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Bottlenecks and Countermeasures of High-Penetration Renewable Energy Development in China

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ABSTRACT

China has become the world's largest producer and consumer of energy, and ranks first in its wind and solar power installation capacity. However, serious wind and solar curtailment in China has significantly hindered the development and utilization of renewable energy. To address problems in the consumption of renewable energy, this paper analyzes four key factors affecting the capacity of power generated from renewable energy sources: power balance, power regulation performance, transmission capacity, and load level. Focusing on these bottlenecks, we propose seven solutions: centralized and distributed development of renewable energy, improving the peak-load regulation flexibility of thermal power, increasing the proportion of gas turbines and pumped-hydropower storage, construction of transmission channels and a flexible smart grid developing demand response and virtual power plants, adopting new energy active support and energy storage, and establishing appropriate policies and market mechanisms. The Chinese Government and energy authorities have issued a series of policies and measures, and in the past three years, China has had remarkable achievements in the adoption of renewable energy. The rate of idle wind capacity decreased from 17% in 2016 to 7% in 2018, and that of solar decreased from 10% in 2016 to 3% in 2018.

1. Introduction

Fossil fuel depletion, environmental pollution, and climate change have become common problems. The clean and efficient utilization of traditional energy sources, development and utilization of new energy sources, improvement in power system flexibility, and development of intelligent power systems are coping strategies on which most countries have reached consensus [1].

China's power industry ranks first in the world in terms of the scale of development. In 2018, the installed capacity reached 1.9×10^9 kW, and power generation totaled 7×10^{12} kW·h [2]. China's power supply structure and power generation capacity in 2018 and 2019 are illustrated in Figs. 1 and 2, which show that the proportion of non-fossil-fuel-based (hereafter, non-fossil) energy installed increased by 1% and power generation increased by 1.6% from 2018 to 2019. In China, the two main sources of renewable energy are wind power and photovoltaic (solar) power. China is the world leader in the development of wind and solar power generation. By the end of 2018, installed wind power and solar power were 1.84×10^8 and 1.74×10^8 kW, respectively, accounting for 9.7% and 9.2% of total installed power. In addition, the power generation of wind and solar total 3.658×10^{11} and 1.769×10^{11} kW·h, respectively, accounting for 5.2% and 2.5% of total power generation [3,4]. As shown in Figs. 3 and 4, China's wind power and solar installations increased 15-fold and 1740-fold, respectively, from 2005 to 2018, demonstrating that the development and construction of renewable energy in China has risen to a new level. In recent years, China's distributed renewable energy has grown rapidly—especially distributed solar power. By the end of 2018, the distributed solar installed capacity was 50.61 gigawatts (GW), an increase of 20.96 GW (71%) over 2017.

In addition, in its Energy Development Strategic Action Plan 2014–2020, the State Council of the People's Republic of China proposed vigorously developing decentralized wind power and steadily developing offshore wind power [5]. Furthermore, offshore wind power has strong development momentum, as shown by China's large offshore wind power reserves, in which offshore wind power with a depth of 5–50 m and a height of 70 m could generate about 5×10^8 kW of power. As of the end of 2018, China's offshore wind power had a total installed capacity of 4.45×10^6 kW, with

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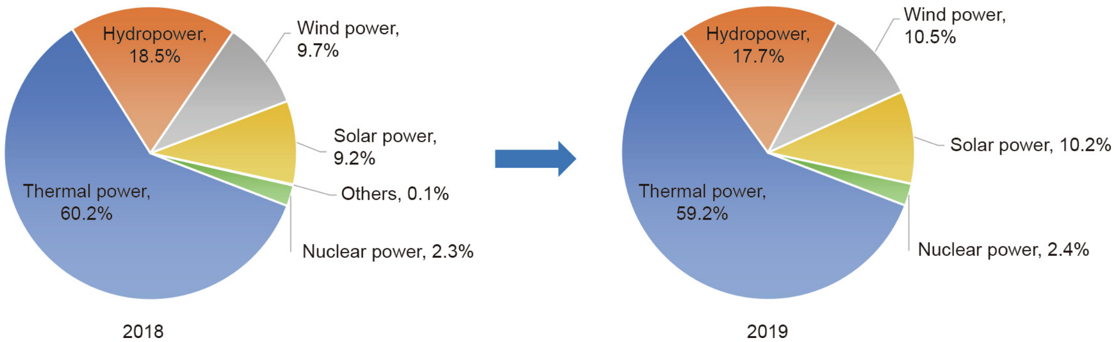

Fig. 1. China's power supply structure in 2018 and 2019.

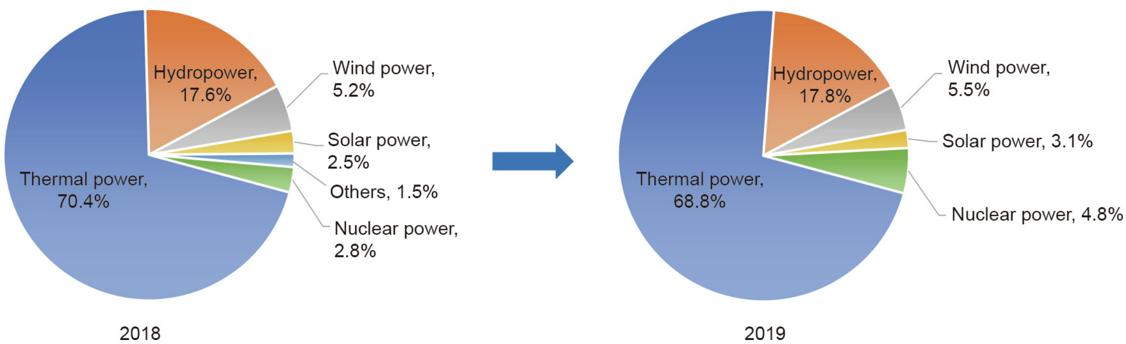

Fig. 2. China's composition of power generation in 2018 and 2019.

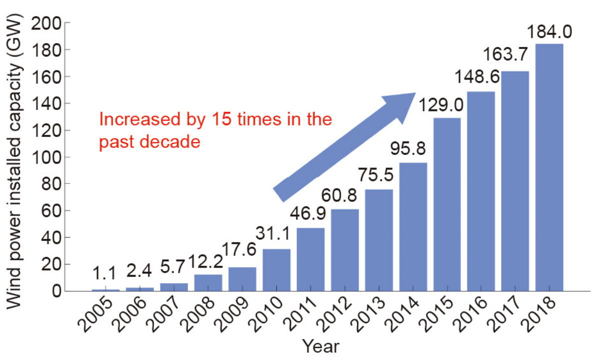

Fig. 3. Installed wind power in China (2005–2018).

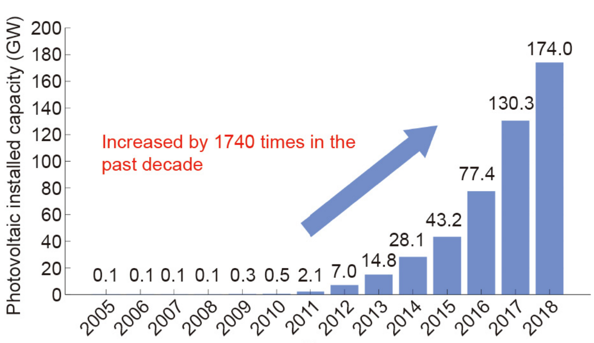

Fig. 4. Solar installations in China (2005–2018).

an additional 6.47 $\times$ 10^6 kW under construction. Thus, China ranks third in offshore wind power, after the United Kingdom and Germany [6–8].

