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Challenges of developing a power system with a high renewable energy proportion under China's carbon targets

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ABSTRACT

For China, one of its most important commitments is to realize its "3060" targets of achieving a CO_2 emission peak by 2030 and carbon neutrality by 2060. However, for a developing country with heavy carbon utilization, achieving carbon neutrality in a short period necessitates tough changes. This paper briefly introduces energy and electricity scenarios and analyzes the challenges based on the current power system in China. Moreover, it summarizes the six characteristics of China's future power grid and highlights some partially representative projects in the country.

KEYWORDS

3060 targets, energy and electricity scenarios, impossible trinity, novel power system.

In 2020, COVID-19 swept the globe, triggering deep contemplation of the relationship between humankind and nature. Consequently, global climate governance has been drawing greater attention, and in December 2020, the Climate Ambition Summit was convened. China has made active efforts and important contributions to implementing the Paris Agreement. The report to the 19th CPC National Congress identified the way forward for China's energy development, proposed to promote a revolution in energy production and consumption, and aimed to build a clean, safe, and efficient low-carbon-energy society. To address climate change, China made a firm commitment to peak its CO_2 emissions by around 2030 and achieve carbon neutrality by 2060. CO_2 emissions per unit of gross domestic product will reduce by 60%–65% in 2030 as compared to the values of 2005; by then, nonfossil energy will account for 20% of primary energy consumption. To fulfill this commitment and meet the requirements for environmental protection and resource conservation, China has established its own energy development goals. Accordingly, it is expected that 50% of electricity will be generated from nonfossil sources, and the total installed capacity of wind and solar power will increase to over 1.2 billion kilowatts by 2030. Nonfossil energy will account for more than 50% of primary energy consumption by 2050[1]. The targets of achieving peak carbon emissions by 2030 and carbon neutrality by 2060 have great significance on a global scale.

China's energy system is centered on the use of coal-fired energy, and as the world's largest developing country, it accounts for a high proportion of the world's carbon emissions. Currently, coal consumption in China accounts for 57% of all energy consumption, and the country is in a period of heavy carbon emission. Thus, overall carbon emissions have been growing continuously over recent years and are yet to peak. China has only 30 years to transition from carbon peaking to carbon neutrality; the European Union will need approximately 70 years, while the United States and Japan are estimated to require about 40 years, as shown in Table 1[2]. China's timescale for achieving the target of net-zero carbon is the shortest in global history; however, this task is arduous.

Table 1 Carbon peaking to carbon neutrality in major countries

Country	Carbon peaking	Carbon neutrality	Period (years)
EU	1990	2050	60
Denmark	1996	2050	54
UK	1991	2050	59
France	1991	2050	59
US	2007	2050	43
Japan	2013	2050	37
China	2030	2060	30

As shown in Figure 1, from the general law of human energy development, a general rule always stands for higher energy-density replacement. However, the use of low-density renewable energy (RE) breaks this rule. In the new round of energy reform, high-density energy is replaced with low-density energy, with electricity as the key to its realization.

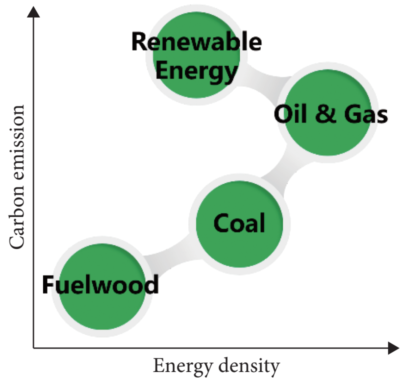

Fig. 1 Global energy development process.

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As electricity is the key to this energy transition, it can be analyzed separately from both production and consumption perspectives. On the one hand, the main goal is to reduce the share of coal and oil while increasing the proportion of RE (RE refers mainly to nonhydro RE sources); its conversion into electricity is the main solution for realizing energy transition on the production side. On the other hand, on the consumption side, the ratio of electricity in end-user energy consumption needs to be increased, and the acceleration of electricity replacement in sectors such as transport, building, and industry is urgently required. China has estimated that the share of electricity in end-user energy consumption will increase from 26% in 2020 to 45%–50% in 2050. Accordingly, the realization of its carbon targets can be expected soon.

