

Optimization of CCUS Source-Sink Matching for Large Coal-Fired Units: A Case of North China

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Abstract. Climate change has become an important part of the human destiny community, China faces dual pressures both at home and abroad for carbon dioxide (CO₂) emission reductions, and the clean coal utilization and low-carbon development in China will be the key development direction in the future. This study takes the city or country with a coal-fired unit above 300 MW in North China as a CO₂ source and the basin in North China and its surrounding area as a CO₂ sink, and estimates distances between sources and sinks by ArcGIS. Through modelling and optimizing the cost of carbon capture, utilization and storage (CCUS) source-sink matching for North China in the next 30 years, it results that the best solution for source-sink matching is obtained, the total CO₂ capture volume from coal-fired power plants reaches approximate 22.8 billion tons, the total CCUS cost is about \$1.78 trillion, the unit cost is about \$78/ton CO₂, and the CO₂ transport pipeline network is about 52,876 km, which provides a data support and methodological reference for further research on China's CCUS source-sink matching.

1. Introduction

Climate change has become an important part of a community with shared future for humanity. To achieve the goal of global average temperature rise no more than 2°C at the end of this century, the deployment scale of global CCUS technology needs to reach about 1.2 billion tons in 2030, and it should attain to about 5.5 billion tons in 2050, which accounts for about 14% of the total CO₂ emission reduction [1]. As the world's largest emitter of CO₂, China is facing both domestic and international pressures for emission reductions that it has to shoulder the task of CO₂ emission reduction at abroad and to control environmental pollution at home especially to solve the problem of haze in North China.

China's energy resource endowments are characterized by rich coal, poor oil, and lean gas. Although the '13th Five-Year Plan' has reduced the proportion of coal to 58%, coal is still the main energy source in China. In order to ensure national energy security, the implementation of clean coal utilization in the short term cannot be avoided. CCUS not only can solve the problem of large-scale CO₂ emissions, but also can solve the problem of pollutant emissions through the dust removal, desulfurization, and nitrogen removal processes before the CO₂ capture [2]. Therefore, CCUS is a key technology for future low-carbon development and clean coal utilization.



Approximate 39% of China's CO₂ emissions come from power plants [3], and the power sectors have become the preferred target for emissions reduction in China. In 2017, the Chinese government launched the national carbon trading market, and the power units became the first to be included in the market. As the carbon trading market continues to develop, large-scale coal-fired units will select CCUS retrofit as one of their low-carbon development methods.

Table 1. Annual CO₂ emissions and total installed capacities in cities and countries

City/ County	Capacity (MW)	CO ₂ (Mt/year)	City/ County	Capacity (MW)	CO ₂ (Mt/year)	City/ County	Capacity (MW)	CO ₂ (Mt/year)
Alashanyouq	600	3.78	Huozhoushi	3000	22.14	Tuoketuqi	600	3.05
Bayanzhuoer	1200	8.96	Jinzhongshi	1260	9.58	Tuoketuoxian	5400	43.98
Baotoushi	4200	30.94	Jingjingxian	1800	13.07	Wulatezhongqi	1320	8.46
Baodingshi	600	4.76	Keyouzhongqi	330	1.71	Wuanshi	600	4.61
Changzhoushi	3180	25.25	Liangchengxian	2400	18.65	Xilinhaotesi	600	4.80
Chenbaerhuqi	1200	9.11	Linfenshi	600	4.53	Xilinhaotesi	1200	7.32
Chengdexian	990	7.41	Liulinxian	1500	10.82	Xingtaixian	600	3.92
Cifengshi	2400	16.06	Luchengshi	1200	9.68	Yangchengxian	600	4.43
Datongshi	5520	43.97	Luanchengxian	600	4.25	Yijinhualuoqi	3300	26.18
Dengkouxian	660	4.46	Pingdingxian	1200	9.51	Yijinhualuoqi	1320	10.70
Dingzhoushi	2520	18.16	Pingshanxian	1860	14.11	Youyuxian	600	4.55
Eerduosishi	2020	12.52	Shanheshi	1200	8.23	Yushexian	660	5.02
Ewenkezuzizhi	3400	21.90	Shanyinxian	1300	9.68	Yuanpingshi	600	4.60
Fengzhenshi	1800	13.05	Shexian	600	4.50	Yunchengshi	2640	20.72
Handanshi	1920	14.87	Shijiazhuanshi	1200	8.59	Yunchengshi	1200	8.72
Hequxian	2400	18.37	Shouzhoushi	1260	9.94	Zhangjiakoushi	600	4.55
Hengshuishi	1260	9.48	Taiyuanshi	600	4.53	Changzhishi	2760	21.82
Huhehaotesi	5080	38.08	Tangshanshi	3000	23.64	Zhenglanqi	2460	19.35
Hunlunbeiershi	1200	8.15	Tianjinshi	3040	23.15	Zungeerqi	3720	27.43
Huaianxian	660	4.83	Tongliaoshi	7390	58.79	Zuoquanxian	2580	19.90
Huolinguoleshi	1200	7.62	Tumutezuqi	1200	8.21	Zuoquanxian	2692	20.72

