# Research on the Development Trends of Green Power in the New Era

**Jianfeng Li***

*Zhuhai City Polytechnic, Zhuhai Guangdong, China,519000*
**corresponding author:lijianfeng@zhcpt.edu.cn*

***Abstract:*** *Against the dual backdrop of the steady advancement of global climate governance and the in-depth evolution of the energy revolution, green power has gradually emerged as the core backbone supporting China in advancing the strategic goals of carbon peaking and carbon neutrality, with its development level directly shaping the realization path and progressive effectiveness of the "dual carbon" vision. From the macro perspective of energy structure transformation, this paper systematically traces the evolutionary context and in-depth deepening process of the core connotation of green power, focusing on four core development trends—grid connection and consumption of high-proportion renewable energy, pathways to enhance the flexibility of power systems, refinement of market-oriented allocation mechanisms, and empowerment of digital technological innovation—to conduct systematic analysis and in-depth exploration. Studies indicate that green power is currently breaking free from the constraints of the traditional single supply model, moving toward a systematic development paradigm featuring full-chain coordinated linkage of "source-grid-load-storage". This transformative process is not only an indispensable requirement for optimizing the energy structure, but also a pivotal link in constructing a new power system. From the perspective of future development orientation, to accelerate the high-quality development of green power and build a safe, reliable, low-carbon, efficient, and intelligently coordinated new power system, it is imperative to establish a coordinated effort pattern across three key dimensions: breakthroughs in core technological R&D, improvement of institutional and mechanism innovation, and consolidation of policy system guarantees. Through multi-dimensional and coordinated measures, we can address the technical bottlenecks, institutional obstacles, and policy deficiencies in the development process, thereby providing robust driving force for the timely achievement of the "dual carbon" goals.*

***Keywords:*** *Green Power; Energy Transformation; New Power System; Renewable Energy;Digitalization*

## 1. Introduction

As we enter the mid-to-late stage of the "14th Five-Year Plan" implementation, a critical juncture for advancing the 2030 carbon peaking goal, the global energy system is undergoing a fundamental transformation—shifting from a fossil energy-dominated model to one centered on non-fossil energy. This profound transition has reshaped the overall landscape of global energy supply and consumption in an unprecedented way. As the core carrier for achieving decarbonization in the energy production sector, the development logic of green power has gradually transcended the single-minded focus on expanding installed capacity, evolving toward a multi-dimensional holistic consideration of power system operational quality, safety and stability, and economic efficiency. This shift in development focus aligns perfectly with the in-depth demands of energy transformation. In the context of new-era development, the evolution of green power exhibits distinct epochal and distinctive characteristics: the intensification of complex geopolitical games has further heightened the strategic demand of countries worldwide for energy self-sufficiency and security capabilities, driving renewable energy to accelerate toward localized deployment and large-scale development; the frequent occurrence of global extreme weather events has posed unprecedented and rigorous challenges to the power system's anti-disturbance capacity, emergency response capabilities, and overall resilience construction; the leapfrog breakthroughs and widespread application of artificial intelligence technology have not only spurred new demand growth in the power consumption field, but also injected fresh momentum into the intelligent dispatching and precise control of the power system, with technological empowerment as its core. Based on a systematic collation of relevant domestic and foreign research findings and a comprehensive judgment of industry development trends, this paper aims to deeply analyze the development laws and core trends of green power in the new-era context, extract key development pathways and optimization strategies, thereby providing valuable theoretical support and practical reference for the deepening of academic research and the formulation and implementation of policies in related fields.

