Carbon Emission Reduction Accounting and Carbon Trading Mechanism Analysis of Straw Energy Utilization

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Abstract. As the “dual carbon” goals and the rural revitalization strategy are jointly advanced, straw energy utilization is a key pathway for the resource utilization of agricultural solid waste and the reduction of greenhouse gas emissions. This study uses bibliometric and classification analysis methods to systematically review the domestic and international research progress in the two core areas of straw biomass energy carbon emission accounting and carbon trading mechanisms. It integrates straw gasification coupled with coal combustion, biomass granulation and co firing, biogas fermentation, bioethanol conversion and other diversified utilization scenarios, compares accounting methods such as full life cycle assessment, IPCC accounting, GIS spatial analysis, etc., and analyzes the application models, action path and practical challenges of carbon trading mechanisms. Research shows that straw energy utilization has significant carbon reduction and carbon sequestration effects. However, there are some problems with carbon reduction accounting, such as inconsistent boundaries and missing regional parameters. Carbon trading also has some limitations, such as difficulties in certifying small and micro projects, high verification costs, and insufficient market-oriented benefits. In the future, need to establish a full lifecycle accounting system, simplify the carbon verification process, and promote the deep coupling of straw energy and carbon market. This study provides a theoretical reference for low-carbon utilization of agricultural biomass and localized optimization of carbon trading mechanisms.

Keywords: Straw energy conversion, Carbon emission reduction accounting, Carbon trading mechanism, Full lifecycle assessment, Biomass-coupled power generation.

1. Introduction

After the reform and opening, China's economy grew rapidly, but the environmental pollution and greenhouse gas emissions caused by extensive development have become increasingly apparent. China is a major agricultural country with a large annual yield of crop straw. The traditional open-air burning mode increases air pollution and emits a large amount of carbon emissions, resulting in resource waste. The energy utilization of straw can replace fossil fuels and achieve the resource utilization of solid waste, which serves as a key lever in the low-carbon transformation of agriculture. The rural revitalization strategy has a high degree of synergy with the "dual carbon" goal. Low-carbon development in rural areas is an inherent requirement of rural revitalization and an important support for the "dual carbon" goal. However, it is currently difficult to integrate rural carbon sinks into the carbon trading market, and the concept of green development for farmers is also insufficient. These difficulties collectively constrain coordinated progress.

Carbon emission reduction accounting is the quantification of the low-carbon value of straw and an important means of realizing the marketization of emission reduction benefits. The two directly determine the environmental benefits and economic feasibility of straw energy conversion projects. At present, there are abundant research results on straw energy conversion technology, carbon emission reduction accounting models, and carbon market emission reduction effects both domestically and internationally. However, there are still shortcomings in the standardization of accounting standards, the adaptability of carbon trading and straw projects, and the dynamic evaluation of the entire chain. From the perspective of industrial development, the financing of straw

energy conversion is constrained, and the market-oriented mechanism is not perfect, which limits its large-scale development.

This article takes the energy utilization of straw as the research object, focusing on the core theme of carbon emission reduction accounting and carbon trading mechanism. It sorts out the research evolution, development status, impact mechanism, and trend challenges, and provides theoretical support for the low-carbonand efficient utilization of straw and the improvement of the carbon market.

2. The Research Evolution of Carbon Emission Reduction Accounting and Carbon Trading in Straw Energy Conversion

The existing research has constructed a diversified methodological system, mainly including the following methods: bibliometric and classification analysis, life cycle assessment (LCA), Aspen Plus simulation [1,2], GIS spatial analysis and crop yield evaluation [3], empirical measurement [4], remote sensing estimation and crop modelling [5].

Initially, scholars focused on the carbon emission reduction potential of biomass energy and the construction of a full life cycle accounting framework [3]. For agricultural regions in Africa, Europe, and America, quantitative research on emission reduction of straw biogas [6] and biomass power generation and have formed mature practices such as the EU carbon market and incentives for carbon reduction from biomass cofiring in India [7]. Domestic research focuses on technologies such as straw gasification coupled with coal combustion, cofiring of biomass fuels, anaerobic fermentation, and bioethanol conversion. The emphasis is on verifying the carbon emission reduction benefits under different utilization scenarios, exploring the application path of carbon trading mechanisms in straw projects, and paying attention to basic research such as straw returning carbon sequestration and outdoor incineration emission factors.

