Optimization Study on the Comprehensive Benefits of Straw Biogas Power Plants Participating in Electricity-Carbon Coupled Trading Based on Dual-Carbon Background

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Abstract. With the goal of "carbon peaking and carbon neutrality", China has accelerated the development of biomass energy, and straw biogas power generation, as a clean energy technology for converting agricultural waste, which has significant environmental and economic value. As a new energy generation enterprise, straw biogas power generation enterprises can gain profits from both the electricity market and the carbon market at the same time. This paper establishes a model for maximizing the daily operating revenue of straw power plant participating in the coupled electricity-carbon trading market by considering the revenue, cost, and relevant constraints of the power plant, then applies the model to practical cases to obtain the maximum daily operating revenue of the power plant of 90.16 yuan, and finally conducts a sensitivity analysis of the results to draw the relevant conclusions about the optimization of the economic benefits of straw biogas power plant.

Keywords: Straw biogas power plant coupled electricity-carbon trading, optimization modeling, sensitivity analysis.

1. Introduction

Global climate change and environmental degradation pose major challenges to the world today. As human activities continue to exert a growing influence on the environment, governments and international organizations are vigorously pursuing viable solutions to curb greenhouse gas emissions and foster sustainable development. In light of these circumstances, the advancement of clean energy and the drive for energy structure transformation have garnered widespread support on a global scale. Under the guidance of the national strategic goal of "carbon peak and carbon neutrality," China is ramping up the revolution in energy production and consumption while actively developing renewable energy sources. Among these, straw in biomass energy stands out as an important natural resource with vast development prospects. As a by-product of agricultural production, straw is generated in massive quantities annually, yet it has not been fully harnessed for a long time. This not only leads to resource wastage but also contributes to environmental pollution problems. Biogas power generation from straw, as a technology to convert agricultural waste into clean energy, holds significant economic value and environmental importance. It can effectively mitigate environmental pollution and offer a new energy supply. At present, more than 70% of straw biogas power plants are in a state of loss, so it is essential to study the optimization of economic benefits of straw biogas power plants, not only to ensure the sustainable development of the biomass power generation industry but also to provide help for China's energy transformation process.

At present, scholars have conducted a rigorous academic discussion on the operational benefit optimization of straw biogas power plants under the background of carbon emission reduction. Chen Jinpeng[1] built a low-carbon and economical IES optimization scheduling model by considering the demand response model of the electric-gas-heat load side as a whole. Ma Guojie[2] made a feasibility analysis of three technologies for biogas power generation based on the life cycle assessment method and the time value dynamic analysis method, assessed the environmental and economic characteristics of the three power generation technologies. Based on the integration of LCA and LCC methods, Wang Keyi and Wang Huogen[3] obtained the comprehensive cost calculation data set under the whole life cycle of biogas power generation. Ma Yue [4] made a comprehensive analysis of the effectiveness of China's carbon market by using F-test, runs up and down test and Rescaled Range Analysis. Zhang Wenyu [5] built a low-carbon joint trading optimization strategy based on the carbon trading mechanism. Ding Yuhao [6] established a day-ahead optimal scheduling model of integrated energy systems with the goal of lowest economic cost and minimum carbon emission, and compared and analyzed the optimal scheduling results of different scenarios. At present, there have been a lot of studies on the benefit optimization of biogas power plants under the background of "dual carbon", but there are few thoughts about the operation benefit optimization of biogas power plants participating in the power market and carbon trading market at the same time. Therefore, it is necessary to build a model to study the optimization of comprehensive benefits of straw biogas participating in electric-carbon coupling trading.

Taking the strategic goal of "carbon peak and carbon neutral" as the starting point, this paper explores the resource advantages and potentials of biomass resources of energy enterprises, takes the carbon emission trading market as the medium, conducts an in-depth analysis of the simultaneous participation of straw biogas plants in the electricity market and the carbon trading market for operation scheduling, and establishes a model for maximizing the daily operation income of straw power plants, concluding the practical application and sensitivity analysis of the results. Through the practical application of the model and the sensitivity analysis of the results, the conclusion of the study is drawn to provide a reference for the further development of straw biogas power plants in the future.

