot b_j - \text{revenue} + p_c \cdot \sum_{i \in S} (E_i - a_i)\right) \tag{10}$$

2.2.2.5. Non-Negativity.

$$a_i \geq 0 \tag{11}$$

$$b_j \geq 0 \tag{12}$$

$$0 \leq x_{ij} \leq 100 \tag{13}$$

$$0 \leq l_{ij} \leq l_{\max} \tag{14}$$

where l_{ij} is the CO_2 transportation distance from node i to node j and $l_{\max}$ represents the maximum transportation distance.

2.2.3. Decision Variables and Model Parameters. The main decision variables and key parameters of SSM are listed in Table 1.

Table 1. Variable Declaration

category	symbol	unit	value or description
decision variable	a_i	Mt/year	Model output
	b_j	Mt/year	Model output
	x_{ij}	Mt/year	Model output
	$N_{ij}{}^{d}$		Model output
input parameters	t	ton CO_2/ton oil	3.18
	q	mol CO_2/mol CH_4	2
	k_{oil}	ton oil/barrel	7.33
	$v_{\max}{}^{d}$	Mt/year	depending on pipe type
	C_i^{cap}	¥/ton CO_2	300
	p_{oil}	¥/barrel	238
	p_{gas}	¥/m^3	0.754
	I_j	Mt/year	depending on geological conditions
	T	Mt/year	scenario indicator
	$l_{\max}$	km	scenario indicator
set	**S**		CO_2 emission sources
	R		CO_2 storage sites
	U		nodes connected to the current node
	D		pipeline diameters

2.3. Soft-Link between China TIMES and ChinaCCUS DSS 2.0. This research innovatively links the China TIMES model and ChinaCCUS DSS 2.0 to analyze the impacts of competition between CCUS and other technologies on national-scale CCUS layouts. Figure 1 shows the linkage framework. Under the constraints of cumulative CO_2 emissions in 2010−2050 being 290 Gt and the CO_2 emissions for 2050 being 0.5 Gt, the decarbonization pathways generated in China TIMES meet the requirements of China's carbon neutrality goal and the 1.5- and 2-degree targets.[47,48] Being both the output of the energy system optimizer and the input of the CCUS layout generator, the amount of CO_2 capture (denoted as T) reflects various uncertainties in aspects ranging from technology competition to public acceptance while greatly affecting the proposed CCUS layouts and the total cost (composed of capture, transportation, storage, and product revenue) decided by ChinaCCUS DSS 2.0. Furthermore, the CCUS layouts can be used as feedback for the energy system optimizer to regulate the decarbonization pathways determined by China TIMES. Therefore, the linkage between them cast light on underlying factors to be considered for policy makers.

3. SCENARIOS AND MATERIALS

3.1. Scenarios and Assumptions. Besides deployment potential, the transport scale of the CO_2 pipeline also matters to CCUS planning, which is divided into three categories according to the transportation distance.[49] Thus, nine scenarios (S1−S9) are established to explore representative CCUS layouts based on different combinations of CO_2 reduction target T and the maximum transportation distance $l_{\max}$, as shown in Table 2.

