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A Review of Optimization Technologies on the Power Generation Side in Low-Carbon Power Systems

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Abstract. This study, grounded in the context of the "Dual Carbon" goals, focuses on the decarbonization of power generation sector within the power system. From the three dimensions of power supply structure optimization, unit operational regulation, and intelligent scheduling, it systematically reviews key technologies and optimization approaches for the generation side in low-carbon power systems. The paper highlights the challenges posed by the high grid integration of renewables, explores the application of operational characteristics of low-carbon technologies such as carbon capture power plants in generation forecasting and scheduling, and provides an outlook on future research directions. Low-carbon optimization on the generation side represents a core pathway for driving the power system toward achieving the "Dual Carbon" goals. To realize this transition, coordinated efforts across multiple dimensions are necessary, including establishing a green power supply structure, adopting flexible operational modes, implementing incentive-based market mechanisms, and fostering integrated technological innovation. In terms of power supply structure, the portion of power supplied by wind and solar should be significantly increased, while the scale of coal-fired power should be rationally controlled and its transformation toward cleaner and more flexible operation promoted. Regarding operational modes, it is essential to enhance the system's regulatory capacity and promote the efficient utilization of renewable energy through multi-timescale scheduling optimization. At the market mechanism level, a coupling mechanism between carbon trading and electricity markets should be established and improved, along with ancillary service markets and green power trading systems, to guide low-carbon power investments and optimize resource allocation through economic incentives. In the realm of technological innovation, future efforts should focus on advancing the large-scale application of carbon capture, utilization, and storage technologies, accelerating the development of system flexibility enhancement technologies such as electrochemical energy storage and hydrogen energy, and ultimately building new-type power system that is secure, reliable, cost-effective, and environmentally sustainable through multidimensional systematic advancement.

Keywords: Low-carbon power, Power generation optimization, Renewable energy, Carbon capture and storage (CCS), Unit combinations

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1. Introduction

Global climate change is a serious challenge to the sustainable development of human society. Promoting the clean and low-carbon transformation of energy and actively responding to climate change have become the common consensus and urgent task of the international community. Against this backdrop, China has solemnly proposed the "dual carbon" strategic goals of peaking carbon emissions on a pathway to carbon peaking by 2030 and full decarbonization by 2060. This not only reflects the responsibility of a major country, but is also an inherent requirement for promoting economic and social high quality and building a modern energy system.

As the largest contributor to global carbon dioxide emissions, the low-carbon transformation of the power sector constitutes a critical and central pathway to fulfilling the "dual carbon" goals. Deep decarbonization on the generation side (power source side) serves as the starting point and foundation for the comprehensive systemic transition across the entire value chain of the power system: generation, grid, load, and storage. The fundamental restructuring of the power generation mix directly shapes the subsequent evolution of grid architecture, load profiles, and energy storage requirements. Therefore, it is of significant theoretical and practical importance to thoroughly investigate the profound impacts, transition pathways, and key technical challenges that the "dual carbon" goals impose on the power generation side.

This paper focuses on the optimization strategies needed for the power generation side in a low-carbon power system, such as the core contradictions of the low-carbon transformation of the power generation side, system stability challenges, operation scheduling challenges, optimization of the low-carbon power source structure, flexible power generation resources and operation optimization, market and policy mechanism drives, and current problems, etc. This study aims to explore optimization techniques on the power generation side of low-carbon power systems, which is of great significance. To achieve the "dual carbon" goals, the power system must integrate renewable energy on a large scale and at a high proportion. However, its intermittency and volatility pose fundamental obstacles to achieving reliable grid operations. Power generation-side optimization technology, by coordinating the output of various power sources and the allocation of energy storage resources, serves as a crucial support for enhancing system regulation capability, ensuring power supply security, and reducing overall electricity costs for society. It holds key significance for driving the green transition of the energy structure and achieving high-quality development.

2. Challenges to power generation systems with a high proportion of renewable energy access

2.1. System stability challenges

In the context of the accelerated energy transition, while the high proportion of renewable energy grid connection brings significant low-carbon benefits, it also profoundly changes the dynamic characteristics of the power system, posing severe challenges to its safe and stable operation.