1 Energy and electricity scenarios under the "3060" targets

According to the above prediction, China's total primary energy consumption by 2060 will be approximately 4.6 billion tons of standard coal, almost 80% of which will come from nonfossil energy sources[3]. The main sources will be wind and solar power, which will be predominantly converted into electricity (see Figure 2).

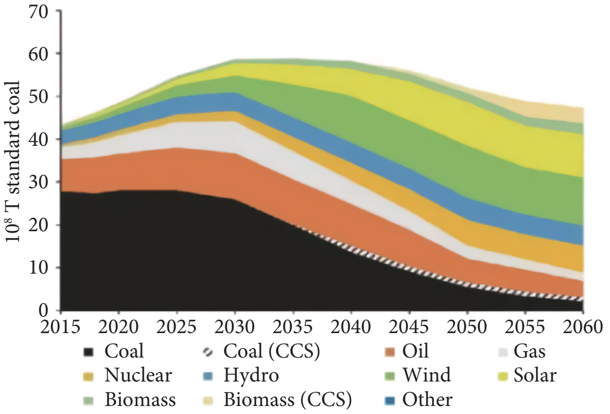

Fig. 2 Total amount and structure of China's primary energy consumption (reprinted with permission from Ref. [3], © Xiliang Zhang) .

In terms of end-user energy consumption, transportation, construction, industry, and other sectors have adopted electrification as an important measure for achieving the "3060" targets. As shown in Figure 3, the share of electricity in end-user energy consumption will increase by up to approximate 80% in 2060[4].

The State Grid Energy Research Institute Co. Ltd. predicted China's total electricity consumption in 2060 to be approximately 15 million GWh, with a total installed power supply of 8,000 GW. Within this, the installed capacity of RE will reach 5,000 GW, accounting for more than 60%. Hydropower, nuclear power, thermal power, and other synchronous generating units will comprise approximately 23% of the installed capacity, as shown in Figure 4 and Table 2.

In 2060, although synchronous generators will account for approximately 23% of all sources, they will provide nearly 40% of the electricity and will still account for a significant share. The electricity supplied by RE sources will account for more than 55% and will gradually become the main electricity generators[5].

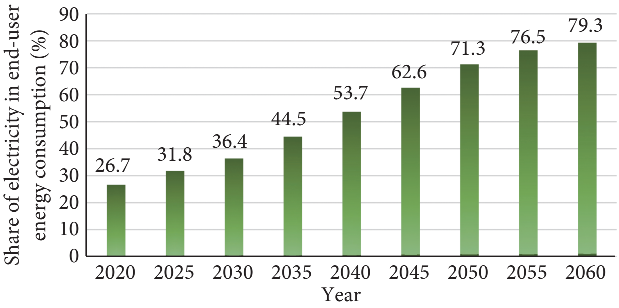

Fig. 3 Share of electricity in end-user energy consumption[4].

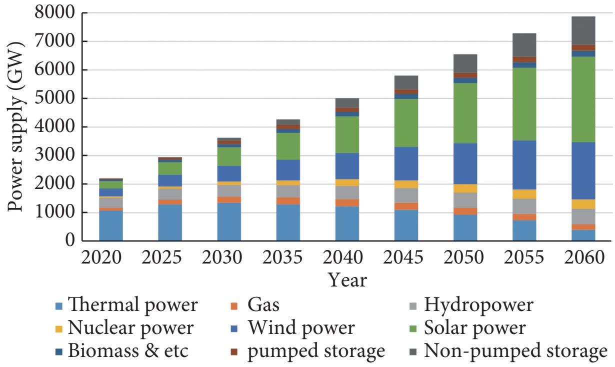

Fig. 4 Predicted power-supply installation development.

