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Typical Scenarios and Technical Requirements of China's Power Grid Towards 2030 for Power System Transformation

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As the critical milestone for China's Nationally Determined Contributions (NDCs) [1], 2030 is a pivotal benchmark year for the transformation of China's power system. From now to 2030, the rapid growth in installed capacity and power generation of wind and solar power will lead to profound changes in the stability mechanisms and balancing characteristics of power systems [2–5], posing new challenges to system security and reliability. Technological innovation is, therefore, urgently required to propel the transformation and upgrading of energy and power systems. However, the traditional technology-driven innovation paradigm is prone to path dependence [6–8]. Against this backdrop, it is necessary to focus on the development trend of power system transformation, taking the scenario-driven approach as the core idea to derive technical requirements and identify directions for scientific and technological innovation, thereby supporting the construction of a new power system during the 15th Five-Year Plan period. Aiming at the NDCs, this study analyzes the key characteristics of power system transformation, constructs typical scenarios of China's power grid towards 2030, summarizes the relevant technical requirements, and puts forward targeted suggestions. This paper is organized as follows: Section 1 outlines the macro transformation trends of China's power system in the new era, followed by the construction and characteristic analysis of five typical scenarios for power grids in Section 2. Section 3 further extracts the main challenges faced by power systems and proposes three critical technical research directions. Finally, Section 4 presents the conclusions and policy suggestions.

1. Transformation trends of China's power system

To construct targeted development scenarios of the power grid, this section assesses the macro trends of the power system transformation, including clean and low-carbon transition of the power supply structure, profound changes in power grid morphology, and restructuring of end-use electricity consumption.

1.1. Clean and low-carbon transition of power supply structure

The clean and low-carbon transition of the power supply mix, characterized by a rising share of wind and solar power generation, constitutes an inevitable evolutionary path for China's power system. This transition primarily manifests in the following three aspects. ① New energy will gradually transform from a supplementary power source to the majority of the installed capacity and ultimately emerge as the main source of electricity. According to relevant research, by 2030, the share of wind and solar power in China's total installed power capacity will increase from 42% to over 50%, while their share in total electricity generation will rise from 18.6% to more than 30% [9,10]. ② The new energy development mode gradually exhibits the characteristics of both centralized and distributed generation, as well as onshore and offshore generation, which will directly reshape the power flow patterns. For instance, the rapid expansion of distributed photovoltaic (PV) and offshore wind power in power-receiving regions, such as east and central China, may potentially reduce the demand for "West-to-East Power Transmission." ③ Coal-fired power units are shifting from base-load power sources (power generation facilities designed to operate continuously at near-constant output, providing the minimum level of power demand) towards flexible regulating resources. As the critical support of inertia (the kinetic energy stored in the rotating masses of synchronized generators across the grid, providing the intrinsic capability to resist grid frequency deviations following a disturbance on generation or load) and voltage stability, coal-fired power will continue to play a vital role in grid security. Its installed capacity will gradually decline after peaking, and its average annual utilization hours will persistently decrease.

1.2. Profound changes in power grid morphology

To adapt to the unexpectedly rapid growth of wind and solar power generation and to ensure large-scale, long-distance, safe, and efficient energy dispatch, power grids will evolve with three key characteristics: expanded transmission scale, complex grid structure, and transformed distribution network functionality. ① The scale of cross-provincial and cross-regional transmission capacity and the proportion of transmitted renewable energy will increase further. The number of ultra-high-voltage direct current (UHVDC) transmission lines is projected to exceed 40 by 2030, which is more than double that of 2024. Meanwhile, the proportion of renewable energy in the electricity transmitted through these channels will increase significantly. ② The power grid structure will become increasingly complex. In power sending ends, which are dominated by the centralized development of new energy in large-scale energy bases (e.g., those in sandy areas, rocky areas, and deserts), grid structures will present various configurations such as alternating current (AC) collection at multiple voltage

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levels combined with conventional direct current (DC) transmission, and AC collection combined with voltage-source converter (VSC) DC transmission. In power receiving ends, multiple UHVDC lines are integrated, leading to centralized DC terminal locations, large infeed capacities, and a low system short-circuit ratio (SCR), which is a key indicator to quantify the strength of the power system. A higher SCR indicates a stronger system at the connection point, meaning that the equipment has less influence on the system performance. ③ The functions of distribution networks are expanding further. The widespread integration of distributed PV, new energy storage (ES) systems, and electric vehicle (EV) charging/discharging facilities will introduce bidirectional and uncertain power flows. Consequently, distribution networks will shift from electricity delivery systems to platforms for optimizing resource allocation.

