



Views & Comments

A Comparison of Incentive Policies for the Optimal Layout of CCUS Clusters in China's Coal-Fired Power Plants Toward Carbon Neutrality



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1. Introduction

China has announced that it will adopt forceful policies and measures and strive to achieve peak carbon dioxide (CO₂) emissions before 2030 and carbon neutrality before 2060—aims that are largely consistent with the goal to limit warming to 1.5 °C [1]. Achieving this target requires the deep decarbonization of China's entire economy, with a particular focus on coal-fired power plants (CFPPs). China's installed capacity of coal-fired power was estimated to be 1040 GW in 2019 [2], with the CO₂ emissions from CFPPs reaching 3.5 Gt, accounting for approximately 35.6% of China's total CO₂ emissions [3]. However, the overwhelming magnitude of the existing coal infrastructure makes it impossible to entirely phase out CFPPs that have operated for less than 15 years and have more than 30 years remaining in their lifetime [4]. Thus, avoiding the high risks of asset stranding due to the early phaseout of CFPPs should be considered in the decarbonization strategies of the power sector. In this context, carbon capture, utilization, and storage (CCUS) is an indispensable option to achieve huge mitigation potential in these existing CFPPs [3]. As of 2020, there are 65 commercial large-scale CCUS facilities in operation or under development internationally, involving numerous large power-generation projects [5]. This implies that several CCUS technologies have reached the commercial phase of development [6]. At present, the engineering capacity in China is ready to capture and store CO₂ on a large scale and is actively preparing for a full-process CCUS industrial cluster [7]. Nevertheless, the high cost of CCUS infrastructure and the lack of related supporting policies are still the main challenges for CCUS commercialization. Experiences with the promotion of other low-carbon technologies [8] have demonstrated the importance of government support for the development and deployment of CCUS technologies. Furthermore, CCUS deployment strategies that shift the focus from large, stand-alone facilities to the construction of CCUS industrial clusters support the development of CCUS. Therefore, it is necessary to investigate optimal incentive strategies that promote the construction of CCUS industrial clusters in CFPPs for the cost-effective achievement of

CO₂ emission reduction requirements in order to achieve the carbon neutrality target.

Achieving the 1.5 °C target requires a large-scale deployment of CCUS to reduce more than 710 million tonnes of CO₂ per year (Mt·a⁻¹) from CFPPs by 2050 [9]. With a focus on formulating optimal incentive strategies that promote CCUS in CFPPs in order to achieve this target, this paper develops multiple methods. Based on the distribution patterns of CFPPs and CO₂ storage sites, an optimal source–sink matching assessment model is applied to evaluate the priority CCUS layout under the 1.5 °C climate target. In order to reduce unit costs through economies of scale, a hybrid of hierarchical cluster analysis (HCA) and the minimum spanning tree (MST) method is used to identify CCUS cluster-hubs and construct optimal CO₂ transport pipeline networks for CFPPs that require CCUS retrofitting. This research also assesses the economic feasibility of CFPPs with CCUS along with three policy incentives (i.e., a carbon price, feed-in tariff, and storage subsidy) to explore the best incentive scheme. The findings have great significance as practical guidance for identifying large-scale CO₂ hubs and CCUS clusters, as well as for putting forward an optimized incentive mechanism to achieve this CCUS deployment goal.

2. Techno-economic analysis and optimal source–sink matching for CCUS

On the pathway to meet China's carbon neutrality goals, the rate of CCUS deployment for existing CFPPs would reach 710 Mt·a⁻¹ in 2050 [9], and the deployment milestones would peak in the period 2035–2045 [10]. Based on the optimal source–sink matching assessment results (Appendix A Note 1), 128 plants (267 units) with an installed capacity of approximately 159 GW are selected as final samples for CCUS layout. The Integrated Environmental Control Model (IECM), which was developed by Carnegie Mellon University [11], is applied to calculate the costs of the selected CFPPs with CCUS. (Details for the data source and screening criteria of coal power plants are included in Appendix A Note 2.) This study applies the published component-based

