Technology Review for Carbon Neutrality

Review

A systems-oriented review of China's wind and solar power development toward carbon neutrality

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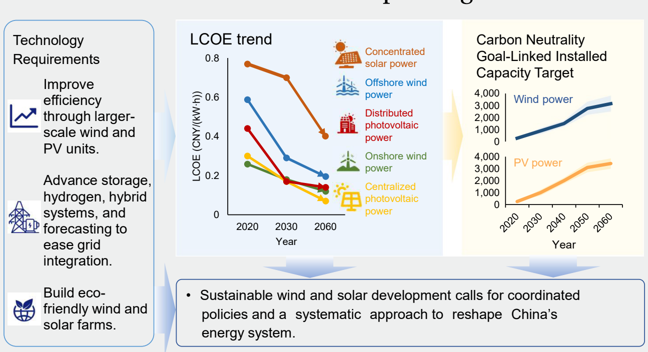
ABSTRACT

Wind and solar power are central to China's carbon neutrality strategy and energy system transformation. This review adopts a system-oriented perspective to examine the future development of wind, photovoltaic (PV), and concentrated solar power (CSP), situating technological progress within a broader framework that includes forecasting approaches, power system flexibility, energy storage integration, and sectoral coupling. It summarizes the spatial potential and projected capacity trajectories under carbon neutrality goals, with estimates suggesting a combined capacity of 5,496 to 7,662 GW of wind and solar power by 2060, constituting more than 83% of China's total installed power capacity. While notable progress has been made in technological maturity and the reduction of power generation costs, supported by robust domestic supply chains, persistent challenges remain across technical and systemic dimensions, including limited generation efficiency, the high cost of supporting energy storage technologies, and constraints on grid flexibility and policy coordination. This review further proposes a strategic roadmap for sustainable development, emphasizing the integrated deployment of wind and solar as the dominant sources of power generation.



KEYWORDS

Wind and solar power; photovoltaic (PV); concentrated solar power (CSP); forecasting technologies; energy system transformation

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1. Introduction

Decarbonizing energy systems is fundamental to mitigating climate change, particularly given the expected long-term increase in electricity demand[1,2]. On September 22, 2020, China pledged at the 75th United Nations General Assembly to peak carbon emissions by 2030 and achieve carbon neutrality by 2060[3], marking a major step towards a low-carbon future. However, China's power system has historically relied heavily on coal[4,5], with thermal power generation producing nearly 5.5 billion tons of carbon emissions and continuing to increase over the past two decades, now accounting for more than 45 percent of national emissions[6,7]. This heavy dependance on coal-fired power poses a major challenge to achieving the carbon neutrality targets, making the shift to wind and solar energy a critical step for building a "zero-carbon" electricity system[8-11].

Over the past fifteen years, China has rapidly expanded its wind and solar capacity, making them central components of the national power system. By the end of 2024, China's combined wind and solar installations had reached 1,407 GW, accounting for 42.0% of total power capacity and contributing 15.4% of national electricity consumption[12]. As of the first quarter of 2025, China's wind and solar power capacity reached 1,482 GW, surpassing coal-fired power capacity (1,451 GW) for the first time[13]. Looking ahead, deployment of wind and solar power is expected to accelerate as China pursues its long-term decarbonization goals. This trajectory aligns with the commitment made at the 18th G20 Leaders' Summit in September 2023 to triple global renewable capacity by 2030[14]. In this context, China's continued expansion of wind and solar power is set to play an increasingly important role in supporting global climate action[15-17].

Amid the anticipated large-scale expansion of wind and solar energy, improving their efficiency and reliability will require continued innovation in both core technologies and supporting systems[18,19]. The transition to wind and solar power presents a unique set of challenges. Unlike traditional thermal power generation, the efficiency of wind and solar power generation primarily depends on technological advancements, such as the efficiency of wind turbine generators and the conversion efficiency of photovoltaic cells[20,21]. Wind and solar energy performance is also influenced by factors like wind speed and solar irradiance, which vary considerably across different geographic locations and times of day[22-24]. In particular, given the long-standing reliance on coal-fired power in China's electricity system, the large-scale rollout of wind and solar requires careful system-level planning to maintain reliability and meet residential electricity demand during the transition[7,25].

Against this backdrop, this review provides a comprehensive examination of the development trajectory of wind and solar power (including both photovoltaic and concentrated solar power, thereafter referred to as PV and CSP, respectively) in China. It explores the unique advantages and key challenges associated with wind and solar power deployment, while analyzing how technological innovation and power system transformation are creating new opportunities for future growth. Drawing on existing studies and policy related to China's future power system, the review outlines prospective installation pathways and development timelines for wind and solar energy. In doing so, it also examines the development of supporting technologies for wind and solar power, providing insights into building a reliable, cost-effective, and sustainable electricity system aligned with China's long-term decarbonization goals.

2. Wind and solar resource and development patterns in China

The potential development of wind energy technologies ranges from 29.3 to 45.1 trillion kW·h[26-28], and solar energy technologies from 66.5 to 92.9 trillion kW·h[29-31]. This theoretical wind and solar potential far exceeds the electricity demand for carbon neutrality, with wind estimated at 4 to 6 times and solar at 9 to 13 times the 2020 consumption level (7.51 trillion kW·h)[29]. These abundant wind and solar resources form the basis for China's large-scale renewable energy deployment. By reviewing the literature (Fig.1(a)), the installed capacity in operation of wind and solar power in China is forecasted to reach between 1,582 to 2,130 GW by 2030[32-35], expected to soar to between 5,496 and 7,662 GW by 2060[33,34,36].

