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CCUS Development in China and Forecast Its Contribution to Emission Reduction

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Abstract: Nowadays environmental issues have been of great concern to the world, among which the problem of global warming caused by greenhouse gas emissions is particularly prominent. All countries in the Kyoto Protocol and the Paris Agreement have committed to control greenhouse gas emissions, and China, as the largest carbon emitter, has assumed a heavier burden. China has been striving to develop low-carbon technologies such as hydrogen, nuclear, wind, and solar energy, but the most attention should be paid to CCUS, which many scholars have high expectations that CCUS can help China reduce emissions to some extent. Therefore, this paper presents a prediction that CCUS can reduce 3.8% of carbon emissions for China in 2040 when CCUS emission reductions increase at a rate of 30%. The power and chemical industries could reduce carbon emissions by 2.3% and 17.3%, respectively.

Keywords: carbon capture; economics; China; emission reduction

JEL Classification: C51; O14; Q56

1. Introduction

Since industrialization, human activities have caused global temperatures to rise by about 1 ℃, and if global warming continues at its current rate, temperatures will rise by 1.5 ℃ between 2030–2052. In turn, greenhouse gas emissions are one of the main causes of warming, with carbon dioxide emissions accounting for the majority of greenhouse gas emissions (Ipcc, 2013). In the Paris Agreement, countries have pledged to address this environmental issue by proposing their own climate solutions. As of April 2021, 44 countries and the EU have announced net-zero emissions targets, and these countries and regions have pledged to reduce emissions by 70% of global CO_2 emissions.

In order to reduce the increasing concentration of CO_2 in the atmosphere, countries have made many efforts in the last few decades to reduce the consumption of fossil energy, to develop renewable energy sources such as wind, nuclear and hydrogen, to use fuels with shorter carbon chains and CO_2 capture and storage technologies, etc. (Pacala et al., 2007). In particular, carbon dioxide capture and storage (CCS) is considered to make a significant contribution to global emissions reduction by being used in conjunction with a number of emission reduction options (Pacala et al., 2007). CCS technology could reduce global emissions by 50–85% by 2050 (IEA, 2012).

China's resource endowment determines the country's "coal-rich, oil-poor, and gas-poor" energy mix, making most of China's CO_2 emissions come from fossil fuel combustion (Liu et al., 2017). In 2012, 68% of the country's CO_2 emissions came from burning coal, with oil accounting for about 13% and natural gas for about 7%. As the world's largest emitter of CO_2, China's economy is highly dependent on fossil energy sources, and the advent of CCUS technology can greatly mitigate the impact on China's economy when dealing with climate issues. The first CCUS project ran smoothly in 2005, and as the country's attention to climate issues has grown, CCUS technology has gained significant momentum in China, with about 40 projects currently in operation or running intermittently. In September 2020, China proposed a "double carbon goal" of achieving peak carbon by 2030 and achieving carbon neutrality by 2060. Compared to developed countries, China has only 30 years to reach peak carbon and become carbon neutral. As an important technology in the field of carbon emission reduction, CCUS is crucial to China's emission reduction. According to relevant research institutions, under the carbon neutrality target, China's CCUS emission reduction

Table 1. Summary of previous CCUS studies

Reference	Study area	Main conclusions
Rubin et al., 2007	Cost study	The capture costs of PC, NGCC and IGCC were compared under the influence of rising natural gas prices, plant utilization differences, IGCC financing and operating assumptions.
Fan et al., 2019	Cost study	Comparing the full-chain CCS project of coal-fired power plants with other low-carbon power plants, it is concluded that the full-chain CCS project of coal-fired power plants has cost advantages but is greatly affected by coal price and transportation distance.
Fuss et al., 2007	Investment decision study	By analyzing the uncertainty of electricity price and carbon price as well as the policy and market uncertainty based on this, the real option model is used to obtain the optimal time to invest in CCS projects.
Abadie et al., 2008	Investment decision study	Considering the uncertainty of European electricity price and carbon emission market, the binary tree model is used to solve the CCS optimal investment scheme.
Oda et al., 2011	Investment decision study	Under the premise that carbon price and natural gas price are uncertain, this paper compares the break-even between rebuilding environmental power plants and renovating old coal power plants by using discounted cash flow method and obtains the energy price at the best time for CCS investment.
Sen et al., 2016	Forecast carbon emissions	The ARIMA model is used to predict the energy consumption and GHG emissions of pig iron manufacturing industry in India.
Mohamed et al., 2005	Forecasting electricity consumption	The AIRMA model was used to forecast electricity consumption in New Zealand by adding economic and demographic variables.
Xu et al., 2017	Forecast carbon emissions	At the same time, STIRPAT model and GREY (1,1) model are used to divide the total energy consumption into five types, and STIRPAT model is used to predict the consumption of each type of energy, and grey model is used to predict the economic growth, industrial structure change and energy structure change, and the prediction result of carbon emission is obtained by combining them.

