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Techno-economic Analysis of Biomass-Based Carbon Capture and Storage—"Negative Emissions"

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Abstract. To address global climate change and achieve the temperature control goals of the Paris Agreement, "negative emission technologies" that actively remove carbon dioxide from the atmosphere have become an indispensable strategic pillar, alongside deep emission reductions. Among them, biomass-based carbon capture and storage technology is highly anticipated in many climate governance pathways due to its ability to combine biomass energy utilization with carbon removal. However, there is a huge gap between its ambitious emission reduction potential and slow commercial deployment, with the core bottleneck being the dual challenges of technology and economy. This article focuses on the core issue of "technical economy" in Bioenergy with Carbon Capture and Storage (BECCS) for research. By studying the full chain technology system model of BECCS, the technical characteristics and cost composition of each link from biomass supply chain, conversion and capture path, to CO_2 transportation and storage were finely analyzed. This technology innovatively introduces a "negative emissions" value mechanism, which can comprehensively evaluate its economic feasibility, and through sensitivity analysis, identify the birth material price, carbon price, and energy penalty mechanism as key cost driving factors.

Keywords: Biomass energy, carbon capture and storage, negative emissions, technical economy.

1. Introduction

With the continuous progress of technological civilization and the rapid development of world industrialization, the combustion of fossil fuels such as coal, oil, and natural gas has led to a large amount of greenhouse gas (CO2) emissions into the atmosphere, causing a series of global environmental and ecological disasters, which have had an undeniable impact on the world. The climate and environmental changes on Earth are gradually becoming more severe, with global warming, frequent extreme weather events, rising sea levels, and other weather disasters affecting us. Therefore, China needs to strengthen in-depth research on carbon capture and storage (CCS) technology to alleviate the burden on the Earth's environment and improve living environment. China proposed the great and far-reaching goal of 'striving to achieve carbon peak before 2030 and carbon neutrality before 2060' at the 75th United Nations General Assembly, always adhering to the development concept of green environmental protection and ecological environment protection.

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Realizing the "dual carbon" goal is a major decision for China to address climate change and an important part of China's ecological civilization construction [1]. At the same time, in order to cope with the current harsh natural and ecological crises, the adoption of the Paris Agreement in 2015 set long-term and clear goals for in-depth research on CCS technology and changing the current environment. The 'carbon emissions gap' refers to the huge gap between the 'emission reductions committed by each country' and the 'emission reductions required to achieve the temperature control targets of the Paris Agreement'.Even if all countries fully fulfill their current commitments under the Paris Agreement, it will still result in a global warming of approximately 2.5℃to 2.9℃by the end of this century, far exceeding the 1.5 ℃ or 2 ℃ targets pursued by the Paris Agreement. Therefore, countries need to strengthen their control over carbon emissions and strictly prohibit crossing the carbon emission red line. In short, the global climate change crisis is becoming increasingly severe, and there is a huge and still widening "carbon emissions gap" between the current emission reduction commitments and practical actions of the international community and the safety temperature control targets set by the Paris Agreement. To bridge this gap, countries around the world must take urgent and strong emissions reduction actions before 2030, accelerate energy transition, otherwise the most catastrophic impacts of climate change will be unavoidable. Among numerous negative emission technologies, it should focus on Bioenergy with Carbon Capture and Storage (BECCS) because it can combine the dual functions of energy production and carbon removal, and its technical feasibility is higher compared to other negative emission technologies. However, its technology is not perfect either. Although BECCS has received much attention in terms of technical principles and models, its scale in practical applications is very small and progress is slow. Therefore, reducing its technical cost and scaling up its application is the top priority for the development of BECCS, and it is also the research direction of this article.

2. BECCS technology full process

The core of BECCS technology lies in the conversion of biomass and energy production, which is also the first step of BECCS technology. Whether there is sufficient biomass supply and utilization is the foundation of this technology.BECCS technology is a comprehensive technical system that integrates biomass energy utilization technology and carbon capture and storage technology, and its basic operating principle is similar to a carbon cycle process [2]. The first step is for plants to absorb carbon dioxide from the atmosphere through photosynthesis and convert it into organic matter (biomass), achieving the first carbon fixation in their bodies. The second step is for plants to convert their biomass into energy products through combustion, fermentation, gasification, and other methods. During the conversion process, CO_2, which is fixed during the growth of the biomass, is released. The third step is to use CCS technology to collect and transport biomass during the conversion process to stable geological structures for storage or conversion into other long-term biomass products. Due to the fact that these CO_2 come from the atmosphere, completely sequestering and converting this portion for reuse is equivalent to achieving negative emissions from biomass carbon capture and sequestration.