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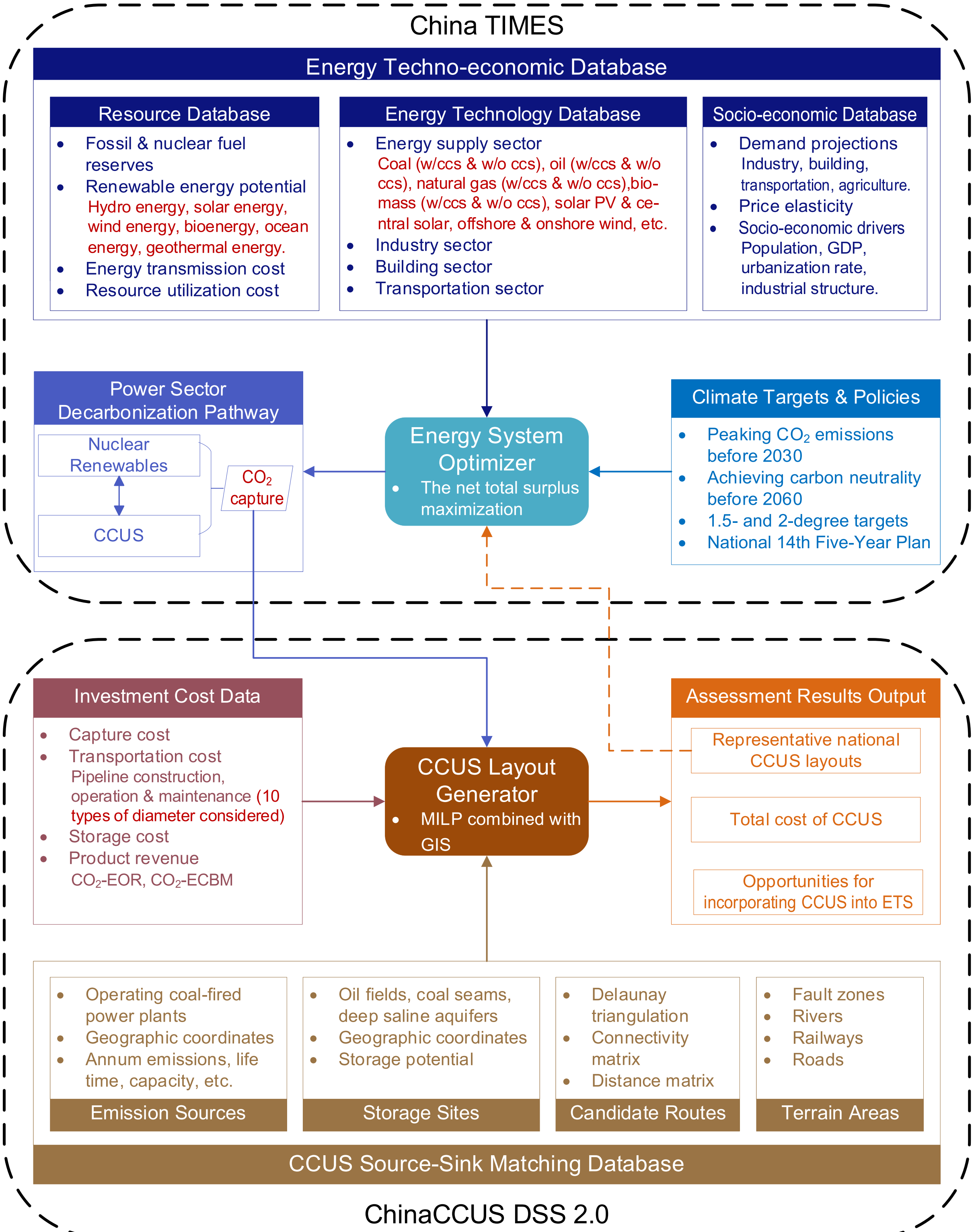

Figure 1. Linkage framework between China TIMES and ChinaCCUS DSS 2.0. The solid lines in different colors represent the module coupling and workflow of this soft-linking modeling. The orange dotted line reflects the feedback regulation effect of the system, which will be the direction of our further efforts to pursue a hard-link.

External uncertainties including technology competition and social cognition can lead to different levels of CCUS deployment, while internal limitations featured by the maximum transportation distance influence the feasibility of certain construction plans. It is by comparisons between scenarios that the effect of each factor is identified and the economic performances of different layouts are indicated.

Besides, necessary assumptions are made to simplify the analysis without losing scientific values and instructive significances: (i) with the life time being 40 years, the coal-fired power plants (CFPPs) selected in SSM were established

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Table 2. Scenario Definition

scenarios	the level of CCUS deployment			maximum transportation distance (km)		
	low	medium	high	100	300	800
S1	√			√		
S2	√				√	
S3	√					√
S4		√		√		
S5		√			√	
S6		√				√
S7			√	√		
S8			√		√	
S9			√			√

post-2010 with an installed capacity of more than 300 MW (except for very few), thus ensuring the existence of all the emission sources during research periods and (ii) the storage sites matched with emission sources have to meet the corresponding CO_2 emission requirements for at least 30 years.

3.2. CCUS SSM Database. This study constructs the latest database of China's CCUS SSM including the emission source data set and the storage site data set. The original data resources refer to the Global Coal Plant Tracker,[3] Sun[50] and Li et al.[51] The annual CO_2 emission for each power plant is estimated as

$$E_i = IC_i \times HR_i \times CF_i \times EF_i \times 9.2427 \times 10^{-12} \quad (15)$$

where E_i, IC_i, HR_i, CF_i, and EF_i represent the CO_2 emissions (Mt), installed capacity (MW), heat rate (Btu/kW h), capacity factor, and emission factor ($kgCO_2$/TJ) of the i-th plant, respectively. Based on the assumptions, 531 power plants are considered in this study, with the total annual CO_2 emissions of about 2 Gt.

The way of CO_2 storage, in this research scope, is either to be sequestered in DSA or used for CO_2 enhanced oil recovery or CO_2 enhanced coal bed methane. 106 onshore storage sites with potential exceeding 100 Mt are identified by applying the K-means clustering algorithm to the intersections of the storage potential layer and the administrative division layer. Assuming the CO_2 storage capacity is evenly distributed within the given reservoirs, the storage capacity of each site is then determined by the ratio of its area to the area of the reservoirs to which it belongs. Additionally, terrain information including roads, railways, rivers, and fault zones are used to evaluate the feasibility of pipeline construction comprehensively.