demand is 20–408 million tons in 2030 and 0.6–1.45 billion tons in 2050. However, after fifteen years of development from 2005 to 2020, the total emission reduction from operating CCUS projects is only 3.298 million tons. Most scholars have focused on CCUS emission reductions by 2040 or 2060 but have neglected the development process of how to achieve these desired reductions.

This paper sets three development rates, high, medium, and low, to obtain the emission reduction contribution of CCUS at the year 2040. The emission reduction contribution of CCUS is obtained from another perspective and compared with the expected value to consider what growth rate we use to develop CCUS technology is the most appropriate and beneficial for China's economy.

2. Methodology

This paper analyzes and predicts the potential of CCUS technology to contribute to emission reduction in China based on the aggregated data of emission reduction from operating or intermittently operating CCUS projects in China, combined with historical carbon emission data and predicted carbon emission data from some scholars.

2.1 Forecast Contribution to National Emission Reduction

By the end of 2020, China's CCUS emission reduction is 3.298 million tons. The emission reduction potential of CCUS is projected in two growth ways: one is the emission reduction potential under the growth of the number of CCUS projects, and the other way is the emission reduction potential under the growth of CCUS emission reduction.

Contribution under the growing number of CCUS projects

Referring to the development history of CCUS projects in China, in the early stages (2006–2010), one new CCUS project was added each year, while in 2010–2016, the state and government increased their attention and increased funding for research projects related to CCUS program development accelerated during this period, allowing for an average of 3 new projects per year. According to Table 1, it can be concluded that 70% of the CCUS projects that have been proposed or established are above 1 million tons of emission reduction, and large-scale projects are the development trend of future CCUS projects, thus setting the amount of emission reduction for new projects in the future at 1 million tons. Combined with the pace of China's energy consumption restructuring and the 2030 carbon peak target, the CCUS project should grow faster than the previous phase, or at least maintain the growth rate of the previous phase. Therefore, based on the past development rate, we set the number of new CCUS projects in each year in the future as k_1= 1, 2, 3 forecast contribution of emission reductions from CCUS projects by 2040.

The emission reduction contribution can be calculated by the following equation:

$$r_t = \left[\sum CCUS_{cap_{t-1}} + k_1 * CCUS_{cap_{2020}} \times (t - 2020)\right] / emis_t \quad (1)$$

where, r_t represents the emission reduction contribution of CCUS in year *t*, $\sum ccus_{cap_{t-1}}$ is the cumulative emission reduction of national CCUS projects in year *t-1*, $ccus_{cap_{2020}}$ represents the emission reduction of CCUS in 2020, k_1 represents the number of new

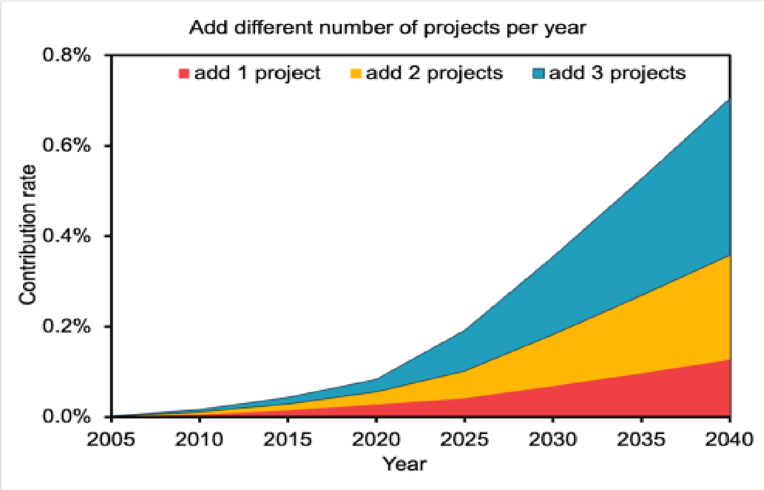

Figure 1. Add different number of projects per year

projects each year, $emis_t$ represents the total national CO2 emission in year t, and t represents the year.