1.3. Restructuring of end-use electricity consumption

To support high-quality economic and social development, electricity consumption will feature persistent load growth, ongoing structural adjustment, and increasingly complex characteristics. ① The total electricity consumption (TEC) will rigidly increase. It was projected that China's TEC will exceed 13 trillion kW·h by 2030, an increase of over 32% from the 2024 level [11–13]. With the deepening of new urbanization and comprehensive rural revitalization, China's energy and power consumption will continue to grow in the foreseeable future. ② The electricity consumption structure will undergo structural transformation. Accelerated industrial restructuring is slowing down electricity demand growth in heavy industries, while increasing the share of the tertiary sector and residential electricity consumption. Information technology and modern service industries will emerge as the main driving forces for the growth of electricity consumption. ③ The load characteristics will be influenced by diverse factors. First, the widespread integration of distributed power generators, new ES systems, EVs, and other emerging loads, coupled with market-driven user behaviors, will significantly increase the spatiotemporal uncertainty of the load distribution. Second, frequent extreme weather events significantly impact the peak loads, thereby straining the power supply. Third, the rapid growth in cooling and heating demand results in dual-peak characteristics in both summer and winter, considerably complicating the integration of high-penetration renewable energy and the maintenance of supply–demand balance. Additionally, regional socioeconomic development levels and economic structures directly influence power load, resulting in significant disparities in load profiles across different regions.

2. Typical scenarios of China's power grid towards 2030

These trends outline the main characteristics of power system transformation from a macro perspective, including generation, transmission, and consumption. This section proposes five typical power system scenarios for the year 2030. The principles and basis of scenario classification and the characteristics of each scenario are described.

2.1. Principles and basis for scenario classification

To accurately assess the technical requirements of future power grids, it is necessary to further focus on how to realize the power grids' function of resource allocation, aiming to ensure both the secure, efficient electricity transmission and reliable power supply for consumers. To this end, five typical development scenarios are proposed. S1: power transmission of large-scale wind and solar PV power bases in sandy areas, rocky areas, and deserts; S2: power transmission of large-scale deep-sea offshore wind power bases; S3: power transmission of large-scale hydropower bases in southwest China; S4: cross-regional UHVDC power infeed into load centers; and S5: high-proportion development and utilization of distributed new energy. Among these scenarios, S1, S2, and S3 are targeted at the reliable transmission of centralized renewable energy bases, S4 is aimed at the secure power infeed via UHVDC in load centers, and S5 focuses on users' requirements for safe, efficient, and reliable power supply.

The correlation between typical scenarios and the overall transition trends of the power systems discussed in Section 1 is illustrated in Fig. 1. In terms of power structure, all scenarios involve the transformation of the power supply structure, including the increase in the proportion of new energy (S1, S2, and S3), transformation of power development modes (S1, S2, S3, and S5), and transition of power functional positioning (S1 and S4). In terms of grid morphology, S1, S2, S3, and S4 involve both the improvement of cross-regional transmission and the complexity of the grid structure, whereas S5 is more related to the change in the distribution networks. In terms of consumption structure, S5 involves the total consumption increase and the transition of consumption structure as well as load characteristics, whereas S4 is mainly related to the rapid growth of TEC.

To ensure a more comprehensive derivation and analysis of technical requirements, the following four principles are considered in typical scenario identification and classification: ① representativeness, where each scenario can reflect a specific category of the core challenges faced by power system operation; ② foresightedness, where scenarios should be oriented towards the construction and operation requirements of power systems in 2030 and beyond; ③ implementability, where each scenario should correspond to one or several actual regions in China, providing relatively clear guidance for grid planning, construction, and operation; and ④ coverability, where the collective set of all scenarios should basically reflect the core characteristics of power system transformation in 2030 and cover key issues faced by power system operation through an extreme envelope approach.