2. Model Construction and Preparation

2.1. The objective function

The background of this model is that all the preliminary inputs such as plant and equipment have already occurred, and have been completed, have reached the state of use, the cost of the preliminary inputs is a silent cost, and the subsequent decision-making will not affect this part of the cost, this paper does not take into account this part of the cost, and only consider the actual operation of the cost of the changes that occur in the operation.

Taking the maximization of the daily operating profit of the straw biogas power plant as the objective, considering the profit of the power plant participating in the electricity market and the carbon trading market in one day, as well as the relevant costs incurred in the actual operation, the objective function is established as shown in the following formula.

$$maxI = Re + Pc + Rf - Co \tag{1}$$

In equation (1): max denotes the daily operating revenue of the straw biogas plant; Re denotes the power plant's revenue from electricity sales in a day; Pc denotes the revenue of the power plant from trading in the carbon market; Rf represents the by-product income of the power plant for the day; Co indicates the cost of operating a power plant for one day.

(1)Revenue from the sale of electricity in the electricity market

Revenue from the sale of electricity in the electricity market is equal to the total amount of electricity generated daily multiplied by the selling price per unit of electricity generated, where the selling price per unit of electricity generated is the feed-in tariff.

$$Re = Wd * Pe \tag{2}$$

In equation (2): Wd is the total amount of electricity generated by the plant in one day; Pe is the feed-in benchmark tariff for the unit's electricity generation.

(2)Revenue from carbon market transactions

Straw biogas power plants not only participate in the electricity market but also participate in the carbon market. To participate in the carbon market, it is necessary to determine the initial carbon quota. Referring to the research result of Wei Huo [7], the initial carbon quota is determined by using the industry benchmark method, and the actual carbon emission is determined by using the carbon emission factor method, which is equal to the product of the daily consumption of biogas resources and the carbon emission factor of biogas energy.

$$Pc = (CEAd - ACE) * Fc \tag{3}$$

$$CEAd = n * IB * Wd * Mo \tag{4}$$

In equations (3) and (4): $CEAd$ denotes the initial carbon allowance of the power plant based on the industry level; ACE denotes the actual carbon emissions from the power plant. Fc denotes the price of carbon allowances; n is the number of units; IB denotes the baseline value of carbon emissions from the power sector; Mo is the correction factor.

(3)Revenue from by-products

The straw goes through a fermentation process, followed by solid-liquid separation, after which the remaining digestate and digestate can be used to produce solid and liquid fertilizers. The income from the sale of solid and liquid fertilizers is the by-product income.

$$Rf = a1 * Wd * Pf1 + a2 * Wd * Pf2 \tag{5}$$

In equation (5): $a1$ denotes the conversion efficiency between solid fertilizer and daily electricity generation; $Pf1$ denotes the market price of solid fertilizer; $a2$ denotes the conversion efficiency between liquid fertilizer and daily electricity generation; $Pf2$ denotes the market price of liquid fertilizer.

(4)Daily Operating Costs

Variable costs are costs whose total incurred cost varies linearly with the amount of electricity generated by the plant, within a relevant range. Fuel costs, equipment maintenance costs, and water costs are typical variable costs. In this paper, only two variable costs are considered, namely, the operation and maintenance costs incurred during the daily operation of the plant and the straw fuel costs for generating electricity by using straw fermentation to produce biogas, the total amount of which varies in proportion to the amount of electricity generated over a certain period.

$$Co = Cm + Cf \tag{6}$$

In equation (6): Cm denotes the daily operation and maintenance cost of the power plant; Cf indicates the daily fuel cost of the power plant.

For the O&M cost, this paper relates the O&M cost to the daily generation capacity, and there is a positive linear relationship between the total O&M cost and the daily generation capacity.

$$Cm = Wd * ci \tag{7}$$

In equation (7): ci indicates the unit O&M cost of a power plant in one day.

For the fuel cost, referring to the study of Zhai Mingling [8], the fuel cost is equal to the daily consumption of straw multiplied by the price per unit of straw, and there is a linear relationship between the daily consumption of straw and the daily power generation. The coefficients between the two can be obtained by the conversion of the relevant parameters.

$$Cf = Nfm * Pfm \tag{8}$$

$$Pfm = a3 * Wd \tag{9}$$

In equations (8) and (9): Nfm denotes the amount of straw purchased per day; Pfm denotes the market price of straw; $a3$ denotes the conversion efficiency between straw purchase and daily electricity generation.

