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Current Status and Future Prospects of Biomass Power Generation

Zhengyang Dai

School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai, China

2135051609@st.usst.edu.cn

Abstract. The global energy crisis and the intensifying pressure of climate change have driven the accelerated development of renewable energy. Biomass energy, due to its unique carbon cycle characteristics and the value of waste resource utilization, is regarded as an important path to achieving carbon peaking and carbon neutrality. This article systematically analyzes the core technology types, industrial status quo, and future development directions of biomass power generation. Starting from the three mainstream technical paths of direct combustion, gasification, and anaerobic fermentation, a comparative assessment was conducted on the adaptability of different raw materials, cost per kilowatt-hour, and carbon reduction potential, revealing the application scenarios and economic performance differences of each technology. Based on typical cases from regions such as the European Union, North America, and Japan, this paper sorts out the global diversified development models and policy mechanisms, and points out the bottlenecks existing in China's industries in terms of raw material purchase and storage systems, the continuous stability of technical equipment, and the implementation of subsidy policies. This paper proposes to achieve efficiency improvement and negative carbonization breakthroughs through technologies such as supercritical CO_2 cycles, gene-edited methanogens, plasma gasification, and BECCS, explore a multi-product synergy model of "power generation + heating/organic fertilizer/bio-based materials", and construct a policy system that links green certificates, carbon sinks, and financial tools. Biomass power generation will play a strategic supporting role in optimizing the energy structure, promoting rural revitalization, and transforming the green economy.

Keywords: Biomass Power Generation, Techno-Economic Analysis, Carbon Reduction, Policy Synergy

1. Introduction

The global energy crisis and climate governance are accelerating the development of renewable energy. Biomass energy, with its carbon cycle characteristics and the advantage of waste resource utilization, has become an important support for energy transition. As the core form of biomass energy utilization, biomass power generation achieves the synergy of "solid waste-energy" through multiple conversion technologies, demonstrating unique value in distributed power supply and the

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rural energy revolution. Although the current industry is developing rapidly, it is still constrained by key bottlenecks such as technical and economic viability, raw material purchase and storage systems, and policy mechanisms.

This article conducts a multi-dimensional assessment of the global biomass power generation technology paths and business models, and combines typical regional case studies to systematically analyze the technical and economic aspects of each link in the industrial chain. It aims to propose targeted development strategies to provide decision-making references for optimizing the energy structure and achieving the resource utilization of waste.

2. Core technology types of biomass power generation

2.1. Direct combustion power generation

Direct combustion power generation is an effective technology for utilizing agricultural and forestry waste, mainly through layer-fired furnaces or fluidized bed boilers for combustion to achieve energy conversion. The advantage of this technology lies in its ability to convert waste into electricity while reducing the environmental burden [1]. In practical applications, the pretreatment of fuel is crucial. It is necessary to reduce its particle size to less than 5 cm to ensure the completeness and efficiency of combustion. Maintaining a combustion temperature of 800–1000°C helps suppress the formation of harmful substances, thereby improving environmental performance [2].

China's biomass direct combustion power generation technology started relatively late. In 2006, Shandan County in Shandong Province introduced a 130 t/h water-cooled vibrating high-temperature high-pressure grate furnace from BWE, establishing China's first biomass direct combustion power generation demonstration project [3]. China's biomass direct combustion power generation technology has developed rapidly, and in recent years, the growth rate of domestic biomass installed capacity and power generation in China has been significantly higher than the global average [1].

However, the system's thermal efficiency is relatively low, mainly limited by the main steam pressure, which is somewhat inferior compared to ultra-supercritical coal power. In addition, the seasonal fluctuations of the raw materials affect the boiler's load rate. In terms of emissions, the concentration of nitrogen oxides exceeds 200 mg/m³, so a denitrification device must be installed, which also increases operation and maintenance costs [4]. These factors need to be addressed in future technological improvements and optimizations to enhance overall economic and environmental performance.