2.2. Characteristics of the typical scenarios

(1) S1: power transmission of large-scale wind and solar PV power bases in sandy areas, rocky areas, and deserts. Locations: Qinghai Province, south Xinjiang, west Inner Mongolia, and so forth. Main characteristics: large construction scale, with a 10 GW-class installed capacity; a high proportion of new energy, with its installed capacity accounting for nearly or even reaching 100%; far from the main grid, and lacking support from thermal power [14]; transmissions through multi-circuit DC lines, where cascading failures are likely to increase the risk of power grid accidents [15,16].

(2) S2: power transmission of large-scale deep-sea offshore wind power bases. Locations: coastal provinces such as Shandong, Jiangsu, Zhejiang, Guangdong, among others. Main characteristics: large construction scale, with gigawatt-class installed capacity [17]; comprising numerous wind farms; offshore distance exceeding 100 km; and complex meteorological and sea conditions [18,19].

(3) S3: power transmission of large-scale hydropower bases in southwest China. Locations: Dadu River, Jinsha River, Lancang River, and so forth. Main characteristics: cascaded development and utilization of hydropower together with new energy in riverine basins [20,21]; remote from load centers and the main grid; transmission through multi-circuit UHVDC lines, where cascading failures are likely to increase the risk of power grid accidents; harsh environments, and high seismic intensity in some local areas.