4. RESULTS AND DISCUSSION

4.1. Decarbonization Pathways of China's Energy System. The contributions of CCUS to China's carbon neutrality goal is meticulously examined by China TIMES. After reaching a peak of 10.4 Gt in 2030, China's CO_2 emissions will decrease to 0.5 Gt in 2050 at an annual average rate of 0.5 Gt (Figure 2a). The power sector has to undertake the largest emission reduction in the near future and take the lead in realizing negative emissions between 2040 and 2045, thus ensuring that the entire energy system achieves net-zero emissions before 2060. To understand the interaction between CCUS and other technologies, three representative roadmaps for energy transition, referring to three levels of CCUS deployment, are optimized under the constraints of emission pathways in line with China's climate goals and policies.

Figure 2b shows the CO_2 capture amounts required by CCUS applications toward carbon neutrality. All the transition routes under these scenarios indicate that CCUS should be deployed on a large scale from 2035. Specifically, CCUS and BECCS may act as key pillars to decarbonize the CFPPs, which will contribute to about 0.4, 1.1, and 1.7 Gt CO_2 capture in

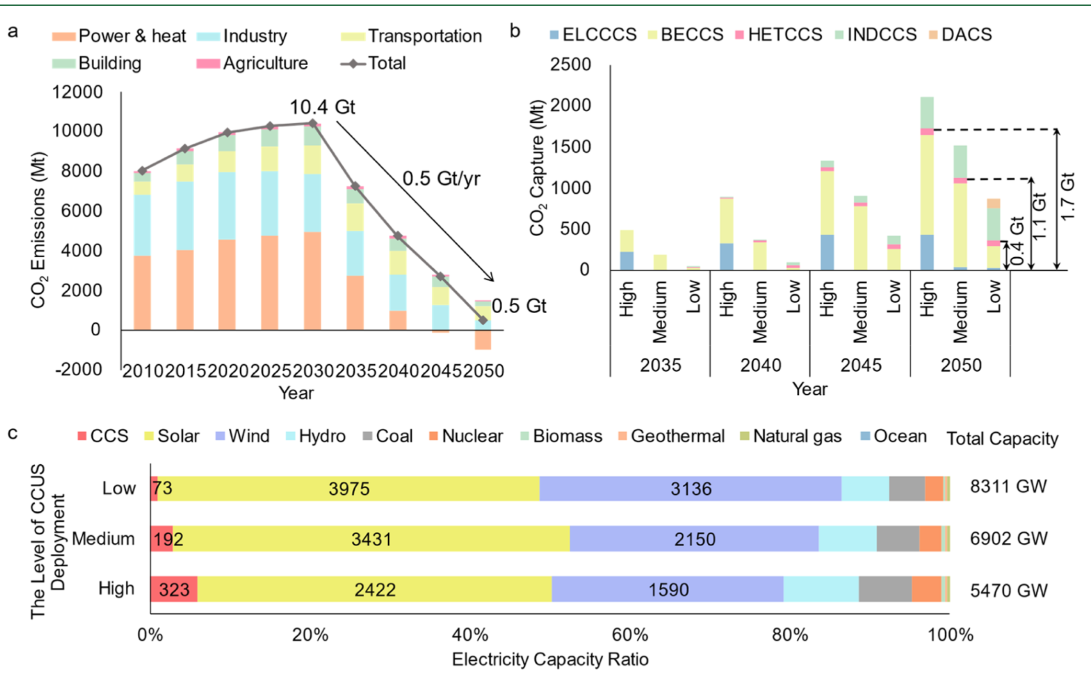

Figure 2. Role CCUS plays in achieving China's carbon neutrality target. (a) China's CO_2 emission pathways from 2010 to 2050; (b) CO_2 capture under scenarios with different deployment rates. ELCCCS—CCS in electricity production; BECCS—bioenergy with CCS; HETCCS—CCS in heat production; INDCCS—CCS in cement production, iron and steel making, petroleum refining, and so forth. DACS-direct air capture with storage; and (c) electricity generation capacity structure in 2050.