When three new megaton CCUS projects are added each year, the national CO_2 emissions in 2040 will be about 17,269 million tons, and the amount of CO_2 captured by CCUS projects will be about 76,798,000 tons, and the contribution of CCUS technology will be about 0.34%.

Contribution under the growth of CCUS emission reductions

At the end of 2020, the total amount of carbon dioxide captured by the CCUS project is 3.298 million tons, and the annual growth rate of CCUS project emission reduction is set at k_2, k_2 takes 10%, 20%, 30% respectively, to obtain the emission reduction contribution rate:

$$r_t = \left[\sum CCUS_{cap_{t-1}} + CCUS_{cap_{2020}} \times (1 + k_2)^{(t-2020)}\right] / emis_t \quad (2)$$

When CCUS emission reductions are set to grow at different rates, the difference in emission reduction contribution is more significant compared to the way the number of projects grows. When CO_2 capture is increased at a 30% increase per year, the contribution can reach 3.8%, compared to an abatement contribution of about 0.016% when it is increased at a 10% rate. The difference between the two is about 20 times.

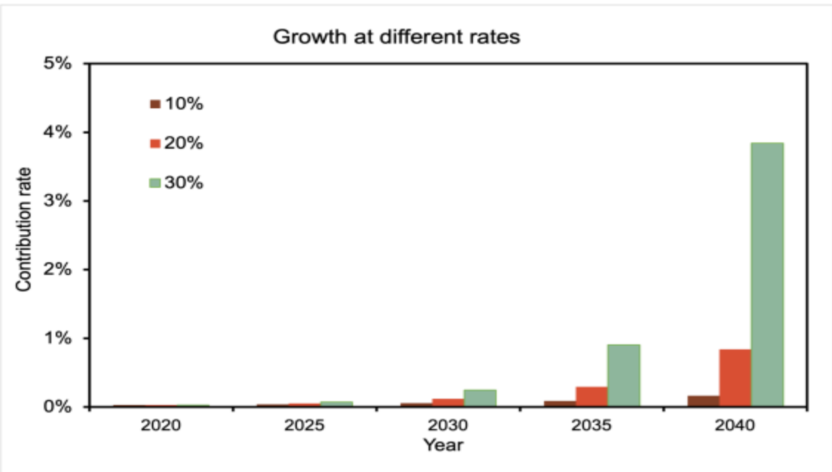

Figure 2. Differences under CCUS emissions reduction growth

2.2 Forecast CCUS Sub-Sector Emission Reduction Potential

To further clarify the emission reduction contribution potential of CCUS technologies, the industrial sectors are subdivided, the actual utilization of CCUS projects and industries are combined to compare the emission reduction contribution potential of CCUS technologies from an industry perspective.

At present, CCUS technology in China's industrial sector is mainly applied in the power industry, chemical industry and petroleum and cement industries, while there are no mature CCUS emission reduction projects of a certain scale in other industries. Therefore, we only predict the potential of CCUS to contribute to emission reductions in four industries: power industry, chemical industry, oil industry, and cement industry. The number of CCUS projects and captures in different industries by the end of 2020 are shown in Table 3.

