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Energy Storage for Renewable Energy in China: A Review of Development, Technological Progress, and Socioeconomic Considerations

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Abstract. As of the close of 2025, the cumulative installed capacity of wind and photovoltaic (PV) power in China had exceeded 1.84 billion kilowatts, surpassing coal power for the first time. However, as the installed capacity continues to increase, the problem of wind and solar curtailment has intensified again. During the initial six months of 2025, national wind curtailment rate climbed to 5.7%, and the PV curtailment rate reached 6.6%. To address the intermittency and volatility of renewable sources, the integration of storage systems has become a key pathway. This paper systematically reviews the status, geographical distribution, and technological trends of wind and PV expansion in China, centering on how storage technologies enhance the consumption capacity of renewable energy. The study finds that the combination of pumped hydro installations and lithium-ion battery configurations constitutes a pivotal mechanism for enhancing both system flexibility and stability. The Yalong River Basin Water-Wind-Solar Hybrid Green and Clean Renewable Energy Demonstration Base is taken as an example to explore the multi-energy complementary operation mode. Attention also needs to be paid to regional differences, social issues during the transformation process, and the improvement of policy mechanisms in the future.

Keywords: Energy Storage, Renewable Energy Integration, Wind and Solar Power, Pumped Hydro Storage, Multi-energy Complementary System

1. Introduction

Amid escalating global climate change and the active promotion of energy transition, the large-scale development of renewable energy has become one of the core issues. As the world's largest emitter of carbon dioxide and the largest investor in clean energy, China has achieved substantial progress in wind and photovoltaic (PV) power generation over recent years [1]. By the close of 2025, China's installed wind and PV power capacity will rank foremost globally, establishing the nation as the principal engine driving worldwide renewable energy expansion [1]. However, the rapid growth of installed capacity also makes the problem more prominent, and the instability of wind and PV power generation is becoming more obvious. In some areas, the frequency of power outages caused by wind and solar power plants is increasing, which puts additional pressure on the grid.

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In order to meet this challenge, energy storage technology is an indispensable tool because it can help smooth fluctuations in power supply and increase the flexibility of the grid. In recent years, the rapid development of pumped storage power stations and lithium-ion batteries has laid a technical foundation for the realization of integrated wind, light and storage systems [2]. The continuous operation of the hybrid clean and renewable energy demonstration power station built in the Yalong River Basin Water-Wind-Solar Hybrid Green and Clean Renewable Energy Demonstration Base (referred to as the Yalong River Base), which integrates hydropower, wind power and solar energy, has provided important practical experience for China and the world.

Although there has been a lot of research on renewable energy utilization and energy storage technology, there is still a lack of systematic analysis of the current situation, challenges and future trends of the combination of wind energy, solar power and energy storage systems in China. This paper summarizes the scale, geographical distribution and technological development trend of wind and PV in China. In addition, the role of energy storage technology in enhancing the ability of power grid to integrate renewable energy is analyzed in detail, and the effectiveness and challenges of this integrated system are investigated with specific examples. This paper also analyzes the current situation of China's clean energy development from two different perspectives of technology and system, considers the key policies and the latest data, and emphasizes the social challenges in the process of transformation, emphasizes the necessity of a "just transition", and provides suggestions for the initial stage of transformation.

2. Development status of wind and solar power generation in China

2.1. Scale and structure

Between 2022 and 2025, China's installed wind and solar power capacity skyrocketed (Table 1). In general, it increased by 1.31 billion kilowatts (kW) [3]. By the end of 2025, the total installed capacity of wind and solar power in China had reached more than 1.84 billion kW, accounting for about 47.3% of the country's total power generation capacity, exceeding the capacity of thermal power plants for the first time. Installed capacity of solar power was about 1.2 billion kilowatts and that of wind power was about 640 million kilowatts.

In 2025, installed wind power capacity increased by approximately 100 million kW, and installed solar power capacity reached 1,200 gigawatts (GW) by the end of the year, a 35.4% increase from the previous year. According to forecasts, in 2026 the capacity of new wind power plants will reach 120 million kW, while the capacity of new solar power plants is expected to range from 180 to 240 million kW [3].