## 2. Connotation and Structural Evolution of Green Power

### *2.1 Expansion of Connotation*

From the perspective of connotation definition, green power in traditional cognition mainly focused on two core fields—wind power generation and photovoltaic power generation—presenting a relatively singular technical application orientation. Since entering the new era, the connotation of green power has been significantly expanded and enriched, evolving gradually into a diversified zero-carbon power supply system. This system not only covers renewable energy sources such as solar energy, wind energy, biomass energy, geothermal energy, and marine energy, but also includes green hydrogen that meets carbon neutrality development standards, achieving all-round upgrading in both coverage scope and technical forms. Meanwhile, with the continuous improvement and large-scale promotion of the "renewable energy + energy storage" integrated development model, the core "green" attribute inherent in green power is gradually breaking free from the single constraint of the production side, extending in depth and penetrating comprehensively into the consumption side. The orderly development of the green power trading market, the continuous refinement of the green power certificate mechanism, and the in-depth integration with the carbon accounting system have further clarified the accounting standards for the environmental value of green power. This enables the environmental value to be clearly demonstrated and effectively released in the process of market-oriented allocation, injecting sustained market-driven momentum into the high-quality development of green power[1].

### *2.2 Fundamental Transformation of Installed Capacity Structure*

By the end of 2024, the cumulative installed capacity of wind power and photovoltaic power generation in China had achieved a historic breakthrough, surpassing the installed capacity of traditional coal-fired power for the first time and emerging as the core mainstay in the growth of power installed capacity. This milestone signifies that China’s power installed capacity structure has undergone a fundamental adjustment. This structural transition, characterized by the coexistence of "gradual replacement in the stock sector" and "dominance in the incremental sector", is not only a crucial milestone in China’s energy transformation process, but also marks the official entry of the power system into a new development stage dominated by renewable energy—its operational logic and development model are poised to undergo profound changes[2]. According to industry reports released by the National Energy Administration and special forecasts by relevant scientific research institutions, by 2030, the proportion of China’s non-fossil energy power installed capacity in the total national power installed capacity is expected to exceed 60%. Meanwhile, the proportion of non-fossil energy power generation in the total national power generation will also rise steadily, gradually approaching the key 50% threshold, further consolidating and strengthening the dominant position of green power.

## 3. Key Technology Development Trends

### *3.1 "Dual Improvement of Quality and Efficiency" in New Energy Power Generation Technology*

Currently, new energy power generation technology is accelerating its breakthrough from the constraints of the traditional extensive growth model, moving toward an in-depth stage of refined operation and efficient development. This transformative trend aligns with the inherent demand for the large-scale development of renewable energy and serves as the core pathway to enhance the quality of green power supply. In the field of photovoltaic technology, N-type TOPCon and HJT (Heterojunction) batteries have fully replaced the traditional P-type PERC technology, firmly securing their dominant position in the market, with their advantages in conversion efficiency, energy consumption control, and long-term stability fully demonstrated. Perovskite tandem batteries have continuously achieved breakthroughs in laboratory R&D, repeatedly the records for photoelectric conversion efficiency, and are currently in the critical transition stage from pilot line R&D to large-scale mass production. Their industrial application pathway is becoming increasingly clear, and they are expected to become a new growth engine for the high-quality development of the photovoltaic industry in the future. In the field of wind power technology, offshore wind power, leveraging its advantages of superior resource endowments and stable power generation efficiency, has gradually emerged as the core growth pole of the wind power industry[3]. The trend toward large-scale unit development continues to accelerate, with the current single-unit capacity having successfully exceeded 20 megawatts, and the benefits of large-scale development becoming increasingly prominent. Meanwhile, deep-sea floating wind power technology has successfully completed demonstration project verification, with various technical indicators meeting commercial application standards, and is steadily entering the preliminary preparation stage for commercialization. This technological breakthrough has effectively addressed the technical bottlenecks in deep-sea wind power development, laid a solid technical foundation for expanding China's offshore wind power development from nearshore to deep sea, and further broadened the development space of the wind power industry.