2.2. Gasification power generation

Biomass gasification refers to the thermochemical process in which biomass is converted into combustible gases such as CO, H2, CH4, and low-molecular hydrocarbons under high temperature and limited oxygen conditions with the action of a gasifying agent. It mainly involves four stages: drying, pyrolysis, oxidation, and reduction [5]. The Datang Changshan Thermal Power Plant coal-fired biomass gasification power generation project has been put into operation, with an equivalent power generation capacity of 20 megawatts, surpassing the 12.5 megawatts of the coal-fired biomass gasification furnace at Guodian Jingmen Power Plant, becoming China's first national-level demonstration project [6]. The plant is located in the center of the Northeast commercial grain base. The biomass fuel mainly consists of agricultural residues such as corn stalks, and the surrounding resources are abundant. The project can utilize 91,200 tons of biomass fuel annually. After the coal-

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fired coupled biomass gasification power generation technology retrofit project is completed and put into operation, it will effectively alleviate the air pollution caused by the open burning of straw in the local area. Compared with the same quality of straw burned openly, the project can reduce annual emissions by approximately 3,018 tons of particulate matter, 65 tons of sulfur dioxide, and 302 tons of nitrogen oxides. The annual power generation is expected to reach 114 million kilowatt-hours, which helps reduce coal consumption. The project relies on the high-efficiency and environmentally friendly facilities of the coal-fired power plant to achieve ultra-low emission standards. Compared with traditional direct biomass combustion power generation, this not only saves about 40% of construction costs but also increases the biomass power generation efficiency by more than 10%, achieving low-cost and harmless efficient utilization of biomass resources such as straw.

2.3. Anaerobic fermentation power generation (biogas power generation)

Biogas is a mixed gas produced by various microorganisms under anaerobic conditions through the decomposition and transformation of organic matter. Its main components are methane and carbon dioxide, with small amounts of impurities such as hydrogen sulfide and ammonia. Taking straw as an example, in an anaerobic fermentation tank, the macromolecular organic matter in straw, such as cellulose and hemicellulose, is first hydrolyzed into small molecular sugars by enzymes secreted by microorganisms, and then further fermented to produce biogas. This process requires suitable conditions such as appropriate temperature, pH, and anaerobic environment. In general, when the temperature is between 35-55°C and the pH is around 6.8-7.5, the gas production efficiency is higher [7].

The project in Taizhou City, Zhejiang Province, adopts anaerobic power generation from straw [8]. Given the local population size of 33,544 and the average annual electricity consumption per capita of 761 kilowatt-hours, it is estimated that the total annual electricity consumption of local households is approximately 25.5 gigawatt-hours. The total annual power generation from biogas in this area is approximately 2.9 gigawatt-hours, and the biogas power generation accounts for about 11% of the local household electricity demand. This data indicates that although biogas is an important renewable energy source, it still needs to be supplemented by other energy sources to meet all local demands [9].

2.4. Comparison of various power generation methods

Table 1 compares the parameter items of three types of biomass power generation technologies in China, including the moisture content of raw materials, cost per kilowatt-hour, annual operating hours, and carbon reduction potential.

Table 1. Technical performance of biomass power generation in China

Indicator	Direct Combustion Power Generation	Gasification Power Generation	Anaerobic Fermentation Power Generation
Applicable Raw Material Moisture Content	<50%	<20%	>60%
Cost per kWh (CNY/kWh)	0.45-0.55	0.50-0.65	0.60-0.75
Annual Operating Hours	6500-7500	5500-6500	7500-8500
Carbon Reduction Potential	Medium	Relatively High	High

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In terms of raw material distribution, areas rich in straw resources, due to their small raw material transportation radius and low cost, are suitable for giving priority to direct combustion technology. This technology has strong adaptability to the treatment of dispersed raw materials, can reduce transportation costs, and improve energy conversion efficiency. High-concentration organic waste generated in areas with concentrated livestock and poultry breeding (such as livestock and poultry manure, sewage, etc.) is more suitable for anaerobic fermentation technology, which can efficiently utilize high-concentration organic substrates and achieve the synergy of waste reduction and energy utilization [10].