China's Renewable Energy Outlook 2018 states that China's wind and solar power generation installations are expected to reach 1.826 $\times$ 10^9 and 1.962 $\times$ 10^9 kW, respectively, by 2035, accounting for 34.0% and 36.6% of the estimated total installed capacity of 5.366 $\times$ 10^9 kW—an increase of 1.642 $\times$ 10^9 and 1.788 $\times$ 10^9 kW over 2018 levels. The proportion of renewable energy is growing rapidly, and renewable energy is likely to become China's main energy source in the future.

Although the problem of idle wind, solar, and hydropower has been mitigated in China in the past two years, the Thirteenth Five-Year Plan (FYP) for electric power development (2016–2020) states that it is still a serious problem in some parts of China [9]. By the end of 2018, China had 2.77 $\times$ 10^{10} kW·h in idle wind power and 5.5 $\times$ 10^9 kW·h in idle solar power, a decrease of 2.2 $\times$ 10^{10} and 1.5 $\times$ 10^9 kW·h, respectively, compared with 2016 [10]. However, in 2018, the decrease in wind and solar power in Xinjiang, Gansu, and Inner Mongolia exceeded 3 $\times$ 10^{10} kW·h, accounting for more than 90% of their total idle capacity in the country, indicating that idle capacity is a serious issue in some regions. Loose energy supply is one of the reasons for idle wind and solar power in recent years. However, the root causes of the problem are a mismatch between the development of wind power and solar power and the current power system, immature technology, difficulty in absorbing wind and solar power across regions, and a lack of large-scale capability for absorbing wind and solar power on the demand side. Hence, solving the bottleneck problem of idle wind and solar power is the key to energy transformation and development [11–14]. In addition, because of the rapid increase in the installation capacity of renewable energy and the continuous increase in its proportion in the future, the absorption of renewable energy will face more problems than idle wind and solar capacity. Therefore, it is important to study the bottlenecks and solutions in the consumption of renewable energy in China both now and in the future.

From the perspective of balance in electricity generation, the power regulation performance, power grid transmission capacity, and load level are vital factors that affect capacity in renewable energy adoption. In addition, the characteristics of renewable energy, such as the renewable energy layout, power prediction level, and control performance, are significant influencing factors. Moreover, the electricity market mechanism has a significant impact on the adoption of renewable energy [15]. Several studies on the evaluation of renewable energy adoption capability have been carried out to outline further effective approaches. Wang et al. [16] proposed a novel renewable energy adoption ability evaluation approach for power systems with the integration of wind and solar power, in which the uncertainty and correlation of renewable energy are considered in the evaluation process. The uncertainty of renewable energy creates challenges in describing renewable generation, and the existing studies suffer from high computation overhead due to frequently updated data. To address these problems, Liu et al. [17] proposed an algorithm based on deep reinforcement learning to determine the approximate optimal adoption capability. In terms of demand-side management with significant potential for facilitating the integration of renewables, Hungerford et al. [18] integrated a representation of flexible load based on detailed end-use data into a system-level model of the Australian National Electricity Market and proposed a method for representing flexible load by applying an energy-constrained generator. Grid-connected high-penetration renewable energy sources introduce challenges for grid stability, so Al-Shetwi et al. [19] proposed reviewing the recent integration requirements and compliance control methods regarding the penetration of renewable power plants in the power grid. Moreover, Wu et al. [20] proposed a design method using voltage source converter-based high-voltage direct current (VSC-HVDC) to strengthen regional power grids with a high proportion of renewable energy. In addition, market-based approaches can be adopted to mitigate the integration problem. Li et al. [21] applied market-based approaches to renewable energy integration in China that involved the trading of generation rights and peak-regulating ancillary services. Furthermore, Guo et al. [15] introduced a model of China's two-level market and proposed a segment-bidding mechanism based on the minimum dispatchable interval, which demonstrates the effectiveness of renewable energy adoption. Using Tangshan in China as an example, Zhen et al. [22] studied electricity system planning with renewable energy adoption, in which the subsidy policy has a large impact on the development of the electricity system, because it reduces the cost advantage of conventional power generation and enhances enthusiasm for the development of renewable power generation by utility companies.

To deal with the increasing problems of idle wind and solar power, combined with the current conditions and trends in China's power development, this paper proposes the following solutions for consuming renewable energy at a high rate:

(1) Focus on the development and utilization of distributed renewable energy resources in the central and eastern regions and combine the centralized and distributed development of renewable energy in order to alleviate the mismatch between the distribution of renewable energy resources construction and the source load;

(2) Improve the flexible peak regulation capability of thermal power, carry out flexible transformation of thermal power, and develop intelligent power generation technology [23,24] in order to adapt the system to the large-scale adoption of renewable energy power;

(3) Raise the proportion of power supplied by gas turbines and pumped storage to alleviate structural conflicts in the power supply;

(4) Increase power transmission channels and flexible smart grid construction [25] to enhance the delivery of renewable energy;

(5) Construct demand responses [26,27] and virtual power plants [28,29] to guide the increase in demand-side capacity;

(6) Research renewable energy active support technology to improve the grid-connected friendly performance of renewable energy power generation and its active support capability to the grid;

(7) Establish policies and market mechanisms to increase the consumption of high-penetration renewable energy, improve flexible trading mechanisms, and eliminate interprovincial market barriers.

In Fig. 5, the relationship between the proposed bottlenecks and countermeasures is illustrated graphically.

The rest of the paper is organized as follows: Section 2 analyzes and summarizes four major bottlenecks in large-scale renewable energy power utilization. Section 3 looks at these bottlenecks in China's actual context, proposes seven ways to achieve a high proportion of adoption of renewable energy, and outlines some application scenarios and examples in detail. Finally, Section 4 concludes the paper.

2. Bottlenecks in large-scale renewable energy adoption

The basic characteristic of power systems is the real-time balance between the supply of and demand for energy. With the development and utilization of wind power, solar power, and other renewable energy sources, which have strong intermittence, the

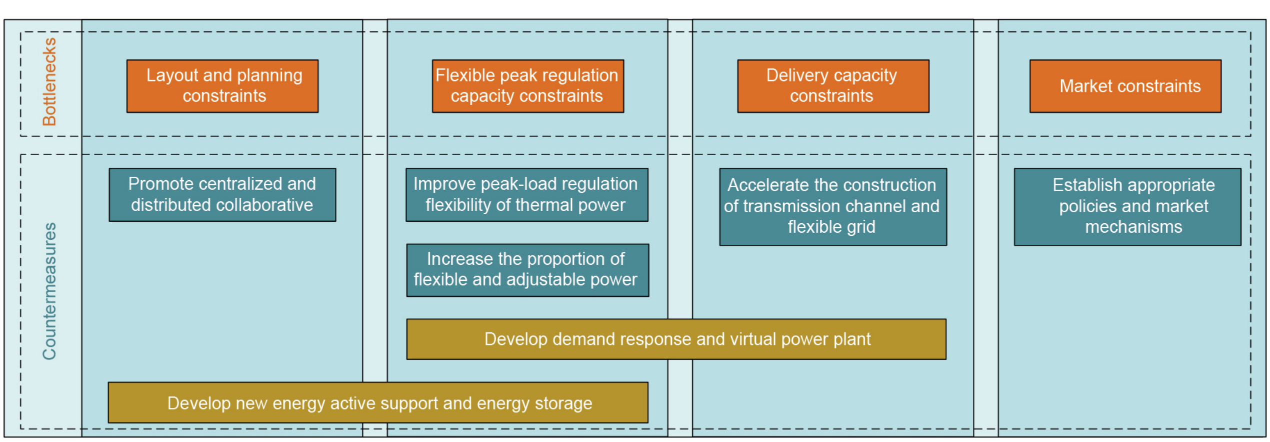

Fig. 5. Proposed bottlenecks and relevant counter measures.