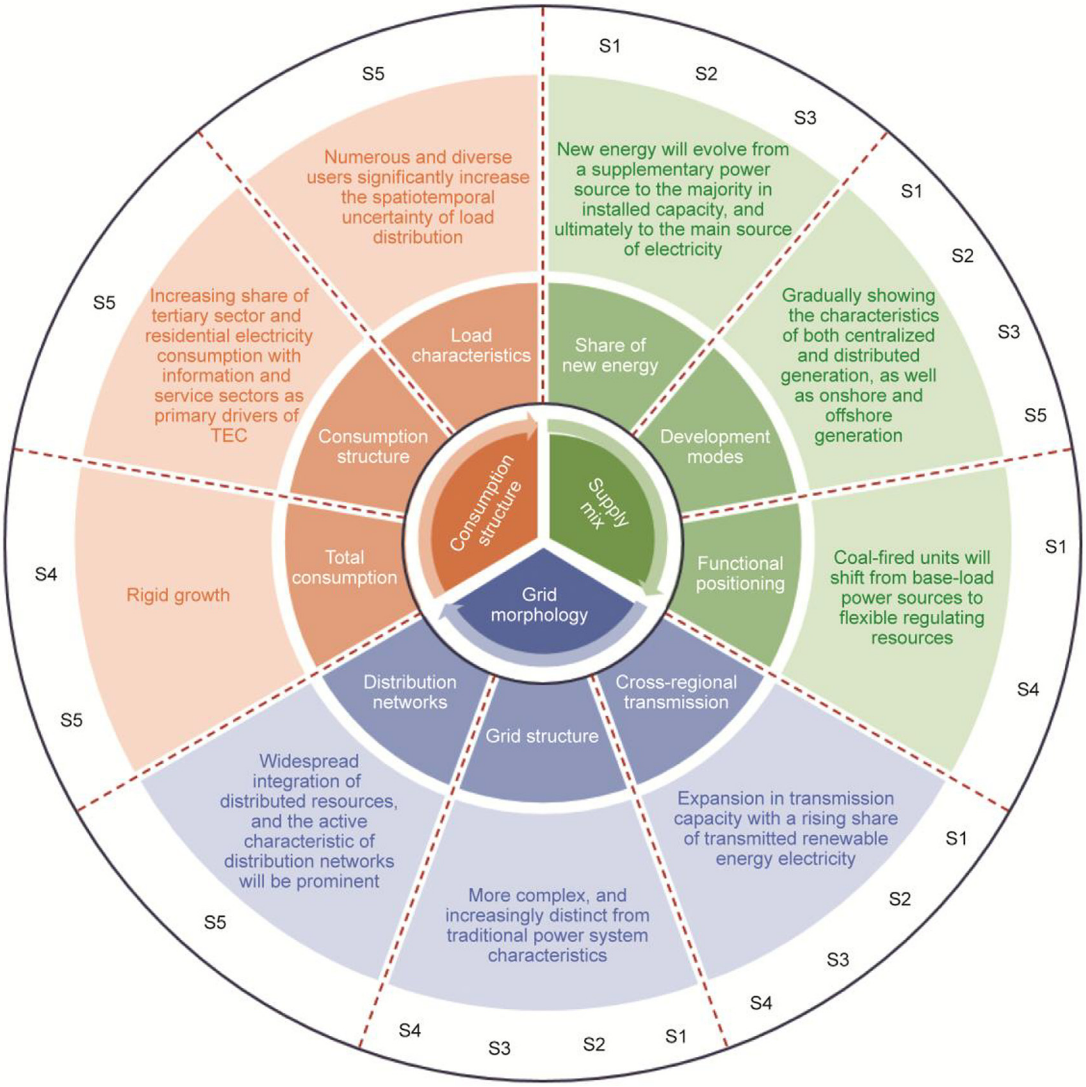

Fig. 1. Correlation between typical scenarios and power system transition trends.

(4) S4: cross-regional UHVDC power infeed into load centers. Locations: east China, central China, Guangdong Province, and so forth. Main characteristics: the proportion of cross-regional infeed power in local TEC approaching 40%; centralized DC infeed terminal locations at the receiving ends [22]; large system short-circuit current (a critical parameter for equipment sizing, protection schemes design, and system strength analysis) [23,24].

(5) S5: high-proportion development and utilization of distributed new energy. Locations: provinces such as Shandong, Hebei, Henan, Jiangsu, and so forth. Main characteristics: the proportion of distributed PV in total installed capacity approaching 40%; numerous entities integrated such as distributed new energy, multi-type ES, EVs, and so forth [25–27].

The common and individual characteristics of these scenarios are summarized via cross-analysis in Fig. 2. Common characteristics include the large-scale installed capacity of new energy clusters (S1 and S2), multi-circuit DC transmissions/infeeds (S1, S3, and S4), remoteness from the main grid/load centers (S1, S2, and S3), extreme/special geological and geographical conditions (S2 and S3), and high penetration of new energy (S1 and S5). As for the individual characteristics of the relevant scenario, S2 presents numerous wind farms with offshore distances exceeding 100 km; S3 presents the cascaded development of hydropower and new energy development in riverine basins; S4 presents the characteristics of cross-regional power infeed proportion approaching 40% and large system short-circuit current; S5 involves numerous integrated entities such as distributed new energy, multi-type ES, EVs, and so forth.

3. Technical requirements

Based on the analysis above, the main technical challenges that may be faced in different scenarios are summarized. Three potential directions for future technological development to address these issues are proposed: reliable power supply, grid security and stability, and equipment performance enhancement.

3.1. Main technical challenges

According to the main characteristics of the above typical scenarios, technical challenges (as shown in Fig. 3) can be categorized into three dimensions:

(1) Reliable power supply. The intermittency and volatility of renewable energy output complicate the supply–demand balance