Table 1. Installed capacity and year-on-year growth rate of China's wind & PV power (in the past four years)

Level	2022	2023	2024	2025
Wind power (GW)	365	441	521	640
Year-on-year growth (%)	11.2	20.7	18.0	22.9
Solar power (GW)	393	609	887	1200
Year-on-year growth (%)	28.1	55.2	45.2	35.4

From January to November 2025, wind and solar power generation accounted for 16.7 % of China's total power generation. Although these data show significant growth, they are still very low

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compared to the proportion of total installed capacity, indicating that grid-connected pressure still exists.

Moreover, China has maintained a world leading position in wind and solar power installed capacity for more than a decade, accounting for nearly half of the world's total installed capacity of wind and solar power. In summary, in recent years, China's wind power and solar power generation have shown a continuous growth trend in terms of total installed capacity and power generation, which indicates that China has great development potential in this field.

2.2. Major geographical distribution

China's wind farms are mainly distributed in the northwest, north and northeast regions with rich wind energy resources, concentrated in Inner Mongolia, Xinjiang, Hebei, Gansu, Shanxi and other provinces [4]. Onshore wind power occupies an absolute dominant position in these areas. At the same time, in the southeast coastal areas with high demand for electricity and dense power grids, wind farms are also concentrated, especially in Guangdong, Jiangsu, Shandong, Fujian and Zhejiang provinces. However, the wind farms in these areas are mainly at sea [4].

The distribution of solar power stations in China has the regional differentiation characteristics of "large-scale centralized power stations in the west and scattered small power stations in the east". At present, large-scale solar power stations are being built in the vast desert and Gobi areas in western China, which are becoming the strategic hub of clean energy in China. For example, per capita solar power generation in Qinghai Province reached 6.2 kW [5]. This "green power" is transported to the central and eastern regions through high-voltage power lines. At the same time, in Henan, Anhui, Hubei and other central regions, as well as Shandong, Jiangsu, Zhejiang, Guangdong and other eastern coastal areas, the power generation of distributed solar power stations should not be underestimated. The solar power station in Shandong Province has the highest power generation potential in the country, about 400 million kW [5].

The location of wind power plants and solar power plants in China is usually geographically highly coincident. In the western region, wind and solar energy resources are rich, focusing on the construction of large-scale wind and solar complementary power stations. The southeastern coastal areas play an important role in the deployment and development of offshore wind and distributed solar power stations.

2.3. Technological development and cost trends

The strategic emphasis within the wind power sector is gradually changing, no longer just increasing the scale, but also enhancing the reliability and utilization rate of power generation. Technological innovation in the field of solar power generation is still very active. The overall trend is shifting from competition based on scale and price to competition leading in the pursuit of technological efficiency. Through technological innovation in the past 10 years, China has reduced the total cost of wind and solar power generation by more than 60% and 80% respectively [6]. It is projected that the mean generation cost for wind and solar facilities stands roughly 30% beneath that of coal-fired installations. Such cost advantage constitutes the pivotal catalyst propelling forthcoming market expansion.

Currently, wind and solar generation technologies in China are relatively mature. In recent years, the capacity utilization rate (actual power generation / installed capacity) has exceeded 90%. This success is mainly due to the support of energy storage technology, especially pumped energy storage

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technology. Going forward, to accommodate the escalating requirements of the power network, storage technologies anchored in pumped hydro principles will persist in fulfilling a vital function.

3. The rationale for integrating energy storage technology with renewable power generation

3.1. The intermittency of renewable energy sources

Owing to the intrinsic properties of wind and solar resources, the yield from wind installations exhibits pronounced variability across daily cycles, while solar facilities produce electricity predominantly during daylight hours and cease generation after dusk. A comparison of these two energy sources shows that solar energy better matches the load on the power grid, whereas wind energy peaks at night, leading to an imbalance with the grid's demand.

Statistical data show that wind power output is high at night and low during the day [7]. Peak wind power output is typically observed from 8:00 PM until early morning. This does not align with societal electricity consumption patterns, leading to poor alignment between supply and demand.

The discontinuous nature of wind and solar generation is inextricably linked to the pressing issue of curtailment, referring specifically to the intentional curtailment of wind and solar output. The magnitude of curtailment affecting these sources in China attained its apex during 2015-2016. In 2015, the aggregate curtailed quantity from wind and solar sources constituted 15% of the overall national curtailment volume, and throughout the initial six months of 2016, this share surged rapidly to 21% [8]. The quantities of wind electricity curtailed in China during 2015 and 2016 reached 33.9 billion kWh and 49.7 billion kWh, correspondingly [9]. Attributable to the incorporation of energy storage technologies, the utilization ratio of wind and solar resources in China has stabilized at approximately 95% in recent years. Since 2017, China has been actively promoting a model that couples extensive wind and solar deployment with energy storage infrastructure. As shown in Table 2, thanks to this model, the share of curtailed wind energy decreased from 17% in 2016 to 4.1% in 2024; however, due to the continued expansion of installed capacity in the first half of 2025, it rose slightly to 5.7% [9].