power system must achieve a balance between intermittent power generation (supply) and a randomly fluctuating load (demand). When imbalance exists between the supply of and demand for electricity, dispatching must take measures to reduce the load (when the supply is less than the demand) or remove restrictions on power generation (when the supply is more than the demand) in order to maintain safe and stable operations in the power system. Therefore, the fundamental reason for idle wind and solar capacity is the failure to ensure a real-time balance between the supply of and demand for energy in the power system. In the following sections, we analyze the bottlenecks that restrict the development of renewable energy in China, based on actual conditions.

2.1. Layout and planning constraints

China's renewable energy installed capacity is unevenly distributed and inversely distributed with the load. In China, the three northern regions (northeastern, northwestern, and northern) have 75% of the country's renewable energy installations but account for only 36% of the country's total load. At the end of 2018, 72% of China's wind power and 56% of its solar power were generated in these regions. However, the vast majority of these regions is relatively backward in economic development and lacks electricity demand, so the electricity market there is small, and the renewable energy load cannot be fully utilized locally.

Table 1 lists the renewable energy installed capacity and penetration rate in some Chinese provinces in 2018 (penetration rate = renewable energy installed capacity at the end of 2018/maximum load in 2018) and shows that the volume of China's load is insufficient. The renewable energy penetration rate in some provinces and area (eastern Inner Mongolia, Ningxia, Gansu, Qinghai, and Xinjiang) exceeds 100%—higher than that in developed countries such as Denmark, Spain, and Portugal.

In this section, we use Xinjiang as an example. By the end of 2018, the installed power generation capacity of Xinjiang's power grid was 8.991×10^7 kW, 3.18 times the maximum power consumption load in the province (only 2.824×10^7 kW). Over the same period, Xinjiang's installed capacity of renewable energy reached 2.871×10^7 kW, which can satisfy 100% of the local maximum power consumption.

Table 1
Installation and permeability of renewable energy sources in some provinces (area) in China in 2018.

Province (area)	Installed capacity (GW)	Penetration rate (%)
Eastern Inner Mongolia	12.41	196
Ningxia	18.28	141
Gansu	21.21	140
Qinghai	12.29	133
Xinjiang	28.44	112

Based on our analysis, Xinjiang's installed power supply is far greater than its local load demand. In other words, even if all its regional power grids use renewable energy power, some wind and solar generation will still be idle, because a certain number of conventional power plants (thermal power or hydropower) must also be reserved for random fluctuation in the renewable energy peak regulation and frequency modulation to maintain the real-time supply and demand balance in the power system. However, Xinjiang is only a microcosm of the three regions studied here, most of which have excess installed capacity but insufficient local absorptive capacity. In contrast, especially in Europe and the United States, onshore wind power is mainly distributed. For example, 90% of onshore wind power in Germany and Denmark is close to the electricity load and can be consumed directly nearby. In addition, renewable energy sources in Portugal and West Germany are mainly distributed, accounting for more than 50%.

2.2. Flexible peak regulation capacity constraints

China mainly uses coal to generate electricity, especially in the three northern regions: 70% of the electricity is generated from coal, and 7.7% from flexible power, which is 37% of installed renewable energy. The maximum regulation capacity of flexible power does not match the fluctuation in renewable energy, thus restricting the adoption of renewable energy in some regions in China. Unlike developed countries, such as those in Europe and North America, China lacks a flexible and schedulable power supply. Fig. 6 compares the power supply structure of China with those of several major countries with a high penetration rate of renewable energy.

By the end of 2018, 4.41% of China's power generation plants used gas-fired power generation, which can respond quickly to random fluctuation in renewable energy. The proportion of hydropower plants is about 18.6%, pumped storage plants comprise 1.5%, and the rest are mostly run-off hydropower stations with obvious seasonal characteristics. In addition to power generation, the water stored in reservoirs should meet the needs of flood control and farmland irrigation, where the peak capacity is also limited. Coal-fired power generation accounts for 53.1% of the total, but the minimum output of pure condensation units is 50% of the rated load, and the minimum output of heating units in the winter is 60%–70% of the rated load. The deep peak-load regulation capability of these plants differs greatly from that of similar units outside China. In addition, the variable load rate of China's coal-fired units is 1%–1.5% per minute of the rated load, which does not satisfy the demand for a high proportion of renewable energy.

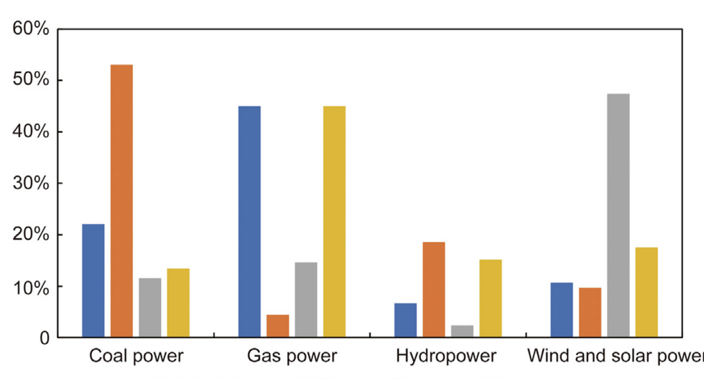

Fig. 6. Comparison of power supply structure in different countries.

Below, we use the examples of Gansu, Inner Mongolia, and Northeast China, where the problem of renewable energy consumption is serious.

First, Gansu Province is a major user of renewable energy in China. As of the end of 2018, installed capacity of renewable energy accounted for more than 40% of total capacity. Although the proportion of hydropower has reached 18.1%, the flexible and adjustable pumped storage capacity is 1.2×10^6 kW, accounting for 2.34%. Therefore, thermal power generation is still its main schedulable resource, 40% of which is for heating, and the existing schedulable capacity does not satisfy the grid-connected demand for renewable energy.

Second, in Inner Mongolia as of the end of 2018, the installed wind power capacity was 2.869×10^7 kW and the installed solar power capacity was 9.45×10^6 kW. Moreover, the installed share of wind and solar power combined is 30.9%. However, flexible and adjustable pumped storage accounts for 0.9% and gas power generation for 0.5%. The proportion of installed thermal power generators, which is the dominant type of power supply, is about 70%, most of which is heating units, accounting for more than 60%. In the winter, most heating plants cannot practice peak shaving, and the peak-shaving capacity of the power grid is greatly reduced. However, the proportion of self-supply power plants is high: The total installed capacity of self-supply power plants in the power grid exceeds 9×10^6 kW, and their power generation accounts for about one-third of the total in the regions. Average utilization hours of the self-supply power plants exceed 6000 h, which seriously occupies the space for clean energy consumption.