Table 3. Sub-sector CCUS project information

Sector	Carbon dioxide capture capacity（MT）	Number of CCUS projects
chemical	2.05	13
electricity	0.744	12
petroleum	0.05	3
cement	0.051	2

To set the growth rate of CCUS project emission reductions for the industry is k_3, k_3 takes 10%, 20% and 30%, respectively. The industry emission reduction contribution is calculated as follows:

$$r_{i,\ t} = \left[\sum CCUS_{capi,t-1} + CCUS_{cap_{i,2020}} \times (1 + k_3)^{(t-2020)}\right] / emis_{i,t} \quad (3)$$

where $r_{i,t}$ denotes the CCUS emission reduction contribution of industry i in year *t*, $\sum ccus_{capi,t-1}$ denotes the cumulative CCUS emission reduction of industry i in year *t-1*, $ccus_{cap_{i,2020}}$ denotes the CCUS emission reduction of industry *i* in 2020, and $emis_{i,t}$ is the CO_2 emission of industry *i* in year *t*.

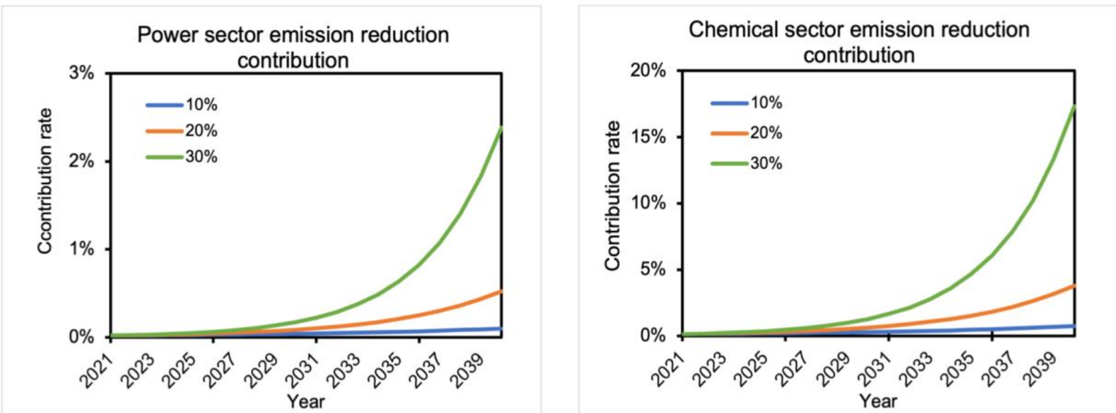

Figure 3. Potential for emission reduction contribution from the power and chemical industries

It can be seen that the contribution of CCUS projects to emission reductions by 2040 varies greatly among industries due to the different current CCUS project emission reductions among industries, resulting in the same growth rate of capture volume. When the capture volume of the power sector grows at 30%, the contribution of CCUS technology to its emission reduction by 2040 only reaches 2.3%. In contrast, the projected emission reduction contribution of the chemical industry can reach 17.3% at a 30% growth rate, which is much higher than the emission reduction contribution of other industries.

2.3 Forecast CCUS Sub-Regional Emission Reduction Potential

The most important considerations for CCUS source-sink matching are the geographic location and environmental suitability of the emission source and the storage site. The geological and geomorphological characteristics of China vary greatly from region to region, making the development potential of CCUS projects vary from region to region. Moreover, regional differences in economic development will also have an impact on CCUS emission reduction potential.

The regional emission reduction contribution is calculated by the following formula:

$$r_{j,t} = \left[\sum CCUS_{cap\,j,t-1} + CCUS_{cap_{j,2020}} \times (1 + k_3)^{(t-2020)}\right] / emis_{j,t} \quad (4)$$

where j represents the region, $r_{j,t}$ denotes the CCUS emission reduction contribution of region j in year t, $\sum ccus_{cap\,j,t-1}$ denotes the cumulative CCUS emission reduction of region j in year *t-1*, $ccus_{cap_{j,2020}}$ denotes the CCUS emission reduction of region j in 2020, and $emis_{j,t}$ is the CO_2 emission of region j in year t.