learning curve theory [12] to estimate the effect of technological improvement on the CO₂ capture cost. The results in Fig. 1(a) indicate that potential CCUS projects can realize 710 Mt·a⁻¹ of CO₂ emissions mitigation, with a total cost ranging from 53 to 87 USD per tonne of CO₂ (tCO₂) by 2050. The cost of post-combustion CO₂ capture from CFPPs in China ranges from 40 to 70 USD·tCO₂⁻¹, and the average CO₂ capture cost is 57 USD·tCO₂⁻¹, which accounts for about 80% of the average total cost. Moreover, with technological improvements, the CO₂ capture cost will be reduced by nearly 30% compared with current capture technology [13,14], which is reduced to between 32 and 46 USD·tCO₂⁻¹.

Regarding CO₂ transport and storage, based on the optimal source–sink matching results (Fig. 1(b)), the Tarim Basin, Ordos Basin, Subei Basin, Songliao Basin, Bohai Bay Basin, Junggar Basin, and Turpan–Hami Basin exhibit good potential for CO₂ sequestration in deep saline formations (DSFs) and CO₂ enhanced oil recovery (CO₂-EOR), as they have a total of 1780 Gt of saline aquifer storage potential and 4 Gt of CO₂-EOR storage potential [15]. In addition, the average CO₂ pipeline lengths for each CFPP to be matched with the Tarim Basin, Ordos Basin, Subei Basin, Songliao Basin, Bohai Bay Basin, Junggar Basin, and Turpan–Hami Basin are 275, 264, 242, 216, 189, 164, and 120 km, respectively. Approximately 29 490 km of transportation pipelines must be constructed in order to achieve single source–sink matching; the total transport equivalent during 2020–2050 will be 1141 Gt·km, which may result in a high transport cost. Therefore, it is necessary to develop CCUS hubs to reduce unit costs through economies of scale and to enable earlier CCUS technology deployment.

3. Priority layouts of CCUS clusters and carbon reduction potential

Based on the source–sink matching results, the HCA is used to classify the CCUS cluster–hub. Next, the MST method is applied to find a least-cost CO₂ transport network among the “hubs,” which are identified through HCA. (Details for the HCA and the MST are included in Appendix A Notes 3 and 4.) By developing industrial hubs with shared CO₂ transport (Fig. 2), the total pipeline length can be reduced to 8708 km (the average pipeline length is 85 km), and the average CO₂ transport cost can be reduced from 10.62 to 4.26 USD·tCO₂⁻¹. Assuming 45 years of plant design lifetime, the cumulative CO₂ emissions reduction potential of these

CFPPs with CCUS is 11.596 Gt, 65.4% of which is sequestered into deep saline formations (DSFs) and 33.6% of which is used for CO₂-EOR. In North China, 20 CFPPs (49 units) with an installed capacity of 26.4 GW can be matched with Bohai Bay Basin within an average of 67 km, with a huge CO₂ emissions reduction potential of 119.6 Mt·a⁻¹ in 2050 and a cumulative potential reduction of 2.364 Gt CO₂. In Northeast China, a cumulative quantity of more than 0.532 Gt CO₂ captured from 11 CFPPs (19 units) with an installed capacity of 9.18 GW can be stored in the Songliao Basin, within an average of 80 km. In East China, more than 36 CFPPs (75 units) with an installed capacity of 57.65 GW can be divided into three hubs and transported to the Subei Basin for CO₂ storage, within an average of 60 km. For the CFPPs in Northwest China, a cumulative quantity of 3.071 Gt CO₂ can be captured from 42 CFPPs (82 units) with an installed capacity of 45.61 GW and transported to the Ordos Basin for storage, within an average of 56 km. In Junggar Basin, Turpan–Hami Basin, and Tarim Basin, the cumulative quantities of stored CO₂ will be 0.868, 0.263, and 0.192 Gt, respectively, matching 20 CFPPs, 3 CFPPs, and 5 CFPPs with CCUS. Identifying suitable CFPPs for CCUS retrofitting and following the optimal plan for deploying CCUS clusters in line with the carbon neutrality goal will provide scientific evidence allowing policymakers to formulate related incentive policies for the large-scale application of CCUS.