Table 2 Predicted development of China's overall power structure

Year	2020	2030	2060
Total installation (TW)	2.2	3.6–4.1	7.8–8.2
Share of thermal power (%)	49.1	31–36	4
Share of synchronous generating units (%)	76	Approximately 59	Approximately 23
Share of installed nonfossil energy (%)	44.8	52–59	88–89
Share of electricity from nonfossil sources (%)	33.9	39–45	86–87

2 Future challenges

In 2020, China's average full-load hours (FLHs) of wind and solar power were 2,097 and 1,160 h, respectively (see Figure 5); offshore wind power was approximately 2,500 h (USA > 3,500 h; Europe > 4,000 h).

Due to the low FLHs of RE, the installed capacity of RE in the scenario of a high-RE power system will be many times larger than the load, causing significant fluctuations in RE output, difficulties in power balance, and problems with operational control. Large-scale access of RE reduces the scale of conventional power supply and leading the difficult consumption when RE has large output. Additionally, there is a contradiction between power consumption and grid safety. The uncertainty of RE provides major challenges to the planning, design, production, and operation of power grids. This market form with abundant of RE installation will certainly give rise to new power business models and drive revolutionary changes to material, information, and value chains. The concept of the impossible trinity describes the relationship between power security, the economy, and the environment (see Figure 6). As they must be contradiction coordinated and optimization compromised, the three elements of the trinity cannot be perfectly realized in every angle.

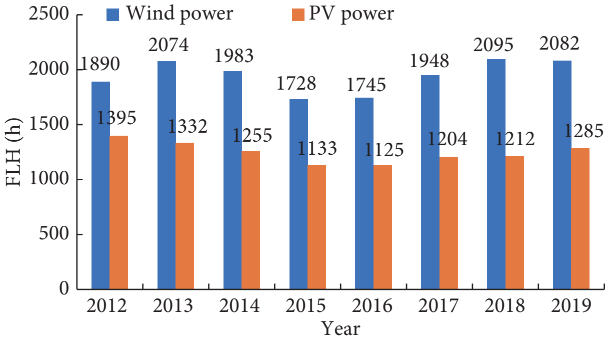

Fig. 5 Full-load hours (FLHs) of wind and photovoltaic (PV) power 2012–2020.

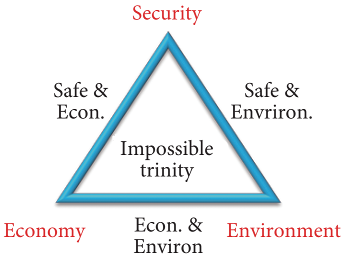

Fig. 6 Impossible trinity of a power system.

The fluctuation and randomness of RE and the low disturbance immunity and weak support of RE generation equipment challenge the efficient accommodation of RE as well as the secure operation of the power grid and market mechanisms. Due to the mismatch between RE characteristics and energy demand, the form and function of the existing power grid, and the future demands of a high-RE power system, the challenges of the three aspects have focused on the development and operation of the power system, i.e., an abundant power supply, safe and stable operation, and a large volume of new energy. It is also the main barrier to realizing the coordination and optimization of demands on security, the economy, and the environment. An analysis of the three challenges was conducted as follows.

2.1 Challenges of accommodating renewable energy

The first challenge in accommodating RE involves the difficulties in coping with large intraday fluctuations of output. In 2019, the maximum daily fluctuation in RE power in the supply area of the State Grid Corporation of China (SGCC) reached 107 GW, which represents approximately 31% of the total installed capacity. In the future, RE power fluctuation will increase further as the installed capacity of RE expands. In 2050, China's maximum intraday fluctuation in RE power may exceed 1 TW, which is close to the total installed capacity of conventional power. Therefore, addressing the intraday power fluctuations of RE poses a major challenge for conventional power systems.

The second challenge is the demand for large-capacity energy storage due to the long duration of high-RE output. Additionally, other power sources are required to balance the power in an extremely low RE output scenario. The large fluctuations in RE output may be lengthy, while RE output can be extremely low in some periods. Using the Xinjiang Uygur Autonomous Region of China wind farm as an example, the longest duration of low power output (less than 0.2 p.u.) exceeded 8 days in 2018. A similar situation occurred at the Shaanxi PV power plant where the maximum duration of PV output below 20% of the installed PV capacity exceeded 4 days in 2018. Conversely, a sustained high-RE output severely challenges RE accommodation, grid security, and energy storage technology. During low RE output, conventional power sources and other non-RE units are required to counteract the power imbalance.