The initial stage of BECCS is the supply of raw materials for life, which includes the cultivation, collection, transportation, and processing of biomass. The supply of raw materials is crucial for this technology, as it affects social ecology, land occupation, and carbon reduction throughout the entire lifecycle [2]. The main raw materials include biomass energy crops, agricultural waste, household waste, etc [3]. The conversion of biomass and energy production in stage two are the technological core. The current mainstream methods are divided into two systems: thermochemical conversion and biochemical conversion [4]. The thermochemical conversion system covers combustion, which

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directly burns biomass to generate electricity and heat energy. Under oxygen-enriched conditions, the concentration of CO_2 released from biomass combustion is significantly increased, making it easier to collect. This technology is currently mature and well-established, and is one of the important methods combined with CCS [5]. And gasification converts biomass into synthetic gas that can be widely used for power generation and hydrogen production under anaerobic and high-temperature conditions. Biochemical conversion refers to the production of ethanol from biomass crops, which produces extremely high concentrations of CO_2 during the fermentation step. Significantly reducing the cost of capture and lowering economic consumption, it is clearly superior to other capture technologies and is currently one of the most widely used BECCS technologies [6]. The third stage is the capture and separation of CO_2, extracting CO_2 from the gas released during biomass conversion. The commonly used methods in this stage include chemical absorption, low-temperature distillation, physical adsorption, and membrane separation. At present, the chemical absorption method is the most mature technology widely used in industry and is the benchmark technology for carbon capture in coal-fired power plants. However, its disadvantages are high energy consumption and the production of corrosive substances that can affect the environment. The low-temperature distillation method can directly produce liquid CO_2, which is convenient for transportation and storage, and also avoids problems such as consumption and pollution. The disadvantage is that it has extremely high energy consumption, complex and expensive equipment, and is suitable for environments with high concentrations of CO_2. The advantages of the physical adsorption method are low energy consumption and non-corrosive issues, but the disadvantage is that it can also adsorb other gases in the air, reducing the adsorption rate of CO_2. It is suitable for areas with a moderate concentration of CO_2 and cheap electricity. The advantage of the membrane separation method is that the equipment is easy to operate and install, with good operational flexibility and no chemical reagent consumption. The disadvantage is that it has high energy consumption and high cost, and is suitable for environments with limited space and specific pressure conditions. Stage four is the storage and reuse of CO_2, compressing the captured CO_2 and transporting it to storage and utilization points through pipelines, ships, and other means. To ensure the implementation of negative emissions, the storage point must be deeply buried in the deep geological structure underground for long-term storage. Its sealing and safety must be ensured to eliminate the risk of omission, which is the key to achieving negative emissions. At the same time, the captured CO_2 can also be turned into chemical products, building materials, etc., to achieve the reuse of CO_2 capture.

3. The strategic value of BECCS

BECCS is not only about achieving the dual carbon goals, but also a global strategic competition for leadership in future energy, industry, and climate. As an indispensable negative emission technology for achieving carbon neutrality, this article analyzes it from three aspects: "essential needs", "multiple benefits", and "global competition".At present, the strategic role of BECCS technology in climate governance is irreplaceable. If countries want to achieve the temperature control goals of the Paris Agreement, in addition to controlling carbon emissions, they must actively remove CO_2 from the atmosphere. This study hoses BECCS because its core advantages lie in three features: firstly, burning biomass to generate electricity and heat, producing marketable products and generating income, thereby offsetting the high cost of carbon absorption. The CO_2 absorbed from the atmosphere during biomass growth is captured and stored after combustion, achieving 'net negative emissions'. This technology can rely on mature power generation, carbon capture, and oil and gas industry storage technology chains to reduce technical difficulty and risks. Therefore, BECCS is

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currently the most widely recognized and influential technology system, and also the most mature and clear path among all negative emission technologies [7]. According to the multiple temperature control path models of the Intergovernmental Panel on Climate Change, it can be found that many large-scale deployed BECCS technologies are essentially standard for achieving the 1.5 °C or 2 °C targets. It is set to bear more than 30% of the global annual CO_2 removal volume [8]. Therefore, BECCS is a necessary technology that it need to persist in developing for the long term. The value of this technology goes far beyond carbon removal. It is also a comprehensive technology that can simultaneously generate energy, economic, and social synergies. While achieving negative emissions, it can also bring us various benefits. In terms of energy and environmental benefits, biomass energy can play a role similar to fossil fuels, compensating for the intermittent shortage of energy sources such as electricity and wind power, and providing stable and dispatchable clean energy for stable grid security. Treating the CO_2 absorbed by biomass during growth through chemical and physical methods to capture the released CO_2 can also achieve a "negative carbon cycle" and synergistically treat agricultural and forestry residual waste; Addressing environmental issues and reducing environmental carrying pressure while generating synergistic benefits of energy, economy, and society; In terms of economic and industrial benefits, it can enrich and create new industrial chains and markets, reduce the total cost of emission reduction, and restore the vitality of existing infrastructure.

4. Reasons for the scale bottleneck

Even though there are already a large number of BECCS demonstration projects both domestically and internationally, there are many problems in expanding from "demonstration projects" to "project popularization". Technical and economic issues are the two fundamental reasons why BECCS is difficult to popularize.