Third, in the northeast as of the end of 2018, the total installed grid-connected capacity of renewable energy resources in the regional power grid reached 2.655×10^7 kW, accounting for 25.62% of the total installed capacity of various power sources. The installed capacity of wind power is 1.873×10^7 kW, and that of solar power is 7.82×10^6 kW. However, the flexible and adjustable pumped storage capacity is 1.5×10^6 kW, accounting for 1.0% of the total. Furthermore, installed thermal power accounts for about 70%, most of which is for heating, and the peak-shaving and frequency-modulation capabilities are far from sufficient.

2.3. Delivery capacity constraints

When a surplus arises in the local load and the local consumption capacity is insufficient, power can be sent to regions with high load demand through the construction of transregional transmission channels. However, in the three northern regions, the transregional transmission channels are seriously lagging behind because of the short construction period for wind and solar power plants and the long construction period for transmission channels. At present, only a few provinces in this region, such as Xinjiang, have completed the construction of large-capacity transmission channels; the transmission channels in most other provinces are still in the planning stage or under construction.

At the end of 2018, Xinjiang's power transmission capacity reached 1.3×10^7 kW, and the total power transmission in 2018 exceeded 5×10^{10} kW. However, the capacity of its outgoing channels still accounts for only 14.5% of the total installed power generation capacity (8.991×10^7 kW) of the power grid, which is even less than the installed capacity for wind power (1.921×10^7 kW) in the region. Moreover, the local electricity load (2.824×10^7 kW) and the capacity of the external transmission channel (1.3×10^7 kW) in Xinjiang reached 4.124×10^7 kW, accounting for 45.8% of the total installed capacity there. The surplus installed capacity exceeds 50%, yet cannot be consumed. Xinjiang's idle wind power in 2018 was 1.0691×10^{10} kW·h, and the rate of idle capacity for wind power is 22.9%. In Altay and Tacheng in Xinjiang, the use of wind power has only begun to develop and is far from even 10^6 kW. Thus, relying solely on the local load, further large-scale development is difficult to achieve. Doing so will require sending wind energy elsewhere.

In contrast, a network structure has formed in continental Europe with close ties between countries, which facilitates the cross-border adoption of renewable energy. At present, Portugal is connected to the Spanish power grid through six circuits of 400 kV and three circuits of 220 kV, with an exchange power of 2.2×10^6–2.8×10^6 kW, supplying 42% of Portugal's 5.26 $(4.83 + 0.43) \times 10^6$ kW of wind and solar power. This network helps to accelerate the development of renewable energy sources and the achievement of a reliable power supply.

2.4. Market constraints

China's electricity market mechanism is still at the initial stage, and peak-shaving auxiliary services are still at the pilot stage. China uses a guaranteed purchase mechanism with fixed electricity prices and preferential access to the Internet. In addition, China has a fully guaranteed purchasing system for renewable energy power generation in which the income from renewable energy power generation consists of power generation expenses paid by power grid enterprises based on the benchmark electricity price of local desulfurized coal-fired power plants and government subsidies for renewable energy.

China has yet to establish a unified national electricity market and has serious market barriers among provinces. Moreover, transprovincial and transregional transactions lack a perfect market environment. Even worse, the quantity and transmission methods for electricity are generally agreed upon by the local governments of the sending and receiving areas through long-term agreements that base electricity transmission prices on those that are approved by the local price administration departments, and the electricity prices for recipient provinces are relatively high. In addition, China's renewable energy consumption across regions and provinces is still subject to government pricing, which diminishes enthusiasm in recipient provinces. Hence, it is essential to clarify policies and electricity pricing mechanisms to reduce interprovincial barriers.

China's electricity market is dominated by medium- and long-term transactions; a short-term flexible trading mechanism has not yet been perfected with a spot market, so it has not achieved the advantage of a low marginal cost of renewable energy. Under the guidance of the European Union (EU)'s goal of building a unified electricity market, countries in the EU have opened up their markets to one another, gradually moving toward a unified electricity market and promoting the consumption of renewable energy. The EU has implemented additional regulations, which require greater market unity and expand the scope of trade and liquidity in the electricity market so as to improve market competition and the efficiency of resource allocation. In recent years, renewable energy resources in the EU have rapidly developed to help ensure the adoption of renewable energy, but it is necessary to break the original pattern of a local balance between power and electricity. For this reason, the EU is also strengthening the construction of transmission infrastructure and cross-border networks. For example, Portugal and Spain belong to the same Mercado Ibérico da Energia Elétrica (MIBEL), which is jointly operated with the markets of Germany's European Energy Exchange (EEX), the Nordic Nord Pool, Central and Western Europe, Italy, and Slovenia. Based on the marginal price in the market over a few days and intraday market joint clearing, Europe has formed a new unified electricity market auction and has achieved adoption in other markets of new energy sources.

3. Countermeasures of high-penetration renewable energy adoption

3.1. Promote centralized and distributed collaboration

The first solution is to adopt the principle of both centralized and distributed development, with an emphasis on strengthening the development and utilization of distributed renewable energy resources in the central and eastern regions. On the one hand, China's renewable energy resources are concentrated in the three northern regions, which is suitable for adopting a centralized development mode. However, while this mode can increase development and utilization efforts, it should also combine a district's own resources, local load characteristics, and renewable energy output characteristics in different regions. Moreover, the construction of an outgoing channel should be completed as soon as possible to enhance the optimal allocation of resources in large power grids.

At the same time, China's east–central and southern regions have more capacity for consumption than the three northern regions. Hence, the development of wind power should be intensified in areas with stronger consumption capacity or in load centers, especially the development and utilization of offshore wind power, so as to improve the nearby consumption capacity of wind power.

Tables 2 and 3 show the operation of wind and solar power generation in China in the first half of 2019, indicating that a large amount of wind power is idle in the three northern regions, but not in the central and eastern regions. Therefore, it would be useful to optimize the layout of renewable energy sources, strengthen the construction of wind power in southeastern coastal cities and offshore areas, and focus on a distributed development model.

3.2. Improve the peak-load regulation flexibility of thermal power

These approaches involve developing low-cost and high-efficiency thermoelectric coupling techniques, reducing the minimum output of coal-fired generation plants, improving the load response rate, ensuring safe and flexible operations, and maintaining high efficiency under low load operations so that the peak regulation range achieves 20%–100% and the rising rate of load reaches 5% $Pe \cdot min^{-1}$. At present, Chinese plants have much shallower peak-shaving capability than plants in Denmark and Germany, and the rapid climbing capability of peak-load regulation is only half that of Germany. Moreover, it is basically impossible to achieve a start–stop cycle.

Second, it is vital to improve thermal power flexibility. The structure of China's power supply is dominated by coal-fired power generation and lacks flexible power supply types, such as pumped storage and fuel gas. By 2030, the total installed capacity of these two types of flexible power supply will be about 10%—still far behind the current ratios in Germany, the United States, Japan, and other countries. Therefore, the flexibility of China's existing thermal power units, especially cogeneration plants, should be improved as soon as possible in strict accordance with the Thirteenth FYP. However, the flexible transformation of thermal power plants should not be "one size fits all," and overall planning should be carried out based on consideration of the region, grade, and characteristics of the plants. The goal is to complete 4×10^8 kW thermal power plant upgrades with peak regulation flexibility and 2.15×10^8 kW coal power plants in the three northern provinces region, including 8.2×10^7 kW of pure condensation power plants and 1.33×10^8 kW of cogeneration power plants. After the renovation is completed, the peak-shaving capacity will be increased by 4.6×10^7 kW.