2.1.1. Absence of inertia

The large-scale replacement of traditional coal-fired and gas-fired units by non-synchronous power sources such as wind power and photovoltaic power has led to a reduction in the number of synchronous generators with rotational mass in the system, resulting in a significant decrease in system inertia. The reduced inertia leads to a faster rate of frequency change in the system when

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power is out of balance, weakened anti-disturbance ability, increased risk of frequency over-limit, and poses a serious threat to frequency stability.

2.1.2. Weakened anti-disturbance capability

Renewable energy grid-connected equipment centered on power electronic converters generally lacks the autonomous response capability of traditional synchronous generators, and its output characteristics are highly dependent on control strategies and grid conditions. As the penetration rate of such devices increases, the Grid Strength shows a weakening trend, and the voltage support capacity and disturbance resistance of the grid decline accordingly, which is prone to new stability problems such as wideband oscillation, further increasing the complexity of the safe and stable operation of the system.

In the process of advancing the low-carbon transformation of the energy structure, it is necessary to attach great importance to the stability challenges brought by system inertia and weakened strength, and adopt multi-dimensional measures such as accelerating Grid-Following/Forming technology, energy storage synergy, flexible transformation of traditional units and market mechanism innovation, Comprehensively enhance the stable operation level of the high-proportion new energy power system.

2.2. Operational dispatching challenges

2.2.1. Reverse peak shaving characteristics

When it is shown as negative in the grid load, it is called the reverse peak shaving characteristic, which makes the peak shaving pressure of the system with wind power connected to the grid even more severe, and the demand for peak shaving capacity of the system is greater [1].

Wind power and photovoltaic output have distinct anti-peak shaving characteristics. Photovoltaic power generation is concentrated during the day, with zero output at night; Wind power output is often greater at night and less matched to the daily power load curve. Especially in areas rich in wind and solar resources, the deep valley load of the "duck curve" is easily formed during the midday peak of solar power generation on a clear day, while the peak load is formed when solar power exits and the load rises in the evening. The sharply increasing peak-valley difference poses a huge demand for flexible regulation of resources.

2.2.2. Uncertainty

Wind and solar power output is significantly affected by meteorological factors and has significant volatility and uncertainty. Both medium - and long-term weather changes and short-term fluctuations can cause actual output to deviate from predictions, which requires system dispatchers to allocate large amounts of positive and negative rotating reserve capacity to deal with emergencies, not only increasing system operating costs but also putting higher demands on prediction accuracy and rapid response capabilities.

To address the dual challenges of reverse peaking characteristics and supply-demand uncertainty, it is essential to advance the coordinated development of flexible resource systems. On the one hand, efforts should focus on accelerating the deployment of flexible regulation resources such as new energy storage systems, pumped hydro storage, and gas-fired power plants. On the other hand, active promotion of demand-side response mechanisms and cross-regional mutual support is required. Through market-oriented approaches and multi-dimensional measures, the system's

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regulation capacity and resilience can be enhanced, ensuring a balanced electricity supply, maintaining system reliability, and supporting safe and stable operation.

2.3. Planning challenges

2.3.1. Determine the optimal proportion and distribution of renewable energy installed capacity

In the process of building a new type of power system with new energy as the main body, scientifically determining the optimal installed capacity ratio and spatial layout of renewable energy is the core planning issue for achieving the energy triangle goal - that is, the balance of "energy security, economic feasibility and low-carbon environmental protection". This complex decision should be based on the matching degree of the spatio-temporal distribution characteristics of wind and solar resources with the load demand, systematically assess the absorption capacity and flexibility resource requirements of different regional power grids, and take into account transmission constraints, system inertia support and various stability requirements. At the methodological level, it is usually necessary to rely on high-precision time-series production simulation and multi-objective capacity expansion planning models to conduct large-scale multi-scenario simulations and robust optimizations under objective functions such as the lowest life-cycle cost or the maximum total social welfare, thereby identifying the Pareto frontier solution with the lowest overall system cost and the highest investment efficiency under given carbon constraints and technical conditions. The final optimization scheme is essentially a dynamic iterative planning outcome, emphasizing the integration of centralized and distributed development paradigms, the coordinated development of Generation, Grid, Load and Storage and it needs to be constantly adjusted in response to the decline in technology costs, the improvement of market mechanisms, and changes in the demand for extreme climate response. Therefore, the determination of the optimal proportion and layout of renewable energy is not only a technical and economic optimization issue, but also a systematic project involving energy strategy, spatial planning and market design.

