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Views & Comments

A Discussion on the Flexible Regulation Capacity Requirements of China's Power System

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A high proportion of variable renewable energy (VRE) is one of the most significant characteristics of China's future power system under the "dual carbon" target [1,2]. However, wind and solar power units are more uncontrollable and less supportive for power system stability than traditional thermal power units, due to their susceptibility to the weather and the grid connection of power electronics [3]. Therefore, as the capacity and generation of VRE grow rapidly and even dominate the power structure [4], the power system's ability to deal with disturbances will continue to decrease [5]. Strong fluctuations and high uncertainty from the source side will bring new challenges to maintaining the balance between power supply and demand [6,7], along with the risks of load loss and power curtailment [8]. These challenges and risks will further hinder the consumption of renewable energy and will profoundly affect the safe and stable operation of the power system [9]. To address this issue, it is vital to enhance the flexibility of the power system in an efficient and economical way to support the construction of the new power system and the energy transition [10,11]. In this context, a great deal of existing research has focused on defining [12] and assessing [13] the flexibility of the power system, as well as analyzing [14], planning [15], and controlling [16] flexible resources.

In this paper, we firstly discuss how the characteristics of the power supply–demand balance will change with the evolution of China's power system. Secondly, we evaluate the requirements for flexible regulation capacity according to the development stages of the energy transition. Finally, several suggestions for improving the flexibility of the power system are proposed from both technical and policy perspectives.

1. The situation of power supply–demand balance in the new energy system

1.1. The inevitable trend toward a growing proportion of VRE in the power system

The clean and low-carbon transition of the power supply, featuring an increasing share of wind and solar power, is an inevitable trend in the development of China's power system. According to a previous study [17], China's installed wind and solar power capacity will rise from 535 GW in 2020 to 6011 GW in 2060 (Fig. 1). The installed capacity of hydropower, bioenergy, and other renewable energy will increase to 818 GW in 2060. The proportion of wind and solar power in China's total installed capacity and annual power generation is expected to approach 76.0% and 60.0% in 2060, respectively, from 24.1% and 9.6% in 2020. The overall development trend of VRE in the power system will undergo a process from a low level of installed capacity and low electricity generation in the early stage to a high level of installed capacity but relatively low electricity generation, and finally to high levels of both installed capacity and electricity generation.

1.2. Changes in the characteristics of the power supply–demand balance

Due to the inherent properties of electricity, the instantaneous balance between supply and demand must be ensured in a power system. However, the power load is usually uncontrollable, as it depends on user behavior. To adapt to load changes, traditional fossil-fuel plants can adjust their power outputs by changing fuel inputs; however, the real-time power outputs of VRE units are highly dependent on weather conditions, which are difficult to forecast precisely, especially on a long timescale. If wind or solar resources are insufficient at peak-load time, a power shortage will ensue. Conversely, the concurrence of valley load and strong wind/solar power generation leads to power curtailments. These issues will obviously be exacerbated by an increase in the proportion of renewable energy.

The influence and characteristics of the supply–demand balance will change over time, along with the rapid deployment of VRE in the power system. The major problems fall into two main categories—namely, weather conditions and temporal scale, as shown in Table 1. From the perspective of weather conditions, an instant power shortfall or curtailment of renewables may occur under normal weather fluctuations, whereas extreme weather conditions may create the risks of both short-term power supply disruption and long-term energy shortage in a high-proportion VRE system. From the perspective of temporal scale, a mismatch between supply and demand may lead to frequency fluctuation over a short

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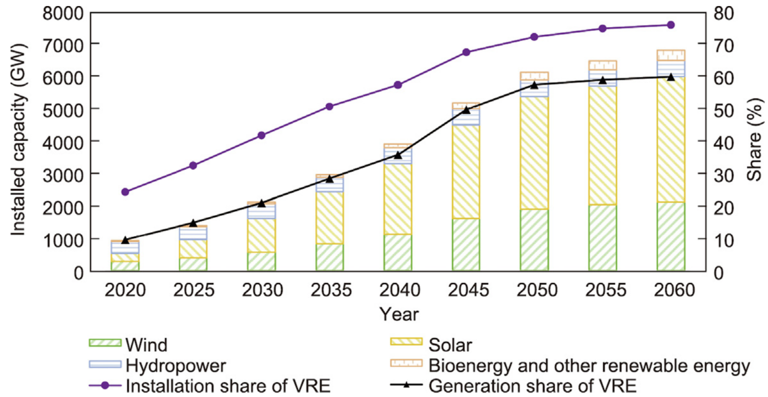

Fig. 1. Projection of renewable energy trends in China's power system.