The large-scale expansion of wind, PV, and CSP will serve as a key driver in reducing their levelized cost of electricity (LCOE), thereby enhancing their cost competitiveness relative to coal-fired power (Fig.1(b)). When considering only the generation-side LCOE, both onshore wind and PV have already demonstrated certain cost advantages. Considering the stability requirements of power systems, previous research[37,38] integrated the levelized cost of storage (LCOS) for four-hour-duration lithium-ion battery systems and calculated the combined LCOE of wind/PV plus storage systems. The results indicate that by 2030, the LCOE of wind and solar power with storage is expected to reach near parity with coal-fired power. Specifically, the average LCOE of onshore wind, offshore wind, centralized PV, and distributed PV with battery storage is projected to decline to 0.44, 0.55, 0.43, and 0.43 CNY/(kW·h), respectively, by 2030, and further to 0.33, 0.41, 0.28, and 0.35 CNY/(kW·h) by 2060. The decline in LCOE driven by the large-scale deployment and application of wind, solar, and storage technologies will enhance the economic viability of renewable-based power systems and provide a solid foundation for their further expansion.

However, regional disparities in wind and solar resources and installations in China pose challenges for the equitable expansion of the nation's power systems[39,40]. The onshore wind power potential is concentrated mainly in the northern, northeastern, and northwestern regions of China, while offshore wind power is promising in east China and the southern coastal areas. Advances in deep-sea wind technologies and declining costs are expected to unlock far-offshore wind potential in eastern and southern China. The solar power potential of PV is substantial in the northwest and north, leading to a concentration of centralized PV power installations in these regions. In contrast, distributed PV power generation, which relies on rooftop space, has a higher installation volume in the northern, central, and eastern regions of China[41,42]. Due to the requirement for large land areas, the resources of CSP are concentrated in the northern and northwestern regions of China, with currently operational CSP plants also mainly located in these areas.

To tackle regional disparities and the integration challenges of intermittent wind and solar power, it is essential to strengthen cross-regional high-voltage transmission grids and develop infrastructure that accommodates regional resource variations[43]. Energy storage solutions, such as batteries, pumped hydro, and flywheel energy storage, can effectively mitigate the variability of wind and solar generation[44]. Additionally, expanding transmission infrastructure, implementing smart grid technologies with advanced forecasting, and adopting demand-side management strategies like time-of-use pricing will improve energy distribution efficiency and grid stability[45,46].

3. Technological and economic evolution of wind and solar power in China

This section provides a comprehensive review of the technological evolution of wind power, PV, and CSP in China, emphasizing key advancements in efficiency, scale, and cost competitiveness. In addition to generation technologies, it also examines the development of forecasting techniques across multiple timescales, which are essential for supporting the stable and flexible operation of renewable energy systems with high penetration levels.

3.1 Wind power technology

Since 1980, the evolution of wind power technology in China has progressed through several distinct phases: initial exploration of wind power technologies and their applications, substantiation and promotion, and preparation for large-scale development and deployment[51]. Currently, China's wind power sector possesses a mature industry chain with robust research and development capabilities, characterized by an ongoing shift towards larger-scale turbines[52]. In 2024, the average unit capacity for newly added onshore and offshore wind power

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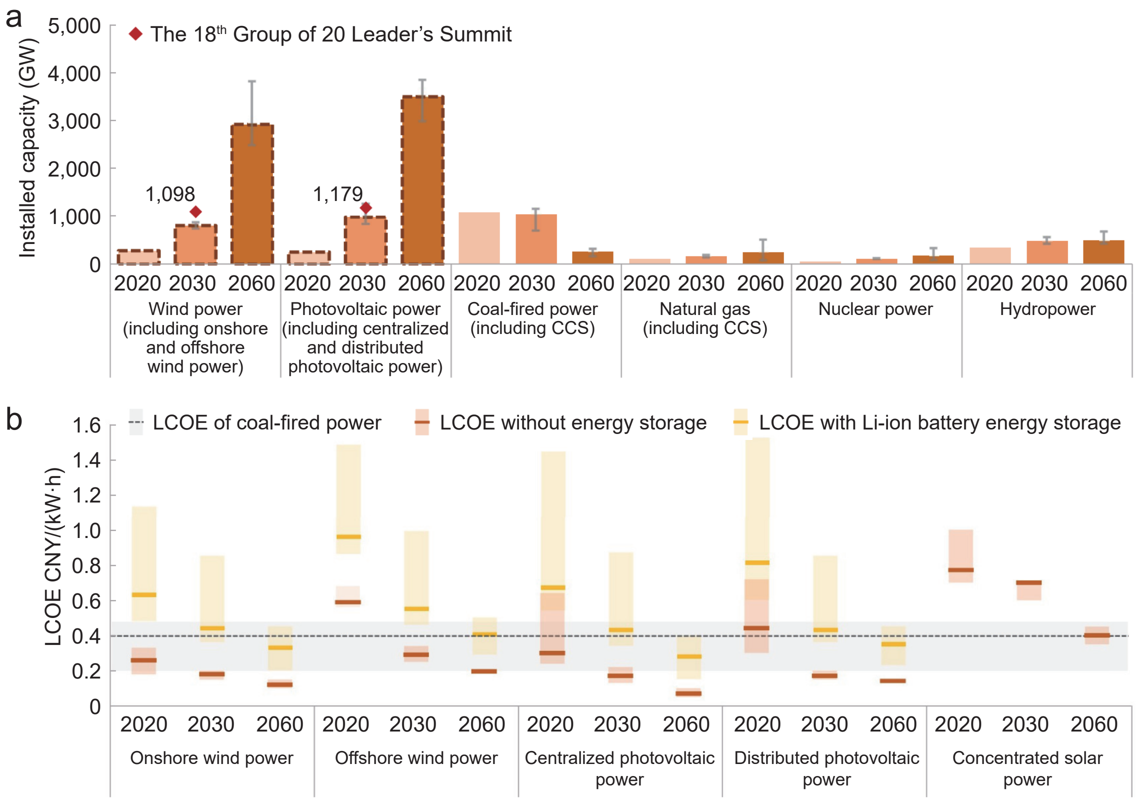

Fig. 1. China's wind power, photovoltaic (PV), and concentrated solar power (CSP) installation capacity, cost trends, and resource distribution. (a) The installed capacity for various power sources in 2020, 2030, and 2060 under the prevailing scenarios of China's carbon peaking and carbon neutrality goals [11, 32, 36, 47]. **(b)** Projected levelized cost of electricity for wind, solar power, and systems combined with lithium-ion storage in 2020, 2030, and 2060 [27, 37, 38, 48-50].

projects reached 5.9 MW and 10 MW, respectively (Fig. 2(a)). Wind power capacity is projected to further increase in the future, with onshore wind turbines expected to exceed 8 MW and offshore wind turbines reaching up to 17 MW by 2035, substantially enhancing wind power generation efficiency[53]. Looking ahead, the continued scaling-up of wind turbines will drive demand for lightweight design in key components such as blades and nacelles, underscoring the need for technological innovation in composite materials and structural optimization[54].