### *3.2 Diversified Breakthroughs in Energy Storage Technology*

As the core hub for solving the temporal and spatial mismatch problem of green power, energy storage assumes an irreplaceable regulatory role in the construction of a new power system. Its technical maturity and large-scale application level directly determine the consumption efficiency of green power and the operational stability of the system. From the perspective of the current energy storage system development pattern, pumped storage, relying on its advantages of mature technology and reliable operation, still holds a dominant position in the energy storage field. However, constrained by multiple factors such as geographical resource endowments and ecological environmental restrictions, its future development space is gradually narrowing, with the growth rate of installed capacity slowing significantly, making it difficult to meet the energy storage demand for the future large-scale development of renewable energy. In the field of new energy storage, lithium-ion batteries, leveraging their core advantages of rapid technological iteration and high energy density, continue to dominate the new energy storage market. Among them, the lithium iron phosphate (LFP) technical route, with its outstanding cost control capabilities and excellent safety performance, has gradually become the mainstream application direction in the new energy storage field, widely used in various energy storage scenarios. Meanwhile, compressed air energy storage and flow batteries (including all-vanadium, iron-chromium, and other technical types) have achieved rapid growth by meeting the power system's regulatory needs such as daily peak shaving and cross-day peak-valley filling, relying on their unique advantages of long-term energy storage and long cycle life. Their technical feasibility and application value have been fully verified, demonstrating strong industrial application potential. In addition, emerging energy storage technologies such as gravity energy storage and sodium-ion batteries are accelerating their iteration and upgrading, gradually moving toward the commercial application stage, further enriching the diversified development pattern of energy storage technologies and injecting new vitality into the high-quality development of the new energy storage industry[4].

### *3.3 Hydrogen Energy and Ammonia-Hydrogen Coupling*

Green hydrogen—zero-carbon hydrogen produced by water electrolysis with renewable energy as the core driving force—has been clearly established as the core strategic fulcrum for cross-seasonal storage of green power. It solves the temporal and spatial mismatch problem of green power and promotes in-depth decarbonization in hard-to-abate industries such as steel, chemicals, and shipping, with its development value and strategic significance becoming increasingly prominent in the energy transformation process. Currently, green power-to-hydrogen (Power-to-X) technology is accelerating its breakthrough from the pilot limitations of "wind-solar-hydrogen-storage" integrated demonstration projects, achieving leapfrog development toward the large-scale industrial application stage, with its technical maturity and industrialization level continuously improving. By constructing a synergistic and coupled industrial chain of "green power-green hydrogen-green ammonia/green alcohol", we can not only effectively expand the consumption channels and application space of green power, improve the utilization efficiency of renewable energy, but also open up a feasible, implementable, and promotable practical pathway for the in-depth decarbonization of traditional high-emission industries such as steel and chemicals, supporting the achievement of full-industry-chain carbon emission reduction goals.

## 4. Evolution of Power System Form: New Power System

### *4.1 Integrated Source-Grid-Load-Storage*

With the large-scale integration of high-proportion distributed green power, the inherent thinking of traditional power grid planning is gradually undergoing a fundamental transformation, with its planning focus shifting from the traditional centralized power supply orientation to a multi-dimensional orientation of coordinated development between distributed energy and the power grid[5]. Among them, park-level and county-level "source-grid-load-storage" integrated projects, relying on their core advantages of strong scenario adaptability and high consumption efficiency, have increasingly become the key carrier for solving the distributed green power consumption problem and improving the utilization efficiency of distributed energy, with their development level directly affecting the large-scale promotion process of distributed green power. Supported by microgrid technology, such projects can realize the coordinated optimization and self-balanced operation of power sources, power grids, loads, and energy storage resources within a local area. At the same time, they can establish an efficient and coordinated interaction mechanism with the main power grid through standardized interfaces, effectively suppressing voltage fluctuations, power impacts, and other issues caused by the integration of high-proportion distributed photovoltaic power, reducing their adverse impact on the safe and stable operation of the main power grid, and providing solid guarantees for the orderly integration and efficient consumption of distributed green power[6].