Table 1
Major problems of high-proportion VRE system from different perspectives.

Classification perspective	Type	Main issues
Weather conditions	Normal	Instant power shortfall or curtailment of renewables
	Extreme	Short-term power supply disruption and long-term energy shortage
Temporal scale	Short timescale	Frequency fluctuation (grid frequency regulation)
	Medium timescale	Hourly active power imbalance (integration of renewables and stable power supply)
	Long timescale	Energy imbalance (seasonal adjustment)

timescale, hourly active power imbalances over a medium timescale, or energy imbalance over a long timescale.

1.3. Existing flexibility resources are insufficient for the future power system

The current power system already contains some flexibility resources, such as retrofitted coal-fired units, pumped hydro storage, new energy storage, and demand response. For example, the minimum stable output of retrofitted coal-fired units can be reduced to 20%–30% of their rated capacity under pure condensing conditions and to around 50% under heating conditions [18]. As of the end of 2022, 45.79 GW of pumped hydro storage and 8.70 GW of new energy storage were in operation [19]. As for demand response, the State Grid Corporation of China cumulatively implemented 18.53 GW of peak-shaving response and 19.25 GW of valley-filling response during the period of the 13th Five-Year Plan [20]. Nevertheless, the existing flexibility resources are still far from sufficient to support the growing proportion of VRE under China's dual carbon goals, and flexibility requirements may grow over time. Although the regulation capacity released from the flexibility retrofitting of coal-fired units is effective and economical, it will be limited in the long term due to the decrease of coal-fired units in future. With increasing renewable energy penetration, the long-term mismatch between power generation and load will become more prominent and may exceed the adjustment capacity of short-term energy storage. Moreover, the availability and regulatory performance of demand response can be affected by many factors, such as user behavior and market mechanisms.

2. Requirements for flexible regulation capacity of the new power system

The technical characteristics of several flexible resources are summarized in Table 2 [18,21–23]. Different technologies perform differently in terms of their regulation timescale and sensitivity to weather conditions. Considering the characteristics of renewables, as the proportion of VRE in the power supply continues to increase, the requirements for system flexibility will vary at different development periods.

2.1. Before the year of 2030

Prior to 2030, thermal power will remain the main source of power generation in China. Therefore, the key to the development of the power system lies in improving the utilization of renewables and promoting the synergy between VRE and thermal power. At this stage, the main challenge is energy imbalance on the short-to-medium timescale, which places higher demands on the system inertia, frequency response, ramp capability, reserve capacity, and minimum unit output. The potential flexibility from existing assets, including traditional units and loads, should be fully utilized.

On the supply side, the flexibility retrofit of unabated coal-fired plants should be vigorously carried out as soon as possible to take advantage of their durable and reliable service, prominent performance, mature technology, and affordable cost. This retrofit is particularly suitable in the "Three-North" region of China (i.e., northeast, north, and northwest China), where combined heat and power units make up the majority of installed capacity, while pumped storage plants are rare. If the minimum output of coal-fired units in operation in China by 2022 can be reduced from 50% of the rated capacity (the current average level) to 40% after flexibility retrofitting, nearly 112.4 GW of flexible regulatory capacity can be unlocked, which is equivalent to 14.8% of the wind and solar installed capacity at that time. Hour-to-hour ramping requirements are projected to increase by 50% during 2020–2030 [24]. In addition to coal-fired units, other renewable energy sources—such as biomass, with its combined usage for cooling, heating, and power—should be studied and demonstrated to utilize their important capabilities in inertia support, negative-carbon emissions, and efficient multi-energy utilization [25]. On the demand side, priority should be given to short-duration demand response capability by formulating contract-driven or price-driven

Table 2
Technical characteristics of relevant flexible resources.