High peak power output and low production also lead to the high cost of the full accommodation of RE. Periods of peak RE power result in high-RE output with low power production, thereby requiring flexible power sources to balance the peak output of RE in the short term. However, this contributes little to annual RE power production. In future power systems with a high proportion of RE, the full accommodation of RE during peak periods will be costly.

The day-ahead power prediction of RE with a large absolute error increases the difficulty of generation scheduling. The complex terrain, diverse climate, and strong random fluctuations inherent in RE make it difficult to achieve high-precision power prediction. At the provincial level, a 15-min fluctuation rate in wind output that exceeds 3% accounts for more than 10% of the total period. This percentage is 7% higher than those in Europe and America. The relative error of day-ahead RE power prediction dropped from 14% in 2011 to less than 10% in 2019, while the absolute error increased from 6.77 to 41.47 GW. Any further rise in absolute error will significantly increase the difficulty of generation scheduling.

To analyze the RE accommodation problem, the China Electrical Power Research Institute conducted two case studies to determine the impact of a fluctuating RE output. Case study 1 analyzed RE accommodation with different RE production ratios under a condition of 50% minimum thermal power output (see Table 3).

In this table, the RE production rate is calculated from the RE power production divided by the total power consumption, while the RE penetration rate represents the RE installed capacity divided by the maximum load. The RE curtailment rate is the difference between the theoretical and actual power generation (abandoned power) divided by the theoretical power generation.

The results in Table 3 reveal that the accommodation problem under a scenario of a high proportion of RE production is severe, although the conventional power output is ensured at no less than 50%. When RE production accounts for 30%, the RE curtailment rate reaches 23%, and a full RE power-supply period ensues. Case study 2 assumed that conventional power sources were fully adjustable, and it analyzed RE power accommodation with different RE production ratios under the condition of convention unit power regulation (0%–100%). The results of case study 2 are presented in Table 4.

Table 3 Results of case study 1

RE production rate (%)	30	40	50
RE penetration rate (%)	113	198	565
RE curtailment rate (%)	23	45	75
Thermal power penetration rate (%)	111	111	111
Full RE supply hour (h)	11	248	918
Full RE supply times	1	13	39
RE annual utilization hours (h)	1562	1124	502
Thermal power annual utilization hours (h)	3438	3034	2490

Table 4 Results of case study 2

RE production rate (%)	30	40	50
RE penetration rate (%)	78	113	150
RE curtailment rate (%)	0.2	3.9	11
Thermal power penetration rate (%)	127	127	127
Full RE supply hour (h)	0	766	1512
Full RE supply times	0	55	83
RE annual utilization hours (h)	2036	1949	1804
Thermal power annual utilization hours (h)	3592	3019	2563

The results reveal that a high proportion of flexible power sources is effective in alleviating the problems of RE accommodation and power curtailment. However, as the proportion of RE production increases, the curtailment of RE power cannot be solved completely by the adjustment of flexible power units. Under conditions of a high or full RE supply, the penetration rate of both RE and thermal power exceeds 100%. Although the system's overall power supply is abundant, the time–space disparity intensifies and the FLHs of both RE and conventional units are reduced.

2.2 Security challenges

The security challenges caused by RE can be divided largely into four problem areas: frequency stability, voltage stability, power angle stability, and others, such as challenges with broadband oscillation and complicated controls.