The contribution of CCUS technology varies significantly between regions at three different growth rates. The contribution is consistently the largest for the Northeast, where

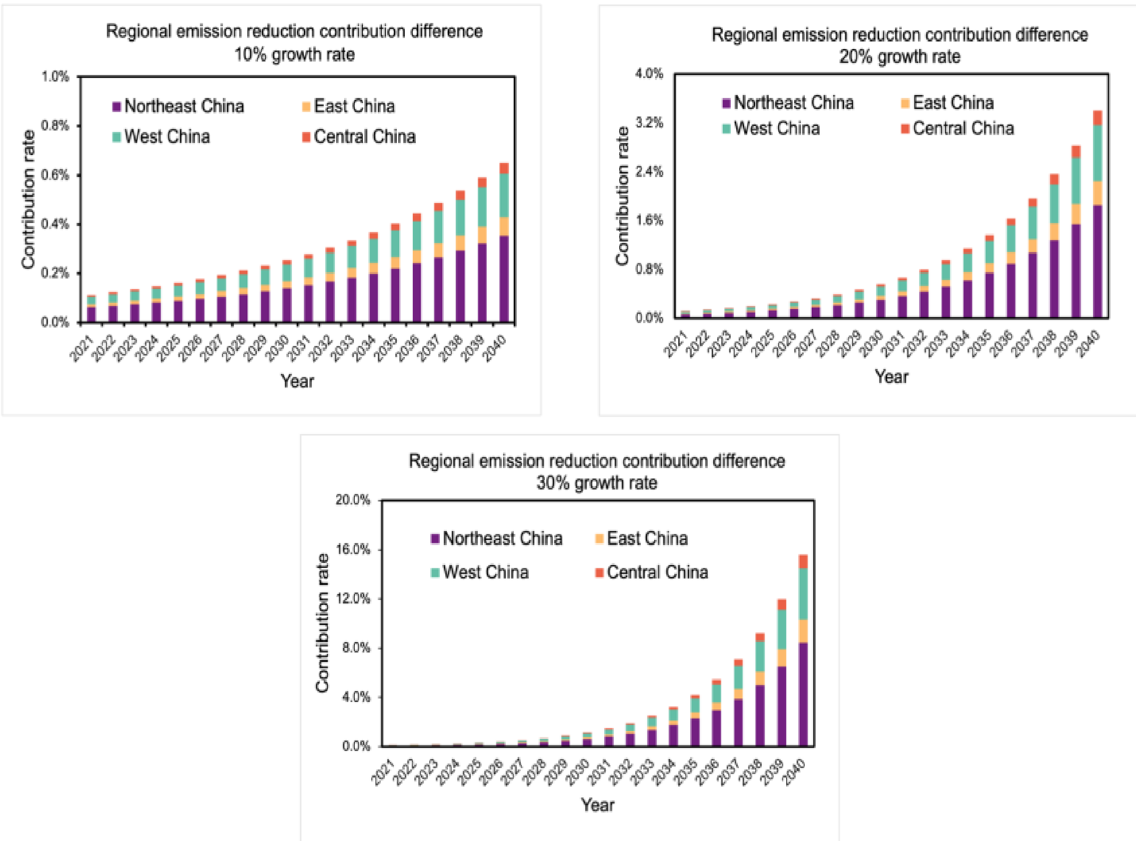

Figure 4. Differences in emission reduction contributions by region

CCUS technology can contribute 8.4% to the Northeast's emissions reduction by 2040 when CO_2 capture grows at 30%. Meanwhile, the contribution of CCUS emission reduction in the eastern region, which is the most developed region in China, is lower than that in the western region, accounting for about 40% of the CCUS emission reduction contribution in the western region. For the central region, the contribution is always the lowest at all three growth rates, and when the emission reduction scale is increased by the largest amount, the emission reduction contribution of CCUS technology is only 1.08%. The reason for this difference in contribution is that the Northeast region has lower carbon emissions compared to other regions, with only 1.641 billion tons of CO_2 emissions projected by 2040, much lower than the Central region's 3.385 billion tons, the Eastern region's 6.181 billion tons, and the Western region's 4.606 billion tons. In addition, the Songliao Basin in northeast China has great geological potential for CO_2 storage due to its good reservoir and cover properties. The large number of oil fields in the northeast also provides a way to utilize CO_2, and the good geological conditions and source-sink match make the CCUS technology the most important contribution to the northeast. The eastern region has a better spatial distribution in terms of source-sink matching, with a large number of chemical companies and coal power plants with high CO_2 concentration emission sources, but the lack of suitable geology for sequestration in the eastern region prevents the large-scale application of CCUS technology, making the predicted contribution lower than that of the western and northeastern regions.