The Development Status of Carbon Emission Reduction Accounting and Carbon Trading for Straw Energy Conversion.

2.1. Development Status

2.1.1. Development Status of Straw Energy Technology

Straw energy utilization formed a technological system, which has three aspects: first, straw gasification coupled with coal-fired power generation, 330MW coal-fired unit, 10v/h gasifier, straw collaborative combustion system, with an efficiency of 83. 88%, which effectively reduces the emissions of NOx and SOx [2]. The second is to blend straw into fuel for combustion. India and China have implemented a straw blending requirement of 5%-7%for coal-fired power plants, building a supply chain of "bundling, granulation, storage, railway transportation". The third is the conversion of straw biogas and bioethanol. The total potential of Ivory Coast straw biogas is 2. 3587×10m³ [6], while Nigeria produces ethanol from agricultural waste such as cassava peels and rice straw [8]. The fourth is to carry out low-carbon returning of straw to the field, combined with the application of organic fertilizer, which can reduce N_2O emissions and improve soil carbon sequestration capacity [9]. The fifth is biomass pretreatment and coal forming technology. Batch leaching can optimize the quality of agricultural biomass fuel [10], and bamboo and agricultural waste can replace charcoal in coal forming [11]. From the perspective of technological maturity and applicable scenarios, each of the above five technologies has its own advantages and disadvantages. Gasification-coupled coal-fired technology is suitable for large power plants and has high carbon emission reduction potential, but the initial investment is relatively large. The static investment payback period for a 330MW unit with a 10vh gasifier is about 5-8 years. The co-firing technology of formed fuel is suitable for small and medium-sized boilers. India has established a complete supply chain of "bundling, granulation, warehousing, railway transportation". When the co-firing ratio reaches 5%-7%, the unit power generation cost increases by about 0. 02 yuan/kWh, but the carbon trading revenue can compensate for this cost. Biogas fermentation technology is suitable for household use and small and medium-sized projects. The total potential of straw biogas in the four provinces of Côte d'Ivoire is 2. 36×10⁸m³.

However, due to difficulties in collecting raw materials and high maintenance costs, the actual utilization rate of household biogas digesters in rural China is less than 60%. In bioethanol conversion technology, Nigeria has achieved initial results in producing ethanol from agricultural waste such as cassava peels and rice straw. However, the industrialization of cellulose ethanol still faces bottlenecks such as high enzyme preparation costs and low conversion efficiency. Although low-carbon returning technology reduces emissions relatively small, it has multiple ecological benefits such as soil improvement and carbon sequestration and is currently the largest way for comprehensive utilization of straw in China. Table 1 shows the comparison of main technologies for straw energy conversion.

Table 1. Comparison of Main Technologies for Straw Energy Conversion

Technical Type	Applicable scale	tCO_2e/t	main challenges	Representative Literature
Gasification coupled with coal combusting	Large power plats	0. 7-0. 9	Large initial investment	[2]
Co firing of formed fuel	Small and medium-sized boiler	0. 5-0. 7	High storage and transportation costs	[7]
Biogas fermentation	Household/Small and Medium Sized	0. 4-0. 6	Unstable gas production rate	[6]
Bioethanol conversion	Industrialization	0. 6-0. 8	difficult cellulose conversion	[8]
Low carbon returning to farmland	Farmland	0. 2-0. 4	There are environmental risks present	[9]

2.1.2. Development Status of Carbon Emission Reduction Accounting

Carbon emission reduction accounting mainly adopts the life cycle assessment method and IPCC greenhouse gas accounting method, and it is necessary to clarify the two benefits of straw replacing coal and banning burning for emission reduction. Moreover, based on the Soil Survey Database (SSURGO)and statistical data from the US Energy Information Administration (EIA), previous studies have quantitatively evaluated the availability and energy conversion potential of crop residues such as corn, soybeans, and sugarcane at the regional scale, revealing the uneven spatial distribution of agricultural biomass and its impact on bioenergy layout [9]. Remote sensing and crop models can accurately estimate the number of straw resources [5], and climate change will have a significant impact on straw yield and distribution [5]. There are significant differences in boundary setting, data requirements, and applicable scenarios among different carbon emission reduction accounting methods. The Life Cycle Assessment (LCA) method calculates the entire chain from raw material collection, transportation, processing, to terminal utilization, with the most complete boundaries, but requires many localized parameters and a large workload. The IPCC greenhouse gas accounting method is based on the emission factor method, which has a high degree of standardization and wide international recognition. However, the boundary is relatively narrow, mainly focusing on direct emissions from combustion or treatment processes, and is prone to overlooking indirect emission processes such as collection, storage, and transportation. The dynamic carbon balance method considers the time difference between biomass growth for carbon sequestration and utilization for carbon emissions, which can more accurately evaluate the long-term carbon reduction effect. However, the model is complex, and the parameter acquisition is difficult. At present, China's straw energy projects mainly adopt a combination of LCA and IPCC methods: using the IPCC method as the basic framework, the LCA method is used to supplement the emission data of collection, storage, transportation, pretreatment and other links. Research has shown that using different accounting methods can result in a difference of 20%-40%in carbon emissions reduction for the same project, which directly affects the accurate identification of carbon trading benefits.