The Renewable Energy Law enacted in 2006, together with the zonal feed-in tariff subsidy policy introduced in 2010[55], significantly accelerated the deployment of wind power in China. By the end of 2024, China's cumulative installed capacity reached 521 GW, accounting for 45.9% of the global total (Fig. 2(b)). Onshore wind has dominated this growth, accounting for 92.1% of total wind capacity in 2024. In contrast, offshore wind development started gaining momentum only after 2017, with installed capacity rising from just 2.8 GW in 2017 to 41.3 GW by 2024. Regionally, the rapid expansion of onshore wind in remote inland areas, combined with the high population density and major urban clusters in eastern China, has strained grid infrastructure and contributed to power curtailment issues[56]. To address the mismatch between resource distribution and electricity demand, large-scale and clustered offshore wind deployment near eastern coastal demand centers offers a more efficient solution. While most of China's current offshore wind capacity remains near-shore, future expansion into deeper and farther waters is anticipated due to higher wind resource quality and reduced spatial conflicts. This shift will not only ease transmission pressures from west to east but also enhance local power supply[57-59]. Realizing this potential will require breakthroughs in deep-sea foundation design, floating turbine technology, and corrosion-resistant materials, which are essential for the reliable and cost-effective development of far-offshore wind power[60,61].

The prices of wind turbines in China have dropped substantially since 2003, offering a considerable cost advantage over those in other major wind turbine manufacturing countries[27,62]. This decline has helped reduce capital expenditures and enhanced the overall competitiveness of wind power development. As shown in Fig. 2(c), the price of onshore wind turbines fell from 8,000 CNY/kW in 2003 to 1,359 CNY/kW in 2024, compared to an average of approximately 4,500 CNY/kW in other countries and regions. Offshore wind turbine prices have also decreased markedly, particularly since 2016 when deployment accelerated, reaching 2,800 CNY/kW in 2024, while the average price in other countries and regions remains above 6,000 CNY/kW (Fig. 2(d)).

The rapid decline in wind turbines costs is the primary driver behind the reduction in the cost of wind-generated electricity[63], with onshore LCOE falling by 70% since 2006[26,50] and offshore LCOE dropping by 56% since 2010[50]. With the ongoing shift toward larger wind turbine models[53], continued cost reductions in wind power are anticipated, mainly due to falling costs of key components[49,64]. Excluding storage costs, the LCOE for onshore wind projects will range from 0.17 to 0.22 CNY/(kW·h) between 2025 and 2030 (Fig.1(b)), while offshore wind projects are expected to have an LCOE of 0.30 to 0.38 CNY/(kW·h) over the same period. Looking ahead to 2060, the LCOE is expected to range from 0.1 to 0.15 CNY/(kW·h) for onshore wind projects and between 0.19 and 0.20 CNY/(kW·h) for offshore wind projects.

3.2 PV technology

The evolution of China's PV technology and industry encapsulates a journey from humble beginnings with small-scale applications to a period of growth propelled by overseas markets[65], followed by a phase of expansive development driven by synergistic demand from both global and domestic markets, leading to the current focus on quality and efficiency[66]. The rapid development of China's PV industry has positioned Chinese PV as a global core product[17]. This growth has also driven advancements in PV cell development and increased conversion efficiencies[67]. Figure 3(a) illustrates the overall improvement in the comprehensive efficiency of China's mass-produced PV cells from 2008 to 2024[68].