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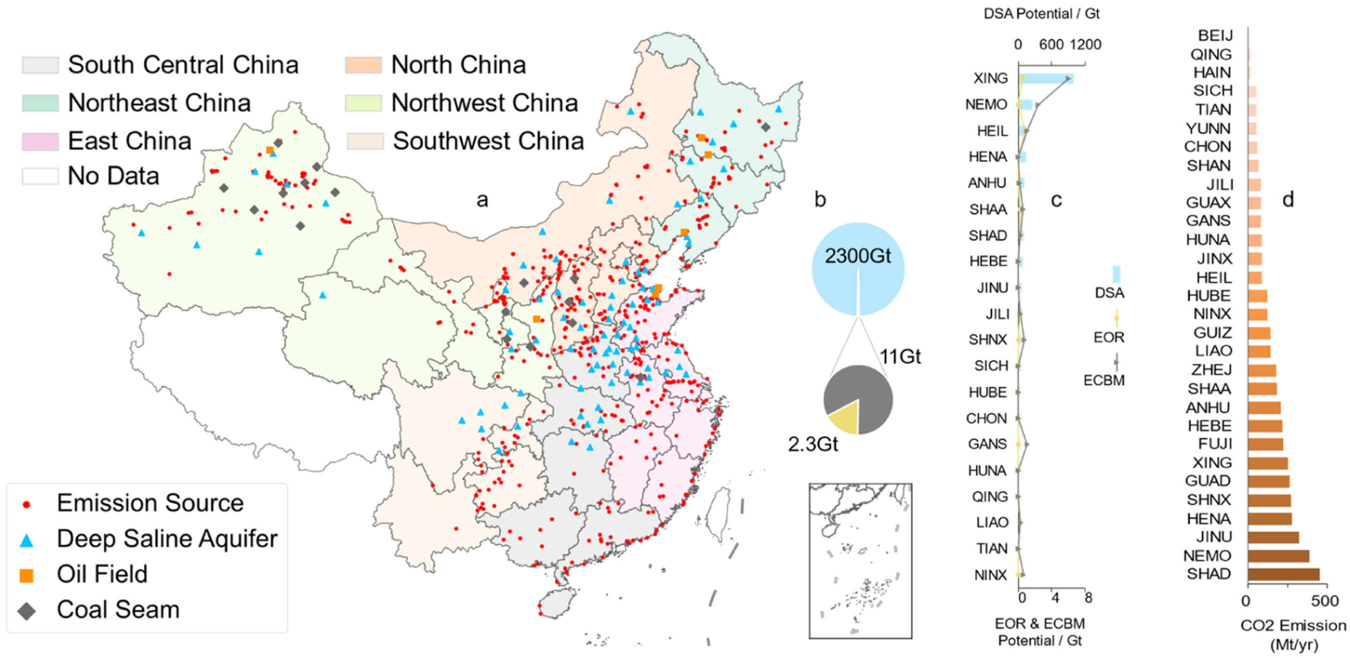

Figure 3. Spatial heterogeneity of CO_2 emissions and storage potential. (a) Distribution of coal-fired plants and storage sites in China's six main regions. (b) Categories of CO_2 storage in China. (c) Province-level assessment of CO_2 storage potential. (d) Province-level characterization of CO_2 emissions. More details for abbreviations of provinces can be found in the Supporting Information.

2050 under scenarios with low, medium, and high deployment rates, respectively.

Figure 2c depicts the electricity generation capacity structure in 2050. The installed capacities of CCUS under three scenarios are expected to reach 323, 192, and 73 GW, accounting for 6, 3, and 1% of the total, respectively. With the reduction of CCUS capacity, the deployment of solar and wind power has to increase from 4011 to 7112 GW significantly, which is a test for China's resource endowment, policy practice, and economic benefits. As a result, the attention paid to technology competition is crucial when determining national CCUS layouts.

4.2. Spatial Heterogeneity of CO_2 Emissions and Storage Potential. This study selects CFPPs built after 2010 as emission sources, which will still suit CCUS retrofitting or implementation in 15−30 years, and 106 onshore storage sites to generate the newest CCUS SSM layer shown in Figure 3a. The spatial heterogeneity is manifested in the fact that emission sources are more in the east and less in the west, while storage sinks are more in the north and less in the south.

DSAs play a dominant role in China's CO_2 storage with the potential of about 2300 Gt, followed by coal seams and oil reservoirs, reaching 11 and 2.3 Gt, respectively (Figure 3b). More specifically, the storage potential is mainly distributed in 20 provinces (Figure 3c), of which Xinjiang ranks first with a potential of about 1003 Gt, accounting for 43% of the total. Unlike Xinjiang's storage potential mostly composed of DSAs, Heilongjiang, Jilin, and Liaoning in Northeast China have reservoir storage potential of 1.3 Gt, accounting for about 56% of the country's oil reservoirs, which might bring considerable product revenue to these provinces.

However, there are still 10 provinces with near-zero storage capacity, whose CO_2 emissions cannot be underestimated. For example, Guangdong, Fujian, Zhejiang, Guizhou, and Jiangxi rank 6 th, 8 th, 12 th, 14 th, and 18 th in annual emissions, and the five together account for nearly 20% of the total (Figure 3d). Everything mentioned above highlights the issue that the spatial heterogeneity of emission sources and storage potential lead to the priority difference in CCUS implementation.

4.3. Proposed Pipeline Network Layouts under Different Scenarios. Based on the soft-link between China TIMES and ChinaCCUS DSS 2.0, this study assesses national-scale CCUS layouts under various representative decarbonization pathways corresponding with scenarios S1−S9 (Table 2).

