Energy Substitution Ratio and Benefit Evaluation of PV-ESS in High-energy-consumption Industrial Aquaculture

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Abstract

To address the industry pain points of high energy cost and high carbon emissions in high-energy-consumption industrial aquaculture, and promote the low-carbon transformation of the aquaculture industry, this study takes the industrial recirculating aquaculture system as the research object. It focuses on the application of photovoltaic-energy storage system (PV-ESS). It calculates the energy substitution ratio of new energy for traditional grid energy by combining field monitoring and data modeling. It also conducts a comprehensive benefit evaluation from three dimensions: economic benefit, environmental benefit and energy benefit. The results show that the rationally configured PV-ESS can cover the energy demand of core high-energy-consumption links in aquaculture, with an energy substitution ratio of 35.00%~48.00%. It not only reduces the comprehensive energy cost of aquaculture but also significantly cuts carbon emissions. This study provides theoretical support and practical reference for the energy structure optimization and new energy supporting scheme design of high-energy-consumption industrial aquaculture, helping the aquaculture industry upgrade towards green, low-carbon, efficient and sustainable development.

Keywords

Photovoltaic-energy storage system, Industrial aquaculture, High energy consumption, Energy substitution ratio, Benefit evaluation

Introduction

Industrial aquaculture has become the core development direction of modern aquaculture due to its advantages of high intensification, controllable breeding environment and insensitivity to natural climate. However, this mode has obviously high energy consumption characteristics. Core links such as aeration, water temperature control, circulating filtration and water quality monitoring consume energy continuously. Energy cost accounts for 25%~40% of the total breeding cost. Traditional energy supply is mainly based on thermal power and features high carbon emission intensity. This not only increases the cost pressure on breeding entities but also runs counter to the agricultural low-carbon transformation requirements under the dual-carbon strategy [1].

The PV-ESS features cleanness, no pollution, on-site energy acquisition and stable power supply. It matches the stable energy consumption characteristics of industrial aquaculture, and serves as an optimal path to solve the high energy consumption dilemma [2]. Current research on photovoltaic applications in aquaculture mostly focuses on fishery-solar complementary pond aquaculture. Research on energy substitution ratio calculation and multi-dimensional benefit evaluation of PV-ESS in high-energy-consumption industrial aquaculture scenarios remain insufficient. There is also a lack of targeted system configuration ideas. Based on this, this study takes high-energy-consumption industrial recirculating aquaculture as the research carrier. It clarifies the adaptation scheme of PV-ESS, accurately calculates the energy substitution ratio, and constructs a multi-dimensional benefit evaluation system. This fills the research gap in new energy applications for industrial aquaculture. It provides a scientific basis for upgrading the industrial energy structure and helps the aquaculture industry achieve the multiple goals of energy saving, cost reduction and emission reduction.

Research objects and methods

Research object

A high-energy-consumption industrial recirculating

Penaeus vannamei breeding base was selected as the research object. Penaeus vannamei is highly sensitive to dissolved oxygen and water temperature, and supporting equipment needs to operate continuously, belonging to a typical high-energy-consumption breeding species [3]. The total area of the breeding workshop is 2000 m^2, with 32 breeding ponds and a single pond volume of 50 m^3. The core high-energy-consumption equipment includes aerators, water circulation filtration units, temperature control heat pumps and water quality monitoring terminals, with daily power consumption of about 860 kW·h. Among them, the energy consumption ratio of aeration, temperature control and water circulation is 42.00%, 35.00% and 18.00% respectively, which is a typical high-energy-consumption industrial aquaculture scenario. The supporting PV-ESS includes: 300 kW·h installed roof distributed monocrystalline silicon photovoltaic modules with a conversion efficiency of 22.50%, maximizing the use of idle roof space. The energy storage unit adopts lithium iron phosphate battery pack with a capacity of 150 kW·h and charge-discharge efficiency of 92.00%, matching the continuous energy demand at night [4]. The system is equipped with an intelligent power control module to realize spontaneous use, surplus energy storage and grid supplement when insufficient, ensuring the stable operation of breeding equipment.

Research methods

Energy consumption monitoring method: Intelligent electricity meters were installed at the interfaces of the PV-ESS, aquaculture energy terminals and power grid. They collected minute-level energy consumption data for 6 consecutive months, covering the entire aquaculture cycle. The method accurately measured photovoltaic power generation, energy storage charge-discharge capacity, grid supplementary power and energy consumption of each link, ensuring the accuracy of energy flow data.

