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The Strategic Imperative of CCS Technology for Fossil Energy's Net-Zero Goals and National Security

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Abstract

Carbon capture and storage (CCS) technology is pivotal in bridging the gap between fossil energy reliance and net-zero ambitions. This paper examines key CCS approaches, including direct air capture (DAC), CO_2 enhanced oil recovery (CO_2-EOR), and bioenergy with CCS (BECCS), and their role in decarbonizing power generation, industry, and hard-to-abate sectors. By capturing emissions at the source or removing CO_2 from the atmosphere, CCS mitigates climate impact while extending the viability of fossil assets during the energy transition. However, scalability, cost efficiency, and regulatory frameworks remain critical challenges. The study evaluates technological advancements, economic trade-offs, and policy drivers to assess CCS's potential in achieving carbon neutrality without sacrificing energy security. It finds that from a long-term and macro perspective, the technical potential of CCS is immense, making it an indispensable tool for achieving carbon neutrality; therefore, its potential outweighs the obstacles.

Keywords

Energy Carbon Neutrality, Carbon Capture and Storage, Direct Air Capture, CO_2 Enhanced Oil Recovery, Bioenergy with Carbon Capture and Storage

1. Introduction

CCS refers to the process of separating and collecting CO_2 generated from emission sources such as thermal power plants, chemical plants and iron and steel mills or in the atmosphere, transporting them through specialized pipelines to a specific storage site, and permanently sealing them by injecting them deep into the rock layers so that they can be isolated from the air for a long time. If the reuse of captured CO_2 is considered, it is Carbon Capture, Utilization and Storage (CCUS) [1]. CCUS mainly includes four segments: CO_2 capture, transportation, utilization and storage. Commercial deployment of CCUS will peak in 2027, with the most significant number of deployments for power plants [2]. Among the CCUS projects in China, using CO_2 to drive oil is one of the most important. In China's currently operating CCUS projects, the use of CO_2 to drive oil for enhanced recovery accounts for the majority of projects, while the scale of integration of CCUS technology in the more prevalent thermal power generation industry is insufficient.

In the Sustainability Scenario, the scale of CCUS deployment in China will be significantly ahead of other countries in 2030, with a substantial increase in scale in 2050 compared to its own country in 2030 (**Figure 1**). In addition, the scale of CCUS deployment in regions other than India, the Middle East, North America, and Europe tends to catch up with China. By 2070, the scale of CCUS deployment will continue to increase in all regions, with rest of the world seeing significant increases in carbon capture, surpassing China by then, reaching 3.3 Gt. During CCUS deployment, regions will prioritize developing different areas of carbon capture based on their respective differences in energy mix. Specifically, China will prioritize carbon capture in coal, cement, steel, and chemicals and low-carbon hydrogen production. India will focus on R&D in coal, cement, steel, and chemicals and negative emission technologies. The Middle East and North America will focus on natural gas, low-carbon hydrogen production, fuel switching and negative emission technologies. Europe and rest of the world will increase the deployment of cement, steel and chemical products and negative emission technologies. In the medium to long term, negative emission technologies will not be a priority for China.

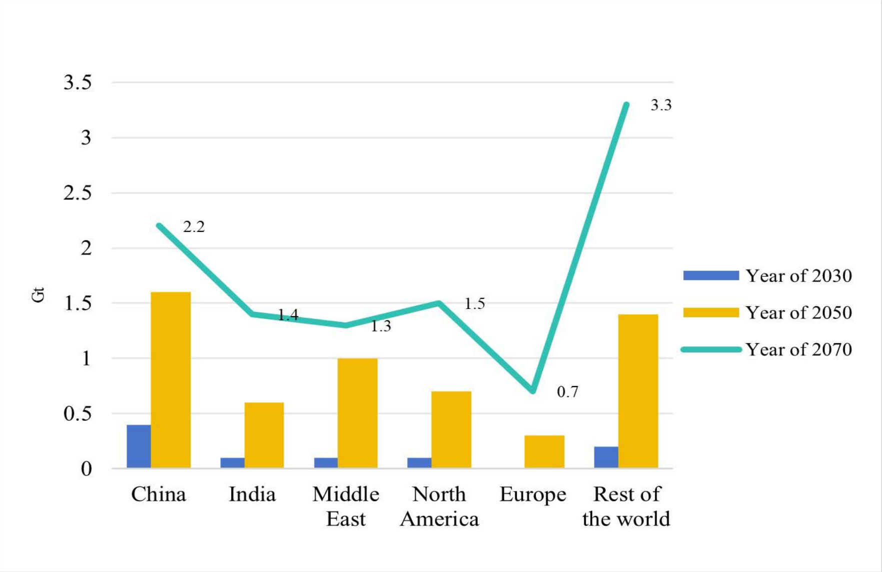

Figure 1. Captured CO_2 emissions by country/region in the sustainable development scenario, 2019-2070. Source: [3].