2.3.2. Transformation of the role of traditional thermal power

Liu et al. [2] mentioned in the literature that under the new power system, thermal power has multiple roles including supply guarantee, peak shaving and system stability. First, thermal power still plays the role of a "ballast stone" in ensuring power generation during the transitional period of China's energy transition. Since 2020, China's power supply has gradually emerged from oversupply, with some areas experiencing tight power supply, mostly due to high coal prices, short-term decline in clean energy generation, and insufficient peak power capacity caused by shrinking investment in thermal power plants year by year. Therefore, in the process of decarbonizing transformation of energy, with the large-scale access of new energy, it is still necessary to ensure a sufficient installed capacity of thermal power units to play a bottom-line guarantee role in the special circumstances of power supply and demand imbalance. Second, the flexibility transformation of thermal power is one of the best peak shaving options for achieving the consumption of new energy under the new power system. In terms of total volume, thermal power flexibility transformation is expected to release major regulation capacity under the 14th Five-Year Plan period. Given the long construction period of pumped storage and the unclear revenue mechanism for new energy storage, we believe that under the 14th Five-Year Plan period, the construction of flexibility resources may be dominated by thermal power. According to predictions

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by the China Electricity Council, State Grid and others, China is expected to add 150 million kilowatts of thermal power unit capacity under the 14th Five-Year Plan period. Meanwhile, the National Plan for the Transformation and Upgrading of Coal-fired Power Units proposes to complete the flexibility modification of 200 million kilowatts of existing coal-fired power units (increasing system regulation capacity by 30 to 40 million kilowatts). In terms of cost, compared with pumped storage and novel energy storage, flexibility transformation of existing thermal power units is still the most economical approach. According to the China Electricity Council, the investment cost for flexibility transformation of thermal power to release peak shaving capacity per kilowatt is about 500 to 1,500 yuan per kilowatt, while that for pumped storage and electrochemical energy storage is about 2,500 to 3,000 yuan per kilowatt (considering that pumped storage releases double regulation capacity per kilowatt of installed capacity). Third, the electromechanical characteristics of thermal power units contribute significantly to the stability and balance of the power system. Thermal power, which uses synchronous generator technology, can instantaneously adjust its active and reactive power output according to the frequency and voltage conditions of the power grid, and has significant advantages over wind power and photovoltaic power in maintaining power system stability and fault ride-through capability. In addition, thermal synchronous generators can provide real rotor mechanical inertia to resist disturbances occurring in the power system, a feature that new energy power generation equipment does not have. Therefore, a certain proportion of synchronous motors still need to be maintained in the new power system to ensure the stability of system frequency and voltage.

3. Key technologies for low-carbon optimization on the power generation side

3.1. Optimization of low-carbon power source structure (planning level)

3.1.1. Large-scale development and integration of renewable energy

Lin et al. [3] mentioned the clean substitution of fossil energy by new energy and the realization of energy autonomy and security based on domestic resources. The emergence of China's energy security problem is largely related to China's energy endowment of "abundant coal, scarce oil and limited gas", as well as the consumption structure dominated by fossil energy. In the context of the global energy transition and the rapid development of new energy technologies, to ensure China's energy security in the future, a new understanding of China's energy endowment is necessary. At present, the developed resources of new energy are less than one-tenth of the technical potential for development. Even at such a level of development and utilization, the share of new energy in China's energy consumption structure will be close to 20% by 2024. If the exploitable resources are raised to one-third of the exploitable resources (3.528 billion tons of standard coal) in the future, new energy will meet about half of China's future peak primary energy use demand. Therefore, a more accurate description of China's energy endowment should be "rich in coal, poor in oil, scarce in gas, and abundant in new energy". With further improvement in future development and utilization, it is expected that new energy will account for 27% of China's primary energy use structure by 2030; By 2045, its share will surpass that of fossil energy; By 2060, it will account for 80%, achieving a status shift between fossil and new energy, and relying on the new energy revolution to achieve energy independence and security. Through the integration of new energy with oil, natural gas, coal and other energy categories, large-scale wind, solar and storage infrastructure will be built in fossil energy mining areas, new production models such as clean substitution, multi-energy complementarity and multi-energy integration will be implemented, and oil fields, gas fields