2.2.1 *Increase in frequency stability risk due to the decrease in system inertia and frequency control capacity*

The integration of large-scale RE will replace conventional units, thereby reducing the system's rotational inertia and frequency control capacity. Consequently, the frequency variation accelerates, while the fluctuation amplitude, steady-state frequency deviation, and frequency stability risk all increase, as described by the following rotor equation:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t}=\frac{1}{J}\left(T_{\mathrm{m}}-T_{\mathrm{e}}\right) \tag{1}$$

where ω denotes the electrical angular velocity, J is the moment of inertia, and T_{m} and T_{e} are the mechanical and electromagnetic torques, respectively. From this equation, the system frequency deviation is observed to be strongly correlated to the moment of inertia and mechanical torque; these correspond to the inertia of the generator rotor and the active power regulation capability of the generator. A strong system always has a large rotational inertia, which leads to a slower frequency change. When RE participates in primary frequency control, the frequency response can be improved. Its participation can also reduce steady-state frequency deviation and maximum transient frequency deviation. However, RE still fails to improve system inertia, although it can provide some inertia support via virtual inertia control. Table 5 below compares the rotational inertia of different power sources.

Table 5 demonstrates that the rotational inertia of a wind turbine is relatively large, and variable-speed wind turbines have the capability of inertia support when using virtual inertia control. Compared with synchronous machines with a rotor speed variation of between 0.95 and 1.05 p.u., the rotor speed variation of a wind turbine is even greater (0.7–1.2 p.u.). However, the energy consumption of a wind turbine during speed recovery may cause the frequency to drop again.

Table 5 Comparison of rotational inertia in different power sources

Conventional units	RE with normal control
Thermal power T_j = 5.8–9.0 s	Doubly fed Induction generator (DFIG) provides little inertia
Nuclear power T_j = 7.6–8.6 s	Permanent magnet synchronous generator (PMSG) provides no inertia
Hydropower T_j = 4.0–6.0 s	Photovoltaic (PV) provides no inertia

2.2.2 *Prominent voltage stability problem due to insufficient reactive power support*

In RE units, the dynamic reactive power support capacity is lower than that in conventional units. As RE units connect to the power grid after several voltage-boosting steps, their electrical distance to the main grid is 2–3 times longer than that of conventional units. As the proportion of RE increases rapidly, the dynamic reactive power reserve and supporting capacity of the system decline sharply, which exacerbates the system voltage stability problem. Furthermore, severe transient overvoltage always occurs at power systems with a high proportion of RE. The large-scale integration of RE decreases the short-circuit capacity of the system and increases its transient reactive power variation, resulting in prominent transient overvoltage risks, tripping of RE units, and equipment damage. The simplified calculation of transient overvoltage can be described as follows:

$$\Delta U=\frac{\Delta Q}{S_{\mathrm{ac}}U_0}=\frac{\Delta Q}{\left(S_{\mathrm{trad}}+S_{\mathrm{cond}}+S_{\mathrm{RE}}\right)U_0} \tag{2}$$

where ΔQ is the transient reactive power variation, S_{ac} is the short-circuit capacity, and S_{trad}, S_{cond}, and S_{RE} are the short-circuit capacity of the conventional units, the condenser, and the RE, respectively. This simplified equation reveals the relationship between the voltage deviation, the transient reactive power variation, and the short-circuit capacity of the system.

2.2.3 *Complication in power angle stability characteristics complicated and increase in uncertainty*

Power angle stability and coupling relationships are affected by factors such as RE control modes, fault ride-through schemes, and the position of grid connection points; additionally, they can result in the introduction of new stability problems. A decrease in inertia accelerates the transient process and shortens the analysis timescale. Large-scale RE integration increases the complexity and uncertainty of power angle stability, making it difficult to configure the pre-plan security control strategy, thereby seriously affecting the security of the grid.

2.2.4 *Broadband oscillation and other risks*

With an increase in the installed capacity of RE, broadband oscillation may occur due to the interaction of various power-regulating devices. Oscillations have been recorded in wind-power bases, such as Hebei and Xinjiang Uygur Autonomous Region of China, China. Since 2015, more than 100 incidences of broadband oscillations with frequency coverage of 10–90 Hz have been recorded in the wind-power-gathering area of Hami. In serious cases, three direct-current system supporting thermal power units have tripped off simultaneously. Broadband oscillation seriously endangers equipment safety and the secure operation of the power grid.