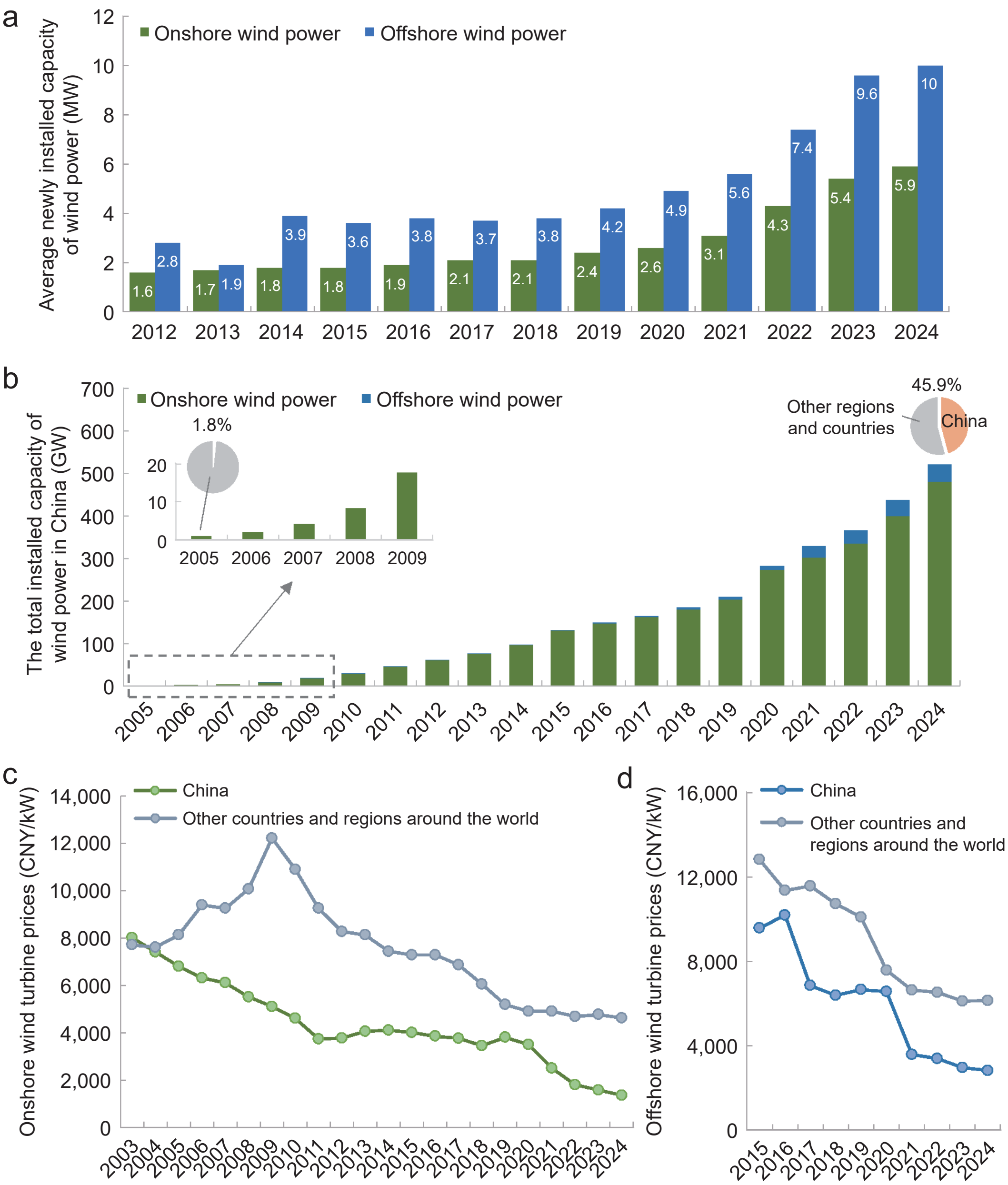

Fig. 2. Average newly installed capacity, total installed capacity, and unit price changes of wind power. (a) Average capacity of newly installed onshore and offshore wind turbines in China from 2012 to 2024. **(b)** Total installed capacity of onshore and offshore wind power in China from 2005 to 2024, including its share of global installed capacity (pie chart). **(c)** Onshore wind turbine prices in China and other countries and regions (2003–2024, excluding towers and foundations). **(d)** Offshore wind turbine prices in China and other countries and regions (2015–2024, excluding towers and foundations).

Since the implementation of the zonal feed-in-tariff subsidy policy in China in 2010[55], the country's PV installed capacity has experienced rapid growth (Fig. 3(b)). By the end of 2024, China's cumulative PV installed capacity had reached 886 GW, accounting for 41.3% of the global total. Notably, PV installation surged between 2022 and 2024, even surpassing wind power additions during this period. Within this overall growth, distributed PV has played an increasingly important role. Since 2017, distributed PV installations have expanded rapidly, with recent growth rates markedly outpacing those of centralized systems. By 2024, distributed PV accounted for 42.3% of China's total PV capacity. This shift toward distributed PV not only enhances the localized utilization of solar resources, but also contributes to energy security and helps reduce the burden on transmission infrastructure, particularly in delivering power from resource-rich northern and northwestern regions to the more energy-intensive eastern and southern areas of the country[69,70].

Continuous advancements in PV technology, coupled with economies of scale, have markedly accelerated the reduction in PV system costs (Fig. 3(c))[10,71]. Between 2010 and 2024, both PV module and system prices have seen substantial declines, with system costs encompassing not only module prices but also inverters, mounting structures, construction, and installation expenses. By 2024, the price of PV modules in China had dropped to 0.84 CNY/W, compared to an average of 1.44 CNY/W in other countries and regions. Meanwhile, the price of PV systems (excluding storage) in China fell to 3.16 CNY/W. The decline in module and system costs is also driving down the LCOE for PV generation. Without accounting for energy storage, projections indicate that by 2030, the LCOE for centralized PV generation in China will further decrease to less than 0.15 CNY/(kW·h), while that of distributed PV generation will see reductions to less than 0.20 CNY/(kW·h). Moreover, it is anticipated that by 2060 the LCOE for both centralized and distributed PV generation will decrease to less than 0.15 CNY/(kW·h) (Fig. 1(b)).