4.3.1. Impacts of the Level of CCUS Deployment. Figure 4 illustrates the proposed overall CCUS layouts considering three levels of deployment determined by China TIMES. As shown in Figure 4a, yellow, green, and purple solid lines represent the pipelines that need to be constructed under S3, S6, and S9, with CO_2 capture of 0.4, 1.1, and 1.7 Gt, respectively. Provinces with abundant oil and coal reserves, such as Heilongjiang, Jilin, Liaoning, Shaanxi, and Xinjiang, are suitable for priority deployment because of the short reachable distance and considerable byproduct benefits. As the capture amount increases, the pipeline network gradually extends southward to some provinces in East, South Central, and Southwest China, where CO_2 is mostly sequestered into DSAs. Even for the high deployment rate, however, there are still some southern coastal provinces (Fujian, Guangdong, Guangxi, Yunnan, and Hainan) that are not recommended to deploy CCUS due to the poor on-shore storage potential and long transportation distance.

With the capture amount increasing, the maximum pipeline length climbs from about 180 km to nearly 600 km, and the maximum CO_2 flow for the transportation routes goes from around 20 Mt up to 60 Mt (Figure 4b−d). Although the growing involvement of southern provinces leads to significant expansion of the pipeline network, transportation routes within 200 km still account for the majority in all three scenarios. Additionally, pipes of medium diameters (12, 16, and 20 in) are most frequently used, accounting for about 80% of the total

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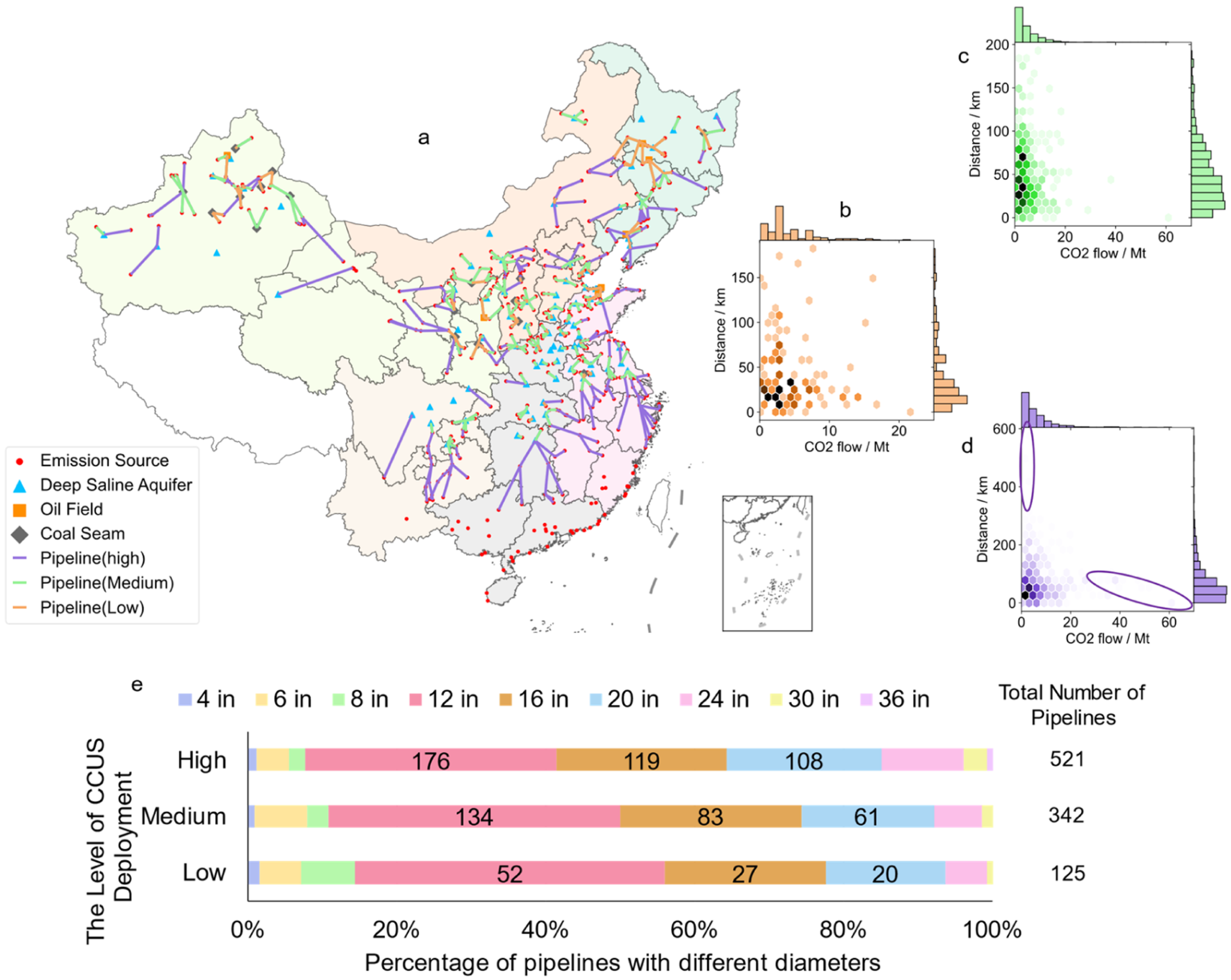