2.2. Constraints

(1)Daily generation constraints

$$24 * Pmin \leq Wd \leq 24 * Pmax \tag{10}$$

In equation (10): $Pmin$indicates the minimum output power of the generator set; $Pmax$ indicates the maximum output power of the generator set.

(2)Biogas digester temperature response constraints

$$Em = (at^2 + bt + c) * SCm \tag{11}$$

In equation (11): Em indicates the amount of biogas consumed by the power plant daily; SCm represents the average daily consumption of straw for gas production at the power plant; t denotes the digester temperature, and a quadratic function was used to approximate fit the relationship between gas production and temperature, the a， b denotes the fitting constant of gas production per unit of straw per day to temperature.

(3)The constraint between daily power generation and actual carbon emissions

$$ACE = EFm * Em \tag{12}$$

$$Em = a4 * Wd \tag{13}$$

In equations (12) and (13): EFm denotes the carbon emission factor of biogas. Indicates the amount of biogas consumed per day; $a4$ indicates the electric-to-gas coefficient.

3. Case Simulation

3.1. Case presentation and data description

The data in this paper is derived from the current published literature, which was obtained from the https://www.cnki.net/. A small-scale straw direct-fired biogas power plant in the middle and lower reaches of the Yangtze River is selected as a case study, which is constructed in a rural area and utilizes abundant local straw resources for straw biogas power generation. The annual consumption of gas-producing straw is about 50,000 tons, the feed-in tariff of straw power generation in the area where the plant is located is about 0.66 Yuan/kwh, and the price of carbon quota is 55 Yuan/ton, and the average daily consumption of gas-producing straw can be approximated by dividing the annual consumption of gas-producing straw by 365, and the average daily consumption of gas-producing straw can be approximated by dividing the annual consumption of gas-producing straw by 365, and the annual consumption of gas-producing straw by 365. Referring to the research data of Bai Na et al.[9] , this paper selects corn stover, and fits the data of daily gas production per unit of stover and the reaction temperature of the digester to obtain the quadratic function corresponding to the daily gas production of 1 kg of stover and the temperature with the quadratic term coefficient of -0.054, the primary term coefficient of 5.256, and the constant term of -70.05. For the calculation of the initial carbon allowances, this paper adopts the industry benchmarking method based on the carbon emission benchmarks of the electric power industry released by the government of the People's Republic of China (PRC) in 2022, which is the most important benchmarking method for the power industry. The carbon emission benchmarking document for the electric power industry released in 2022 determines the carbon emission power supply benchmark value of a straw power plant as 0.3901kg/kwh, with a correction factor of 1, without considering heat supply. In terms of by-products, referring to the research data of Yilin Xu[10], the conversion efficiency between solid fertilizer and electricity generation is 0.0013, the conversion efficiency between liquid fertilizer and electricity generation is 0.0139, and the unit price of straw is 350 RMB/ton. At the same time, based on the examination of the local straw purchase situation, it was obtained that the selling price of straw digestate as solid fertilizer in the area was 120 yuan/ton, and the selling price of digestate as liquid fertilizer was 8 yuan/ton. In addition, considering the operation of the power plant, it was determined that the unit operation and maintenance cost of the power plant for one day of operation was RMB 0.03/kwh, and the specific data of the rest of the parameters, such as the utilization rate of straw in the generating unit of the power plant, the gas production rate of straw dry matter, and the gas-to-electricity coefficient, were shown as follows Table 1.