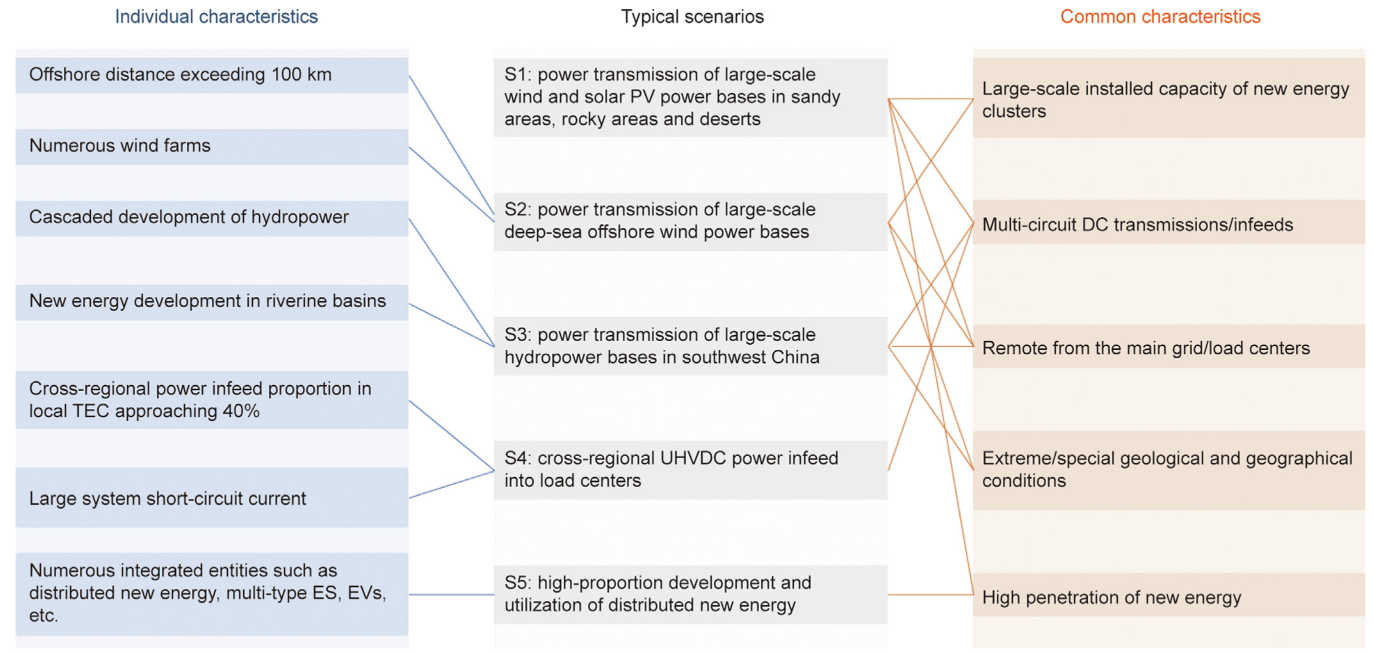

Fig. 2. Common and individual characteristics of typical scenarios.

of electric power and energy, posing challenges to renewable energy consumption and reliable power supply (mainly faced by S1 and S5).

(2) Power grid security and stability. A weak grid structure results in insufficient system support, difficulties in renewable energy collection, and increased risks of grid oscillation. Dense DC transmission corridors exacerbate fault impacts and weaken voltage support at both the sending and receiving ends. The declining proportion of thermal power units reduces the system inertia, posing risks to frequency stability (mainly faced by S1, S2, S3, and S4).

(3) Equipment performance enhancement. Challenges include equipment research and development (R&D), operation, and maintenance under complex geological and geographical conditions, as well as engineering construction and disaster prevention in such environments (mainly faced by S2 and S3).