Conversely, one of the characteristics of RE is the small capacity of a single unit in large quantities. Thus, RE always requires a complicated control and dispatch strategy. Currently, there are more than 1,500 RE stations in Northwest China, more than 4,000 large RE stations in the SGCC service area, and approximately 1.7 million distributed generation systems connected by a low-voltage grid. In the future, the use of large RE units will complicate the dispatch and operation of the system as well as the configuration and execution of its control.

2.3 Challenges of market mechanisms

The development of RE has been accompanied by the advent of RE price parity. In 2019, the levelized cost of energy of onshore wind power and PV power was approximately ¥0.315–0.565 and ¥0.290–0.800/kWh, respectively. On August 5, 2020, the National Development and Reform Commission and the National Energy Agency announced RE grid parity projects, including 11.4 GW of wind power and 33.1 GW of PV power. From January 1, 2021, China's newly approved onshore wind projects will achieve grid parity. As generation costs decrease further, RE is predicted to enter a growth period.

The operation cost of RE stations involves expenditure on personnel, maintenance, materials, and other costs. When compared with the cost of thermal power, the marginal cost of RE is extremely low. Thus, negative power prices might even appear in the electricity market. The requirement for green development and low marginal costs coupled with the high demand for RE ancillary services are challenging the design of the market.

Additionally, low development thresholds, short construction periods, and diverse developmental modes are also posing challenges. Generally, it takes several months to a year to construct a sub-50-MW wind-power project and between 4 and 6 months to construct a MW-level ground PV power station. RE power stations have a short construction period that is mismatched with that of grid planning. Moreover, financing models (e.g., crowdfunding, internet finance, physical finance/lease) drive RE development. Diversified market players and disorderly construction pose challenges for both market mechanisms and operational management.

3 Power scenario

The power system embodies the realization of "3060" targets, which involve creating a novel power system with RE as its major power source. To achieve this, all possible power scenarios of a novel power system must be carefully considered, and the key technologies that can realize those scenarios should be identified and studied (seen Figure 7).

3.1 Electrical characteristics

During the construction and development of a novel power system, RE will gradually dominate in terms of the number of installed units. To sum up, the novel power system will have the following six characteristics:

3.1.1 Converter and synchronous generator-based hybrid power generation system

The novel power system will be a hybrid power system comprising converters and conventional synchronous generators. In the novel power system, converter-based RE will become the main power supply. However, a certain proportion of the new system will be achieved from conventional synchronous power, among which, hydro and nuclear power will remain important nonfossil energy sources; coal and gas power with carbon capture, utilization, and storage will achieve near-zero emissions, and biological energy with carbon capture and storage will continue to affect both supply and regulation.

3.1.2 Comprehensive energy system

In the future, the proportion of electricity in the energy structure will continue to increase, the centrality of the energy will continue to strengthen, and the comprehensive energy system grid as the major point will be established. The replacement of electricity in industry, transportation, and construction will realize multi-type energy conversion and complementation to improve the security, flexibility, and comprehensive utilization efficiency of the energy system.

3.1.3 Elastic system

In the future, as the basic energy for other industries, power security will increase in significance as a guarantee of energy security. To enable a greater response to political, social, and economic influences, the power system must be constructed as an elastic and resilient system. In the face of extreme events, the system must encompass prevention, resilience, response, and rapid power restoration capabilities.

3.1.4 Cyber–physical social systems

The network and the informatization of the power system further integrate information and physical systems. The openness and diversification of integrated energy systems interconnect them with human social activities and the external environment, thereby embodying the characteristics of a cyber–physical society system (CPSS).

3.1.5 Complex giant system

The novel power system with RE at its core is a huge and complex multihierarchy system characterized by multisystem coupling at a multitemporal scale. It features novel energy-power-generation-wide distribution, huge units, and complex operational characteristics.

3.1.6 Intelligent system

The novel power system will be configured into an intelligent system to solve its complexity. The new generation of information technology can effectively realize the secure, efficient, and intelligent green application of energy. In every state of energy production, transmission, storage, and utilization, intelligent systems can ensure compliance with regulations via active monitoring, intelligent analysis, optimal control, and interactive sharing.

3.2 Practices in China

As the proportion of RE has continued to increase over recent years, the characteristics of the novel power system have gradually appeared. The enterprises and research institutions represented by State Grid Corporation of China have been practiced and tested in many scenarios.