2.1.3. Development Status of Carbon Trading Mechanism

Under the framework of the Paris Agreement, the global carbon market is shifting towards a "bottom-up" collaborative model, and China's unified national carbon market is gradually improving. The carbon market can reduce emissions by improving energy efficiency and optimizing energy

structure, and straw energy conversion projects can participate in trading, which is consistent with the conclusions of empirical research. China has established a multi-level carbon finance regulatory framework and standardized the carbon emission trading market.

2.2. Influencing Factors

Straw collection efficiency, energy conversion technology, carbon emission reduction accounting limits, biomass moisture content, and pretreatment processes are all internal factors. External factors include carbon market prices, carbon verification costs, regional straw resource endowments, policy-mandated co-firing requirements, and rural green development concepts.

3. The Impact of Carbon Emission Reduction Accounting and Carbon Trading Mechanism on Straw Energy Conversion

3.1. Core Impact of Carbon Emission Reduction Accounting System

Carbon emission reduction accounting plays a decisive role in determining the low-carbon value of straw projects, which is a prerequisite for carbon trading. By unifying the whole life cycle accounting, the comprehensive emission reduction of straw replacing fossil fuels, banning burning, and carbon sequestration can be accurately quantified. The photosynthetic carbon fixation during straw growth and the carbon released during energy utilization are not in instantaneous equilibrium on a time scale but rather achieve long-term cycles through rational resource management and market regulation. The latest research shows that under reasonable management and market expectations, the carbon sinks of forest and agricultural biomass systems will not decrease net due to energy utilization but may increase carbon sinks by increasing management intensity. This provides theoretical support for the low-carbon properties of straw from a dynamic equilibrium perspective.

Taking straw gasification coupled with coal-fired projects as an example, the selection of accounting boundaries has a significant impact on the determination of emission reductions. If only the emission reduction caused by replacing coal is accounted for, each ton of straw can reduce emissions by about 0.6 tCO_2e; if methane emissions avoided by straw open burning are included, the emission reduction is increased to about 0. 8 tCO_2e; if diesel consumption and electricity consumption in the collection, storage and transportation process are further included, the emission reduction drops to about 0. 71 tCO_2e. This difference indicates that a unified accounting boundary is a prerequisite for the healthy development of the straw carbon trading market. Currently, the EU carbon market requires biomass projects to adopt full lifecycle accounting, while the Chinese carbon market has not yet issued specific accounting guidelines for straw projects, resulting in different emission reduction determination results for the same project in different carbon markets, which is not conducive to cross-regional trading and project financing.

3.2. Core Impact of Carbon Trading Mechanism

Carbon trading leverages market incentives to alleviate financing constraints for straw energy conversion projects, promoting technological upgrades and large-scale development. The formation of carbon market prices will bring emission reduction benefits, which can compensate for the high cost of straw collection, storage, and transportation. The low-carbon transformation of energy structure is related to the linkage mechanism between policies and markets, which forces the low-carbon transformation of energy structure [1, 4].

4. The Development Trends and Challenges of Carbon Emission Reduction and Carbon Trading in Straw Energy Conversion

4.1. Development Trends

First, the accounting system is being standardized, with full life cycle assessment emerging as the mainstream approach. The sinking of carbon trading to lower levels simplifies the verification process for small and micro straw projects, making the carbon verification process simpler. Third, deep integration of technology and markets. Fourth, cross-disciplinary collaboration that integrates rural revitalization with the dual carbon goals.