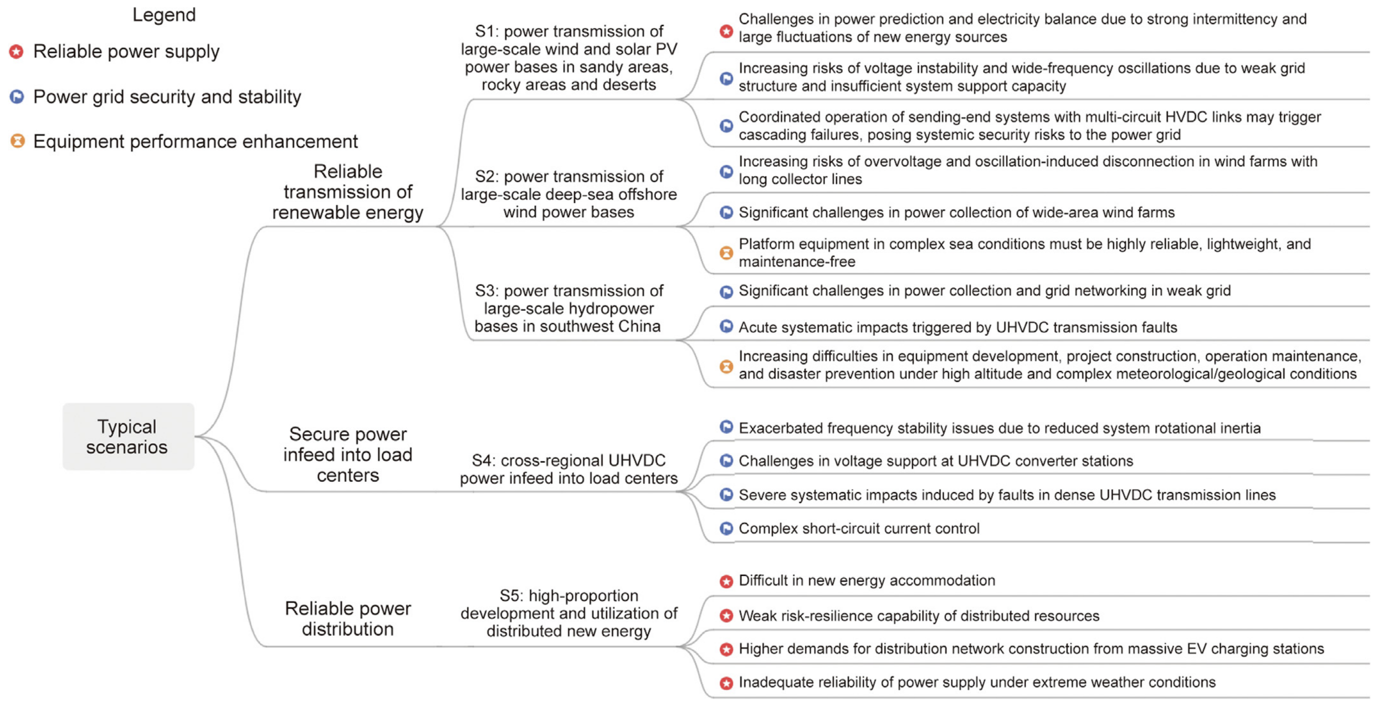

Fig. 3. Main technical challenges in typical scenarios.

3.2. Critical technical research directions

In response to the aforementioned challenges, demand-driven technology R&D should be prioritized in the following key areas to ensure the safe and stable operation of the power grid towards 2030 and to achieve reliable integration and efficient accommodation of large-scale renewable energy.

3.2.1. Reliable power supply

Considering the characteristics of variable renewable energy (VRE) units, such as the high volatility of power generation and low credible capacity, research efforts should focus on the following aspects: developing probabilistic power balance mechanisms, advancing methods for flexible resource evaluation and optimal configuration in power systems with a high proportion of VRE, and studying optimization methods and performance improvement technologies for conventional power sources. Research on power supply strategies under extreme weather conditions is essential to address the increasingly tight power–supply–demand balance. Furthermore, to mitigate the high uncertainties of VRE generation, efforts should be made to clarify the spatiotemporal coupling mechanism between climate/meteorology and new energy output and to develop high-accuracy, long-term VRE forecasting methods.

3.2.2. Power grid security and stability

In view of the characteristics of power electronic devices such as low inertia, low disturbance resistance, and multi-timescale response, in the dimension of system cognition, it is necessary to master the stability mechanisms and quantitative analysis methods for power systems with high-proportion power electronic equipment, develop advanced modelling and simulation methods and tools, and study fault response analysis methods for new power systems. In the dimension of system operation, continuously innovate key technologies in power system operation control, fault defense, and relay protection to ensure the safety and stability of power grids. Efforts should be made to research large-scale new energy DC transmission technologies, propose grid-forming topologies and control methods for new energy generation, and develop multi-resource coordinated fault defense strategies.

3.2.3. Equipment performance enhancement

Power equipment requires improvements in supporting capacity, condition monitoring, and operation and inspection to adapt to complex environments, such as sandy areas, rocky areas, and deserts, deep-sea areas, and high-altitude zones. To this end, ongoing research will focus on enhancing the reliability and performance of traditional transmission and transformation equipment, developing highly reliable flexible grid-supporting equipment, and developing highly autonomous and reliable materials and components for power grid equipment. These efforts aim to resolve "bottleneck" issues in the core materials and components, thereby laying a solid foundation for the construction of new power systems.