### *4.2 The Rise of Virtual Power Plants*

Against the backdrop of the explosive growth of various distributed energy resources such as distributed photovoltaic power, electric vehicles, and industrial and commercial energy storage, virtual power plants (VPPs)—as the core hub for awakening such "sleeping resources" and tapping their potential utilization value—have become increasingly prominent in their strategic position in the construction of the new power system[7]. With digital management and control platforms as the carrier and intelligent control technology as the core support, virtual power plants can efficiently integrate and coordinately dispatch a large number of scattered distributed resources, break the fragmented barriers between various resources, and form a large-scale aggregation effect of "gathering sand into a tower". On this basis, virtual power plants can deeply participate in auxiliary services such as power grid peak shaving and frequency modulation, and actively integrate into the power market trading system. Through the optimal allocation and refined scheduling of resources, they realize the intensive utilization and efficient management of green power resources, further enhancing the flexibility and operational economy of the power system[8].

## 5. Marketization and Policy Mechanism Innovation

### *5.1 Synergy among Green Power, Green Certificates and Carbon Market*

During the two-year period from 2023 to 2024, the trading scale of green power and green power certificates in China has shown an exponential growth trend, with remarkable market expansion speed and development momentum. It has rapidly developed into a core supporting tool for domestic enterprises to respond to the EU Carbon Border Adjustment Mechanism (CBAM) and fulfill the RE100 green energy commitment, providing an important pathway for enterprises to avoid carbon trade barriers and fulfill their green development responsibilities. Judging from the current industry development trend, green power consumption is gradually breaking free from the constraints of the voluntary consumption market, accelerating its transition to the mandatory consumption market. This transformation will further standardize the order of green power consumption and expand the demand for the green power market. Meanwhile, the coordinated connection mechanism between green power certificates and the national carbon emission rights trading market is in the stage of accelerated construction and improvement, and the in-depth integration of the two will further improve the accounting and realization pathway of the environmental value of green power. Against this development backdrop, the environmental premium inherent in green power is expected to be fully released and reflected in the existing carbon price system, with the accounting standards for its market value becoming increasingly clear. Its market positioning and core competitiveness will be further strengthened, injecting lasting momentum into the market-oriented high-quality development of green power[9].

### *5.2 Reform of the Electricity Price Mechanism*

To adapt to the development needs of the new power system with the continuous increase in the proportion of new energy power generation, China’s electricity price reform is steadily advancing into the deep water zone, gradually breaking free from the constraints of the traditional electricity price mechanism and iteratively upgrading toward a market-oriented, diversified, and refined direction. Specifically, the reform presents two core orientations: first, the formal establishment and implementation of the coal-fired power capacity price mechanism have provided solid revenue guarantees and institutional support for the role transformation of coal-fired power, promoting coal-fired power to gradually move away from its positioning as a traditional main power source and transform into a regulatory and supporting power source, giving full play to its role in peak shaving, frequency modulation, and emergency support in the power system; second, the full integration of new energy into power market transactions has become an inevitable trend in industry development. With the increase in the proportion of new energy power generation, the price fluctuation range of the electricity spot market has expanded significantly. This market environment is forcing new energy projects to actively optimize their development models, effectively mitigating the operational risks caused by negative electricity prices and improving the stability and sustainability of project returns by supporting the configuration of energy storage facilities or participating in aggregated optimization models such as virtual power plants. From the perspective of the overall development pattern, China’s electricity price mechanism is gradually moving away from the single mode of simple energy pricing, transforming toward a multi-dimensional value accounting system of "energy + capacity +

auxiliary services". This transformation not only meets the operational needs of the new power system, but also fully reflects the multi-dimensional value of various power sources, providing market-oriented pricing support for the high-quality development of green power.