Type			Operational range (rated capacity)	Ramping rate (rated capacity·min^{-1})	Start-up time	Storage duration	Whether affected by weather [a]	Regulation timescale [b]		
								Short timescale	Medium timescale	Long timescale
Supply	Coal-fired unit	Normal	50%–100%	1%–2%	6–10 h	—	×	☆	☆☆	☆☆☆
		Retrofitted	30%–100%	3%–6%	4–5 h	—	×	☆	☆☆☆	☆☆☆
	Coal-fired combined heating and power	Normal	80%–100%	1%–2%	6–10 h	—	×	☆	☆	☆☆
		Retrofitted	50%–100%	3%–6%	4–5 h	—	×	☆	☆☆	☆☆☆
	Gas plant		20%–100%	8%	2 h	—	×	☆☆	☆☆☆	☆☆
	Dispatchable hydropower		0–100%	20%	< 1 h	—	√	☆☆☆	☆☆	☆
Load	Demand response		3%–5% of maximum load	Instantaneous	—	—	√	—	☆☆☆	☆
Energy storage	Pumped hydro storage		−100%–100%	10%–50%	< 0.1 h	6–12 h	√	☆☆☆	☆☆☆	☆
	Electrochemical energy storage		−100%–100%	100%	< 0.1 h	Hourly	×	☆☆☆	☆☆	—
	Hydrogen (generated from VRE)	ALK	10%–110% [21]	< 0.8% [22]	< 50 min [23]	Hourly/ seasonal	×	☆	☆☆☆	☆☆☆
		PEM	0–160% [21]	< 1.7% [22]	< 20 min [23]	Hourly/ seasonal	×	☆	☆☆☆	☆☆☆
		SOEC	20%–100% [21]	—	—	Hourly/ seasonal	×	☆	☆☆☆	☆☆☆

[a] Physical damage to infrastructure caused by extreme weather is not considered.
[b] "Short timescale" refers to the second- or minute-level response capability, "medium timescale" refers to hourly or daily regulation, and "long timescale" refers to regulation across weeks, months, or seasons. A greater number of star symbols (☆) indicates better performance. ALK: alkaline electrolysis; PEM: proton exchange membrane electrolysis; SOEC: solid oxide electrolysis cell.

mechanisms. As an auxiliary measure, the type and capacity of energy storage should meet the need of certain application conditions. Research has shown that, by 2030, 106.6 GW/426.8 GW·h of energy storage (excluding pumped hydro storage) will be needed for VRE consumption and electric vehicles in China [26]. Although short-duration energy storage is currently prioritized, research on long-duration energy storage should be accelerated. It is also important to optimize end-use energy structures in the electrification process in order to improve the load characteristics. For example, solar-assisted heat pumps can be explored to fully utilize renewable energy [27].

2.2. The period between 2030 and 2060

At this stage, the penetration of renewables will reach a high level, and the main contradiction in the development of the power system will lie in the interweaving of long-timescale electricity imbalance with short-timescale power imbalance. The threat of and damage caused by extreme weather to the high-VRE power system will become increasingly severe. Thus, the flexible regulation capacity of the system will be not only crucial for the development and integration of renewable energy but also the cornerstone of ensuring the safe operation of the system.

In order to achieve stable and economic operation of the power system, the principles of tapping the potential of existing resources and optimizing incremental resources should be followed. It is advisable to deeply upgrade and decarbonize retrofitted coal-fired power units by more diverse means, so as to reliably provide inertia, ramping flexibility, and sufficient capacity. For example, a traditional coal-fired plant could be transformed into an integrated energy production unit by introducing carbon capture, hydrogen production from renewables, methane/methanol synthesis, and hydrogen gas turbines [28]. Accurate predictions and active support capability for new energy sources should be strengthened to