There were many references on cost analysis of power units and CCUS [4-6]. E. S. Rubin [7] compared predecessors' assessment methods of power plants and CCUS and found out the reasons for the deviation of economic evaluation. With the in-depth study of CCUS, there is more and more research on the whole process of CCUS, and the literature on China is also rich. Z. Zheng, et al. [8] combed large-scale CO₂ emission sources and basins where China can store or utilize CO₂, and used economic evaluation techniques to assess where the CCUS full-flow demonstration projects could be implemented early. With ArcGIS, J. Li, et al. [9] firstly determined CO₂ sequestration basins and their storage capacities in Guangdong Province, secondly used ultra-supercritical power plants in Shenzhen as the CO₂ sources, and finally evaluated the cost of source-sink matching. X. Li, et al. [10] summarized the locations of large-scale CO₂ emission sources in China, provided the specific locations of the basins and oil fields for CO₂ storage or utilization, and described the calculation methods of effective storage capacities of basins and oil wells in detail. N. Wei, et al. [11] gave a complete assessment method for CO₂ sequestration in China's terrestrial aquifers, and macroscopically provided a detailed geographical map based on the overall cost of CCUS deployment. At present, as coal-fired power plants and CCUS are very important for low-carbon development and clean utilization of coal in China's regional power sectors, there are many studies on the macroscopic source-sink matching in China, but the study for specific areas in China, especially for specific regions' coal-fired power plants and CCUS, is rare. Besides, there are not only many large-scale coal-fired units that result in a large number of CO₂ emission in North China but also many basins that are

suitable for the dedicated geological storage or enhanced oil recovery in North China and its surrounding area. In addition, because there are few large mountains in this region, transporting CO₂ in pipelines is possible. Therefore, it is feasible and necessary to study the cost optimization of CCUS source-sink matching for coal-fired units in North China.

2. Data and Methods

The data of 272 coal-fired units with installed capacities above 300 MW related to 108 coal-fired power plants in North China comes from the literature [12], and their locations (61 counties or cities) are collated in accordance with the Google map, shown in Table 1. The total installed capacity of coal-fired units is 116,602 MW, and the total CO₂ emission is 873.85 Million tons per year.

The data of basins in North China and its surrounding area [8, 10, 11, 13] is organized in Table 2.

Table 2. Effective storage capacities and costs of basins in North China and its surrounding area

Basin	Dedicated geological storage			Enhanced oil recovery		
	No.	Capacity (10 ⁹ t)	Cost (\$/t)	No.	Capacity (10 ⁹ t)	Cost (\$/t)
Hailar	1	16.1	2.93	7	0	-12.9
Songliao	2	227.8	2.93	8	1.57	-12.9
Bayanhuxu-Eren	3	85	2.93	9	0.031	-12.9
Bohai Bay	4	0	2.93	10	1.49	-12.9
Ordos	5	256.5	2.93	11	0.36	-12.9
Quinshi-Linfen	6	0	2.93	12	0	-12.9