4. Conclusions and suggestion

This study provides a scenario-driven perspective for studying the issues of energy and power transformation. To capture the significant demands of China's power grid in its low-carbon transition towards 2030, this study began by outlining the macro-transition trends of the power system. Then, five typical scenarios were constructed: power transmission of large-scale wind and solar PV power bases in sandy areas, rocky areas and deserts; power transmission of large-scale deep-sea offshore wind power bases; power transmission of large-scale hydropower bases in Southwest China; cross-regional UHVDC power infeed into load centers; and high-proportion development and utilization of distributed new energy. Finally, potential challenges and technical research directions are proposed in terms of reliable power supply, grid security and stability, and equipment performance enhancement.

This study presents the following suggestions based on research process and findings:

(1) Conduct a top-level design for technological innovation using scenario-oriented and function-driven principles. Considering evolving factors such as the power source, grid, and load, it is essential to further identify and extract key scenario characteristics, analyze and uncover technical challenges, and strategically plan research directions.

(2) Promote breakthroughs in key technologies for new power systems from a systemic perspective. Use scenario-driven approaches to advance research on equipment, devices, and material technologies while intensifying studies on power system cognition, operational control, and fault defense. The deep integration and application of digital and intelligent technologies in power systems, such as artificial intelligence (AI), should be strengthened. Soft science research is also necessary, for instance, to conduct energy strategy studies integrated with modeling and optimization analysis technologies for complex systems.

(3) Strengthen fundamental and interdisciplinary technological innovation, and propel power science research towards "Four Extremes": the ultra-macro, the ultra-micro, extreme conditions, and highly integrated cross-domain frontiers. The new power system involves multiple disciplines, such as electrical engineering, materials science, meteorology, and information technology, exhibiting distinct big science attributes, such as extreme complexity and strong interdisciplinary coupling. To address the systemic and structural challenges encountered during the transformation and upgrading of traditional power systems, it is urgent to accelerate breakthroughs in fundamental theories and foster cross-disciplinary integration and innovation.

CRediT authorship contribution statement

Qiang Zhao: Writing – review & editing, Writing – original draft, Conceptualization. **Yuqiong Zhang:** Writing – review & editing, Writing – original draft, Conceptualization. **Ziwei Chen:** Writing – review & editing, Writing – original draft. **Xiaoxin Zhou:** Conceptualization. **Jiameng Gao:** Writing – review & editing, Writing – original draft. **Honghua Yang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Statement by H.E. Xi Jinping President of the People's Republic of China at the General Debate of the 75th Session of The United Nations General Assembly [Internet]. 2020 Sep 22 [cited 2025 May 1]. Beijing: The State Council Information Office of China. Available from: http://english.scio.gov.cn/topnews/2020-09/23/content_76731466.htm.

[2] Zhou X, Zhao Q, Zhang Y, Yang H. Analysis of the development trend of China's energy and power system under the dual carbon target: green electricity substitution and green hydrogen substitution. Proc CSEE 2024;44(17):6707–20. Chinese.

[3] Zhao Q, Zhang Y, Zhou X, Chen Z, Yan H, Yang H. A discussion on the flexible regulation capacity requirements of China's power system. Engineering 2024;33(2):12–6.

[4] Xu T, Wang G, Dong Y, Wang C, Li Z. Research on power balance mechanism and evolution of new power system. Proc CSEE 2025;45(1):1–13. Chinese.

[5] Li H, Liu D, Yao D. Analysis and reflection on the development of power system towards the goal of carbon emission peak and carbon neutrality. Proc CSEE 2021;41(18):6245–58. Chinese.

[6] Zhang Z, Kang C. Challenges and prospects for constructing the new-type power system towards a carbon neutrality future. Proc CSEE 2022;42(8):2806–19. Chinese.

[7] Zhang C, Yang H, Zhao Y, Ma L, Larson E, Greig C. Realizing ambitions: a framework for iteratively assessing and communicating national decarbonization progress. iScience 2022;25(1):103695.