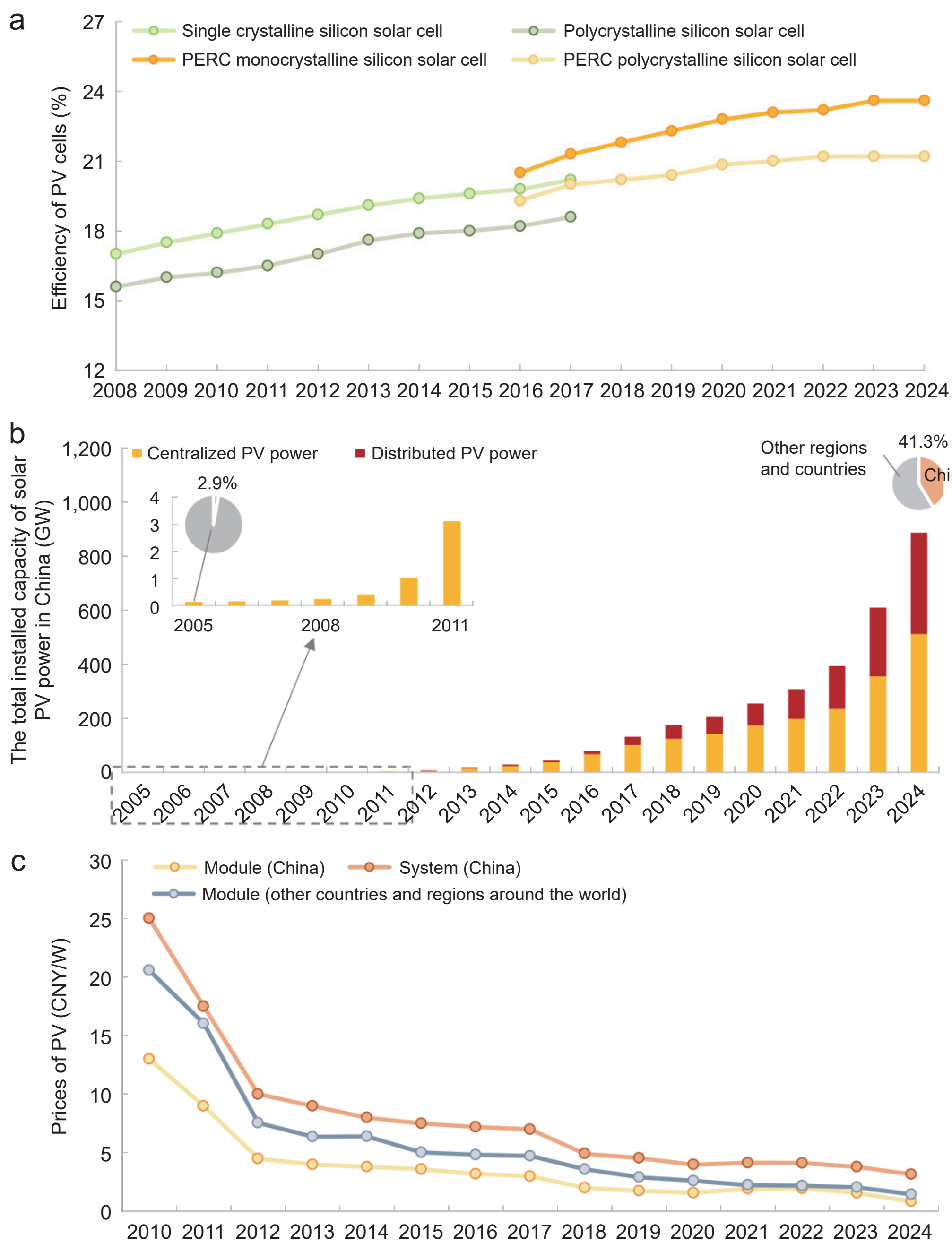

Fig. 3. Changes in the production efficiency of China's main PV cells, total installed capacity of PV, and cost trends of PV technology in China. (a) Efficiency of PV cells from 2008 to 2024 in China. **(b)** Total installed capacity of centralized and distributed PV power in China from 2005 to 2024, including its share of global installed capacity (pie chart). **(c)** Price trends of PV modules and PV systems in China and other countries and regions from 2010 to 2024.

3.3 CSP technology

CSP technology is another pivotal element within renewable energy, playing a crucial role in power generation, energy storage, heating and carbon reduction[72–74]. With its first CSP experimental system established only in 2004[75], and the CSP is currently in the early stages of broad-scale deployment in China[76]. China's new CSP generation demonstration projects achieve a high domestic sourcing rate, with up to 95% of equipment and materials being locally produced[77]. This local production provides China with a notable cost advantage. Currently, China's operational CSP capacity constitutes 8% of the global total, placing it fourth worldwide (Fig. 4(a)). China's dominance in CSP technology arises from the advantages of tower-type power plants (Fig. 4(b)), which excel in high temperatures, operational conditions, and efficiency, making them the primary configuration for China's CSP generation[78].

The establishment of CSP plants is not only related to solar radiation resources but also to the adaptability of natural geographic conditions, such as land slope, type, elevation, and road accessibility[79,80]. Considering these conditions, the northwestern and northern regions of China, which possess abundant solar radiation resources and favorable land and geographic conditions, are ideal for CSP plants construction. Notably, the Xinjiang, Inner Mongolia, Qinghai, Tibet, and Gansu provinces collectively account for 95% of the national potential for CSP installations[81]. Reflecting the distribution of solar thermal resources, 538 MW of China's currently operational CSP capacity is concentrated in the northern and northwestern regions. However, the existing installed capacity is still far below its potential, indicating growth opportunities for solar thermal power in China. Moreover, the development of CSP in China will not only contribute as a power source but also enhance the overall stability and reliability of the energy system by integrating with local wind and PV power through its thermal storage capabilities[82–84].

The LCOE for new CSP generation projects in China is notably higher than that for wind and