3. Results

As a key emission reduction technology, technical economics of CCUS technology is also of great concern in the process of promoting its utilization. Since the current investment cost of CCUS technology is too high, and the utilization of CO_2 is mainly focused on EOR, industrial and food processing, and geological storage, which have multiple uncertainty effects, it is difficult for CCUS projects to have sustainable and stable income. In the absence of stable revenue, if policies and funds are heavily tilted to support CCUS technology, it is likely that satisfactory emission reduction results will not be achieved.

In order to evaluate the economics of CCUS in future development, we predict the annual cost of new CCUS technology abatement compared with our GDP (Gross National Product) in that year to obtain the ratio of CCUS technology abatement cost to domestic GDP as a measure of the economics of CCUS technology abatement.

The cost of CCUS technology includes economic cost and environmental cost, where economic cost includes fixed cost and operation cost, and environmental cost includes environmental risk and energy consumption emission. The cost per unit of CO_2 reduction is obtained by combining them. The investment cost of CCUS technology will tend to decrease year by year due to the scale effect. In the early stage of CCUS utilization, new CCUS projects are constrained by technology and immaturity of operation management, so the cost is high in the early stage. With the breakthrough of technology bottleneck, the increasing maturity of operation management, some cluster projects share the infrastructure of pipeline, etc., the cost will keep decreasing.

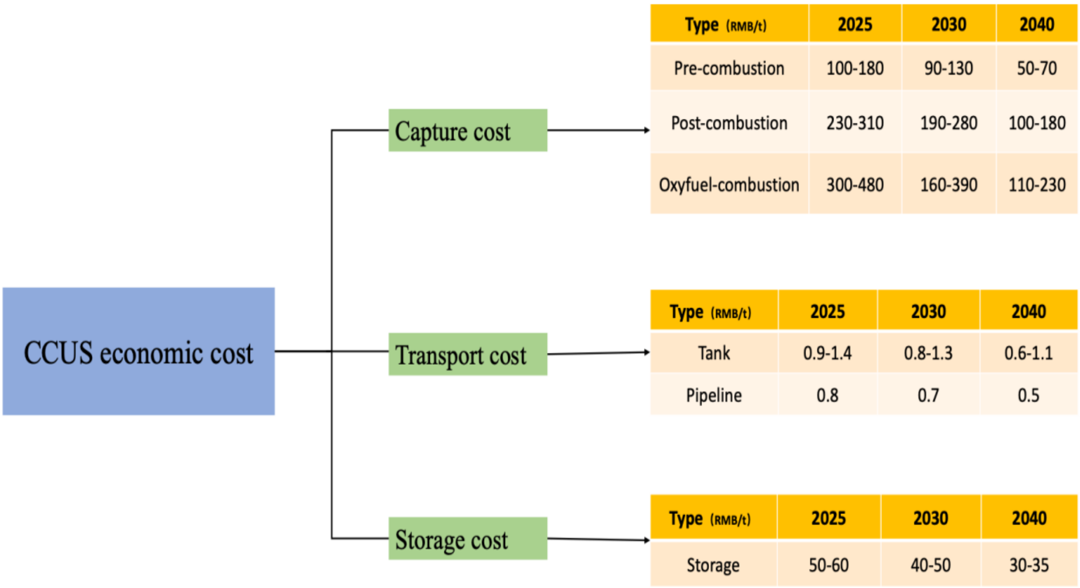

Figure 5. Diagram of CCUS cost

The application of CCUS technology for emission reduction is mainly in the power industry. Compared to pre-combustion capture and oxygen-enriched combustion, post-combustion capture provides a solution for carbon reduction in coal-fired power plants and is currently the most widely used capture method. Therefore, when calculating the economics of CCUS, we make the important assumption that post-combustion capture is the primary capture method used to calculate costs.

The rate of CCUS development is influenced by external uncertainties, so we set different rates of CCUS development. The emission reductions of CCUS technology were obtained for annual growth of 10%, 20%, and 30%. The results are shown in Table 4.