As mentioned in the discussion on challenges, wind, solar, and other RE accommodation problems are becoming increasingly severe. Accordingly, measures to facilitate RE accommodation have been researched by different companies and research institutions since 2016. State Grid Corporation of China developed RE

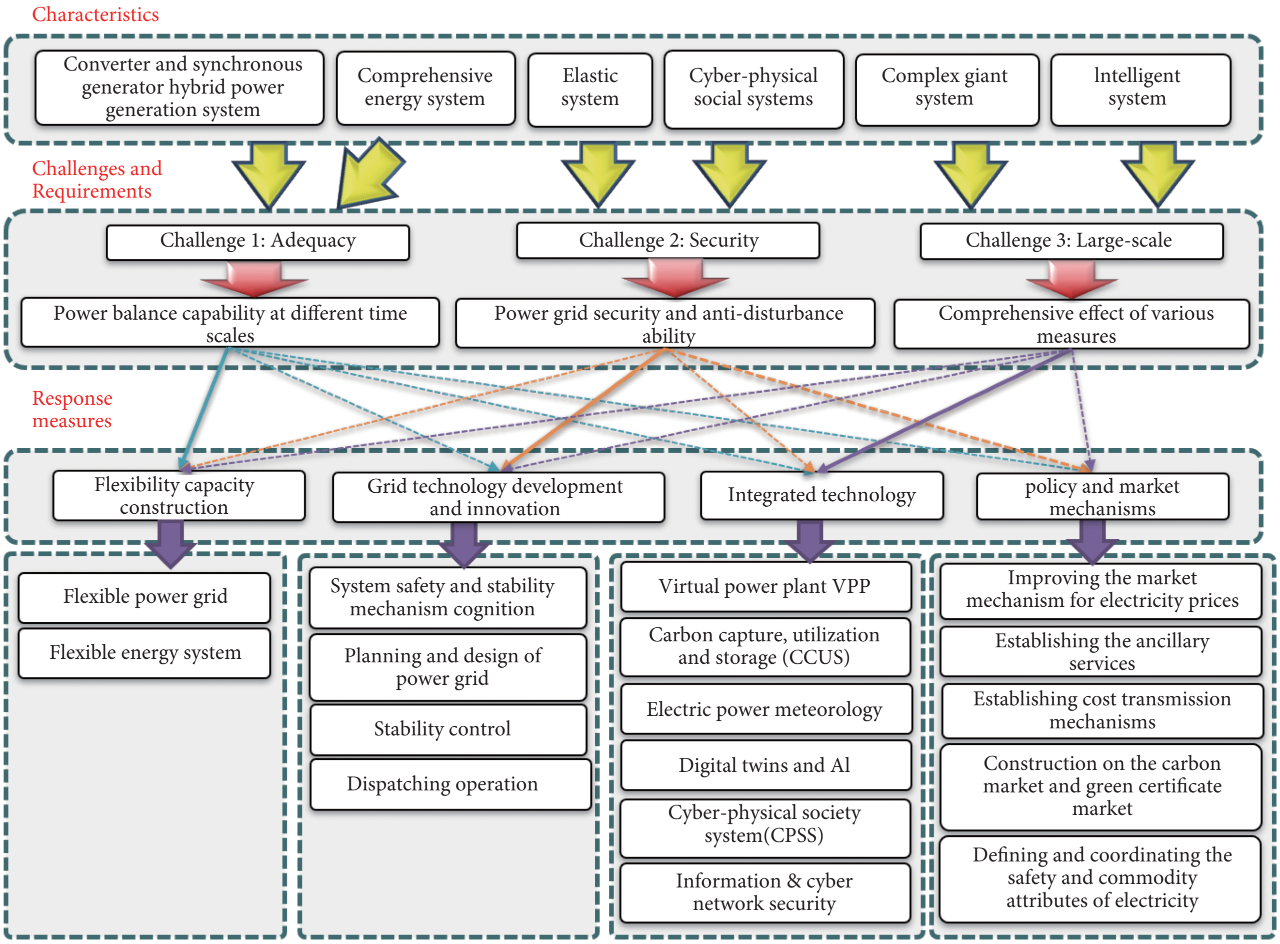

Fig. 7 **Block diagram of key technology route.**

production simulation software to simulate the time–series production of RE accommodation and analyze the effects of accommodation measures to support the planning and operation of RE.

