

Application Analysis of Multi Energy Complementary System in Regional Energy Optimization and Scheduling: Taking the Guangdong Hong Kong Macao Greater Bay Area as An Example

Leibing Qu

Beijing Normal-Hong Kong Baptist University Zhuhai City, Guangdong Province, China

ABSTRACT

The Guangdong Hong Kong Macao Greater Bay Area, as the core economic area and energy intensive region of China, faces prominent problems such as high dependence on fossil fuels, high pressure on the consumption of renewable energy, and regional energy supply-demand imbalance. Data shows that the consumption of coal and oil products in Hong Kong accounts for 91%, while the combined consumption of coal and oil in Guangdong Province accounts for 58.5%. The consumption structure dominated by fossil fuels has not fundamentally changed. The multi energy complementary system integrates multiple energy sources such as wind power, photovoltaics, natural gas, and energy storage to achieve coordinated optimization of production and consumption, which is the key path to solving the energy dilemma. This article takes the Guangdong Hong Kong Macao Greater Bay Area as the research object, and combines green finance policies such as green credit with ESG constraints to explore the application logic and practical path of multi energy complementary systems in regional energy optimization and scheduling. By analyzing the characteristics of regional energy supply and demand and complementary needs, a scheduling mechanism that integrates green finance incentives and ESG evaluation is constructed. A multi-objective model is designed and simulated for verification, and the application effects and inspirations are summarized. Research has shown that deep integration of the three can significantly improve energy utilization efficiency, reduce carbon emissions, optimize regional energy investment structure, provide practical solutions for the low-carbon transformation of energy in the Greater Bay Area, and also provide reference for similar regions.

KEYWORDS

Multi energy complementary system; Guangdong Hong Kong Macao Greater Bay Area; Energy optimization and scheduling; Green finance, ESG constraints.

1. INTRODUCTION

The deepening of the "dual carbon" goal has made the low-carbon and efficient transformation of regional energy systems inevitable. As one of the most open and economically vibrant regions in China, the Guangdong Hong Kong Macao Greater Bay Area has seen a continuous increase in energy consumption demand, with a high proportion of fossil fuels. The contradiction between energy supply and demand and environmental constraints is becoming increasingly prominent. The Greater Bay Area has a superior endowment of renewable energy resources, with offshore wind power planning and installation leading the country. The Yangjiang and other sea areas have been connected to the grid with over 5 million kilowatts, and photovoltaics have the conditions for large-scale development. However, due to issues such as insufficient energy coordination, weak adaptability of scheduling

mechanisms, and long funding cycles, the consumption of renewable energy is facing structural pressure [1].

Multi energy complementary systems can effectively stabilize renewable energy fluctuations and enhance supply stability and flexibility through the synergy of "source network load storage". The Greater Bay Area has built the world's largest pumped storage power grid, with nearly 10 million kilowatt units providing important support for the consumption of new energy. Green finance and ESG constraints are important supports for the sustainable development of energy projects. The Greater Bay Area has established the country's first regional green finance alliance, and the balance of green loans in core cities such as Guangzhou and Shenzhen has exceeded one trillion yuan. The ESG information disclosure rate of listed companies in the region for the 2023 fiscal year will reach 76%, providing a solid foundation for constraining energy dispatch.

Existing research mostly focuses on optimizing multi energy complementary technologies, with insufficient integration of green finance and ESG constraints, and a lack of precise analysis in specific regions. Based on this, this article focuses on the Guangdong Hong Kong Macao Greater Bay Area, and combines green finance incentives, ESG evaluation, and multi energy complementary scheduling models to explore the energy optimization path of technology and institutional synergy, providing theoretical support and practical reference for the low-carbon transformation of energy in the Greater Bay Area and similar regions.

2. ENERGY SUPPLY AND DEMAND CHARACTERISTICS AND MULTI ENERGY COMPLEMENTARY DEMAND IN THE GUANGDONG HONG KONG MACAO GREATER BAY AREA

The Guangdong Hong Kong Macao Greater Bay Area covers 9 cities and 2 districts, with significant differences in industrial structure and prominent spatial heterogeneity and structural imbalance in energy supply and demand. From the perspective of energy supply, the self-sufficiency rate of primary energy in the Greater Bay Area has remained at a low level of around 10% for a long time, and fossil fuels such as coal and oil are highly dependent on external inputs. In 2022, the proportion of imported electricity from the West East Power Transmission exceeded 30%, putting sustained pressure on energy supply security. The development of renewable energy presents the characteristics of "uneven distribution and supply-demand mismatch". Offshore wind power is concentrated in the waters of Shantou, Jieyang, and Yangjiang in eastern Guangdong, while photovoltaic projects are mostly located in Zhanjiang, Maoming, and other places. The supply of renewable energy in consumption core areas such as Guangzhou, Shenzhen, and Dongguan is seriously insufficient, forming a spatial mismatch of "scattered supply side and concentrated demand side".