Figure 4. Proposed CCUS layouts under S3, S6, and S9. (a) Cost-effective pipeline network layouts constructed by CCUS SSM; (b−d) two-dimensional histograms of transportation distance and CO_2 flow rate for CCUS layouts under the low (S3), medium (S6), and high (S9) levels of deployment; and (e) percentage of pipes with various diameters selected.

for all these proposed layouts (Figure 4e). However, higher level of deployment means more pipes of large diameters (24 in and above) will be selected, increasing from 6 to 15%.

4.3.2. Transport Scale and Economic Performance of the Layouts. The shorter the maximum transportation distance, the shorter the total length of the pipeline network and the average transportation distance (Figure 5a). Specifically, the total length is expected to reach about 37,000 km to meet a 1.7 Gt CO_2 capture, with the average distance being around 140 km. However, if the maximum distance is limited to less than 100 km (S7), there will be no layout that can achieve this ambitious goal. The constraints of transportation distance result in accessibility differences for storage media, while increasing CO_2 capture requires more DSA sequestration (Figure 5c), thus altogether influencing the economic performances of the layouts (Figure 5b). The gap in unit cost between different distance constraints is obvious at a low capture level since the maximum distance determines whether the captured CO_2 is transported to nearby oil reservoirs and coal seams or DSAs with no revenue. For example, the unit costs under S1 and S3 differ by about 25 RMB/t CO_2 (Figure 5d). Furthermore, the average transportation distance of pipes becomes longer under less strict constraints, resulting in higher unit transportation cost. For instance, the unit transportation cost under S3 increases by nearly 20% compared to that under S1 (Figure 5b).

4.3.3. Impacts of Terrain Obstacles. This study preliminarily evaluates the impacts of four terrain areas (fault zones, rivers, railways, and roads) on real-world applications of CCUS in China. The layout may be very different with terrain factors considered. For example, the Jinzhong fault zone in Shanxi, the Weihe Plain fault zone in Shaanxi, and the Tianshan fault zone in Xinjiang can significantly lead to high safety risks of pipeline construction (Figure 6a), thus weakening the engineering feasibility and economic benefits of CCUS in these areas. Taking the layouts under S6 in Figures 4a and 6a (both marked in green) as examples, the total length increases from 18000 to 21000 km, with the average transportation distance climbing from 72 to 104 km. This expansion of layouts mainly results from inaccessibility of nearby storage sites on previous transportation routes. Therefore, other longer routes are selected to meet the same level of CCUS deployment. Additionally, the unit cost of CCUS also witnesses an increase, going from 297 RMB/tCO_2 up to 304 RMB/tCO_2.

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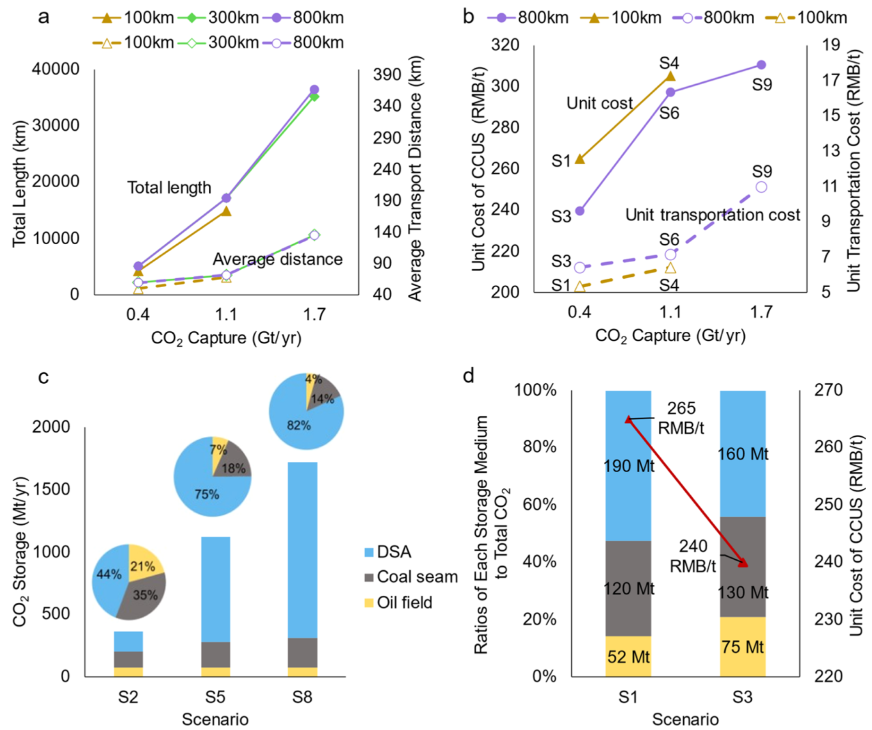

Figure 5. Key parameters and economic indicators for pipeline network construction. (a) Transport scale of the layouts; (b) economic performance of the layouts; (c) CO_2 sequestered by three storage media under different levels of deployment; and (d) economic performance difference due to different maximum transportation distances.