In terms of peak shaving demands in the power grid, gasification power generation technology has a significant advantage in response time. By optimizing the dynamic control strategy of the gas production-power generation system, it can control the response time from start-up to stable power output within 15 minutes, which is much lower than that of traditional biomass power generation technology. It can quickly match the fluctuations in power grid load and enhance the flexibility of peak shaving.

Given the sensitivity of subsidy policies, anaerobic fermentation projects, due to their high initial investment and long payback period, are highly dependent on policy subsidies. After subsidies are reduced or cancelled, their cost advantages significantly decline, and their market risk resistance capacity is relatively weak. In contrast, direct combustion or gasification power generation projects, due to their high technological maturity and controllable operating costs, still have strong market adaptability in scenarios with no or low subsidies [11].

3. Current status of biomass power generation applications

3.1. Diversified technological pathways and differentiation of progress in various countries

The EU biomass energy system has formed a model driven jointly by policy, technology, and market. Among them, forestry resources occupy a dominant position in the energy structure. Take Sweden as an example. Biomass power generation accounts for approximately 35% of the country's renewable energy. The Vartan thermal power plant in Stockholm has achieved 100% biomass energy supply, with an installed capacity of 215 MW and an annual heat supply of about 750 GWh [12]. The strengthening of the EU's carbon pricing mechanism has effectively promoted the growth of the biomass fuel market. The carbon price of the European Union Emissions Trading System (EU ETS) has exceeded 90 euros per ton in recent years, stimulating an annual growth of approximately 15% in the demand for wood pellet fuel, with consumption reaching 23 million tons by 2023. Technology export plays a key role in the internationalization of the biomass industry in the European Union. The global market share of BWE's straw direct-fired boilers from Denmark exceeds 40%, and their thermal efficiency can reach 38%, demonstrating the competitive edge of the European Union in the field of clean combustion technology.

The development of biomass energy in North America relies on abundant agricultural and forestry raw materials and is supported by fuel substitution policies. The U.S. Renewable Fuel Standard (RFS II) requires that by 2025, the total blending volume of biomass fuels reach 36 billion gallons. This policy has driven the expansion of corn stover power generation projects, with the related installed capacity expected to increase to 8.5 GW [13]. At the same time, advances in co-firing technology have become an important means of reducing carbon emissions from power generation. The four 660 MW units at the Drax power plant have been converted to co-fire biomass pellets with coal dust, with a blending ratio of up to 70%, reducing the carbon emissions per megawatt-hour to 0.16 tons of CO_2/MWh.

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The development of biomass energy in Japan focuses on refined and regional applications. Some cities have established biomass demonstration towns, improving energy self-sufficiency through a microgrid model of 'biogas from kitchen waste and combined heat and power from forestry residues,' with an energy self-sufficiency rate of about 65% [14]. Japan is actively promoting the high-value-added utilization of biomass. For instance, the production cost of lignin-based carbon fiber has dropped to approximately 15 US dollars per kilogram, a 40% reduction compared to traditional processes, significantly enhancing the competitiveness of the industry.

Overall, the world's major economies have formed diversified technical routes and policy systems in the development of biomass energy, each focusing on different resource endowments and market paths. Driven by sustainable policy mechanisms and carbon pricing systems, the European Union has built a relatively complete biomass energy ecosystem and strengthened its international influence through technology export. In North America, relying on agricultural resources and fuel substitution policies, both large-scale and market-oriented growth have been achieved simultaneously, and significant breakthroughs have been made in co-combustion technology. Japan's approach places greater emphasis on refinement and regional adaptation, promoting the organic integration of biomass energy and urban energy systems, and expanding the application space of high-value-added materials. The development of global biomass energy technology is showing a trend of "policy guidance - technological innovation - market expansion". Countries are jointly promoting the low-carbonization of the energy structure and the transformation of the green economy through diversified technical routes, and will play an increasingly important supporting role in the future global energy system.