Table 2. Wind curtailment rates before and after large-scale deployment of integrated wind-solar-storage systems

	2015	2016	2024	2025
Wind curtailment rate (%)	15	17	4.1	5.7

3.2. Key energy storage technologies

Currently, the main energy storage technologies are PHS, compressed air energy storage (CAES), flywheel energy storage (FES), lithium-ion batteries, flow batteries, and supercapacitors.

Storage solutions may be categorized by duration into short-term high-frequency, medium-short duration, and long-duration categories, each with distinct technical characteristics and application scenarios (Table 3). Among all technologies, pumped hydro storage represents the most commercially mature, while electrochemical energy storage, mainly based on lithium-ion batteries, is developing rapidly. China has now formed a development pattern based on pumped hydro storage technology and dominated by lithium-ion battery energy storage technology; the cumulative installed capacity and scale of pumped hydro storage remain the largest, but the newly installed capacity of lithium-ion battery energy storage is continuing to grow rapidly [10]. Based on data from

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the National Energy Administration of China at a press conference, in 2025, newly installed independent energy storage will reach 35.43 million kW, with lithium-ion battery storage occupying a dominant position, accounting for 96.1% of the installations [10].

Table 3. Installed capacity and year-on-year growth rate of China's wind & PV power (in the past four years)

Level	2022	2023	2024	2025
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Pumped hydro storage technology belongs to long-duration energy storage technology, generally with a discharge duration of several hours to several days; under the condition of having a very large reservoir, it can achieve storage across weeks or even seasons, to match the seasonal variations of wind and solar energy [11]. However, the disadvantages are also obvious: slower response speed, site selection depends on terrain, long construction period, and high initial investment.

Lithium-ion battery energy storage, as a medium- to short-term energy storage technology (the general energy storage time is within four hours), has a fast response time ranging from seconds to milliseconds, and its construction period is relatively short, allowing it to be put into use relatively quickly [12].This is a supplement to pumped storage hydropower generation technology ; by combining the two technologies, the power generation of wind energy and solar energy can be adjusted more comprehensively, thereby improving energy efficiency.

A pumped hydro storage facility is a storage system that uses hydropower to store and generate electricity [11]. This system is usually composed of two or more reservoirs at different heights. The upper and lower reservoirs are connected by pipelines to form a closed loop of water flow. The operation principle of pumped hydro storage rests upon the transfer of water between two reservoirs. The power station operates in the same operational mode as the conventional hydropower plant in the power generation mode. Water from the top level of the reservoirs flows down to generate electricity. In the pumped storage mode, the system obtains electricity from the power grid to elevate water from the lower impoundment to the upper one. Through this process, water is stored as potential energy in higher reservoirs and can be released as needed to generate electricity.

The principle of lithium-ion battery storage technology hinges upon redox reaction. In this reaction, lithium ions migrate between the cathode and anode, and electrical energy and chemical energy are converted to each other. During the energy storage process, lithium ions are released from the positive electrode and move to the negative electrode, while electrons flow from the positive electrode to the negative electrode through an external circuit, thereby converting electrical energy into chemical energy. During the discharge process, the lithium ion returns from the negative electrode to the positive electrode, and the direction of the electron flow is reversed compared with the charging.

3.3. Integrated wind-solar-storage operation mode: the case of China's Yalong River Base

When wind and solar generation is abundant, surplus electricity that would otherwise be curtailed can be stored. Conversely, when output from these sources is insufficient, the storage system discharges electricity to compensate. As the real "brain" of wind-solar-storage complexes, the energy

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storage system could ensure that new energy power stations can be more stably and safely integrated into the power grid by offsetting fluctuations and alleviating operational instability.

At present, the largest wind-solar-storage integrated power station in China is located on the Yalong River [13]. The power station is located in the Yalong River Basin of Sichuan Province in Southwest China. It utilizes the region's plentiful wind and solar resources and has rich hydropower potential. It ranks among the nine clean energy power stations under China's "14th Five-Year Plan". The goal is to become the world's foremost integrated installation using renewable sources such as hydropower, wind, and solar energy (see Figure 1).