Table 2
Grid-connected operation of wind power in the mainland of China's provinces (region, city) in the first half of 2019.

Province/municipality	Cumulative grid-connected capacity (MW)	Generating capacity ($\times 10^8$ kW·h)	Abandoned electricity consumption ($\times 10^8$ kW·h)	Rate
Beijing	190	2.0	–	–
Tianjin	520	6.6	–	–
Hebei[a]	14 650	170.3	7.4	4.2%
Shanxi	11 340	113.7	1.2	1.0%
Inner Mongolia[a]	28 960	356.2	30.5	8.2%
Liaoning	7 890	104.8	0.6	0.6%
Jilin	5 140	64.7	2.2	3.3%
Heilongjiang	6 020	74.7	1.5	2.0%
Shanghai[b]	710	7.9	–	–
Jiangsu[b]	9 270	91.4	–	–
Zhejiang[b]	1 570	15.1	–	–
Anhui[b]	2 580	22.6	–	–
Fujian[b]	3 250	36.3	–	–
Jiangxi[b]	2 470	24.8	–	–
Henan[b]	5 620	42.6	–	–
Guangdong[b]	4 020	35.5	–	–
Guangxi[b]	2 600	30.8	–	–
Hainan[b]	290	2.3	–	–
Chongqing[b]	560	5.2	–	–
Sichuan[b]	2 640	44.4	–	–
Hubei[b]	3 710	35.3	–	–
Hunan	3 810	37.7	1.1	2.9%
Shandong	11 910	126.2	0.2	0.2%
Guizhou	4 250	42.5	0.3	0.7%
Yunnan	8 630	159	0.5	0.3%
Tibet	8	0.1	–	–
Shaanxi	4 400	34.3	0.4	1.1%
Gansu[a]	12 820	118.9	13.3	10.1%
Qinghai	3520	34.8	0.5	1.4%
Ningxia	10 110	90.4	2.3	2.4%
Xinjiang[a]	19 260	207.9	42.4	17.0%
Total	192 690	2 145.0	104.6	4.7%

[a] Regions with major idle wind power.
[b] Regions without idle wind power.

Table 3
Solar power generation construction and operation in the mainland of China's provinces (region, city) in the first half of 2019.

Province/municipality	Cumulative installed capacity (MW)		Newly installed capacity (MW)		Idle electricity capacity ($\times 10^8$ kW·h)	Rate
	Total	Solar power plant	Total	Solar power plant		
Beijing	430	50	40	0	–	–
Tianjin	1 380	1 020	100	50	–	–
Hebei	13 190	8 990	850	440	1.6	1.8%
Shanxi	9 760	7 850	1 120	1040	0.1	0.2%
Shandong	14 370	6 520	760	40	0.1	0.2%
Inner Mongolia	9 780	9 560	500	440	0.6	0.6%
Liaoning	3 100	2 220	80	30	–	–
Jilin	2 710	2 050	60	20	0.4	1.9%
Heilongjiang[a]	2 210	1 450	60	40	–	–
Shanghai[a]	1 000	60	120	0	–	–
Jiangsu[a]	14 050	8 130	730	210	–	–
Zhejiang[a]	12 360	3 930	980	310	–	–
Anhui[a]	11 540	6 980	360	210	–	–
Fujian[a]	1 570	400	90	30	–	–
Jiangxi[a]	5 670	3 110	300	160	–	–
Henan[a]	10 120	6 000	210	0	–	–
Hubei[a]	5 510	3 550	410	190	–	–
Hunan[a]	3 110	1 380	190	120	–	–
Chongqing[a]	630	580	200	200	–	–
Sichuan[a]	1 850	1 680	50	10	–	–
Shaanxi	8 050	6 790	890	660	1.9	3.9%
Gansu	8 660	8 130	370	340	4.3	6.9%
Qinghai	10 790	10 680	1 230	1 220	5.2	6.3%
Ningxia	8 320	7 660	160	40	1.9	3.2%
Xinjiang (including XPCC)	10 660	10 610	740	700	7.7	10.6%
Tibet	1 020	1 020	40	40	2.1	25.7%
Guangdong	5 600	2 820	330	0	–	–
Guangxi	1 340	1 040	100	100	–	–
Hainan	1 400	1 270	40	40	–	–
Guizhou	1 780	1 600	80	0	0.1	0.7%
Yunnan	3 640	3 460	210	150	0.1	0.3%
Total	185 590	130 580	11 400	6 820	26.1	2.4%

XPCC: Xinjiang production and construction group.
[a] Regions without idle solar power.

Third, it is essential to develop intelligent power generation and control technology for the deep utilization of unit energy storage, which consists of carrying out research on intelligent detection and control technology of power generation processes, intelligent instrument control system equipment, and the key problems of advanced operation control technology and the demonstration application of power generation units. In addition, carrying out condensate throttling fast variable load control technology, high feed water throttling fast variable load control technology, heating extraction throttling fast variable load control technology, and so forth, will be significant in future.

For example, the Liaoning power grid has greatly improved its adoption of renewable energy resources for when heating is needed, after enhancing its thermal power flexibility. Table 4 compares specific data on the Jilin and Heilongjiang power grids. The Liaoning power grid has an operating capacity of 1.5×10^7 kW for heating and 2.4×10^6 kW for pure condensation. Assuming that the capacity of heating and pure condensation is raised by 20% and 15%, respectively, a calculation of the peak-shaving capacity with fixed capacity shows that the peak-shaving capacity could increase by 3.36×10^6 kW—54.8% and 66.3% higher than the Jilin and Heilongjiang power grids, respectively. Moreover, Liaoning power grid could increase wind power to 1.9×10^9 kW·h, making Liaoning the province with the least idle wind power in Northeast China—at 1.6×10^8 kW·h in 2019, 79.2% and 72.4% lower than Jilin and Heilongjiang, respectively—which would help to solve the problem of idle wind power in the winter months. In addition, the power grid could achieve reductions of 6.27×10^5 t of coal, 1.5×10^6 t of CO_2 emissions, 8000 t of SO_2 emissions, and 44 000 t of nitrogen oxide (NO_x) emissions.

3.3. Increase the proportion of flexible and adjustable power

At the end of 2018, China's installed gas power generation capacity was 8.33×10^7 kW and its installed pumped storage capacity was 2.999×10^7 kW, accounting for 5.8% of China's total installed capacity. Therefore, the installed capacity of pumped storage has great room for improvement. The Thirteenth FYP for energy development aimed to accelerate the construction of large-scale pumped storage power stations, with an additional 6×10^7 kW of construction and 4×10^7 kW of operation in 2020.

Pumped storage is a method of mechanical energy storage. The energy storage power of pumped storage ranges from 100 to 2000 MW and lasts for 4–10 h, and the energy storage cost is

Table 4
Comparison of flexible peak regulation capacity of thermal power in three northeast provinces.