China Electric Power Research Institute (CEPRI) predicted that by 2060, the power balance gap in China will exceed 1 billion kW, and tackling it will require the use of flexible adjustment sources. However, China's resource endowment determines that its installed power generation capacity is based mainly on coal, and the development of gas is limited. The flexible transformation of coal-fired plants, construction of pumped storage, and development of a variety of energy storage technologies are important methods proposed by China to enhance the flexible regulation capacity of the system and ensure power-supply capacity.

From the perspective of trans-regional and inter-provincial channels, China is facilitating the construction of trans-regional grids to increase its power transfer capacity and promote RE accommodation. CEPRI pointed that by the end of 2019, China had completed the construction of 11 UHV AC (ultra-high voltage alternating current) projects and 14 UHV DC (ultra-high voltage direct current) projects, with three UHV AC projects and four UHV DC projects under construction. In July 2020, China's trans-regional maximum power transfer reached 92.08 GW, and its inter-provincial maximum power transfer reached 80.5 GW.

The novel power system involves the improvement of not only the generation and grid but also the load side. Demand-side management can enhance the power transmission and accommodation capabilities of RE power. For example, a user friendly interaction system was constructed in Jiangsu province for power generation, the transmission and distribution system, and load demand. When the commutation failure of multi-feed DC lines occurs, the system can shed a 2.8-GW load within 1 ms.

In the novel power system, the uncertainty of RE leads directly to stability and consumption problems; this issue is currently being addressed by Chinese researchers. The RE forecasting system was developed based on numerical weather prediction and an optimal dispatching system to facilitate the operation of China's power system. The Zhangbei national wind and solar energy storage and transmission demonstration project has been constructed. It realizes the complementary and intelligent power transmission of wind, solar, and energy storage systems, leading to a stable and controllable RE output. The project provides a solution for the global problem of large-scale RE integration.

However, the establishment of a novel system is not only a technological innovation as the technical standards also require improvement. China has established a technical standard system for RE integration, of which almost 100 have been formulated at the national, industrial, or enterprise level. Supported by the International Electrotechnical Commission's (IEC) SC 8A working document, 13 IEC standards are being formulated and revised, three IEC technical white papers have been released, and two IEC standard proposals have been submitted.

4 Conclusions

As technology advances and the cost of generation decreases, it is anticipated that RE will experience a long period of rapid growth.

Gradually, power systems with a high proportion of RE will evolve from local areas for supplying the entire grid. The prominent conflicts between the surplus of RE power and electricity, unbalanced distribution of supply and demand, accommodation of RE, and security of the system will pose huge challenges for market mechanisms, planning and design, production and management, and operation and control.

Furthermore, as the proportion of RE generation increases, the analysis and stability of the system will face tough challenges, including a sharp increase in the demand for generation equipment as well as mounting uncertainty, complexity, and nonlinearity with accelerated dynamic processes of the power system. Additionally, the large amount of electronic equipment involved will prompt big changes to the system's characteristics and active/reactive power-balancing capabilities, exacerbating the problems of multi-timescale coupling and decreased controllability.

In terms of technical aspects, urgent research is needed into new technical conditions and requirements for RE equipment, operation, and control to construct an RE-dominated power system. When RE serves as the main power supply, the due responsibilities and obligations of RE will be well defined. Different measures can be used to address the issue of large power fluctuations, including power utilization, multi-energy complementary, and integration, together with other new technologies such as state-of-the-art meteorological forecasting, sensing, communication technology, artificial intelligence, and coordinated producer–network–consumer storage.

Conversely, as an effective technical solution for a high-RE system, the energy internet, which is a complex CPSS and an intelligent energy system, will face increasingly complex challenges, particularly in terms of cyber security.

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Additional information

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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