[8] Zhuo Z, Zhang N, Xie X, Kang C. Key technologies and developing challenges of power system with high proportion of renewable energy. Autom Electr Power Syst 2021;45(9):171–91. Chinese.

[9] The National Energy Administration released the national power industry statistical data for 2024 [Internet]. 2025 Jan 21 [cited 2025 May 1]. Beijing: National Energy Administration of China. Available from: https://www.nea.gov.cn/20250121/097bfd7c1cd3498897639857d86d5dac/c.html. Chinese.

[10] Zhou X. Research on the development trend of China's energy and power systems under dual carbon targets: on a new energy system with non-fossil electricity coupling with hydrogen. Report. Beijing: 10th Anniversary of Tsinghua University Energy Internet Innovation Institute; 2025.

[11] State Grid Energy Research Institute. Analysis report on the development of new power system 2024. Report. Beijing: China Electric Power Press; 2024.

[12] China energy transformation outlook 2024. Report. Beijing: Energy Research Institute; 2024.

[13] China power market outlook to 2035, update 2025—market trends, regulations, and competitive landscape. Report. London: GlobalData; 2025.

[14] Cai X, Huang W, Li G, Guo Z, Cao R, Yuan Z. Research on operation control strategy of large-scale photovoltaic cluster transmission via grid-forming VSC-HVDC. Proc CSEE 2023;43(22):8734–45. Chinese.

[15] Xin B, Guo M, Wang S, Li X. Friendly HVDC transmission technologies for large-scale renewable energy and their engineering practice. Autom Electr Power Syst 2021;45(22):1–8. Chinese.

[16] Liu T, Yan J, Liu Y. Frequent pattern growth-based identification of critical lines in cascading failures for renewable-dominant hybrid AC/DC power systems. Engineering 2025;51:158–70.

[17] Yao G, Yang H, Zhou L, Li D, Li C, Wang J. Development status and key technologies of large-capacity offshore wind turbines. Autom Electr Power Syst 2021;45(21):33–47. Chinese.

[18] Pan E, Yue B, Li X, Zhao Z, Zhu Q. Integration technology and practice for long-distance offshore wind power in China. Energy Convers Econom 2020;1(1):4–19.

[19] Li Z, Hu P, Ma J, Gao M, Huang H, Liu X, et al. Analysis and prospect of offshore wind power development in China. China Offshore Oil Gas 2022;34(5):229–36. Chinese.

[20] Zhang J, Cheng C, Yu S, Cheng C, Zhang Z, Yang Y. Progress, challenges and prospects of research on hydropower supporting the flexibility of new power systems. Proc CSEE 2024;44(10):3862–85. Chinese.

[21] Liu X, Guo C, Chi Y. Study on the power transmission capacity of multiple type power bundled HVDC transmission system under different wind–PV–hydro ratio conditions. Proc CSEE 2024;44(13):5051–63. Chinese.

[22] Li G, Wang T, Xin Y, Jiang S, Wang W, Liu X. A rapid identification method for commutation failure risk area in multi-infeed high voltage direct current receiving-end power grid. Proc CSEE 2022;42(1):140–53. Chinese.

[23] Li P, Shu Y, Gu C, Liu T, Zhao L. Development and prospect of UHV transmission technology. Renew Energy Syst Equip 2025;1(1):8–19.

[24] Song F, Yu X. Adaptability analysis of UHV interconnection to metropolitan 500 kV power network. Electr Power Constr 2021;42(7):58–64. Chinese.

[25] Chen W, Jin X, Wu M, Lv J, Zhang Y, Ning X, et al. Thinking on the rapid evolution of distribution network form under the carbon peaking and carbon neutrality goals. Proc CSEE 2024;44(17):6811–8. Chinese.

[26] Fu Y, Chong C, Arras M, Ma L, Li Z. A holistic picture of China's distributed energy systems: tracing energy use from energy sources, infrastructure to final demand. Energy 2025;328:136235.

[27] Shu Y, Tang Y, Zhang Z, Zhang F, Yang L, Zhong W, et al. Construction of new distribution network and its key technologies. Proc CSEE 2024;44(17):6721–33. Chinese.