Table 1. Operational parameters related to straw biogas power plants

parameters	retrieve a value	unit (of measure)
unit capacity	2	1MW/unit
Straw utilization rate	88.1	%
Straw dry matter gas production rate	220.1	m^3/t
gas-to-electricity conversion factor	2	kwh/m^3
calorific value of straw	20900	kJ/m^3
Carbon content per unit calorific value	15.3	t/tJ
carbon oxidation rate	99	%
Carbon conversion factor	3.67	/
Minimum power of genset	0	kw
Maximum output power of generator set	300	kw

3.2. Sensitivity analysis

In the above case of a straw power plant participating in coupled electricity-carbon market trading, some uncertain factors will affect its economic evaluation results. To scientifically analyze the uncertain factors and thus analyze the potential uncertain risks, referring to the sensitivity analysis idea of Yong Wenqian[11], this paper selects the daily operating income of straw power plant as the evaluation index, and selects five variable factors, namely, the price of biogas residue, biogas liquids, feed-in tariffs, straw price, and the price of carbon quota, to carry out the single-factor sensitivity analysis of the project. The change value of the uncertain factors is selected between -20% and +20%, and the impact of each uncertain factor on the daily operating income is calculated individually; other factors remain unchanged during the calculation of each uncertain factor, and other related changes arising from the change of each uncertain factor should be calculated, and the sensitivity analysis diagram is drawn as follows Figure 1.

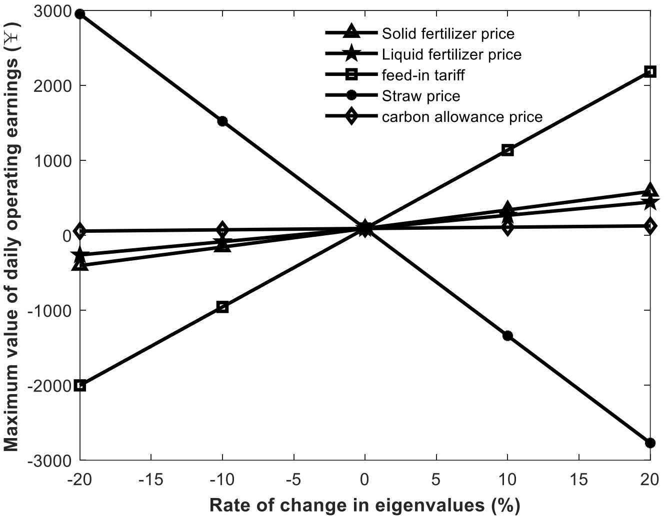

Figure 1. Sensitivity analysis diagram

According to Figure 1, it can be seen that the maximum daily operating earnings of straw power plants differ in their sensitivity to these five uncertainty factors. The slope of the straight line corresponding to the straw price factor is negative, indicating that the daily operating revenue varies inversely with the straw price. The slopes of the straight lines for the other three factors are positive, indicating that the daily operating income varies positively with the three factors of digestate price, digestate price, and feed-in tariff. Meanwhile, according to the steepness of the corresponding straight line for each factor, it can be seen that the daily operating income is most sensitive to the change of straw price, followed by the feed-in tariff, and less sensitive to the three factors of digestate price, digestate price, and carbon quota price. In addition, the maximum daily operating revenues corresponding to a 10% and 20% change in each factor were calculated and presented in tabular form as follows Table 2.

Table 2. Sensitivity Analysis of Daily Operating Earnings (￥)

sensitive factor			rate of change		
	-20%	-10%	0%	+10%	+20%
Solid fertilizer price	-404.31	-157.07	90.16	337.39	584.63
Liquid fertilizer price	-262.31	-86.07	90.16	266.39	442.62
feed-in tariff	-2001.81	-955.82	90.16	1136.14	2182.13
Straw Price	2950.71	1520.43	90.16	-1340.12	-2770.39
carbon allowance price	55.33	72.74	90.16	107.58	124.99

According to Table 2, it is concluded that the price of straw is the key factor in determining the maximum benefit of the daily operation of the power plant, and the excessively high cost of straw fuel will affect the economic operation of the power plant, reduce the economic benefit of the power plant operation, and cause the power plant to fall into a state of loss. Secondly, the power plant should also control the selling price of solid and liquid fertilizers so that the price is not too low leading to excessive losses. Combined with further analysis of the model, it can be seen that the feed-in tariff determines the income from electricity sales, and the income from electricity sales is the main source of income for straw power plants, so the determination of the appropriate feed-in tariff is essential for the profitability of straw biogas power plants. For the carbon quota price, only when this factor changes, the maximum daily operating income of the power plant does not have a negative value, and the carbon quota price is an important factor affecting the income of the power plant in the carbon trading market, which can show that the participation in the carbon trading market is favorable for the power plant to obtain better economic benefits, and the limited change of the carbon quota price will not be helpful to make the power plant fall into a loss situation. In addition, according to the above table, it can be obtained that, within the maximum allowable charge of 20% for each factor, when the straw price is reduced by 20%, the straw biogas power plant can obtain the maximum daily operating income of 2182.13 Yuan.