2. DAC Application in the Coal Sector

In DAC technology, CO_2 can be chemically or physically separated from other gaseous air components in a facility that can be started and stopped on demand, making DAC technology highly controllable. Ideally, DAC is powered by renewable energy generation or waste heat. This is feasible in a future where the electricity network is completely decarbonized or for smaller plants that can utilize the limited available waste heat. Combining renewable energy sources with the CO_2 capture process can reduce the cost of CO_2 capture and achieve net zero or negative emissions. The drawbacks of renewable energy integration (e.g., high initial investment and fluctuating CO_2 capture rates) can be minimized through flexible designs that optimize the contribution of renewable energy and address the intermittent nature of renewable energy. Integrating renewable energy with CO_2 capture processes, including DAC technologies, could provide a promising source of revenue. However, this approach has not yet received much attention [4].

CCUS is critical to China's carbon neutrality goals, particularly in the coal-fired power and chemical industries. Although costly, CCUS is cost-competitive with natural gas and wind under certain conditions [5]. According to the China Statistical Yearbook (2024), coal accounts for 2/3 of China's energy structure, and in order to reach the goal of carbon neutrality, coal cleanup is a key investment area [6]. This status quo coincides with the domestic policies of coal-to-gas conversion, electrical cleanup, and elimination of low-quality coal in recent years, and the corresponding technological innovations have gradually entered the commercialization or commercial trial stage. It can be seen that China's coal industry has now entered an important transition period. Before achieving carbon neutrality by 2060, fossil fuels such as coal will be a ballast to ensure energy security.

Currently, the disruptive innovation in the coal industry is mainly DAC technology. The levelized cost of electricity from coal-fired power plants with CCS can be lower than that of nuclear, wind, and solar energy, especially when the CO_2 transportation distance is shorter and the price of coal is lower [7]. DAC deployment will rapidly ramp up in 2028-2029 and peak in that time frame. However, China's commercial deployment of CCUS by 2030 will account for a very low percentage, far less than that of the EU and North American countries. While the country will not significantly increase the coupling of CCUS with the coal industry in the short to medium term (before 2030), it is likely to significantly increase the deployment rate of CCUS in the coal cleanup process in the medium to long term. Carbon dioxide removal (CDR) technologies are expected to reach a technology maturity level suitable for industrial applications within five years. DAC is seen as a potential solution for reducing CO_2 emissions. CDR technologies like DAC are progressing but are not yet ready for full-scale industrial deployment because of the time and investment required to move from pilots to industrial-scale scale. DAC large-scale validation is still missing or not planned, hindering its deployment [8]. By 2060, DAC technology could require an additional 600 GW of wind and solar capacity and \$330 billion to \$530 billion in investment. Despite these challenges, DAC technologies can reduce mitigation costs by up to \$6 trillion, making them an attractive option [9].

3. CO_2-EOR to Increase Oil/Gas Production

The technical principle of CO_2-EOR is to inject captured CO_2 into underground oil and gas reservoirs through injection wells and then utilize the property that CO_2 can make the oil expand to reduce the oil's viscosity and improve the recovery rate. The technology has gone through stages of research, field trials and industrial applications. China has established theories and technologies suitable for its land-phase sedimentary reservoirs, including engineering design and anti-corrosion technologies [10]. As the industry transitions from field testing to industrialization, CCUS projects in China are currently dominated by EOR. However, China faces technical, facility, and policy challenges in scaling up and industrializing CCUS [11]. There are 12 EOR projects in China with an annual capture capacity of 100,000 tons and above, of which seven are in operation, and five are under construction. The Chinese Academy of Sciences (CAS) is a global leader in CCUS research results, focusing on geologic sequestration technologies and EOR. CCUS-EOR has become a key technology for large-scale carbon reduction in China's pursuit of carbon neutrality goals. Prospects include establishing multiple CCUS-EOR clusters in key regions and promoting large-scale applications to drive high-quality development of CCUS in China. Multiple CCUS-EOR clusters are expected to be established in the Bohai Bay Basin, Songliao Basin, Ordos Basin, Yangtze River Delta, and Pearl River Delta regions, driving the high-quality development of CCUS applications in China [12]. Mature oil fields with good carbon source conditions are favourable for deploying CCUS-EOR projects, which can bring significant economic and long-term social benefits [13]. CO_2 capture, transportation, injection and storage technology has been successfully demonstrated and implemented in Jilin Oilfield, thus significantly increasing oil exploitation and realizing CO_2 storage [14].