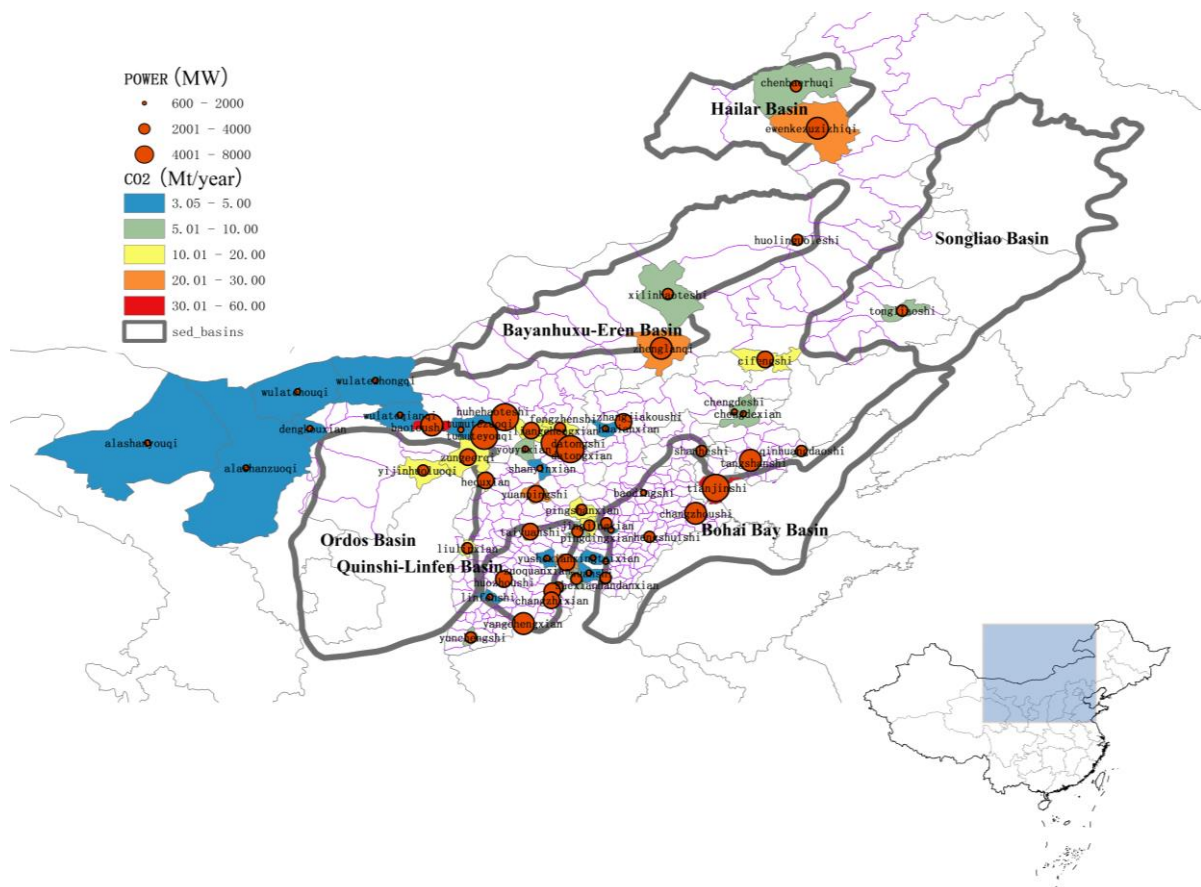


Figure 1. The geographical distribution of CO₂ sources and sinks in North China

North China includes five provinces, i.e., Beijing, Tianjin, Hebei, Shanxi, and Neimenggu. As its population density is large, Beijing's power plants do not participate [14]. The geographical distribution of CO₂ sources and sinks at the city and country level in North China is shown in Figure 1.

A self-built cost optimization model of source-sink matching is used for the practical problem of coal-fired units above 300MW in North China. Assumptions are that i) after the installation of CCUS, the life cycles of sources, sinks and pipelines are the same, ii) all the CO₂ emissions captured in sources are transported to sinks by pipeline, and there is no loss during transportation, therefore, the amount of CO₂ captured in each source is equal to the amount of CO₂ entering the pipeline from that source, iii) sources and sinks are directly connected, a single source can be connected to multiple sinks, and a single sink can also be connected to multiple sources, and iv) the total CO₂ delivered to each sink must not exceed the effective storage capacity of that sink, therefore, the total CO₂ captured from all sources does not exceed the sum of the effective storage capacities of all sinks. The objective function is as follows

$$\left\{ \begin{array}{l} \min f = \sum_{i=1}^n \sum_{j=1}^m [(CC_i + CT_j + L_{ij}) \times tX_{ij}] \\ L_{ij} = \begin{cases} a, & L_{ij} \leq 50 \\ b, & 50 < L_{ij} \leq 200 \\ c, & 200 < L_{ij} \leq 500 \\ d, & L_{ij} > 500 \end{cases} \end{array} \right. , \quad (1)$$

And the constraint conditions are

$$s.t. \left\{ \begin{array}{l} \sum_{j=1}^m X_{ij} = \eta E_i \\ \sum_{i=1}^n tX_{ij} \leq PQ_j \\ \sum_{i=1}^m \eta tE_i \leq \sum_{j=1}^m PQ_j \\ X_{ij} \geq 0 \\ i \in [1, n] \\ j \in [1, m] \end{array} \right. , \quad (2)$$

where $i=1,2,\dots,147$ is the CO₂ source, $j=1,2,\dots,26$ is the CO₂ sink, f is the total cost (\$), $\eta=0.85$ is the capture rate, P is the storage rate, X is the transport volume (ton), Q is the total storage volume of basins (ton), E is the total CO₂ emission of cities and countries (ton), CC is the capture cost (\$/ton), CT is the storage cost (\$/ton), and L is the direct distance between the source and the sink (km), and $t=30$ years is the CCUS run time. Parameter settings are shown in Table 3.