Province	Heating unit capacity (GW)	Pure condensing unit (GW)	Peak regulation capacity improved (GW)	Wind power consumption increased ($\times 10^8$ kW·h)	Wind power abandoned in 2019 ($\times 10^8$ kW·h)
Liaoning	15.0	2.4	3.36	19	1.6
Jilin	10.4	0.6	2.17	18	7.7
Heilongjiang	9.8	0.4	2.02	14	5.8

480–800 USD per kilowatt. Pumped storage has incomparable technical and economic advantages, which will enable the construction of pumped storage power stations to be further accelerated. Moreover, pumped storage power stations have the dual functions of peak-load regulation and valley filling, which are characterized by a quick response, flexible operation, and convenient start–stop. It takes only 2–4 min to generate electricity from a static state to a full load, 30–35 s from a no-load state to a full load state, and only 3–4 min to quickly switch from a pumping state to a full load state, thus meeting the requirements for various operational modes in the system. In terms of technical reliability, economic cost, and other factors, pumped storage power has incomparable advantages over other energy storage technologies at present, making it one of the best sources of peak power in modern power grids. Therefore, China should speed up the construction of pumped storage power stations, especially in areas in the three northern provinces with urgent need and where conditions permit, so as to give full play to the role of pumped storage power stations in providing backup and enhancing system flexibility.

In addition, the application scenarios for energy storage are extensive, such as smoothing the output of renewable energy power on the power-generation side, peak shaving and frequency modulation on the transmission side, improving the utilization rate of distributed solar power on the distribution side, and improving the demand response characteristics on the user side. Therefore, it is of great significance to carry out in-depth research and demonstration of battery energy storage, compressed air energy storage, heat storage, and other related technologies.

3.4. Accelerate the construction of transmission channels and flexible grids

The construction of transmission channels is the most direct method for the adoption of a high rate of renewable energy. At the end of 2018, China completed eight alternating current (AC) and 13 direct current (DC) ultrahigh voltage (UHV) transmission channels, and four AC and two DC UHV transmission channels are under construction. The UHV cumulative power transmission and line length of the state grid are shown in Figs. 7 and 8. Considering that flexible DC transmission is internationally recognized as the most technically advantageous type of wind farm grid connection and the best way to connect long-distance offshore wind power, which can greatly improve the grid-connection performance of large-scale wind farms, the construction of flexible smart grids should be increased.

In addition, in order to realize intelligent transmission and distribution networks in the future, the following important goals should be achieved: a new generation of smart grid dispatching control systems, transparent distribution network architecture and intelligent operation and maintenance, intelligent control of multiple information fusion, operation optimization driven by big data, and panoramic information fusion and security protection.

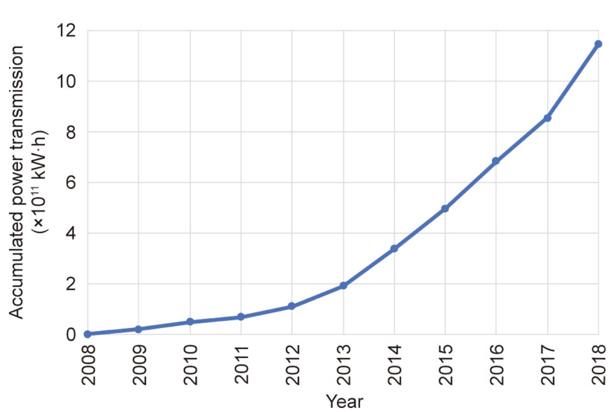

Fig. 7. UHV cumulative power transmission in the state grid.

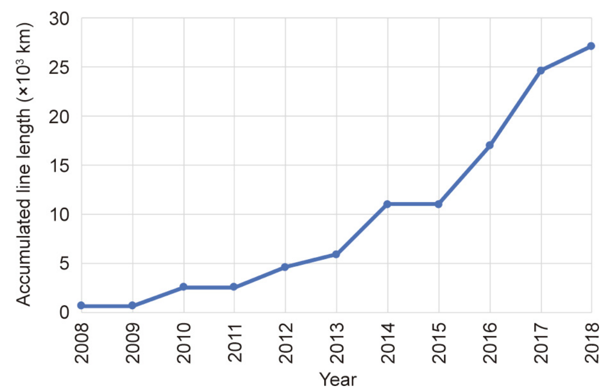

Fig. 8. UHV cumulative line length of the state grid.

For example, regarding the construction of UHV transmission lines in the state grid, Figs. 7 and 8 respectively show the cumulative length of transmission lines and of electricity delivered from 2008 to 2018. Over this period, UHV transmission lines increased from 640 to 27 114 km—a 42-fold increase. Furthermore, cumulative power transmission increased from 7.7×10^7 kW·h in 2008 to 1.145777×10^{12} kW·h in 2018, a 14 880-fold increase. The construction of UHV transmission lines has helped bridge the source and load imbalance and enhanced the ability to access renewable energy.

3.5. Develop demand response and virtual power plants

The power system involves many adjustable loads (e.g., air-conditioning, heating) and deferrable loads (e.g., washing machines, disinfection cabinets) that work well with the power grid. The statistics show that about 15%–20% of electricity used by Chinese consumers is at peak load, about half of which is translatable load. Electric vehicles (EVs) can both charge and discharge power. The application scenario for EV vehicle-to-grid (V2G) is shown in Fig. 9, which assumes that China will have 5×10^6 EVs in 2020. The current charging and discharging power of EVs is as much as 7 kW, so they can upload 7×10^7 kW in adjustment capacity to the power grid (bidirectional), which is about 4% of the current installed capacity in China's power grid.

Therefore, many environmentally friendly demand-side resources have not yet been fully utilized. With a fuller understanding of the characteristics of this kind of resource, we should vigorously develop and use flexible dispatch resources on the demand side and construct a ubiquitous power Internet of Things, with extensive interconnection of new energy stations, energy storage, and a load and power grid dispatch center. This will make it possible to fully detect the operations, status, and environmental information on load storage equipment in the source network, guide users in renewable energy consumption with market methods, and exploit the potential for demand-side consumption. Through the establishment of an appropriate price mechanism to guide users in load shifting, peak cutting, and valley filling, as well as coordination and optimization in both supply and demand, the system's ability to consume renewable energy will be expanded.

Virtual power plants are cloud-based control systems that operate based on distributed energy production data. In addition, the multiple integration mode provided by a virtual power plant and its stable output characteristics under cooperative regulation open