Table 4. CCUS emission reductions at different growth rates

Year/ Reduction	10% growth rate	20% growth rate	30% growth rate
2025	422.83	598.86	824.84
2030	680.98	1,490.14	3,062.58
2035	1,096.72	3,707.96	11,371.14
2040	1,766.27	7,688.82	42,220.26

The growth rate of our GDP is 4.4% and 3.6% during 2021-2030 and 2031-2040, respectively, using the data measured by Goldman Sachs Group. According to the Goldman Sachs Group forecast growth rate, the National Bureau of Statistics 2020 China's gross national product as a starting value, GDP forecast values are shown in Table 5.

Table 5. China's GDP forecast

Year	GDP（Trillion)
2025	1,260,057.3
2030	1,562,761.8
2035	1,865,054.7
2040	2,225,821.6

The cost projections for the CCUS sub-segments are summed to obtain a range of values for the unit cost of abatement of CCUS technology, using the following equation:

$$Cost_t = uc_t * ccus_{cap_t} \tag{5}$$

where, $Cost_t$ represents the meaning of the total cost of CCUS investment in that year, uc_t represents the unit cost, $ccus_{cap_t}$ is the amount of emission reduction at year t, to get the total cost of CCUS emission reduction in that year, and with the GDP forecast value of that year to calculate. Based on the results of the above equation, the ratio of China's CCUS abatement investment to GDP is measured as follows.

Table 6. Percentage of CCUS investment in GDP

Year	Percentage of CCUS investment in GDP
2025	0.00097–0.00243%
2030	0.00101–0.00649%
2035	0.00115–0.01592%
2040	0.00104–0.04099%

The data in the table reflects the CCUS in the continuous development process, due to the growing scale of the deployed projects, although the investment cost per unit of CO2 abatement is decreasing, the cost of investing in CCUS is increasing, from the initial less than 0.001% of the current year's GDP all the way up to about 0.04% of the current year's GDP in 2040. In 2040, CCUS will reduce about 2.44% of the national emissions, which is a capital-saving emission reduction technology with good overall emission reduction economics and a small investment in GDP.

4. Discussion

In this paper, we forecast the contribution of CCUS projects to the nation, industry, and region in 2040 under different development approaches from three perspectives: national, industry, and regional.

The results of the study show that (1) when the number of new CCUS projects is 1, 2, and 3 per year nationwide, and the annual capture scale of the new projects is 1 million tons, the emission reduction contribution of CCUS technology is 0.22%, 0.32%, and 0.44%, respectively. When the amount of carbon dioxide captured by CCUS projects nationwide grows at different percentage rates, with growth rates of 10%, 20%, and 30%, the emission reduction contribution of CCUS projects is 0.51%, 2.08%, and 7.68%, respectively. (2) The types of CCUS project capture are divided into power industry, chemical industry, petroleum industry, and cement industry by industry. At present, the application of CCUS technology is mainly concentrated in the power and chemical industries. By 2040, the ease of reducing emissions using other technologies will be different for different industries due to the different carbon emissions in different industries. Therefore, the industry emission reduction contribution of CCUS technology at 2040 varies. The contribution of CCUS to industry emission reduction is 0.09%, 0.52%, and 2.38% when the annual CO_2 capture scale of power industry grows at 10%, 20%, and 30%, respectively. When growing at the same rate, the contribution of CCUS to the industry's emission reduction in the chemical industry is 0.72%, 3.78%, and 17.31%, respectively. (3) When the country is divided into eastern, western, central, and northeastern regions according to the economy, the northeastern region has been the largest contributor to emission reduction by CCUS technology because the industry is less developed than other regions but has the Song Liao Basin and a large number of oil fields that can utilize CO_2, and the regional contribution to emission reduction by 2040 is 0.35%, 1.85%, and 8.47%. The main reason behind this is that the central region lacks the geological conditions to promote the use of CCUS and cannot generate profit for the project.