4. A comparison of subsidy incentives for the layout of CCUS clusters

As the deployment and commercialization of CCUS technology is encountering huge cost pressures, the government needs to provide financial support to overcome economic barriers, especially in the early stages [16]. Based on incentive policies around the world, three different subsidy schemes—namely, a carbon price, feed-in tariff, and storage subsidy—are taken into consideration to investigate the influence of government incentives on CCUS technology investment and to identify the optimal policy incentives based on the interaction of various policy options. (Details of the incentive policy analysis model and data are included in Appendix A Note 5 and Table S1.)

The break-even values of the three incentive measures for 128 CFPPs with CCUS under different scenarios (Fig. 3) indicate that the average critical carbon price will reach 72.42 USD·tCO₂⁻¹

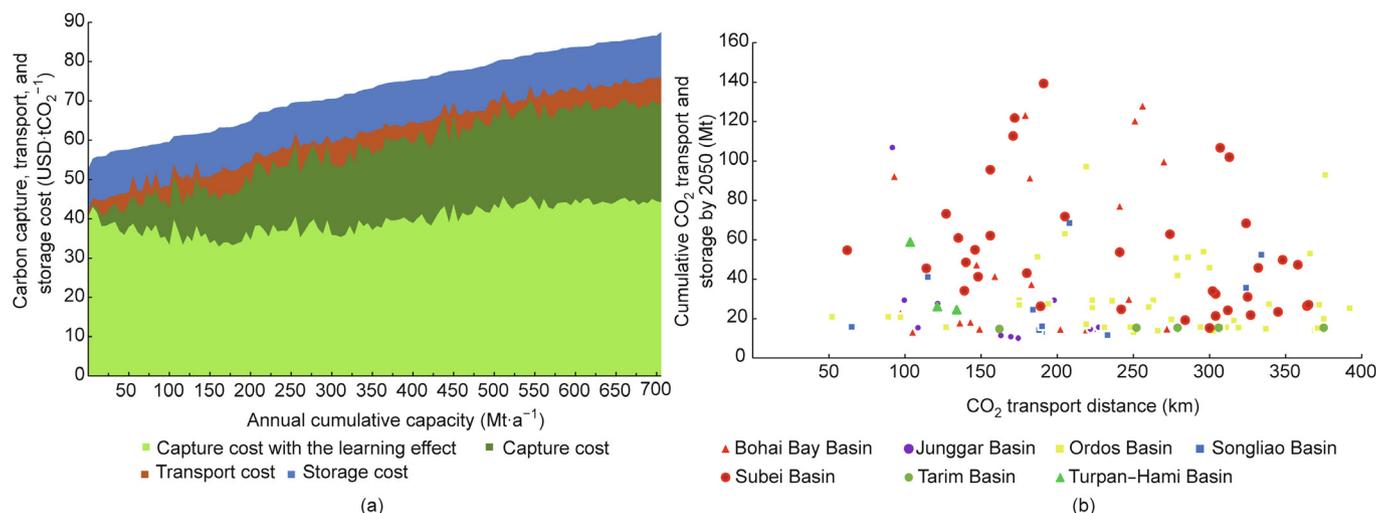


Fig. 1. Cost-benefit results, the amount of stored CO₂ by 2050, and the transport distances of the CFPPs matched with the storage sites. (a) Carbon capture, transport, and storage costs versus annual cumulative capacity; x-axis represents the amount of CO₂ stored in the formation yearly by 2050; y-axis indicates the estimated costs for CO₂ capture with/without technology improvement, CO₂ pipeline transportation, and storage. (b) Cumulative CO₂ transport and storage by 2050 versus carbon transport distance; x-axis represents the average CO₂ transport distance; y-axis indicates the cumulative CO₂ transport and storage by 2050.