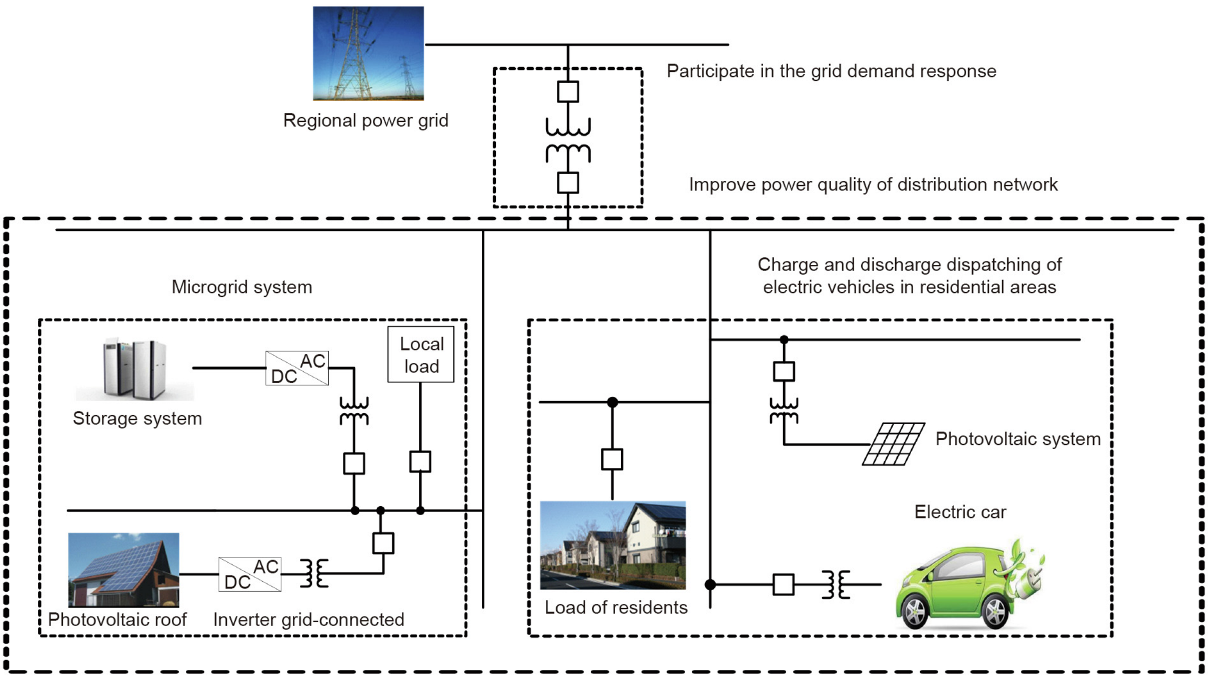

Fig. 9. Application scenario for the EV V2G. AC: alternating current; DC: direct current.

up new methods to achieve the efficient utilization of renewable energy.

For example, with respect to the source-network-load friendly interaction technology adopted by the Jiangsu power grid, illustrated in Fig. 10, Jiangsu has incorporated massive dispersed micro-loads into controllable resources, connected them to the power grid, and realized large-scale friendly interactions between the source network and the load. The traditional mode of "the source follows the grid" has changed to the intelligent interaction mode of "the source follows the load, and the load follows the grid." Through large-scale millisecond/second/minute precise load control, friendly interactions between power generation, power supply, and electricity consumption are enabled in which controllable resources are effectively expanded in case of power grid failure, safety control measures for large power grids are improved, and full indemnificatory consumption of renewable energy as well as structural reform on the energy supply side are promoted.

On 15 June 2016, the first large-scale source-network-load friendly interaction system in China was completed and put into operation in Jiangsu. After expansion in the second and third stages of the system, an accurate load control capability of 3.76×10^6 kW·s and 2.6×10^6 kW·ms was achieved. The project achieved clear results and is now being promoted. It was estimated that the six provinces and one municipality (Jiangsu, Zhejiang, Anhui, Shandong, Hunan, Henan, and Shanghai) in the state grid operation area would have 8.6×10^6 kW in interruptible load control capacity by the end of 2019. The total DC power transmission capacity outside of the area was expected to increase by 6.6×10^6 kW, accounting for about 7% of the rated UHV DC transmission capacity in this area, with a new quarterly profit of about 3.564×10^8 CNY.

3.6. Develop new energy active support and energy storage

The challenges due to the rising rate of renewable energy within the safe and stable operation of the power system in the future cannot be ignored. Large-scale renewable energy should become the responsibility of the main power source. It is necessary to study the key technologies in renewable energy power generation, including peak shaving, frequency modulation, and inertia support. Figs. 11 and 12 illustrate the virtual synchronous machine technologies for wind power generation and solar power generation, which are important in improving the grid-connected friendly

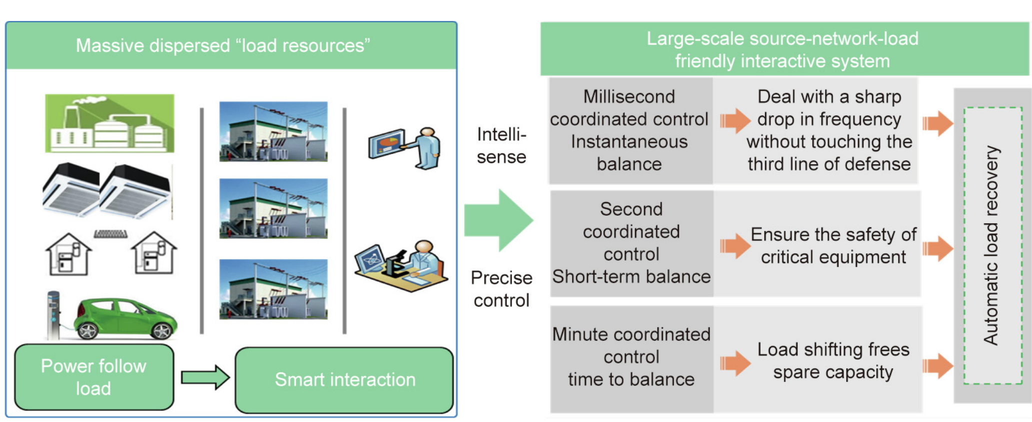

Fig. 10. Schematic diagram of source-network-load friendly interactive technology.

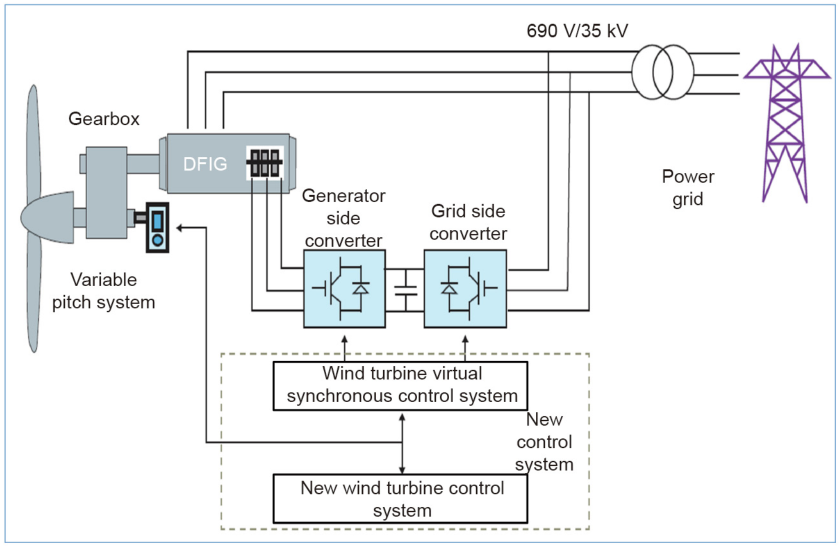

Fig. 11. Virtual synchronous machine for wind power generation. DFIG: doubly fed induction generator.