Table 3. Model parameter settings

Parameter	Symbol	Value	Unit	Note
Capture Cost	CC	45	\$/ton	[15]
Storage Cost	CT	Table 2	\$/ton	
Transport distance	L	Table 4	km	
$L \leq 50$	a	11.2	\$	[16]
$50 < L \leq 200$	b	20.7	\$	[16]
$200 < L \leq 500$	c	39.5	\$	[16]
$500 < L$	d	49.5	\$	[16]

3. Results

Using ArcGIS calculates the central coordinates of 61 cities and countries with coal-fired units above 300 MW and those of 6 basins for dedicated geological storage or enhanced oil recovery in North China. Through the point-to-point distance calculation, the 61*6 source-sink distance matrix is obtained in Table 4. Due to space limitations, Table 4 only shows partial results.

Table 4. The partial direct distance matrix between sources and sinks (km)

Sink\Source	Chenbaer.	Ewenkezu.	Xilinhaote.	...	Changzhi.	Yangcheng.	Yuncheng.
Hailar	96.63	121.46	386.04	...	1500.37	1583.84	1662.04
Songliao	570.44	452.90	369.99	...	1415.06	1509.06	1619.99
Bayauhuxu-Eren	671.08	592.68	358.50	...	928.81	1009.34	1084.11
Bohai Bay	1245.94	1130.60	802.51	...	494.41	587.24	714.06
Ordos	1584.78	1515.63	1256.74	...	421.69	400.43	342.28
Quinshi-Linfen	1532.61	1440.74	1139.69	...	93.72	145.25	230.60

In the case that the total installed capacity of large-scale coal-fired units in North China is constant, and the operating times of both coal-fired power units and CCUS are 30 years, the cost optimization results of the source-sink matching show that the total CO₂ storage volume within 30 years is about 22.8 billion tons, the average annual CO₂ capture volume is about 760 million tons, the total cost is about \$1.78 trillion, the annual investment is about \$59.287 billion, the unit cost is approximately \$78/ton CO₂, and 52,876 km of CO₂ transport pipeline network needs to be constructed. The detailed CO₂ transport volume from each source to each sink is shown in Table 5.

Table 5. Source-sink matching results after optimization (Mt CO₂)

Sink\Source	Chenbaer.	Ewenkezu.	Xilinhaote.	...	Changzhi.	Yangcheng.	Yuncheng.
Hailar	232.32	558.53	33.33	...	0	0	0
Songliao	0	0	44.27	...	0	0	0
Bayauhuxu-Eren	0	0	20.98	...	0	0	0
Bohai Bay	0	0	0	...	0	0	0
Ordos	0	0	0	...	484.70	658.46	214.81
Quinshi-Linfen	0	0	0	...	0	0	0
Hailar	0	0	0	...	0	0	0
Song Liao	0	0	94.57	...	0	0	0
Bayauhuxu-Eren	0	0	1.22	...	0	0	0
Bohai Bay	0	0	0	...	0	0	0
Ordos	0	0	0	...	8.74	9.12	7.56
Quinshi-Linfen	0	0	0	...	0	0	0

4. Conclusions and discussions

This study investigates 272 coal-fired units above 300 MW of installed capacities involving 108 coal-fired plants in 61 cities or counties in North China and it also reviews the capacities and costs of the dedicated geological storage and enhanced oil recovery for 6 basins in North China and its surrounding area, which provides the reliable data support for further research on the CCUS source-sink matching in North China.

The distances from 6 basins where CO₂ are stored or utilized to 61 cities or counties where large coal-fired power plants are located are estimated. Using the cost optimization model of CCUS source-sink matching, the optimal solution for CO₂ transport volume, the CO₂ transport pipeline network, the total storage volume, the total cost, and the unit cost for CCUS retrofitting of large coal-fired units in North China are given, providing a reference for specific engineering technical evaluation.

Although a lot of data research and calculations are done in this study, the location of the power plant can only be specific to the central coordinate of its city or county, and there is a certain error with the actual distance. Besides, because of the large area of the basin, this study refers to existing

studies that only determine the central coordinate of a basin as a sealed site, which is also a certain error with the actual. There should be more than one storage site per basin, and this requires further geographic surveys. In addition, this study assumes that the cost of capture, transportation, and storage will not change for 30 years, while in reality as the CCUS technology continues to progress, the scale effect develops, and the future CO₂ trading market impacts, the actual cost should be smaller than the cost of this assessment.

Acknowledgments

This work was financially supported by the National Natural Science Foundations of China (Grant No. 51274206 & 51404277) and the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. 2010YZ05).

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