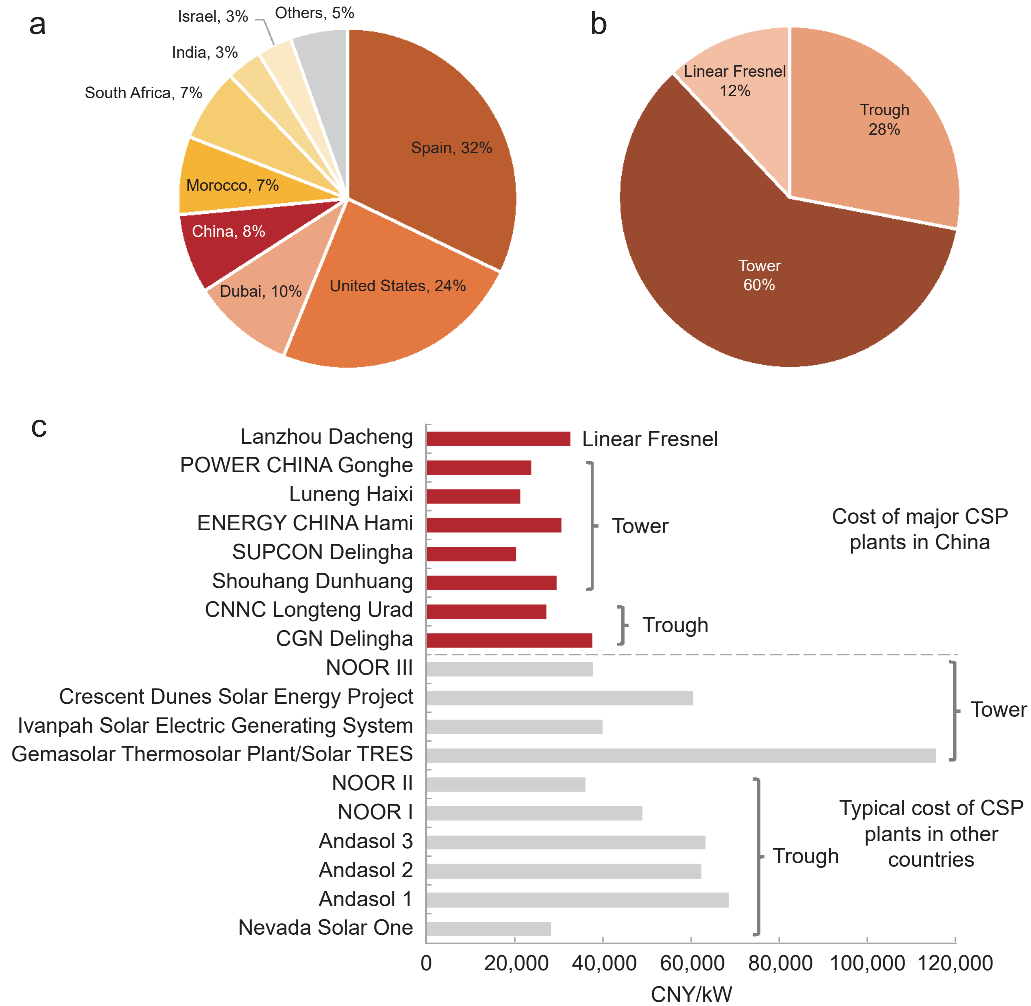

Fig. 4. Installed capacity shares of CSP in various countries, the proportion of different types in China, and cost comparisons. (a) Global distribution of operating CSP plants by the end of 2023 (total capacity of 6,494 MW). **(b)** Installed capacity distribution of trough, tower, and linear Fresnel CSP plants in operation in China by the end of 2023 (total capacity of 546 MW). **(c)** Cost comparison of typical CSP plants between China and other countries.

PV power, ranging from approximately 0.7 to 1.0 CNY/(kW·h)[85,86]. The discrepancy primarily stem from the hefty upfront investment required for CSP technology[87]. For instance, a standard 100 MW CSP station equipped with 8 hours of thermal storage costs between 12,000 and 17,000 CNY/kW (Fig. 4(c)). A considerable portion of this initial cost, approximately 77%, is dedicated to the concentrators, heat absorption, storage, and exchange systems[86,88]. The elevated costs of key equipment and materials are further exacerbated by the relatively small scale of domestic CSP projects and market volatility due to policy fluctuations. An analytical breakdown of the cost structure for CSP stations in China has identified three primary dynamics influencing the cost of electricity: economy of scale, operational and maintenance expenses, and the contributions of technological advancements and management efficiencies[88,89]. Projections suggest a downward trend for LCOE of CSP in China, with expectations for it to drop below 0.70 CNY/(kW·h) by 2030[89]. Between 2050 and 2060, the cost is expected to decrease to an LCOE between 0.35 and 0.45 CNY/(kW·h)[89].

Both CSP and PV technologies contribute to the expansion of renewable energy in China, but their competitiveness varies by region and application. CSP excels in areas with high direct normal irradiance (DNI), such as western and northern China, offering dispatchable power through thermal storage and supporting grid stability. However, its higher costs, land requirements, and reliance on DNI-rich regions limit its broader adoption. In contrast, PV systems are characterized by lower costs, higher technical maturity, shorter construction periods, and broader geographic suitability, making it applicable for most regions.

3.4 Wind and solar power generation forecasting technology

The meteorological risks associated with climate changes and the inherent variability of wind and solar power introduce uncertainties in grid integration[66,90–100]. In China, advancing wind and solar power generation forecasting technology is crucial due to regional mismatches between renewable energy resources and electricity demand, as well as limited power system flexibility[101]. Accurate forecasting enables precise planning and reliable operations within the power system, optimizing energy deployment and storage, reducing energy expenses, and enhancing revenue. Future improvements in forecasting capabilities will rely heavily on advances in numerical weather prediction, power forecasting algorithms[102–104], and the integration of artificial intelligence in meteorological modeling[105,106].

Forecasting across different timescales serves diverse yet complementary purposes, each offering practical value in supporting the operation, planning, and resilience of renewable power systems (Fig. 5). Short- and ultra-short-term forecasting integrates satellite data, ground-based observations, and machine learning with operational data from wind and solar power plants to support real-time dispatch and enhance system flexibility[107,108]. Medium- and long-term forecasting relies on numerical simulations and sub-seasonal to seasonal (S2S) models for scheduling and strategic planning[109,110]. Across all timescales, statistical extrapolation, machine learning, and AI have demonstrated significant advantages over traditional numerical models, particularly in terms of computational efficiency, accuracy,

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uncertainty quantification, and multi-scale prediction[111,112]. Notably, AI-based models such as Huawei Cloud's Pangu-Weather and Google's Neural GCM have substantially accelerated forecasting speed while maintaining, and in some cases improving, prediction accuracy, highlighting the transformative potential of data-driven approaches in weather and climate modeling[111,112]. These advances are expected to enhance power system management, strategic planning, and climate resilience, especially in complex and data-rich operational environments.

4. A system-oriented development roadmap for wind and solar power in China

By analyzing the parallel technological trajectories of wind and solar power, this section outlines the future requirements for installed capacity, core technological advancements, and the need for coordinated development with supporting industries. In recent years, the faster-than-expected expansion of wind and solar power in China has created substantial challenges for grid integration, which in turn has affected the operational efficiency of these resources. Despite significant progress in wind and solar power technologies, systemic barriers remain, such as limited generation efficiency, inadequate energy storage, and insufficient grid flexibility, which continue to constrain the reliable and cost-effective deployment of renewable energy[39,113]. In response, this section adopts a system-oriented perspective to explore future development pathways for wind and photovoltaic technologies, emphasizing an integrated roadmap to guide their sustainable expansion within China's broader energy transition framework.