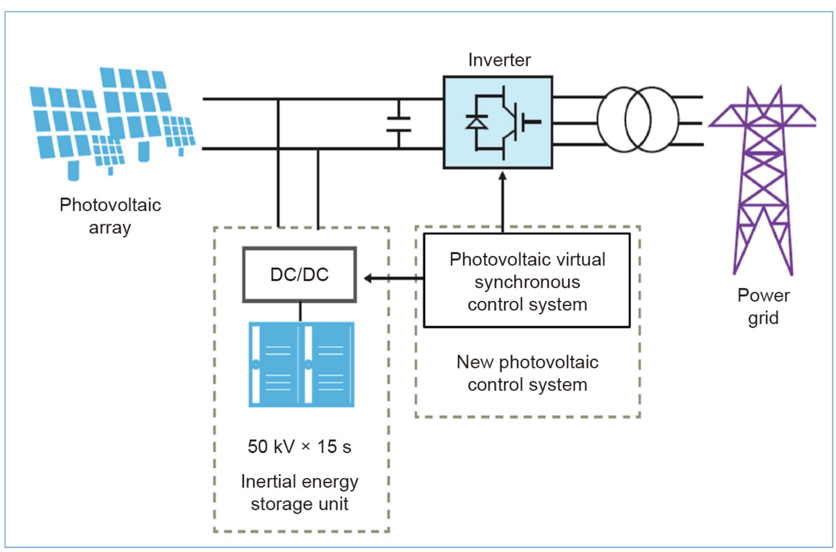

Fig. 12. Virtual synchronizer for solar power generation.

performance of renewable energy power generation and active support capability for the power grid.

3.7. Establish appropriate policies and market mechanisms

The development of the power market will inevitably require engaging in market bidding for the power generation capacity of power plants. Hence, flexibility in thermal power generation, low carbon content, and the sustainability of renewable energy sources should be the main consideration in market bidding. Moreover, it is the only way for China to transform its energy structure and guide thermal power enterprises to improve their operational flexibility and promote the consumption of large-scale renewable energy. Therefore, market mechanisms, such as auxiliary service market policies, are urgently needed to enhance the flexibility of various types of power supply. In 2012, the UK Government first proposed cost-reduction policies for offshore wind farms to minimize greenhouse gas emissions generated from fossil fuels, which have been copied by other countries. The president of China promoted an energy revolution and a fight against pollution, emphasizing an energy policy based on clean technology. Its policies, which aim at expanding the adoption of renewable energy from 2016 to 2018, are listed in Table 5.

At the same time, considering that the current barriers between provinces in China severely restrict the optimal allocation of energy resources in a wider range, it is difficult to give full play to the benefits of large markets and large power grids. It is necessary to promote interprovincial electricity trading in which the intergovernmental barriers should be broken down, priority power generation rights among provinces should be liberalized, and an effective market trading mechanism should be established in the process of electricity trading.

Therefore, national and local governments should speed up the electricity market reform, give full play to the market regulation function, improve the medium- and long-term electricity trading mechanism, expand the transprovincial market trading of clean

Table 5
Renewable energy consumption policy issued by government and energy authorities.

Time	Department	Policy name
2016-02-05	National Energy Administration (NEA)	Circular on the consumption of renewable energy in the three northern provinces areas
2016-03-24	National Development and Reform Commission (NDRC)	Measures for the administration of full guarantee purchase of renewable energy power generation
2016-05-27	NDRC, NEA	Notice on the full guarantee purchase and management of wind power and solar power generation
2017-01-18	NDRC, Ministry of Finance, NEA	Notice on the trial issuance of renewable energy green power certificates and a voluntary subscription trading system
2017-02-14	NEA	Response letter on the pilot project of incremental spot trading in renewable energy across regions and provinces
2017-07-19	NEA	Guidance on the implementation of the Thirteenth Five-Year Plan for the development of renewable energy
2017-08-14	NEA	Reply to agree to start the pilot implementation of the Fujian electric power auxiliary service market
2017-11-08	NDRC, NEA	Implementation plan to address the problem of idle water, wind, and solar power
2018-03-23	NDRC, NEA	Guidance on improving the regulatory capacity of power systems
2018-12-04	NDRC, NEA	Clean energy consumption action plan (2018–2020)

energy, and promote the construction of the spot electricity market as a whole. Moreover, macro-policy guidance needs to be strengthened, an institutional mechanism that is conducive to clean energy consumption should be formed, a renewable energy electricity quota system should be studied and implemented, a yearly subsidy plan for slope removal should be formulated, and the process of affordable access to the Internet should be accelerated so as to establish a market mechanism that can integrate renewable energy power generation, schedulable resources, and power grids to enable large-scale renewable energy adoption. As a result, enterprises will be able to improve their competitiveness and have evidence to rely on while reducing costs within a framework of rules that are consistent with market reforms. Finally, a fully competitive, open, orderly, and healthy market system can be created to accelerate the transformation of China's energy structure.

For example, let us look at the clean energy adoption in the Guangxi power grid. Guangxi is located in a coastal area, where frequent typhoons in the summer bring heavy rainfall in a short time, making the reservoir level rise sharply. Moreover, during typhoons, because the load is low, it is difficult to consume hydropower, resulting in a great risk of idle capacity. The total installed capacity of wind power in Guangxi is 2.7×10^6 kW, and the output of wind power has reverse peak regulation, which intensifies the mismatch between supply and demand during a low load period. The Guangxi power grid encourages users to use more clean energy through its market-oriented role and guides large enterprises to switch from self-supply power plants to the main power supply. Since 2018, the rights transfer of hydropower and thermal power generation has been carried out in a total of 17 tradings, which account for about 7.5×10^9 kW·h in surplus water and electricity, achieving a "win–win" situation of clean energy adoption and market-oriented contract performance, while easing the operating pressure of thermal power enterprises.

4. Conclusions

Based on the current conditions in China in renewable energy development, combined with resource endowment and distribution characteristics, this paper discusses four bottleneck constraints in the adoption of renewable energy by a high proportion of users: layout and planning, peak-load regulation flexibility, delivery capacity, and market transformation. We offer seven solutions to these problems: centralized and distributed development of renewable energy, improving the peak-load regulation flexibility of thermal power, increasing the proportion of gas turbines and pumped-hydropower storage, constructing transmission channels and flexible smart grids, developing demand responses and virtual power plants, adopting technology for new energy active support and energy storage, and establishing appropriate policies and market mechanisms.

In practice, the Chinese Government and energy officials have issued a series of policies and measures—including those on renewable energy monitoring and early warning, liberalization of the power generation market, transprovincial and transregional power transactions, green power certificates, flexible renovation of thermal power plants, and clean heating with renewable energy—to address the problems of renewable energy planning, grid connection, subsidies, trading, and energy consumption. Between 2016 and 2018, China had remarkable achievements in expanding the consumption of renewable energy. The rate of idle wind and solar power dropped sharply from one year to the next. The rate of idle wind power decreased from 17% in 2016 to 7% in 2018, and the rate of idle solar power decreased from 10% in 2016 to 3% in 2018.

China's energy structure will be in a transition period for a long time. Judging from China's strategic development plan in electricity and all parties' forecasts, China's renewable energy power development is expected to maintain a rapid pace in the future. The adoption of renewable energy will also encounter greater challenges in which departments must cooperate with each other and implement targeted measures to promote an energy production and consumption revolution so as to build a clean, low-carbon, safe, and efficient energy system.

Our study does not present any fixed standards with regard to technical bottlenecks and their countermeasures for a high share of adoption of renewable energy, because each technology has its own technical bottlenecks, which could be the research focus in corresponding fields. For example, one of the technical bottlenecks in China in offshore wind power is that the technologies of unit, construction, transmission, and operation do not match the demands of offshore wind power development. Hence, in the long term, one effective countermeasure is to increase investment in the core technology in each field.

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Compliance with ethics guidelines

Jizhen Liu, Qinghua Wang, Ziqiu Song, and Fang Fang declare that they have no conflict of interest or financial conflicts to disclose.

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