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and coal fields will be built into comprehensive energy bases to achieve the dual goals of increasing the supply of oil, natural gas and coal and consuming green electricity. To ensure energy security during the energy transition, we will focus on domestic efforts. Some studies, taking the Ordos Basin as an example, have proposed the concept of a "super energy system" with a high degree of integration of underground coal, oil, natural gas, geothermal energy and above-ground wind and solar energy, characterized by a high degree of integration and coordinated utilization of underground energy and above-ground new energy, including 1 billion tons of clean coal production projects and 100 million tons of green oil and natural gas production projects. 100 million kilowatt-level wind and solar development and utilization projects, as well as 100 million tons of carbon capture, utilization and storage (CCUS) demonstration projects.

3.1.2. Carbon Capture, Utilization and Storage (CCUS) technology

The principle of CCUS is to convert conventional thermal power plants into carbon capture power plants (CCPS) to capture CO_2 produced by combustion. It requires the CCUS to be optimally configured to achieve the core path of deep decarbonization of thermal power at the power plant level. Essentially, at the system or power plant level, the optimal deployment and capture strategies are modeled to balance the complex relationship between high retrofit costs, significant energy consumption penalties, and carbon reduction benefits. At the power plant level, the capture technology route and capture rate need to be optimized to minimize the cost per kilowatt-hour; At the system level, it is necessary to identify priority retrofit units, coordinate the planning of renewable energy and transport and storage infrastructure, and respond to carbon market price signals, ultimately achieving economic optimality of the power system while meeting carbon emission constraints.

3.1.3. Distributed power source (DG) planning

Pu Yunhao [4] mentioned that distributed power sources in smart grids are a power generation mode that directly generates electricity near the power demand point by utilizing renewable energy or efficient energy conversion technologies. The core principle is to miniaturize and decentralize the power generation equipment and bring it as close as possible to the center of the power load, thereby reducing energy loss due to long-distance transmission and improving energy utilization efficiency. Solar panels and wind turbines can generate electricity based on the actual conditions of sunlight and wind speed, which often coincide with areas of human activity, allowing distributed power sources to provide sufficient electricity during the day or when the wind is strong. In addition, distributed power sources are highly flexible and responsive, which can quickly adapt to changes in load and play a role in peak shaving and valley filling for the power grid. Especially in terms of renewable energy access, distributed power sources can effectively alleviate grid stability problems caused by intermittency and volatility, and optimize energy dispatching through energy storage devices and intelligent control systems. Distributed power sources, through their unique structural design and working principle, enhance energy efficiency while also improving the safety and reliability of the power grid.

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3.2. Flexible power generation resources and operational optimization (operational level)

3.2.1. Flexible operation of Carbon Capture Power Plants (CCPS)

Kong et al. [5] mentioned that in order to achieve multi-level utilization of energy and further reduce pollution emissions, a combined operation virtual power plant of "wind power - photovoltaic - carbon capture power plant - electricity to gas" was designed. The front end is composed of wind power and photovoltaic power generation units, which, in combination with carbon capture technology and electric-to-gas technology, efficiently convert the electricity generated by new energy into natural gas and store the natural gas. The input ends of the system include carbon capture power plant output, wind power output, and photovoltaic output; The output ends are electrical load (electricity) and gas load (natural gas). In addition, carbon storage and gas storage devices are installed in the system. Carbon storage can avoid the problem of temporal and spatial asynchronization between carbon capture power plants and electric-to-gas equipment, and gas storage can facilitate the storage and transportation of natural gas. The workflow for jointly operating the virtual power plant is as follows. During peak hours, when users have a high demand for electricity and natural gas, all the output from wind and solar power is fed into the grid. If it still fails to meet the electricity demand, the shortfall is filled by carbon capture power plants. After the carbon capture units are put into operation, carbon dioxide is captured from the combustion of coal and stored in carbon storage equipment. During off-peak hours, when users' demand for electricity and natural gas is low and the feed-in power of wind and photovoltaic power is large, new energy generation can meet users' demand while still having a certain surplus. At this time, the electric-to-gas system is put into operation, using the excess wind and photovoltaic power to consume the carbon dioxide stored in the carbon storage equipment, converting the carbon dioxide into natural gas and storing the natural gas in the gas storage equipment. After entering the next peak electricity consumption period, the gas storage equipment releases natural gas to fuel the gas-fired units.