In order to predict the contribution of CCUS technology to national, industry and regional emission reduction, and in the light of the specific development situation in China, the following policy recommendations are made for the cause of emission reduction in China:

1. The future development of CCUS technology should be aimed at clustering and commercialization. the biggest advantage of CCUS projects, when they are scaled up, is that they can reduce costs. For example, after the establishment of CCUS industrial parks, some of the infrastructure can be shared to a certain extent, reducing the initial investment cost of the project. After the commercialization of CCUS technology, the project itself will be able to form a certain "blood-making" capacity with "CO_2" as the core value, which will enable the project to maintain long-term operation.
2. National policies subsidize the cost of CO_2 transportation process. From the predicted results, the contribution of CCUS varies greatly from region to region. Less economically developed regions have good geological storage conditions, while economically developed regions lack geological conditions for utilization and storage. However, the transportation of CO_2 captured in developed regions to geologies where it can be sequestered will incur high costs, so the state can subsidize the CO_2 transportation link in CCUS to further promote the resource allocation and utilization in each region.
3. Pay attention to other renewable energy sources and energy restructuring. When the amount of carbon dioxide captured by CCUS technology increases at 30%, the contribution to China's emission reduction is still only 7.68%. Therefore, in addition to CCUS technology, we should also focus on other green energy technologies and energy structure adjustment to work together to achieve carbon neutral.

Conflict of interest: None

References

Abadie, L. M., & Chamorro, J. M. (2008). European CO_2 prices and carbon capture investments. *Energy Economics, 30*(6), 2992–3015. https://doi.org/10.1016/j.eneco.2008.03.008

Fan, J. L., Wei, S. J., Yang, L., Wang, H., Zhong, P., & Zhang, X. (2019). Comparison of the LCOE between coal-fired power plants with CCS and main low-carbon generation technologies: evidence from China. *Energy, 176*, 143–155. https://doi.org/10.1016/j.energy.2019.04.003

Fuss, S., Szolgayova, J., Obersteiner, M., & Gusti, M. (2008). Investment under market and climate policy uncertainty. *Applied Energy, 85*(8), 708–721. https://doi.org/10.1016/j.apenergy.2008.01.005

Huang, J., Ma, Q., Shi, M. W., Peng, X. T., & Zhang, X. (2022). The development process of CCUS technology from the perspective of carbon neutrality and suggestions for countermeasures. *Environmental Impact Assessment*, 2022, 44. https://doi.org/10.14068/j.ceia.2022.01.008

International Energy Agency. (2012). *Energy technology perspectives. 2012: energy technology perspectives 2012: pathways to a clean energy system*. OECD/IEA. https://doi.org/10.1787/energy_tech-2012-en

IPCC 2013. (2013). *Climate change 2013: the physical science basis*. https://www.ipcc.ch/report/ar5/wg1/

Liu, H. J., Were, P., Li, Q., Gou, Y., & Hou, Z. (2017). Worldwide status of CCUS technologies and their development and challenges in China. *Geofluids, 2017*, 1–25. https://doi.org/10.1155/2017/6126505

Mohamed, Z., & Bodger, P. (2005). Forecasting electricity consumption in New Zealand using economic and demographic variables. *Energy, 30*(10), 1833–1843. https://doi.org/10.1016/j.energy.2004.08.012

Oda, J. (2011). An analysis of ccs investment under uncertainty. *Energy Procedia*, *4*, 1997–2004. https://doi.org/10.1016/j.egypro.2011.02.081

Pacala, S., & Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science, 305*(5686), 968–972. https://doi.org/10.1126/science.1100103

Raza, A., Gholami, R., Reazaee, R., Rasouli, V., & Rabiei, M. (2019). Significant aspects of carbon capture and storage – A review. *Petroleum, 5*(4), 335–340. https://doi.org/10.1016/j.petlm.2018.12.007

Rubin, E. S., Chen, C., & Rao, A. B. (2007). Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy, 35*(9), 4444–4454. https://doi.org/10.1016/j.enpol.2007.03.009

Sen, P., Roy, M., & Pal, P. (2016). Application of ARIMA for forecasting energy consumption and GHG emission: A case study of an Indian pig iron manufacturing organization. *Energy, 116*(1), 1031–1038. https://doi.org/10.1016/j.energy.2016.10.068

Xu, L., Chen, N., & Chen, Z. (2017). Will China make a difference in its carbon intensity reduction targets by 2020 and 2030? *Applied Energy, 203*, 874–882. https://doi.org/10.1016/j.apenergy.2017.06.0