The development of carbon dioxide-driven gas (CO_2-EGR) is also receiving increasing attention due to its potential benefits to energy security and carbon emission reduction. CCUS-EGR is based on injecting CO_2 into reservoirs to increase gas permeability, generate favourable displacement flow ratios, extend the anhydrous and low-water production period in sidetracked gas reservoirs, and improve gas recovery through gravity separation. China is rich in natural gas resources with several suitable closures for CO_2 storage, mainly in the Ordos Basin, Sichuan Basin, Yinggehai Basin, Tarim Basin, Junggar Basin and Bohai Bay Basin, with a storage capacity of about 304.8×10^8 t. Natural gas reservoir closures have a higher integrity compared to depleted oil reservoirs. Because of the higher compressibility of natural gas, the CO_2 sequestration capacity per unit volume of pore space is greater. However, natural gas reservoirs may contain a certain amount of CO_2 themselves, which increases the risk of CO_2 leakage during geological storage of

CO_2 [15]. From the perspective of public acceptance, however, the risks of CO_2 leakage and long-term safety concerns associated with CO_2 storage in depleted oil and gas reservoirs transcend purely technical considerations, representing fundamentally a socio-governance challenge involving risk perception, social trust, and environmental justice. For example, the public might associates the high-pressure injection of CO_2 with hydraulic fracturing and their potential link to seismic activity. Even if the probability and scale of induced seismicity are minimal, any minor tremors can amplify public concerns about formation stability and leakage risks. This apprehension readily leads to significant not-in-my-backyard (NIMBY) opposition: even while supporting carbon neutrality goals, community residents may strongly oppose CO_2 storage projects near residential areas or drinking water sources.

Most CCUS technologies in China are deployed to enhance CO_2 in oil and gas recovery. This scenario is also mostly true in foreign countries and has a good development prospect. China's theoretical CO_2 storage capacity ranges from 1.21 to 4.13 trillion tons, mainly in deep saline aquifers, depleted oil and gas fields, and through CO_2-EOR/EGR. China has made remarkable progress in CO_2 utilization, including chemical utilization, bio-utilization, and CO_2 oil driving, bringing considerable economic benefits [16]. Furthermore, China has a sizable offshore CO_2 storage capacity for CO_2-EOR, with the Bohai Bay and Pearl River Estuary basins representing early development opportunities.

4. BECCS to Achieve Negative Emissions

Biomass energy has become an ideal alternative to fossil fuels due to its abundant reserves, good renewable performance and zero carbon emissions [17]. The CO_2 released in the process of biomass energy conversion and utilization can be offset by the CO_2 captured by photosynthesis in the process of biomass growth, and this process is net-zero emission. The carbon sequestered by BECCS technology while producing energy is the atmospheric CO_2 absorbed by biomass through photosynthesis, which not only does not emit CO_2 but also realizes negative emission of CO_2, and its maximum emission reduction can theoretically be twice as much as that of solar energy and wind energy, which can offset some of the carbon emissions that cannot be avoided in the future industrial process [18]. It can offset some of the unavoidable carbon emissions in future industrial processes. Some BECCS configurations, such as direct biomass combustion and gasification power plants (using 100% biomass combustion) and gasification-based biohydrogen processes, can potentially achieve negative emissions [19].

Currently, BECCS technology is in the R&D growth stage globally and has not yet been put into widespread commercial application. However, countries have begun gradually deploying BECCS demonstration projects, and good progress has been made in related industrial demonstration projects. For example, China's Inner Mongolia Maowusu biopower plant utilizes planted salal as fuel. It collects and utilizes CO_2 from the flue to cultivate algae, realizing the application of BECCS technology with negative emissions [20]. When considering the large-scale application of BECCS technology, the availability of biomass resources, geographic location, supply chain, collection, and transportation must be considered first. The policy difficulties in deploying BECCS technology in China are greater than the technical difficulties due to the serious challenges faced by BECCS regarding food security, land and water utilization, and the feasibility of large-scale implementation [21]. Converting crop residues into bioenergy can significantly reduce greenhouse gas emissions in China. From 1950 to 2021, the utilization of straw shifted from open burning to remaining in the field. GHG emissions due to straw utilization increased from 100 million tons/year in 1950 to 446 million tons/year in 2021. Converting unnecessary crop straw use to bioenergy could avoid 122 million tons of GHG emissions, and replacing fossil fuels with this bioenergy could reduce emissions by an additional 34 - 86 million tons [22]. The availability of crop straw is high, but due to its geographically dispersed distribution, there are challenges, such as unstable supply chains due to the inconvenience of collection and transportation.