From the perspective of energy consumption, the industrial energy consumption in the Greater Bay Area accounts for over 50%, with industries such as electronic information, chemical engineering, and equipment manufacturing being the main energy consuming areas, resulting in high energy intensity; Transportation energy consumption accounts for nearly 30%, and the large number of motor vehicles has become one of the core sources of carbon emissions. In recent years, emerging industries such as the digital economy and new energy vehicles have driven sustained growth in energy consumption, but the growth rate of renewable energy supply lags behind consumption growth, and the supply-demand gap continues to widen. The current regional energy consumption is still dominated by fossil fuels, and the proportion of clean energy is steadily increasing. However, there is still a gap from the non fossil energy consumption target of the 14th Five Year Plan, and the pressure of low-carbon transformation is prominent.

The core value of a multi energy complementary system is to solve the imbalance of supply and demand structure and spatial mismatch through the synergy of multiple energy sources. For the Greater Bay Area, demand is concentrated in three aspects: firstly, to stabilize the volatility of

renewable energy and solve the problem of new energy consumption through the combination of wind, solar, natural gas, and energy storage [2]; The second is to optimize the allocation of energy space, relying on smart grids and cross regional dispatch platforms, to achieve efficient transmission of renewable energy from eastern and western Guangdong to the core area; The third is to reduce carbon emission intensity and help the Greater Bay Area achieve carbon peak before 2030 through clean energy substitution and energy efficiency improvement. The Greater Bay Area has dense industrial clusters and diverse energy demands, providing rich application scenarios for the system. The region's complete infrastructure and strong technological innovation capabilities provide solid guarantees for implementation.

3. MULTI ENERGY COMPLEMENTARY SYSTEM COMPOSITION AND REGIONAL ENERGY OPTIMIZATION SCHEDULING LOGIC

The multi energy complementary system is based on the core architecture of "source network load storage" collaboration, which is in line with the energy resource endowment and consumption characteristics of the Guangdong Hong Kong Macao Greater Bay Area, and has constructed a diversified composition system. The supply side covers diversified power sources such as offshore wind power, photovoltaics, and natural gas cogeneration. Among them, offshore wind power and photovoltaics are the core renewable energy sources, while natural gas plays a peak shaving role; The transmission end relies on smart grid upgrading projects such as 500kV Shinan Line A and B to build a highly flexible transmission network, while integrating oil and gas resources such as Jieyang Unicom pipeline to form a "electricity gas" coordinated transmission pattern; On the load side, a differentiated demand response mechanism will be established for the three major fields of industry, construction, and transportation. Industry will focus on flexible scheduling, construction will promote the integration of light and energy storage, and transportation will strengthen the coordination between charging networks and power grids; The energy storage end adopts the "electrochemical energy storage+pumped storage+virtual energy storage" mode, with the Xinfeng pumped storage power station in northern Guangdong as the core peak shaving carrier. Electrochemical energy storage is located in the load center, and virtual energy storage aggregates adjustable load resources.

The core logic of regional energy optimization and scheduling is to achieve efficient collaboration of multiple energy sources under the constraints of safety, economy, and environment. Ensuring stable power supply and avoiding the risk of fluctuations in new energy with safety objectives [3]; Economic goals focus on comprehensive cost control and improve efficiency through resource optimization; The environmental goals closely adhere to the requirements of carbon reduction and are in line with the direction of "dual carbon" transformation. The three are mutually supportive and indispensable.

The scheduling process is divided into two stages: day ahead and real-time. Based on meteorological, load forecasting, green finance, and ESG requirements, power output, energy storage strategies, and cross regional transmission plans are formulated; Real time response to output fluctuations and load changes, dynamically balancing supply and demand through natural gas peak shaving, flexible energy storage charging and discharging, and demand side elastic adjustment. Scheduling relies on intelligent platforms to integrate multidimensional data, using AI scheduling algorithms to improve decision-making accuracy and achieve rapid instruction issuance.

Compared with traditional scheduling, this model has three major characteristics: firstly, it shifts from "single energy scheduling" to "multi energy collaboration", breaking down category barriers; The second is to shift from "supply side dominance" to "source network load storage interaction", highlighting the role of demand side and energy storage regulation; The third is to shift from "technology driven" to "technology institutional dual driven", incorporating green finance incentives and ESG constraints into decision-making, and achieving the unity of economic and environmental benefits.