4.1 2025–2030

With China's carbon peak target and renewable energy goals set at the G20 Summit, the total installed capacity of wind and PV is expected to reach 2,200 to 2,400 GW by 2030 (Fig. 6(a)). This projection is based on international policy targets, in contrast to the optimization model-based estimates in Section 2.1. In practice, installation rates over the past two years have already outpaced most modeled scenarios, suggesting a faster-than-expected trajectory. Achieving this target will require an average annual addition of 150 GW of new wind and PV capacity from 2025 to 2030, alongside the commercial development of CSP and integrated renewable energy systems to optimize the development model of renewables and ease pressure on the power grid, thereby facilitating a smoother transition of the electricity system.

Enhancing energy efficiency through materials innovation and technological advancement is the primary focus at the current stage of wind and solar power generation technologies. For wind power, this involves prioritizing the development of large-scale, lightweight blades, modular and intelligent gearboxes, as well as integrated and modular inverter control systems. Advancing offshore wind into deeper waters offers a viable pathway to access more stable wind resources, reduce costs, and enable large-scale deployment through improved grid integration. In solar PV technologies, the emphasis is placed on industrializing high-efficiency cells, advancing module encapsulation techniques, and developing large-size, ultra-thin monocrystalline silicon wafers to improve power generation efficiency[114,115]. Exploring rooftop deployment and integration with industrial parks can also reduce land use pressures and lower costs associated with large-scale ground-based projects. For CSP, continued technological innovation and the establishment of stable pricing mechanisms are crucial to enhancing cost competitiveness and scaling up capacity[87,116,117]. Furthermore, to strengthen the overall quality of the industry and foster technological innovation, it is essential to establish public verification platforms and technical standards for wind and solar power products in China, while aligning these standards with international practices[118,119].

Integrating "wind and solar + various industries" such as agriculture, hydrogen production, and transportation to promote green electricity direct supply mechanisms offers a promising solution to enhance load-side adaptability to fluctuations in wind and solar power, thereby alleviating grid pressure[120–124]. The coordinated development of energy storage supports the creation of a resilient power system, helping to protect grid stability by providing sufficient capacity at power plants. This fosters a positive feedback loop, enabling the acceleration of renewable energy expansion and enhancing energy security. In this context, accurate forecasting will play a key role in facilitating these integrations, ensuring the optimized utilization of green energy[125].

4.2 2030–2050

This period marks a profound transformation in China's power system, shifting the focus from achieving carbon peak to reaching carbon neutrality. The combined installed capacity of wind and solar power is projected to reach 4,700 to 6,731 GW by 2050, reflecting a two- to fourfold increase relative to the expected levels in 2030.

To support the continued growth of wind and solar power, it is recommended that

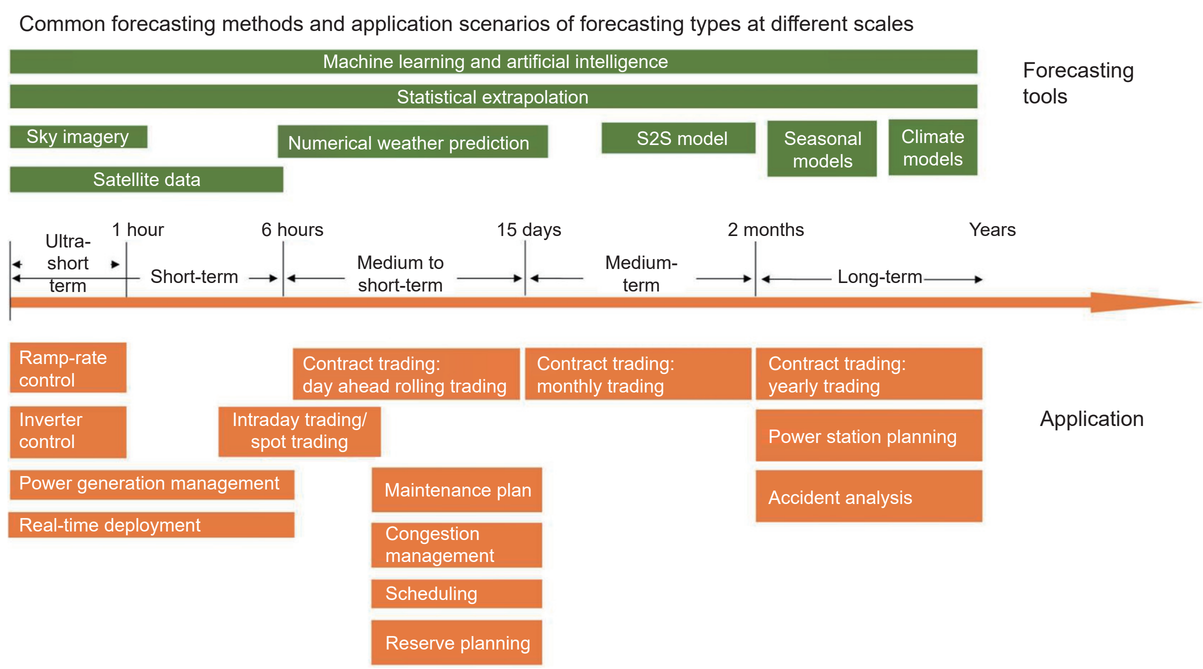

Fig. 5. Forecasting methods and their application scenarios at different scales for wind and solar power.