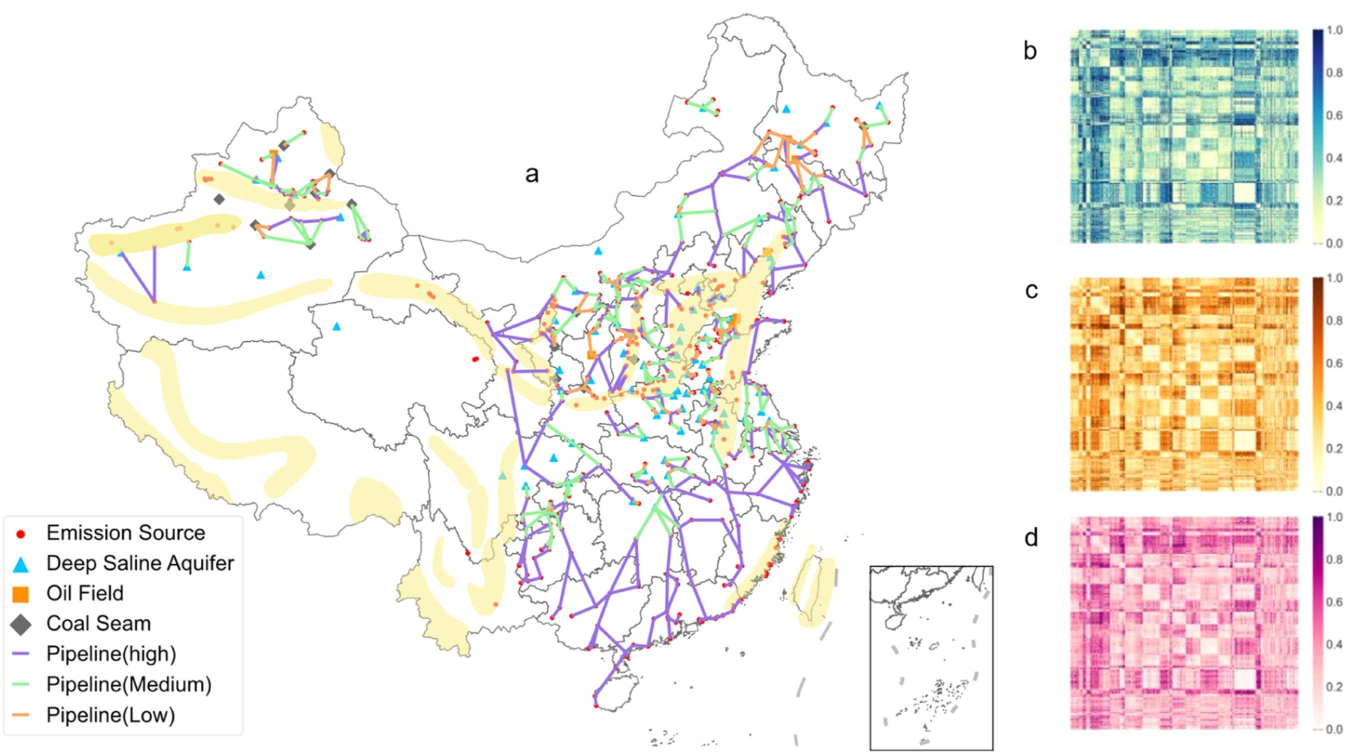

Figure 6. Terrains' influences on the selection of CO_2 transportation routes. (a) Proposed CCUS layout considering fault zones under S3, S6, and S9; (b−d) implementation feasibility assessment of rivers, railways, and roads, respectively. More details can be found in the Supporting Information.