Energy substitution ratio calculation method: Referring to the general calculation specifications for new energy application, the calculation formula of energy substitution ratio was determined as (photovoltaic self-used power + energy storage discharge power)/total aquaculture power consumption × 100%. Meanwhile, the energy substitution ratio of each high-energy-consumption link was calculated to clarify the adaptation difference of the system to different high-energy-consumption equipment [5].

Benefit evaluation method: A three-dimensional evaluation system including economic, energy and environmental benefits was constructed. Using the comparative analysis method, with the period before new energy application as the control, comprehensive evaluation was carried out combining field data and industry standards to ensure the authenticity and reliability of results.

Data analysis method: SPSS software was used to conduct a statistical analysis of the monitoring data. It excluded the interference of extreme weather such as consecutive rainy days on photovoltaic power generation. The method calculated the energy substitution effect and benefit level under normal operation conditions, improving the applicability of the research results.

Calculation results of energy substitution ratio of PV-ESS

Total energy substitution ratio

During the 6-month monitoring period, the total aquaculture power consumption was 154,800 kW·h, the total photovoltaic power generation was 72,300 kW·h, and the cumulative energy storage discharge was 13,600 kW·h. Among them, the self-used photovoltaic power was 51,200 kW·h, and the surplus energy storage was 21,100 kW·h (excluding energy storage loss), with grid supplementary power of 89,900 kW·h. The calculation results show that the total energy substitution of the PV-ESS reached 64,800 kW·h, with an overall energy substitution ratio of 41.86%. This means new energy can replace more than 40.00% of traditional grid energy in this scenario, significantly reducing reliance on thermal power [6].

Energy substitution ratio of each high-energy-consumption link

The energy substitution ratio of new energy in core links was highly matched with energy consumption time period and load characteristics, showing differentiated characteristics: Aeration was continuous energy consumption for 24 hours with stable load, having the highest new energy substitution ratio of 45.23%. Photovoltaic power was given priority to supply aeration demand in the daytime, and energy storage discharge supplemented at night, greatly reducing grid dependence. Water temperature control had high load in the daytime, coinciding with the peak period of photovoltaic output, with a substitution ratio of 42.17%, alleviating grid pressure in the daytime. Water circulation filtration operated intermittently with small load fluctuation, with a substitution ratio of 38.56%. Auxiliary links such as lighting and monitoring had low energy consumption ratio, with a new energy substitution ratio of 52.31%, basically realizing full coverage of new energy.

Difference of energy substitution ratio in different scenarios

Under different weather conditions, fluctuations in photovoltaic power generation resulted in variations in the energy substitution ratio. On sunny days, photovoltaic output was sufficient, with an energy substitution ratio of 48.32%, and the energy storage system could store surplus power to meet nighttime energy demand. On cloudy days, photovoltaic power generation decreased, with a substitution ratio of 36.15%, and energy storage discharge supplemented part of the demand to reduce grid supplementary power. On continuous rainy days, photovoltaic output dropped sharply, with a substitution ratio of only 18.24%, mainly relying on grid power supply, and energy storage only served as an emergency supplement. Under normal operation (excluding continuous rainy days), the system substitution ratio was stable at 38.00%~45.00%, with strong adaptability [7].

Comprehensive benefit evaluation of PV-ESS

Economic benefit evaluation

The economic benefit was calculated from two dimensions: Energy cost saving and investment payback period, based on the local industrial electricity price of 0.85 CNY/kW·h and the total investment of PV-ESS of 360,000 CNY [8]. During the monitoring period, the new energy substitution power was 64,800 kW·h, directly saving 55,080 CNY in electricity fees (64,800 × 0.85). Calculated by 2 breeding cycles per year, the annual electricity fee saving was 110,160 CNY. Meanwhile, the energy storage system avoided the peak-valley electricity price difference of the power grid, saving an additional 8,200 CNY in electricity fees annually, with a total annual saving of 118,360 CNY. The annual operation and maintenance cost of the system was about 9,000 CNY, and the annual net income was 109,360 CNY, with a static investment payback period of about 3.3 years. The short payback period indicates strong industrial promotion feasibility. The service life of photovoltaic modules is 25 years, and that of energy storage batteries is 8~10 years. The long-term operation cost is low, which can continuously improve the profitability of breeding subjects and is suitable for large-scale industrial aquaculture demand.