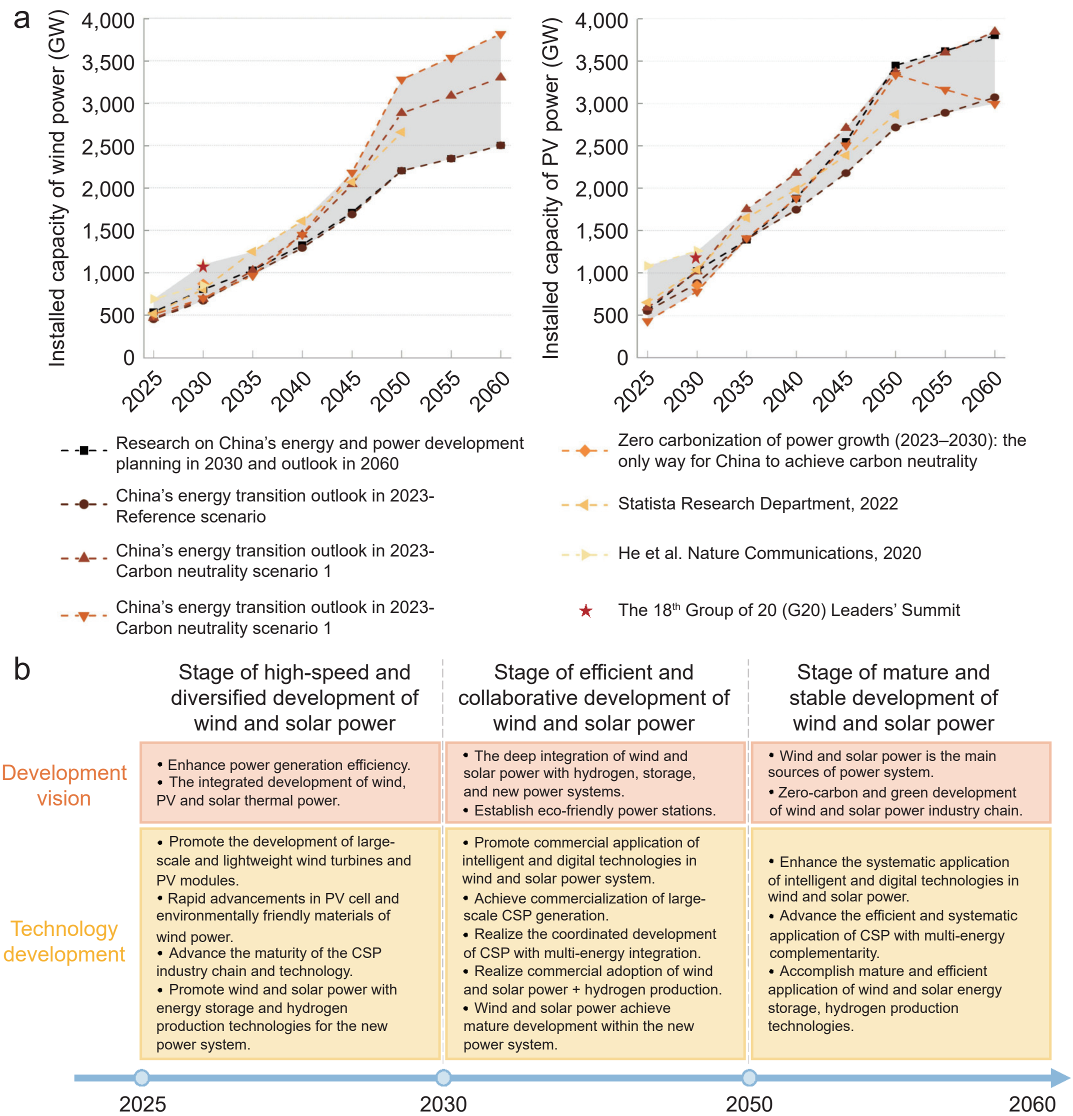

Fig. 6. Future roadmap for wind and solar power in China. (a) Summary of China's wind and PV installed capacity development path from 2025 to 2060 under the carbon peak and carbon neutrality goals. The data are sourced from the reports by CET[36], GEIDCO[33], RMI[35], and Statista[133], as well as research by He et al.[32] and Wei et al.[47]. **(b)** Key stages and technology development of wind and solar power in China.

advancements in generation efficiency and digital applications be prioritized, as these will drive further improvements in power output and integration[126]. The establishment of intelligent platforms for wind and solar power is essential for seamless integration with the grid, enhancing system coordination and reliability, while the development of minute-level meteorological forecasting technologies is crucial for optimizing this integration, improving responsiveness to extreme weather events, and minimizing operational disruptions[127]. Unlike wind and solar PV power, CSP has progressed more slowly toward commercialization. Therefore, achieving large-scale industrialization and commercialization of CSP at this stage will require targeted incentive policies and international collaboration[83,128,129].

This period will witness the large-scale deployment of wind and solar power, requiring deep integration with a multi-energy complementary grid, load-side management, and energy storage technologies to enhance stability, flexibility, and efficiency in renewable energy utilization. A key approach to achieving this integration involves establishing wind and PV station bases in synergy with CSP facilities. By leveraging the storage capabilities of CSP, these integrated bases will enhance system resilience and operational efficiency, supporting the development of a robust multi-energy system[84,130]. Among the critical applications of "wind-solar + various industries", large-scale wind-solar hydrogen production stands out as a strategic focus, especially between 2040 and 2050. This strategy can effectively connect power generation with end-use sectors such as industry and transportation, optimizing energy efficiency, alleviating grid pressure, and enhancing the flexibility of the energy system[131].

4.3 2050–2060

This period represents a pivotal phase in the pursuit of China's carbon neutrality goals. During this decade, wind and solar power are set to become the primary sources for the power system, advancing the deep decarbonization of the energy sector. By 2060, China's installed wind power capacity is projected to reach between 2,500 and 3,817 GW, while installed solar power capacity is anticipated to range from 2,997 to 3,845 GW (Fig. 6(a)).

Throughout this decade, digital technologies in wind and solar power will achieve full maturity, providing systematic support for the smart evolution of the power system[132]. Utilizing big data for optimized day-ahead scheduling of wind and solar resources will drive the full-scale intelligence of the power system. This involves seamlessly integrating sources, the grid, loads, and storage, and deeply incorporating emerging resources like virtual power plants with flexible assets such as energy storage and hydrogen production, thereby enhancing the system's operational efficiency and reliability.

Electronic supplementary material

Supplementary material is available article in the online version of this article at https://doi.org/10.26599/TRCN.2025.9550010.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. The author Xi Lu is the Executive Editor-in-Chief of this journal. The author Kebin He is the Editor-in-Chief of this journal.

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