3.2. The unbalanced development driven by current policies in China

Table 2 summarizes the proportion of biomass installed capacity and core constraints in various regions of China, revealing the structural imbalance caused by the lag in regional raw material density and policy implementation.

Table 2. Structural contradictions in regional imbalances in China

Region	Installed capacity share	Core constraints	Typical project
East China	45%	Raw material procurement radius >100 km	50MW Rice Husk Direct Combustion Power Plant in Yancheng, Jiangsu
Northeast China	25%	Fermentation efficiency drops by 30% in winter	Jilin Songyuan Livestock and Poultry Manure Biogas Project
Northwest China	<5%	Raw material density < 0.3 t/km²	Ningxia Zhongwei 10MW Shrub Gasification Demonstration Plant

In the current entire industrial chain of biomass power generation, there are significant constraints in the three links of raw materials, technology, and market [15]. In terms of raw materials, the mechanization rate of crop straw collection is only about 35%. Due to the widespread adoption of the multi-level supply model of "farmers - brokers - power plants", the transportation and intermediate link costs have significantly increased, raising the average procurement cost of the receiving plants by approximately 80 to 120 yuan per ton. In terms of technical aspects, the continuous stable operation time of some gasifiers is less than 4,000 hours, which is only about 60% of the designed operation time. Frequent equipment maintenance has led to a decrease in capacity utilization. In addition, the catalyst system still lacks high-temperature resistance and carbon fouling

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resistance, and some enterprises need to replace catalysts as often as twice a year, significantly increasing maintenance costs. In the market segment, delays in the issuance of national renewable energy subsidies pose risks of cash flow tightening or disruption for biomass power generation enterprises. At the same time, the trading volume of green power certificates remains limited, accounting for less than 1% of the current biomass power generation, restricting the market-based realization of carbon value.

4. The future development prospects of biomass power generation

4.1. Directions for technological breakthroughs

Table 3 lists the key breakthrough parameters and commercialization timelines for various efficiency-enhancing and carbon-reducing technologies, reflecting the potential development paths of biomass power generation technology in China.

Table 3. Synergistic carbon reduction technologies

Technical direction	Core breakthrough point	Performance Improvement Goals	Commercializatio n timeline
Supercritical CO_2 circulation system	Working fluid parameter optimization (31.1℃/7.38MPa)	Thermal efficiency 45%	2026 Demonstration
Gene-edited methanogens	CRISPR-Cas9 modifies Methanothrix strains	Biogas production 50%	Pilot test in 2025
Plasma gasification	Arc temperature >5000℃ achieves complete tar cracking	The calorific value of syngas is 18 MJ/m³	Application in 2027
BECCS (Bioenergy with Carbon Capture and Storage)	Coupled amine absorption (capture rate >95%)	Negative carbon intensity -0.5 tCO_2/MWh	Promotion in 2030

Typical Cases

Supercritical CO_2 Cycle Validation Project, Shanghai Electric commissioned a 1MW test unit in Jiangsu, with the main steam pressure increased to 25 MPa and a thermal efficiency of 42.3% (an improvement of 12 percentage points compared to traditional steam cycles) [16]. In the application of synthetic biology, a team from the Chinese Academy of Sciences enhanced the hydrogenase activity of methanogens through gene editing, increasing the gas production of a biogas project in Heilongjiang from 0.8 m³/ton of manure to 1.2 m³.

4.2. Industrial integration potential

Table 4 quantifies the economic and carbon reduction benefits of the 'power generation plus heat supply/organic fertilizer/biobased materials' multi-product mode, providing fundamental data for policy frameworks and business model design.