Figure 1. Photo of Jinping level 1 hydropower station on the Yalong River (Provided by POWERCHINA Chengdu Engineering Corporation Limited [14])

With a planned capacity of 78 million kW, the project is scheduled to be fully completed by 2035 [15]. At present, about 23 million kW of installed capacity has been put into operation, and another 12 million kW is under construction. Three dams (Lianghekou, Jinping, and Ertan), with a total storage capacity of 14.8 billion cubic meters, have been built to maximize the large-scale and intensive development of wind and solar energy [15].

The core operational model is hydro-wind-solar complementarity. It utilizes giant hydropower stations with multi-year regulation capacity (such as the Lianghekou Hydropower Station) built in the basin as "super regulators". When solar or wind power is in excess, hydroelectric power plants will reduce the power generation and store the excess electricity by pumping water. If solar or wind power is not enough, hydroelectric power plants will quickly increase the power generation to make up for the shortage. Such an integrated system transforms the volatility and randomness of wind energy and solar energy into stable and high-quality green energy. This integration model will help solve the problem of integrating new energy into the power grid and ensure its stability.

4. Potential future socioeconomic challenges

So far, academic research has focused on the favorable ramifications stemming from the accelerated expansion renewable energy, with less systematic and regional consideration of potential negative socio-economic issues, such as the challenges of the job market. In addition, China pays less attention to issues related to energy transformation and has not yet established a comprehensive strategy or policy to promote energy transformation.

Per data released by Global Energy Monitor, as of the close of 2020, direct employment in the coal industry was estimated at 1.6 million people, of whom about 568,870 were directly employed

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by coal-fired power plants and about 1033,000 were employed by the mining industry, which supplies coal to these power plants [16]. And this does not include the number of indirect employments in related services, construction and transportation. These workers and their families mainly live in 292 different cities in China, concentrated in Shaanxi, Inner Mongolia, Shanxi and other provinces with high coal production. Based on these data, it is estimated that with the sustainable development of renewable energy, if coal-fired power generation is completely stopped in the future, China will face massive unemployment, which will affect 10 % of the urban population and may lead to major socio-economic problems. At the same time, cities heavily dependent on coal will face a sharp drop in tax revenues, which will affect the ability of local governments to provide public services and fund transformation projects.

At present, China is also gradually recognizing this issue and has introduced related policies to establish a transitional framework for a "just transition". Key measures include prioritizing public health strategies, orderly transition plans, and regional support and re-employment assistance aimed at solving employment problems. The public health strategy envisages the phased closure of coal-fired power plants with the greatest health impact, with the goal of maximizing public health benefits and minimizing socio-economic problems. The transformation policy envisages a gradual shift from thermal power generation to renewable energy, the introduction of technological innovation, and the phased reduction of power generation capacity, rather than the sudden massive closure of thermal power plants.

5. Conclusion

This study analyzes the current status of wind and solar power generation in China and the key role played by the combination of these power generation and storage technologies. Despite the swift proliferation of wind and solar installations across China, people's attention has once again turned to the limitations of these technologies. Energy storage technology plays an essential role in improving the grid-connected capacity of the power grid, especially lithium-ion batteries with fast response capabilities and pumped storage power stations that can store energy for a long time. The success of the Yalong River power plant shows that intermittent renewable energy can be converted into stable power supply through the coordination and planning of different energy sources.

However, with the acceleration of energy transition, China is facing increasingly serious economic and social challenges. Coal-fired power plants and their workers and coal-dependent communities face economic and employment pressures. In order to meet these challenges, a fair and balanced transition must be ensured and an appropriate policy framework must be established to meet these needs.

Future research should pay more attention to the regional differences in resource availability and network conditions in western, central and eastern China. The integration of wind energy, solar power generation and energy storage technology must be developed differently according to the specific situation of each region. At the technical level, in order to improve the coordination of real-time operation planning in complex energy systems, advanced numerical optimization technologies, such as artificial intelligence and digital twins, are needed. At the policy level, priority should be given to establishing a mechanism to support the fair transition of the labor market. Specific training plans and financial mechanisms must be developed, especially in coal-dependent areas, to ensure a fair distribution of the benefits of clean energy development. The implementation of these development measures is crucial for China to attain its clean energy objectives while maintaining social stability.

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