4. DESIGN OF SCHEDULING MECHANISM UNDER GREEN FINANCE AND ESG CONSTRAINTS

Green finance and ESG constraints provide institutional guarantees for optimizing and scheduling multi energy complementary systems. Combining the policy environment and market characteristics of the Guangdong Hong Kong Macao Greater Bay Area, it is necessary to establish a scheduling mechanism that emphasizes both incentives and constraints. Green finance incentives guide low-carbon projects through financial support, cost subsidies, and risk sharing. The Greater Bay Area relies on green finance reform and innovation resources to provide diversified financing channels such as green credit, bonds, and funds for projects. Green credit interest rates are usually lower than ordinary loans, reducing financing costs; Local governments provide electricity subsidies for renewable energy projects such as offshore wind and solar power, and investment subsidies for energy storage projects to alleviate initial investment pressure. In scheduling, the low-carbon attributes of projects are linked to the support of green finance. Projects with a high proportion of renewable energy and good emission reduction effects will be given priority in obtaining financing and output allocation qualifications.

The ESG constraint mechanism regulates scheduling behavior through a scientific evaluation system, combined with the energy transformation needs of the Greater Bay Area, and sets standards from three dimensions: environmental, social, and governance. The environmental dimension focuses on carbon emissions and renewable energy consumption rate, with a focus on controlling pollution emissions; The social dimension focuses on the reliability of energy supply and community benefits; The governance dimension focuses on project compliance and information disclosure integrity. In scheduling decisions, ESG benchmark score lines are set, and projects that meet the standards are included in the priority scheduling list. Projects that do not meet the standards are limited in output, and a dynamic adjustment mechanism is established to optimize indicators and standards based on regional transformation progress.

To achieve deep integration of the two, it is necessary to establish a linkage mechanism of "financial support ESG evaluation scheduling priority": green financial institutions will use ESG scores as the key basis for financing approval, and the higher the score, the more sufficient the financing amount and the better the interest rate [4]; The dispatch center formulates strategies based on ESG scores and financial support intensity, prioritizing projects with high scores and key financial support in output and cross regional transmission; At the same time, establish a feedback mechanism and incorporate scheduling results into ESG evaluation. Projects that do not meet the requirements will have their scores lowered, which will affect their eligibility for subsequent financing.

In addition, it is necessary to improve supporting guarantees: strengthen policy coordination among energy, finance, and environmental protection departments to avoid conflicts; Build an information sharing platform, integrate project production, financing, and ESG data, and achieve collaborative supervision; Strengthen market supervision, prevent green finance from "greenwashing", "greenwashing" and ESG fraud, and ensure fair and effective mechanisms.

5. CONSTRUCTION AND SOLUTION OF OPTIMIZATION SCHEDULING MODEL FOR MULTI ENERGY COMPLEMENTARY SYSTEMS

Based on the energy characteristics and scheduling needs of the Guangdong Hong Kong Macao Greater Bay Area, combined with green finance and ESG constraints, a multi-objective optimization scheduling model is constructed. The model takes "the lowest economic cost, the lowest carbon emissions, and the highest ESG score" as the objective function, taking into account multiple constraints such as energy security, technology, and policies, to achieve overall optimization of a multi energy complementary system. The objective function is converted into a comprehensive

objective through weight coefficients, and the weights are determined using the Analytic Hierarchy Process: economic cost weight is 0.35, carbon emissions weight is 0.4, and ESG score weight is 0.25, which is in line with the Greater Bay Area's "low-carbon priority and economic consideration" orientation. Economic costs cover production, transmission, and financing costs, and are controlled by optimizing output and transmission plans; The carbon emission reduction target focuses on the combustion and transmission loss emissions of fossil fuels, relying on the improvement of clean energy output and peak shaving optimization to reduce carbon emissions; The ESG score target is achieved by improving consumption rate, supply reliability, and information disclosure.

The constraints include four categories: energy balance constraints to ensure supply-demand matching, balancing transmission losses and energy storage; Technical constraints clarify the operating boundaries of equipment such as power output, energy storage power, and transmission facility capacity; Green finance constrains financing scale and cost to meet preferential standards; ESG constraints require scores not lower than the scheduling baseline and carbon emissions not exceeding regional quotas.

The model is solved using an improved particle swarm optimization algorithm, with parameters set based on actual data in the Greater Bay Area. The data sources include energy statistical yearbooks, green finance reports, and historical meteorological data [5]. The solution is divided into three steps: preprocessing the data to ensure accuracy; Initialize the particle swarm (with 100 particles, 200 iterations, learning factor of 1.5, inertia weight of 0.9 linearly decreasing to 0.4); Iteratively solve and update the optimal solution to meet the standard.

Through simulation verification using typical daily data in 2023, the results show that the optimization plan significantly reduces comprehensive economic costs and carbon emissions, significantly improves ESG scores and renewable energy consumption rates, and achieves a high level of energy supply reliability. Compared with traditional solutions, the environmental benefits and ESG performance advantages are prominent, and incremental costs can be offset through green finance incentives, presenting a trend of "environmental excellence and stable benefits", confirming that the model can integrate technological and institutional advantages and provide scientific tools for scheduling.