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Table 4. Quantitative analysis of the synergistic effect of 'power generation+X'

Combined production model	Economic gains	Carbon emission reduction contribution	Typical project indicators
Power generation + heating	LCOE decreases by 0.10 yuan/kWh	Reduce emissions by 35% by replacing coal-fired boilers	The Henan Nanyang project supplies 120 TJ/year of heating
Power generation + Organic fertilizer	By-product revenue 15%	Replacing chemical fertilizers with swamp residue reduces emissions by 0.8 tCO_2e per ton.	Shouguang, Shandong, 100,000 tons/year organic fertilizer factory
Power generation + bio-based materials	Product added value increased by 300%	Lignin-based plastics reduce emissions by 1.2 tCO_2e per ton	Zhejiang Ningbo 50,000-ton PLA production line per year

Table 5 presents the implementation models and economic benefit indicators of integrating biomass power generation with rural revitalization, focusing on the comprehensive benefit forecasts of distributed power stations, cooperatives, and smart agricultural grid coupling.

Table 5. Forecast of China's biomass cogeneration market size

Indicator	2025 (forecast)	2030 (forecast)	Core driving factors
Power generation market size	80 billion yuan	120 billion yuan	Supercritical unit penetration rate >30%
Heating market size	30 billion yuan	60 billion yuan	County-level clean heating policies cover 80% of prefecture-level cities.
Organic fertilizer market size	15 billion yuan	40 billion yuan	Fertilizer zero-growth initiative drives demand CAGR of 21.6%
CCUS derivative market	5 billion yuan	20 billion yuan	The maturity of BECCS technology is improving, with carbon prices exceeding 100 yuan per ton.
Total market size	130 billion yuan	240 billion yuan	The cogeneration synergy coefficient has increased from 1.2 to 1.8.

4.3. Policy and market coordination

In terms of carbon trading empowerment pathways, considering the impact of inclusion in the national carbon market, with a carbon price of 60 yuan/ton, a 30MW biomass power plant could see an annual revenue increase of 4.8-6 million yuan (corresponding to an IRR increase of 2.3-2.8 percentage points) [17]; with green certificate-carbon sink linkage, a "Biomass Power Generation Green Equity Package" (including green certificates and carbon sinks) could achieve a premium of up to 0.18 yuan/kWh (25% higher than the benchmark electricity price). Regarding the upgrade of the policy toolbox, fiscal tools are shifting from "fixed electricity price subsidies" to "contract-for-difference capacity incentives," providing an additional subsidy of 0.05 yuan/kWh for combined heat and power projects; financial innovation pilots include biomass REITs (with 50 high-quality projects as underlying assets), with an expected yield of 6.5-7.2%; standard system development includes the "Biomass Multi-Production Project Carbon Emission Reduction Accounting Standards," clarifying the rules for updating the CCER methodology.

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5. Conclusion

Biomass power generation, as a renewable energy technology that integrates energy supply, carbon reduction, and waste resource utilization, holds strategic significance in the global energy transition. At present, the global industry is dominated by direct combustion, supplemented by the coordinated development of gasification and anaerobic fermentation. The European Union, North America, and Japan have formed differentiated paths through carbon pricing, resource optimization, and regional refined application. Although China leads in installed capacity, it is confronted with challenges such as insufficient technical and economic efficiency, unstable raw material supply chains, and regional imbalances. For instance, the raw material acquisition radius in East China exceeds 100 kilometers, and the raw material density in Northwest China is less than 0.3 tons per square kilometer, among other structural contradictions.

Technological breakthroughs are the core driving force. Supercritical CO_2 cycles and genetically edited methane-producing microbes can increase thermal efficiency to over 45%. The commercialization of BECCS technology will achieve the goal of negative carbon power generation. In industrial integration, the multi-output model of "power generation, heating, organic fertilizer, and materials" is expected to reach a market size of 240 billion yuan by 2030. Village-level power plants and straw cooperatives can reduce costs by 30%, promoting rural revitalization. Policies need to integrate the carbon market, green certificate trading, and financial instruments, reduce subsidy dependence through contracts for difference, pilot REITs to activate capital, and build a cross-regional coordination network to mitigate imbalances in installed capacity.

The negative carbon attributes of biomass power generation and its economic empowerment effects in rural areas will accelerate its transition from a supplementary energy source to a primary one, providing key support for global carbon neutrality and becoming a core pathway for the coordinated development of climate crisis response and energy security.

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