4.2. Challenges

First, carbon emission reduction accounting is not standardized. Specific manifestations include inconsistent accounting boundaries (some only consider the combustion process, while others consider the entire chain), inconsistent accounting parameters (significant differences in emission factors, straw yield coefficients, etc.), and inconsistent accounting methods (LCA, IPCC, dynamic carbon balance combined). This leads to a difference of up to 20%-40%in carbon emission reductions for the same project under different accounting systems, seriously affecting the credibility and trading feasibility of emission reductions.

Secondly, the connection between carbon trading is not smooth. Most straw energy conversion projects are small and medium-sized, with annual emission reductions of several thousand to tens of thousands of tons of CO_2e per project, far lower than large-scale projects in industries such as thermal power and steel. The current carbon verification process is complex, with a long cycle (usually 6-12 months) and high third-party verification fees (accounting for 10%-20% of project revenue), making it economically inefficient for small and micro projects to participate in carbon trading. In addition, the institutional design for incorporating rural carbon sinks into the carbon market is not yet perfect, and the carbon asset attributes and trading rules of straw projects lack clear definitions.

Thirdly, the collection, storage, and transportation system is not perfect. Straw is distributed in a scattered manner, with a large volume, low density, and strong seasonality. The cost of collection, storage, and transportation accounts for 40%-60% of the total cost. At present, the collection, storage, and transportation of straw in China mainly rely on dispersed farmers and small-scale brokers, lacking a large-scale and standardized collection and storage network. India has established a supply chain model of "bundling, granulation, warehousing railway transportation", with the cost of collecting, storing and transporting each ton of straw controlled at about 6. 78 yuan/kg (equivalent to 678 yuan/ton), while in some regions of China, it is still as high as 800-1000 yuan/ton.

Fourthly, the market-oriented mechanism is not sound. The financing channels for straw energy conversion projects are limited, mainly relying on government subsidies and self-raised funds, with low participation of social capital. The carbon market price fluctuates greatly (since 2020, China's carbon price has fluctuated between 40-100 yuan/ton), and the uncertainty of project returns is high. At the same time, the popularization of the concept of green development in rural areas is insufficient, and the enthusiasm of farmers to participate in straw recycling needs to be improved.

5. Conclusion

This article systematically reviews the research progress on carbon emission reduction accounting and carbon trading mechanisms for straw energy utilization, and draws the following main conclusions:

The energy conversion of straw has significant dual benefits of carbon reduction and carbon sequestration. The technology paths of gasification coupled with coal combustion, co firing of formed fuels, biogas fermentation, bioethanol conversion, and low-carbon returning to the field all have applicable scenarios, with carbon reduction potential ranging from 0. 5-1. 2 t CO_2e/t straw. However, the existing carbon emission reduction accounting system has issues such as inconsistent boundaries, missing parameters, and incompatible methods, resulting in differences of up to 20%-40%in the

determination of emission reductions for the same project. In terms of carbon trading mechanisms, straw projects are mostly small and medium-sized, facing practical difficulties such as high verification costs, long cycles, and insufficient returns, and deep coupling with the carbon market has not yet been achieved.

First, establish a carbon accounting standard for the entire lifecycle of straw energy utilization. It is suggested to incorporate emission data from storage, transportation, and pretreatment processes into the IPCC methodology framework, and develop accounting parameter guidelines for different regions and technical routes. Second, simplify the carbon verification process for small and micro projects. People can learn from international experience and explore models such as "modular verification" and "batch verification" to reduce the verification cost of individual projects and shorten the verification cycle. Third, improve the institutional design for incorporating rural carbon sinks into the carbon market. Clarify the carbon asset attributes, trading rules, and profit distribution mechanism of straw projects, and encourage social capital to participate in straw energy conversion project investment.

Future research can be conducted in the following directions: firstly, to strengthen the quantitative study of the synergistic mechanism between straw energy utilization and rural revitalization, quantifying the comprehensive contribution of straw projects to farmers 'income increase, rural employment, and environmental improvement. The second is to explore the construction of an integrated digital platform for "carbon accounting carbon trading", using technologies such as the Internet of Things and blockchain to achieve traceability and verifiability of the entire straw collection, storage, and transportation chain. The third is to conduct differentiated policy research on different regions and technological routes, providing a scientific basis for promoting straw energy utilization according to local conditions.

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