6. APPLICATION EFFECT SIMULATION AND PRACTICAL INSPIRATION

Based on the model and solution results constructed in the previous section, analyze the application effect of multi energy complementary systems in energy optimization and scheduling in the Guangdong Hong Kong Macao Greater Bay Area from multiple dimensions. In terms of energy efficiency, through the coordinated operation of "wind solar gas storage", the shortcomings of a single energy source are effectively avoided, the comprehensive utilization efficiency of energy is significantly improved, the consumption rate of renewable energy is greatly increased, and the potential of offshore wind power, photovoltaic and other resources in the Greater Bay Area is fully released, which is in line with the development trend of regional clean energy consumption improvement.

In terms of environmental benefits, optimizing scheduling plans can significantly reduce carbon emissions and pollutant emissions, and alleviate regional environmental pressure. Based on long-term development predictions, the comprehensive promotion of the system can help the Greater Bay Area achieve its carbon peak target as scheduled before 2030, which is consistent with the requirements of the Guangdong Province carbon peak implementation plan [6]. At the same time, the ESG performance has reached an excellent level, in line with the ESG evaluation standards of energy enterprises, demonstrating the sustainable development capability of the regional energy system.

In terms of economic benefits, although the initial investment of the project is relatively high, relying on green finance preferential policies and scheduling optimization, the comprehensive economic

costs are controllable. In the long run, with the reduction of renewable energy costs and the improvement of the carbon trading market, the investment return cycle is in line with the reasonable level of the industry. In addition, the promotion of the system drives the development of industries such as new energy equipment manufacturing and intelligent scheduling technology, which is in line with the direction of cultivating trillion level new energy industry clusters in the Greater Bay Area, and helps to promote employment growth and industrial structure upgrading.

In terms of energy security, diversified energy supply and cross regional coordinated scheduling have enhanced the supply's ability to resist risks. In extreme weather scenarios, natural gas peak shaving power sources and energy storage systems can respond quickly, ensuring stable power supply. The reliability of power supply in the Greater Bay Area has reached the advanced level of major bay areas in the world. At the same time, reduce external dependence on fossil fuels and enhance regional energy self-sufficiency and security capabilities.

Practical insights include five points: firstly, adhering to regional coordination, breaking down administrative barriers, establishing a unified dispatch platform, and strengthening the linkage between renewable energy bases and core consumption areas; The second is to deepen financial empowerment, expand the scope of green finance support, innovate financing products, and promote the synergy between finance and ESG evaluation; Thirdly, we will strengthen technological innovation and increase investment in research and development of key technologies such as intelligent scheduling and energy storage; The fourth is to improve policy guarantees, formulate special policies, clarify ESG evaluation and financial support rules, and establish cross departmental regulatory mechanisms; The fifth is to focus on the implementation of scenarios, prioritize pilot projects in key areas such as industrial parks, and gradually promote them in an orderly manner.

7. CONCLUSION

This article focuses on the Guangdong Hong Kong Macao Greater Bay Area, exploring the application path of multi energy complementary systems in regional energy optimization and scheduling, with a focus on integrating green finance support and ESG constraints, and constructing a "technology finance system" collaborative optimization framework. Research has shown that multi energy complementary systems can effectively solve problems such as energy supply-demand imbalance, insufficient consumption of renewable energy, and high carbon emission intensity in the Greater Bay Area. The deep integration with green finance and ESG constraints can further enhance the scientific and sustainable scheduling.

The study clarifies the system application requirements by analyzing the energy supply and demand characteristics of the Greater Bay Area, elaborates on the core logic of scheduling based on the "source network load storage" architecture, constructs a scheduling mechanism that integrates green finance incentives and ESG constraints, forms a "financial support ESG evaluation scheduling priority" linkage system, designs a multi-objective optimization model and verifies its effectiveness through simulation. Finally, from the four dimensions of energy efficiency, environmental benefits, economic benefits, and energy security, five practical inspirations are proposed, including regional coordination and financial empowerment.

Simulation shows that the optimization plan significantly improves the comprehensive energy utilization efficiency, significantly reduces carbon emissions, achieves excellent ESG performance, and effectively offsets some initial investment costs with the help of green finance policies, achieving the unity of "three benefits". This study provides practical solutions for the low-carbon transformation of energy in the Greater Bay Area, as well as references for similar regions such as the Yangtze River Delta and the Beijing Tianjin Hebei region.

The research has limitations: the model parameters are based on historical and predictive data, and do not fully consider the impact of extreme weather and policy changes; The allocation of ESG

indicator weights is subject to subjective factors. In the future, the robustness of the model can be optimized, the ESG indicator system can be improved, the research scope can be expanded, and the collaborative mechanism with the carbon market and electricity market can be explored to provide support for the deep transformation of regional energy.

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