## 6. Challenges and Response Strategies

Despite the strong development momentum of green power in China in the new era and the breakthrough progress made in installed capacity, technological iteration, and market-oriented advancement, it still faces multiple practical difficulties and development challenges in the process of moving toward high-quality development, which restrict the large-scale and sustainable advancement of green power. First, the system consumption cost remains persistently high. With the continuous increase in the proportion of renewable energy power generation (such as wind power and photovoltaic power) in total power generation, the flexibility cost required by the power system to ensure safe and stable operation and realize efficient consumption of renewable energy is rising rapidly. Such flexibility costs cover a wide range, including the supporting configuration of energy storage facilities, the construction of backup power sources, and the expansion and upgrading of the power grid structure. Their rapid increase not only raises the overall operational cost of the power system, but also triggers the core problem of cost sharing—how to construct a fair, reasonable, scientific, and efficient cost sharing mechanism and clarify the cost-bearing responsibilities of various market entities has become a key bottleneck that urgently needs to be addressed in the current development process of green power. Second, insufficient power grid capacity and prominent transmission bottlenecks persist. Most of China's large-scale wind and solar bases are concentrated in northwest regions such as deserts, gobi, and wastelands, while the main power consumption load centers are distributed in economically developed central and eastern regions. This significant geographical mismatch between energy supply and consumption demand imposes dual pressures on the planning, construction, and efficient utilization of UHV transmission channels, resulting in the persistent problem that renewable energy in some regions "can be generated but not transmitted". Meanwhile, as the core carrier for distributed photovoltaic grid connection, the existing capacity of the distribution network has gradually approached its limit, with problems such as voltage fluctuations and power imbalance becoming increasingly prominent. It is urgent to improve the flexible regulation capacity of the distribution network through digital and intelligent transformation to break the bottleneck constraints on distributed energy grid connection. Third, the constraints of critical mineral resources are becoming increasingly acute. The rapid large-scale development of green power-related industries such as wind power, photovoltaic power, and electric vehicles has formed a high dependence on critical mineral resources such as copper, lithium, nickel, and rare earths. The supply capacity and supply chain stability of such resources directly affect the development process of the green power industry. Currently, the global geopolitical pattern is complex and volatile, and the mining, processing, and trade links of critical mineral resources are all facing interference from geopolitical factors, with supply chain security facing severe challenges, further increasing the uncertainty of green power industry development. In response to the above development challenges, combined with the needs of building a new power system, a coordinated response strategy can be constructed from three core dimensions—technology, system, and planning—to promote the high-quality development of green power. At the technical level, it is necessary to accelerate the R&D and large-scale application of grid-forming energy storage and grid-forming new energy technologies. Through technological iteration and optimization, new energy power generation can acquire active support capabilities comparable to traditional synchronous generators, improving the controllability and flexibility of new energy power generation, thereby enhancing the safety resilience and anti-disturbance capacity of the new power system and laying a solid technical foundation for the grid connection of high-proportion renewable energy. At the institutional level, we should continue to deepen the reform of the electricity market, break down traditional institutional and mechanism barriers, accelerate the construction of a market system adapted to the development of high-proportion new energy, focus on improving the construction of the capacity market and auxiliary service market, refine the long-term regulation mechanism and price formation mechanism, and fully release the potential of various flexible resources through market-oriented means to guide market entities to actively participate in power system regulation and realize optimal resource allocation. At the planning level, we should strengthen the organic connection between territorial space planning and energy development planning, coordinate the rational use of various spatial resources, optimize the land and sea use policies for new energy projects, scientifically delineate new energy development areas, rationally coordinate the spatial layout of new energy development, avoid blind development and resource waste, and lay a solid resource foundation for the sustainable development of the green power industry.