Energy benefit evaluation

First, reducing dependence on traditional energy: the new energy substitution ratio exceeded 40.00%, greatly reducing the dependence on grid thermal power and alleviating the power supply pressure of regional power grid. Especially during peak electricity consumption, photovoltaic self-use could reduce the peak load of power grid. Second, energy utilization efficiency is improved: The PV-ESS mode of “on-site consumption and surplus energy storage” avoids the power loss caused by grid connection of surplus electricity, with a comprehensive energy utilization efficiency of 89.30%. This is significantly higher than that of the single photovoltaic grid-connected mode [9]. Third, the energy structure is optimized: The aquaculture base’s energy structure has shifted from a single thermal power supply to a multi-energy complementary structure of “PV + energy storage + power grid”, with the share of clean energy rising to 41.86%. This promotes the transformation of high-energy-consumption industrial aquaculture toward high efficiency and energy conservation, and provides a demonstration for the optimization of the industrial energy structure.

Environmental benefit evaluation

Based on the calculation benchmark of carbon emission coefficient of thermal power generation of 0.785 $kgCO_2/kW \cdot h$ [10]. The new energy substitution power during the monitoring period was 64,800 kW·h, reducing carbon emissions by 5.0868 tons (64,800 × 0.785), with annual carbon emission reduction exceeding 10 tons, showing significant emission reduction effect. The PV-ESS had no exhaust gas, waste water or waste residue discharge, avoiding the emission of pollutants such as sulfur dioxide and nitrogen oxides from thermal power generation. Meanwhile, roof photovoltaic modules could reduce the cooling energy consumption of the workshop in summer, further reducing carbon emissions, which was in line with the requirements of the dual-carbon strategy. At the same time, it provided a replicable and promotable mode for the low-carbon transformation of aquaculture, helping to achieve the dual-carbon goals in the agricultural field, and had prominent environmental value and industrial demonstration significance.

Problems and optimization suggestions

Core existing problems

First, photovoltaic output was significantly affected by weather, with the substitution ratio dropping sharply on continuous rainy days, and the power supply stability needed to be improved. Second, the initial investment of energy storage batteries accounted for a high proportion. Although the payback period was short, it still increased the initial investment pressure of small and medium-sized breeding subjects. Third, the precision of system intelligent regulation was insufficient, and the adaptability to load changes in each breeding link needed to be optimized.

Targeted optimization suggestions

Optimize system configuration: Equipping with small backup power supply to deal with insufficient photovoltaic output on continuous rainy days and improve power supply stability. Selecting cost-effective energy storage batteries to reduce the threshold of initial investment.

Seek policy support: Promoting local governments to issue subsidy policies for new energy supporting facilities in industrial aquaculture, subsidize equipment purchase and installation costs, alleviate the capital pressure of breeding subjects, and accelerate technology promotion.

Upgrade intelligent regulation: AI load prediction technology is introduced to accurately match the energy demand of each process with the output of photovoltaic and energy storage systems. This optimizes energy utilization efficiency and system adaptability, and further elevates the energy substitution ratio.

Conclusion

Taking high-energy-consumption industrial recirculating aquaculture as the research object, this study explores the energy substitution ratio and comprehensive benefit of PV-ESS. The results show that with the configuration of a 300 kW·h photovoltaic system and a 150 kW·h energy storage system, the overall energy substitution ratio of the system reached 41.86%. It remained stable at 38.00%~45.00% under normal operation, and the substitution ratios for each high-energy-consumption process ranged from 38.56% to 52.31%. In terms of economic benefit, the annual electricity fee saving exceeded 110,000 CNY, with a static investment payback period of about 3.3 years, showing prominent profitability. In terms of energy benefit, it improves energy utilization efficiency, optimizes energy structure and reduces dependence on traditional energy. In terms of environmental benefits, it reduces carbon emissions by more than 10 tons annually, cut pollutant emissions, and complied with the dual-carbon strategy. The PV-ESS can effectively solve the high energy consumption dilemma of industrial aquaculture. Although there are problems such as weather influence and initial investment, it has strong promotion value through optimized configuration and policy support. This study provides data support and scheme reference for the application of new energy in high-energy-consumption industrial aquaculture, helping the aquaculture industry realize green, low-carbon, efficient and sustainable upgrading.

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Conflicts of Interest

The author declares no conflict of interest.

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