4. Conclusions

Straw biogas power plants are not only able to trade in the electricity market, but it is also necessary to become an important participant in the carbon emissions trading market by reducing greenhouse gas emissions. Participation in carbon market trading not only helps to reduce carbon emissions and promote the development of the clean energy industry but also creates new business opportunities for power plants and improves the economic benefits of straw biogas power plants. The development of the carbon trading market also puts higher requirements on the government and related departments, which need to formulate clear laws, regulations, and policy frameworks, establish a perfect carbon market system, improve the transparency and effectiveness of the carbon trading market, and ensure the healthy development of the carbon trading market.

In addition, according to the results of the sensitivity analysis of the case, the feed-in tariff and the straw price factor are the two most sensitive factors to the maximum return of the daily operation of the power plant. Therefore, straw biogas power plants need to pay attention to the feed-in tariff and straw purchase price as the two important factors influencing the benefits, ensuring a stable power sales price, enhancing the competitiveness of the feed-in tariff, and determining the appropriate straw purchase price to reduce the cost of power generation, to provide a guarantee for the sustainable development of the power plant in the future.

In conclusion, this paper establishes a model for maximizing the daily operating revenue of straw biogas plants participating in coupled electricity-carbon trading, provides a research idea and framework for application in the field of energy conservation and emission reduction, and proves the feasibility of optimizing the comprehensive benefits of straw biogas plants participating in coupled electricity-carbon trading through simulation of arithmetic examples, which provides a reference for the economic and stable development of straw biomass power plants.

References

[1] Chen Jinpeng, Hu Zhijian, Chen Jiabin, et al. Optimal scheduling of integrated energy system considering stepped carbon trading and flexible dual response of supply and demand[J]. High Voltage Technology, 2021,47(09):3094-3106.

[2] MA Guojie, ZHU Linying, ZHANG Miaomiao, et al. Life cycle assessment and economic analysis of straw biogasification for power generation [J]. Journal of Agricultural Engineering, 2022, 38 (24): 162-168.

[3] Wang Keyi, Wang Huogen. Comprehensive cost datasets for biogas, straw, and coal power generation over the whole life cycle[J]. Journal of Global Change Data, 2022,6(01):53-57.

[4] Ma Yue, Feng Lianyong. Analysis on the effectiveness of pilot carbon emission trading markets in China [J]. Operations Research and Management, 2022 (8) :195-202

[5] Zhang Wenyu, Xu Xiaochuan, Shen Yu, et al. Research on optimization strategy of low-carbon joint trading of virtual power plants considering aggregatable resources[J]. Modern Electric Power, 2024,41(01):161-172.

[6] DING Yuhao, LU Ganyun, LIU Yongwei, et al. Day-ahead optimal scheduling of integrated energy systems considering carbon emission target constraints and demand-side response[J]. Southern Power Grid Technology, 2022,16(08):1-11.

[7] Wei Hu, Ji Changhui. Carbon emissions trading and corporate competitiveness[J]. Journal of Finance and Economics, 2023,44(24):32-38.

[8] Zhai Mingling, Zhang Xu, Cheng Fei, et al. Cost analysis of straw disposal by farmers and biomass power plants[J]. Journal of Tongji University (Natural Science Edition), 2016,44(03):440-445.

[9] Bai Na, Mei Zili, Fu Zhengge, et al. Study on the fermentation and gas production characteristics of three kinds of straw at different temperatures[J]. China Biogas, 2011,29(01):16-21.

[10] Xu Yilin. Study on the planning of multi-energy complementary renewable energy power generation in rural economic development zones[D]. North China Electric Power University, 2021.

[11] Yong Wenqian. Business plan of "Flying Four Seasons" Self-driving Camp on Dukou Highway [D]. South China University of Technology, 2020.