## 7. Conclusions and Prospects

The core logic of green power development in the new era has gradually moved away from the "quantitative expansion" orientation that solely pursues the growth rate of installed capacity, shifting to the "qualitative leap" stage with the core goal of building a new power system dominated by new energy. Its core connotation has continuously expanded and deepened in terms of coverage and depth, which is in line with the inherent needs of building a new power system. From the perspective of the development cycle, the next five to ten years will become a critical period for green power development to achieve a breakthrough from quantitative accumulation to qualitative change. Combined with the laws of industrial development and the trend of technological iteration, it is expected to present three core deepening trends. First, the production pattern will advance in depth from "centralized dominance" to "coordinated development of centralized and distributed systems". With the popularization of distributed photovoltaic power in thousands of households and the accelerated promotion and application of community-level energy storage technology, the inherent model of traditional energy consumption is being profoundly reshaped, and the traditional boundary between energy production and energy consumption is gradually blurring, forming a new energy development pattern of "production-consumption integration", which further broadens the supply channels and consumption space of green power. Second, the energy form will iteratively evolve from "electricity single-substance dominance" to "electricity-hydrogen-carbon coordinated linkage". Green derived energy products such as green hydrogen, green ammonia, and green alcohol will gradually become important carriers for cross-scenario transmission and utilization of green power, promoting in-depth coupling of multiple high-energy-consuming and hard-to-abate industries such as energy, chemicals, and transportation, building an inter-departmental coordinated decarbonization system, and ultimately forming a clean energy ecosystem with multi-energy complementarity and multi-dimensional coordination to support full-industry-chain carbon emission reduction. Third, the system operation will achieve leapfrog development from "digital empowerment" to "intelligent drive (AI empowerment)". Large artificial intelligence models will fully penetrate the entire process of the green power system, deeply empowering key links such as accurate meteorological prediction, power load forecasting, intelligent operation and maintenance of power generation equipment, and optimization of power market trading strategies, significantly improving the operational efficiency, safety resilience, and economic operational benefits of the green power system, and providing technical support for the safe and stable operation of the new power system. In summary, as the core driving force leading the comprehensive green transformation of the economy and society, the development quality of green power is directly related to the achievement of the "dual carbon" goals and the construction process of the new energy system. Faced with multiple challenges and opportunities in technological iteration, market changes, and institutional improvement, only by adhering to systematic thinking and an overall perspective, coordinating the development of green power and energy security guarantees, and seeking dynamic balance among multiple development goals, can we promote the high-quality development of green power, achieve the carbon neutrality strategic goals as scheduled, accelerate the construction of a clean, low-carbon, safe, sufficient, and economically efficient new energy system, and lay a solid energy foundation for global sustainable development.

**References**

*[1] Zhao Guotao, Qian Guoming, Wang Sheng. Path Analysis of Green Electricity and Low-Carbon Development under the "Dual Carbon" Goals [J]. Huadian Technology, 2021,43(06):11-20.*

*[2] Zhang Xian, Wang Caixia, Xie Kai, et al. Key issues in the construction of China's green electricity market under the "dual carbon" goals [J]. Power System Automation, 2024,48(04):25-33.*

*[3] Ding Feng, Li Xiaogang, Liang Zeqi, et al. International experiences in renewable energy development and their implications for China's related support policies [J]. Electric Power Construction, 2022,43(09):1-11.*

*[4] Zhou Xiaoxin, Chen Shuyong, Lu Zongxiang, et al. Technical characteristics of China's new-generation power system in energy transition [J]. China Journal of Electrical Engineering, 2018,38(07):1893-1904+2205. DOI: 10.13334/j.0258-8013.pcsee.180067.*

*[5] Zou Caicai, He Dongbo, Jia Chengye, et al. The Connotation, Pathways of Global Energy Transition and Their Significance for Carbon Neutrality [J]. Journal of Petroleum Science, 2021,42(02):233-247.*

*[6] Bie Chaohong, Lin Chaofan, Li Gengfeng, et al. Development and Prospects of Flexible Power Systems under Energy Transition[J]. China Journal of Electrical Engineering, 2020,40(09):2735-2745. DOI: 10.13334/j.0258-8013.pcsee.191705.*

*[7] Fan Ying, Yi Bowen. The Laws, Driving Mechanisms and China Pathway of Energy Transition [J]. Management World, 2021,37(08):95-105. DOI: 10.19744/j.cnki.11-1235/f.2021.0109.*

*[8] Zhang Zhigang, Kang Chongqing. Challenges and Prospects in Building a New Power System under the Carbon Neutrality Goal [J]. China Journal of Electrical Engineering, 2022,42(08):2806-2819. DOI: 10.13334/j.0258-8013.pcsee.220467.*

*[9] Shu Yinbiao, Chen Guoping, He Jingbo, et al. Research on constructing a new power system framework with new energy as the main body [J]. China Engineering Science, 2021,23(06):61-69.*