3.2.2. Flexibility transformation of conventional thermal power

Li Qiang et al. [6] mentioned that in the peak shaving technology of combined heat and power units, the electric boiler technology, by directly converting electrical energy into thermal energy to supplement the insufficient heat supply, can ensure stable heat supply while reducing the unit load, such as the application of electrode-type hot water boilers significantly reduces the grid-connected electricity, but the energy efficiency is relatively low; Energy storage technology uses energy storage systems (such as lithium-ion batteries) to balance power supply and demand, enhance automatic power generation control capabilities, and increase system regulation flexibility; Direct extraction heat storage technology can achieve thermoelectric synergy over a wide range of loads by storing the heat from the steam turbine extraction and releasing it when needed, but it is complex and costly to modify; Bypass compensation technology uses the idle capacity of boilers to directly supply heat to heat users under low load conditions, significantly enhancing peak shaving capacity, but with relatively low energy efficiency; By cutting off the operation of the low-pressure cylinder and increasing the extraction flow, the heat supply is guaranteed while the power generation load is further reduced to meet the demand for deep peak shaving.

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3.2.3. Multi-energy complementary and coordinated operation

Zhang et al. [7] mentioned that in order to achieve the dual carbon goals, the objective of the multi-energy joint optimal dispatching model of the power grid is set as: ensuring the supply and demand of electricity, minimizing carbon emissions, and reducing the cost of power generation. In the process of model construction, multiple factors need to be considered, including energy generation costs, carbon emissions, energy storage management, etc. The power generation cost model can reflect the differences in power generation costs resulting from different forms of energy, providing an economic cost basis for the mobilization algorithm. Carbon emission models are responsible for quantifying the carbon emissions of various energy sources in order to achieve the goal of minimizing carbon emissions. Energy storage management models also play a significant role, effectively enhancing energy utilization and reducing carbon emissions by rationally mobilizing energy storage and charging and discharging [8]. In addition, the model needs to take into account the stability and safety constraints of the power system operation to ensure the feasibility and reliability of the scheme. Suppose the system contains multiple generating units, each with an output of Pi, where i represents different generating units (thermal power, wind power, solar power, etc.). The optimization objective can be expressed as minimizing the weighted sum of overall operating costs C and carbon emissions E. The mathematical expression is:

$$\min \left(\mathrm{C}\,(\mathrm{P}) + \lambda \cdot \mathrm{E}\,(\mathrm{P}) \right) \tag{1}$$

In the formula: C (P) is the operating cost of the power system, which typically includes fuel costs, equipment operation and maintenance costs, etc. E (P) represents the carbon emissions of the power system; λ is the weighting coefficient, indicating the balance of economic and environmental benefits.

3.3. Market and policy-mechanism-driven

In the context of the power system's low-carbon transition, the carbon trading mechanism significantly influences the energy mix decisions of power generation companies by internalizing the cost of carbon emissions, effectively incentivizing investments in renewable energy and low-carbon generation technologies. Meanwhile, the establishment of ancillary service markets creates a market-based compensation mechanism for resources that provide system regulation functions such as frequency control and operating reserves—including carbon capture, utilization, and storage (CCUS) units, as well as thermal power units that have undergone flexibility upgrades. This enhances the system’s regulation capacity and ensures grid security under high penetration of renewable energy integration. These two mechanisms work in synergy to drive the power industry toward a cleaner, more flexible, and lower-carbon development path.

4. Analysis of current issues

Li et al [8] mentioned that with large-scale wind power grid integration, photovoltaics, and grid integration of other renewables, the randomness and volatility of their output have become increasingly prominent, and traditional power source planning methods are difficult to meet the demand for flexible regulation capacity of high-proportion new energy systems. At the same time, the high proportion of new energy and multi-loop large-capacity DC feed-in have led to a decrease in the inertia level of the receiving grid and a weakening of its frequency support capacity. In

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systems with a high proportion of asynchronous power sources, if serious faults such as DC lockout occur, it may cause rapid frequency drops or even trigger low-frequency load shedding, threatening system safety. Therefore, in the receiving grid with a high proportion of asynchronous power sources, sufficient inertia response and primary frequency regulation resources must be reserved in the power source planning, and the regulation potential of multiple types of flexibility resources must be explored in a coordinated manner to improve the frequency stability level and suppress off-limit frequency risk under large disturbances.