Firstly, in terms of technology, the difficulty in technological development is due to the insufficient supply of biomass raw materials, which leads to equipment not working or operating for years, resulting in stagnant technological development. Factors such as unstable biomass supply, decentralized distribution of raw materials, and high collection and transportation costs are affecting the development of BECCS technology and project continuity. China is facing a shortage of land, with very little area reserved for biomass crop cultivation except for urban land, industrial land, and grain cultivation, which cannot guarantee a stable supply of biomass energy. Large scale cultivation of biomass crops may lead to controversies such as land disputes, excessive consumption of water resources, and impacts on biodiversity [9]. Secondly, biomass crops are also vulnerable to weather and climate. Extreme weather, such as rainstorms, drought, ice and snow, will affect the production and utilization of biomass crops, and the seasonal impact on biomass crops can not be ignored. For example, the straw harvest in autumn, which leads to no output in other seasons, and biomass supply is decentralized in time and space. Due to insufficient raw material supply, many BECCS projects have a utilization rate of less than 70% per year, and expensive equipment can only be idle, which not only increases the loss of manpower and material resources, but also cannot guarantee the carbon replenishment and work output. In addition to raw material supply, there is also the safety of carbon sequestration. Whether there is a risk of omission in long-term sequestration, pollution and damage to the environment, and other safety issues still need to be verified, requiring multi-level and multi-dimensional integrated testing and protection from all aspects [10].

Then, in terms of economic promotion, the current cost of the BECCS project is extremely high, and the benefits obtained from the project are far from keeping up with the previous investment. The main contradiction at the economic level of BECCS is that the investment returns are not

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proportional. The high cost and long return cycle have led to a lack of motivation and enthusiasm among enterprises to invest in BECCS projects. The business model is also not mature and perfect enough. Due to the lack of expansion and deepening of the project in today's national society, the pricing mechanism for carbon negative emissions in the carbon market is not clear and explicit, and the sources of revenue are relatively single, such as inconsistent methodology and accounting standards, the southern definition of "additionality" and "permanence", market segmentation and chaotic price signals.

5. Economic evaluation analysis

To objectively evaluate the technical and economic feasibility of BECCS, it is necessary to adopt a methodological system of empirical data and multidimensional analysis to ensure its scientific validity and credibility. The core evaluation tools used here are Cost Analysis (CBA) and Life Cycle Assessment (LCA). LCA calculates the full chain emissions from planting to sealing, using a dynamic model to distinguish between short-term storage and permanent storage, and discounting storage with reversal risks. The CBA nuclear economy incorporates long-term costs such as century long monitoring and leakage risks into present value calculations, and evaluates long-term climate benefits at a lower discount rate.CBA quantifies the return on investment of projects under different carbon prices and subsidy policies by constructing an integrated investment operation income model, such as simulating the profit equilibrium point when carbon prices rise to 100 yuan/ton and adding subsidies of 100 yuan/ton; LAC focuses on covering the entire process from biomass cultivation to transportation and energy utilization to carbon sequestration, by calculating the net carbon removal during the lifecycle to avoid false emissions reductions caused by carbon sequestration omissions [4]. In addition to cost-benefit and lifecycle analysis, cross-technology and cross-regional comparisons are also necessary to clarify the positioning and advantages of BECCS compared to other carbon sequestration technologies. Compared with direct air capture (BAC), its cost is greatly reduced and there is enormous potential for scalability. Compared with traditional CCUS, negative emission capacity is a core differentiation advantage and is more suitable for industries that are difficult to reduce emissions. By comparison, BECCS is currently the most competitive and promising emerging technology system in this field [11].

6. Conclusion

From the current development status and comprehensive evaluation, it can be seen that the technical route of BECCS has basically matured, and key demonstration projects at home and abroad have verified the negative emission capacity and environmental benefits of this technology. The main problems come from three aspects of large-scale promotion: firstly, insufficient biomass supply chain; Secondly, the cost of replenishment and storage technology is high; Thirdly, the business model and market in this field lack sustainability and still need to be developed and improved. To develop BECCS, it need to focus on technology research and development, and enhance the core internal driving force; Promote the large-scale production of new complementary materials such as Metal-Organic Frameworks (MOFs) at the material level, and reduce material costs by more than 40% through process optimization; At the supply chain level, it is necessary to establish a regional distribution hub network, promote biomass solidification and molding technology, facilitate biomass collection, and reduce transportation costs; Develop low-cost Internet of Things (IoT) monitoring systems at the monitoring level to reduce the cost of storage and monitoring.

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Based on the current speed of technological development and policy guidance in this field, BECCS will definitely receive attention and be widely applied in the future. With the rise of carbon prices and the maturity of technology, the project will eventually achieve market-oriented profitability, becoming the core supporting technology for decarbonization in industries that are difficult to reduce emissions. At the same time, it will also drive the development of green industries such as biomass processing, carbon detection, and environmental governance. The development of BECCS will rely on continuous technological innovation to reduce costs, as well as strong policy support and improved carbon market mechanisms to create commercial value .

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