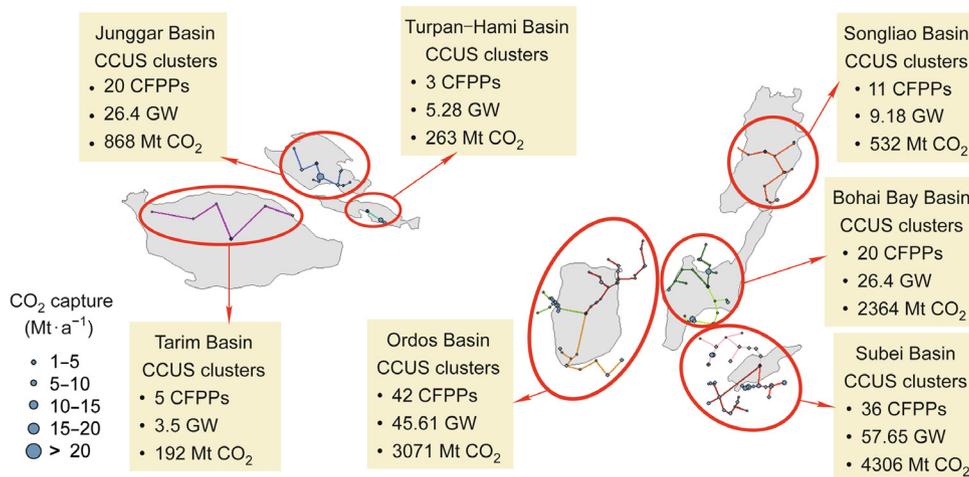


Fig. 2. CCUS clusters of CFPPs and the total lifetime cumulative CO₂ sequestration amount.

without any government subsidy for CO₂ capture, transport, and storage (CCS) technology. The revenue generated from CO₂-EOR and technical innovation (TI) could offset the cost of CCUS, respectively reducing the average critical carbon price by 14% and 29%. If the electricity tariff subsidy is set as 22 USD·(MW·h)⁻¹ (0.015 CNY·(kW·h)⁻¹), the critical average carbon price could decrease to 25.00–50.98 USD·tCO₂⁻¹. A storage subsidy of 20 USD·tCO₂⁻¹ could further lower the critical carbon price to 9–33 USD·tCO₂⁻¹, which is still greater than the current average carbon price of 7 USD·tCO₂⁻¹ (49 CNY·tCO₂⁻¹). Given the insufficient incentives from the immature national emissions trading system (ETS), the government needs to raise the electricity tariff subsidy and storage subsidy to trigger CCUS deployment in order to achieve the carbon abatement potential target. In order to avoid an unprecedented financial expense, a carbon price, as a market-oriented policy tool, is needed to improve the value of CCUS projects. More specifically, the carbon price has a major influence on the other critical subsidy levels. Fig. 3 shows that, with an increase in CO₂ price, both the critical feed-in tariff and the storage subsidy could decrease. As a result, the government’s financial expense from the CCUS subsidy

would decrease significantly. Thus, the government could appropriately raise the carbon price to exert the incentive effect of carbon price on the development of CFPPs with CCUS.

5. Conclusions and suggestions

To achieve the goal of carbon neutrality within the power sector, 128 existing CFPPs (267 units) with an installed capacity of approximately 159 GW must be retrofitted by CCUS. Through the development of industrial “hubs” with shared CO₂ transport and storage infrastructure, the total pipeline length and total CO₂ transport cost for these CFPPs can be largely reduced. The CCUS clusters of CFPPs are mainly distributed in North, Northeast, East, and Northwest China and can be matched with the Bohai Bay Basin, Songliao Basin, Subei Basin, Tarim Basin, Ordos Basin, Junggar Basin, and Turpan-Hami Basin. The cumulative quantity of CO₂ emissions from these CFPPs that could be reduced by means of CCUS is 11.596 Gt; of this, 65.4% can be sequestered into DSFs and 33.6% can be used for CO₂-EOR.