Under the framework of grid modernization, digitalization is crucial., the function of thermal power is gradually shifting from the main power source to the regulatory power source, and load leveling and frequency control potential of thermal power units can be effectively released through flexibility transformation. Existing research has explored from multiple perspectives: an optimized dispatch model including deep peak shaving costs of thermal power has been established, and the impact of the transformation on the economy and operation mode of the system has been analyzed; A capacity planning model for thermal power flexibility transformation was constructed to optimize the transformation scheme while ensuring the uptake of renewable power. The focus is on the coordinated planning of energy storage and clean energy, using the rapid regulation characteristics of energy storage to enhance the System's accommodation limit fluctuating new energy. For distribution networks and microgrids, a "source-grid-load" flexible resource collaborative planning model is proposed.

Although the decline in system inertia and the insufficiency of frequency regulation capacity caused by the increase in new energy penetration have drawn widespread attention, there is still a lack of research considering inertia and frequency safety constraints and coordinating multi-type flexibility resource planning, making it difficult to effectively deal with large disturbance frequency accidents. Some scholars introduce energy storage in their planning to provide virtual inertia and frequency regulation assistance services, but usually do not include the frequency regulation capacity of the new energy units themselves in the resource allocation. In fact, by installing fast active power control systems and station-level active support control systems, new energy units can be retrofitted with frequency regulation capabilities and become an important part of the system's flexibility resources. Therefore, in future flexibility planning, the coordinated configuration and retrofitting needs of various resource types—such as thermal power, energy storage, and renewable energy units—must be systematically taken into account to comprehensively enhance the frequency stability and operational resilience of the receiving-end grid.

5. Conclusion

This paper reviews optimization technologies on the generation side in low-carbon power systems, addressing four key dimensions: energy mix improvement, operational control of power units, intelligent system dispatch, and market design. It examines the challenges related to grid stability, dispatch efficiency, and infrastructure planning faced by power generation systems amid increasing renewable energy integration, and outlines current technical approaches along with their limitations.

The main conclusions are as follows: the transition toward low-carbon power generation is central to achieving the "dual carbon" targets. Building a modern power system characterized by multi-energy complementarity and coordinated interaction among generation, grid, load, and storage requires raising the share of renewable energy, advancing the clean and flexible upgrading of coal-based power generation, and accelerating the deployment of key enabling technologies, notably energy storage and carbon capture, utilization, and storage (CCUS). At the operational level, enhancing multi-time-scale dispatch and coordination of flexible resources is essential. At the

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institutional level, carbon trading and ancillary service markets should be leveraged to incentivize low-carbon investments.

There are still deficiencies in current research: first, there is insufficient overall consideration of inertia and frequency safety constraints in high-proportion new energy systems; second, the coordinated planning of multiple types of flexibility resources has not been systematized; Third, research on system resilience in extreme climates is relatively weak.

Against the backdrop of a rapidly modernizing power grid and intensified efforts toward carbon peaking and neutrality, the operational and control mechanisms of the power system are undergoing profound transformations. Carbon Capture, Utilization, and Storage (CCUS) technology, serving as a crucial pathway for achieving low-carbon operation in thermal power generation, is evolving from a conventional load-following unit to a flexible resource deeply integrated into system regulation. In the future, it is necessary to focus on breaking through the dynamic control strategies and market-oriented business models of CCP's participation in auxiliary services such as frequency regulation and reserve, and clarify the mechanisms for determining regulation capacity, cost compensation and value recovery. The construction of a multi-time-scale power generation optimization framework, the design of mechanisms for the participation of low-carbon technologies such as CCUS in ancillary services, the transformation of the self-regulation capacity of new energy units, and the defense and recovery strategies of systems in extreme weather, in order to fully unleash their rapid carbon capture regulation capacity and load transfer potential, provide flexible support across time scales for the system to enhance the economy, safety and resilience of the new power system.

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