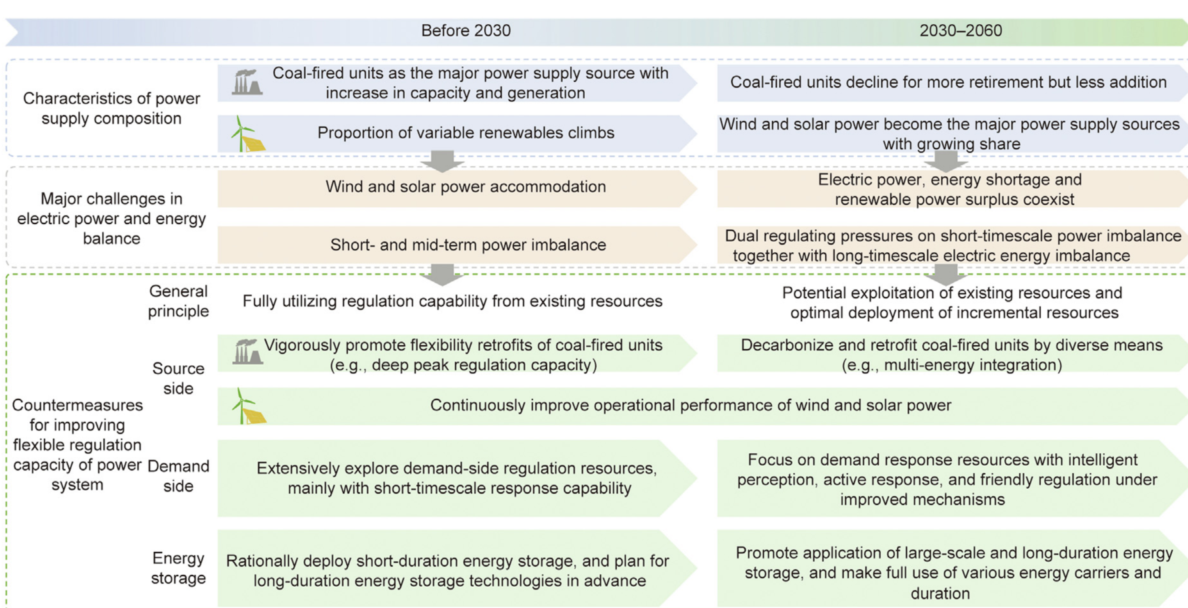

Fig. 2. Main challenges and countermeasures of China's new power system at different development stages.

cope with weather disturbances. On the demand side, the demand response capacity should be continuously stimulated by appropriate mechanisms to promote intelligent perception, active response, and friendly regulation. It is also necessary to determine the duration and types of energy storage based on the characteristics of the power supply–demand balance and economic benefits. According to an analysis [29], it is expected that energy storage (including pumped hydro storage) and demand response will account for 40% of all peak reserve capacity by 2060. Demand response for small-scale momentary ramping needs will account for over 50% of total ramping flexibility while dispatchable plants and energy storage will meet most of the more durable ramping requirements. It is also estimated that nearly 513.0 GW/2083.6 GW·h of energy storage (excluding pumped hydro storage) will be needed by 2050 for a prediction scenario in which the total installed capacity reaches 5546 GW [26]. By 2060, nuclear power, the remaining fossil fuel plants, and renewables such as hydropower and bioenergy will provide most of the rotational inertia to support the stable operation of the power system.

To sum up, considering the adaptability of different flexible resources to the supply–demand balance of the power system, it is necessary to vigorously facilitate the upgrading and retrofitting of coal-fired units in the short-to-medium term, continuously strengthen the controllability of new energy, actively implement demand response from the load side, and steadily promote the application of all kinds of energy storage technologies. The characteristics of the power supply mix, major challenges, and countermeasures are outlined according to development stages in Fig. 2.

3. Suggestions for flexibility improvement

Based on the above discussion of the new challenges presented by China's power system with high VRE penetration and relevant countermeasures, we recommend that actions be taken in five aspects:

(1) **Continuously strengthen the power grid structure.** It is necessary to promote the optimization of China's power grid structure and accelerate the research and application of new transmission technologies. We need to construct a robust power grid with the ability to withstand severe faults, in order to lay a foundation for the normal operation of regulatory measures.

(2) **Improve the accuracy of new energy output and load forecasting.** We recommend carrying out research on numerical weather forecasting and making the power supply and load demand measurable, observable, and predictable under normal and even extreme weather conditions.

(3) **Implement a series of flexible and coordinated regulatory measures considering both short-term and long-term requirements.** In the short term, flexible retrofits of coal-fired power plants, the implementation of demand response, and the rational deployment of short- and medium-duration energy storage should be vigorously promoted. It is also necessary to proactively plan and develop technologies such as active support technology of new energy sources and long-duration energy storage. In the medium-to-long term, it is necessary to leverage the regulation capabilities of coal-fired power units, improve the demand response mechanisms, and promote the large-scale application of the technologies mentioned above.

(4) **Conduct continuous analyses of system-balancing characteristics and corresponding solutions.** We recommend regularly assessing and predicting the state of the power balance in the system, considering factors such as the power structure, grid configuration, and load characteristics. We also suggest improving mechanisms for status tracking, problem analysis, and risk management of the system regulation capability. Analyses should cover aspects such as the real-time monitoring of operational conditions, and short- and long-term planning.

(5) **Formulate incentive policies.** More emphasis should be put on improving the comprehensive regulation capability of the power system and formulating policies in phases to stimulate the research and application of key technologies such as coal-fired power retrofits, energy storage, hydrogen, and bioenergy. Furthermore, it is of great importance to make joint efforts among companies, universities, and institutes to address the systemic issues brought about by the increasing penetration of new energy.

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Compliance with ethics guidelines

Qiang Zhao, Yuqiong Zhang, Xiaoxin Zhou, Ziwei Chen, Huaguang Yan, and Honghua Yang declare that they have no conflict of interest or financial conflicts to disclose.

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