Rivers, railways, and roads also have similar effects on the choice of pipeline transportation routes. Three CCUS source-sink level heatmaps are generated to evaluate the construction difficulty of each candidate route for the aforementioned terrains (Figure 6b). The darker the color, the greater the impacts of the terrain, which is reflected in the higher construction cost. Generally, diverse terrain characteristics bring about kinds of technical bottlenecks and societal

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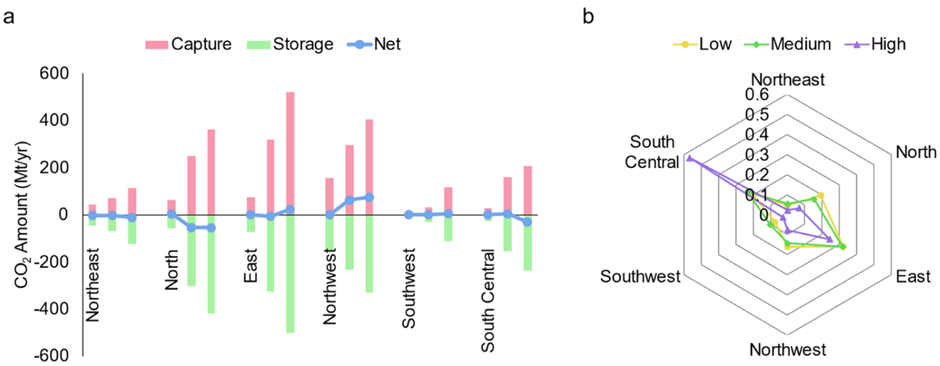

Figure 7. Region interactions under national CCUS layouts. (a) Step-by-step change for CO_2 flow of six regions under three levels of CCUS deployment. There are three bars for each region, representing the amount of carbon capture/storage under the low, medium, and high levels of CCUS deployment. (b) Ratios of regional carbon taxes to the total carbon taxes. The higher the level of the carbon price, the higher the level of overall CCUS deployment.

considerations. Transportation routes passing through fault zones or other sensitive areas (nature reserves and densely populated areas) should be avoided.[12,52] Furthermore, trenchless technology can be considered for crossing linear terrain features including rivers, railways, and roads.[53,54]

4.4. Region Interactions under National-Scale CCUS Layouts. All the CO_2 captured from CFPPs can be stored nearby at first. As the demand for CO_2 capture increases, cross-region transportation occurs. North China and South Central China become CO_2 net-inflow regions, whereas Northwest China and East China reach net CO_2 outflow. However, Northeast China and Southwest China still maintain a relative balance (Figure 7a). Economic interactions are also examined by introducing carbon pricing to drive CCUS deployment. Figure 7b shows the ratios of regional carbon taxes to the total taxes under different price levels. Except for South Central China, the ratios of regional carbon taxes to the total taxes all decrease with the increase in carbon price, which means that the CCUS cost of per unit CO_2 in these regions is still within an acceptable range. Especially for the high carbon price, South Central China bears a much higher pressure than others, which demonstrates that many CFPPs in this region are still inappropriate for CCUS application even with a strong tax stimulus. Hence, it is recommendable to deal with these hard-to-abate emitters with congenital deficiency in CCUS implementation through emission trading system (ETS). Specifically, emitters in South Central China could purchase emission allowances through ETSs. Meanwhile, this provides financial support for CCUS deployment in other suitable regions.

5. CONCLUSIONS AND POLICY IMPLICATIONS

This study links the China TIMES model and ChinaCCUS DSS 2.0 to assess representative CCUS layouts toward China's carbon neutrality target. Three typical energy transition roadmaps suggest that CCUS be widely implemented from 2035, reaching annual CO_2 capture of 0.4, 1.1, and 1.7 Gt in 2050 with the low, medium, and high levels of deployment, respectively. The total lengths of three representative layouts are about 5100, 18,000, and 37,000 km, with the total annual costs of CCUS in 2050 being about USD 14 billion, USD 52 billion, and USD 83 billion, respectively. Northern areas abundant with oil and coal reservoirs should take the lead in real-world applications, followed by central and eastern regions. Even with a strong tax stimulus, however, CCUS is still inadvisable for southern coastal provinces, owing to much limited storage options and long transportation distance.

Based on the combination of energy system modeling and geospatial analysis, this study provides policy makers with fundamental insights listed below. First, the attention paid to significant impacts of the uncertainty of low−carbon transition on CCUS layouts is of vital importance. Technology competition between CCUS and renewables can lead to large-scale fluctuations in infrastructure layout and investment, with maximum variations of 31900 km and USD 69 billion for the total length of layouts and the total CCUS cost in this study, respectively. Only with careful CCUS prospect evaluation can such uncertainties be recognized clearly. Second, candidate CO_2 transportation routes should be planned comprehensively to coordinate climate change mitigation with socioeconomic development. Considering the geographical difference, pipeline construction and CCUS implementation should suit the local circumstances. Moreover, early planning can avoid potential land use conflicts between CCUS and all-round rural revitalization. Finally, accelerated CCUS deployment needs support from policy instruments, among which carbon pricing can improve the overall efficiency of national-scale layouts.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c03401.

Information about 6 major regions and 34 provincial-level administrative regions of China; interpretation of results from the China TIMES model; scenario representation; data for emission sources and storage sites; and geospatial analysis of terrain impacts on CCUS layouts (PDF)

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Notes

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