China has made remarkable progress in Efficient Oxy-Fuel Co-Combustion of Coal and Biomass with CO_2 Sequestration Technology. Biochar has a negative emission potential of up to 0.92 billion tons of CO_2 annually in China. The average net cost of this negative emission potential is US$90 per ton of CO_2. This negative emission potential of biochar can meet the demand for negative emissions in most emission reduction scenarios, thus helping China achieve its 2060 carbon neutrality target [23]. Several domestic research institutes, including the Institute of Engineering Thermophysics of the Chinese Academy of Sciences, Huazhong University of Science and Technology, Southeast University, Xi'an Jiaotong University, and Chongqing University, have explored in depth the mechanism of biomass-coal interaction in the process of oxy-fuel co-combustion and have implemented pilot-scale engineering practices. However, domestic exploration in other BECCS technology research directions is still weak. Compared with some developed countries, there is still a certain gap. In the long run, the cement industry must adopt BECCS technology and demand-side emission reduction measures to achieve carbon neutrality. The share of cement kilns equipped with BECCS is expected to increase to 68% - 75% by 2060, with a corresponding CO_2 abatement cost of RMB 484-676/ton [24]. Negative emissions can be achieved by combusting wood and paper waste with coal through BECCS in New South Wales, Australia. Increasing the proportion of wood and paper waste combusted with coal can reduce the intensity of CO_2 emissions. At 20% - 25% mixed combustion ratios, the emission intensity of BECCS is comparable to other renewable technologies. In contrast, negative emissions can be achieved at more than 30% of mixed combustion ratios. Although the current waste supply is insufficient to support such ratios, in the future, mixed combustion BECCS is likely to be favoured over other coal-fired generation options [25]. China, with its abundant wood, paper waste and coal, does not have the problem of an insufficient supply of waste and, therefore, can learn from Australia's mixed combustion approach to achieve negative emissions from BECCS. In China and most countries, DAC currently incurs the highest costs, primarily due to its extremely high energy consumption. Since the process captures dilute atmospheric CO_2, it generates no direct revenue and remains purely an expense item. BECCS demonstrates moderate costs, though these are significantly influenced by biomass feedstock prices and supply chain stability. However, it offers dual benefits by generating stable cash flow through the sale of bioelectricity or heat. In contrast, CO_2-EOR achieves the lowest costs and can even yield negative net costs. Its primary revenue stems from enhanced oil production, while carbon emission reduction serves as a complementary byproduct.

5. Conclusion

CCS technology offers a pragmatic pathway to reconcile fossil energy use with net-zero targets, particularly for industries where alternatives are limited. Innovations in DAC, CO_2-EOR, and BECCS demonstrate their versatility in emission reduction and negative carbon potential. Policymakers and industries must collaborate to address public acceptance and leakage risks while integrating CCS into broader decarbonization strategies. When combined with renewable expansion, CCS can serve as a transitional backbone for a sustainable energy future, ensuring climate goals are met without abrupt disruptions to global energy systems. Yet, widespread deployment hinges on reducing costs, securing storage infrastructure, and aligning incentives through carbon pricing and subsidies. The application of CCS technology in China faces multiple critical limitations and unresolved research challenges. These include the complex geology of China's terrestrial sedimentary basins, where CO_2 migration and transformation mechanisms differ significantly from marine basins, requiring deeper fundamental investigation. Other key challenges involve planning integrated carbon hubs for centralized transport and storage from multiple emission sources, and developing socially engaged models that foster community trust and local benefits within China's unique socio-cultural context. CCS development in China is now transitioning from technical verification to commercial demonstration. Its success increasingly depends on building a comprehensive ecosystem that integrates technology, economic incentives, regulatory frameworks, and social acceptance-going beyond pure technological advancement. Resolving these limitations is essential to realizing CCS's substantial potential in China.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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