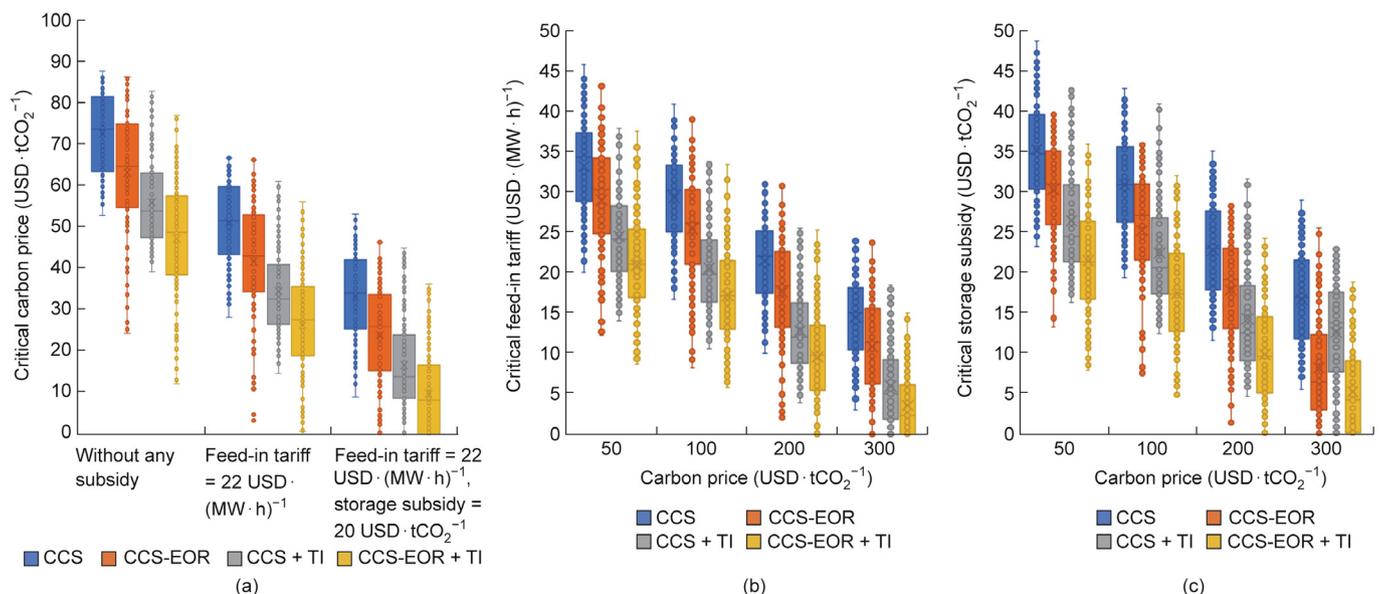


Fig. 3. Break-even value of the three incentive measures for 128 CFPPs with CCUS under different scenarios. (a) Critical carbon price; (b) critical feed-in tariff; (c) critical storage subsidy. CCS: CO₂ capture, transport, and storage in DSFs; CCS-EOR: CO₂ capture, transport, and utilization for CO₂-EOR; TI: considering the technical innovation of CCUS.

Three subsidy schemes, including a carbon price, feed-in tariff, and storage subsidy, could incentivize CCUS deployment; among these schemes, a carbon price could directly achieve economic feasibility for CCUS technology and significantly reduce the government's financial expense. Moreover, economic benefits from CO₂-EOR and CCUS technology innovations could act as a key supplement to these incentives, reducing the policy burden. Thus, building a mature carbon-trading mechanism, increasing research and development investments in CCUS technology, and carrying out large-scale CCUS cluster demonstration are critical to the deployment of a CCUS technology system toward carbon neutrality. Future research can consider various government incentives for full-chain CCUS deployment under different business models.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eng.2021.11.011>.

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