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LETTER
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Power system decarbonization pathway of China

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ABSTRACT

Under the pressure of environmental issues, decarbonization of the entire energy system has emerged as a prevalent strategy worldwide. The evolution of China's power system will increasingly emphasize the integration of variable renewable energy (VRE). However, the rapid growth of VRE will pose substantial challenges to the power system, highlighting the importance of power system planning. This letter introduces Grid Optimal Planning Tool (GOPT), a planning tool, and presents the key findings of our research utilizing GOPT to analyze the transition pathway of China's power system towards dual carbon goals. Furthermore, the letter offers insights into key technologies essential for driving the future transition of China's power system.

KEYWORDS

Power system planning, carbon neutrality, power system transition.

Decarbonization of the entire energy system is increasingly becoming the global consensus[1]. Most developed nations have set ambitious decarbonization targets[2]. In China, the power sector contributes the largest share of carbon emissions. To meet dual carbon goals, China has to dramatically change the generation mix of the power system. By the end of 2022, China's total installed power generation capacity had reached 2.56 billion kW. Over the past three years, the installed capacities of wind power and photovoltaics (PV) have experienced rapid growth, with an average annual increase of 100 GW. By the end of 2022, China's installed capacities for wind power and PV have reached 670 million kW, accounting for one-third of the global installed capacities and surpassing the combined capacities of the United States and Europe. Under the dual carbon goals, constructing a new-type power system with an increasing penetration of new energy will become the main development direction of China's power industry in the next 30 to 40 years.

Currently, the decarbonization pathway of the power system has received widespread attention from academia and industry. Shu et al. conducted an analysis on the evolution of China's power generation portfolio across three transition scenarios: deep low-carbon, zero carbon and negative carbon[3]. Chen et al.[4] delved into the impacts of inter-provincial power balancing on China's power system transition pathway and the associated costs of carbon reduction. Additionally, Luo et al.[5] and Song et al.[6] studied the transition of energy systems in Sichuan and Guizhou, respectively. Furthermore, several researchers have developed software tools for analyzing China's power system transition, such as SWITCH–China[7] and China TIMES-30P[8]. Moreover, extensive research efforts in the United States and Europe have also been dedicated to exploring the transitions within their power systems[9,10].

On December 1st, 2023, a workshop titled "US–China Scientific Symposium on Carbon Neutrality and Climate Change" was held in Harvard University. This letter shares the view of China's power system decarbonization pathway presented in this workshop and also offers some perspectives on the construction of new-type power systems.

1 Challenges and key techniques of power system transition

Despite the rapid growth of variable renewable energy (VRE) in recent years, there is still a long way to go before achieving carbon neutrality. According to the forecasts from the State Grid Energy Research Institute, both peak load and electricity demand are projected to be double by 2060 compared with 2020, with the electrification rate increasing from 27% to about 70%[11]. Equivalently, an additional power system needs to be built during carbon neutrality. Given the considerable distinctions between VRE units and conventional synchronized generators, the transition towards carbon neutrality poses substantial challenges to power system stability, control, dispatch operations, and planning decisions. Figure 1 provides an overview of these challenges and potential technical solutions. When VRE penetration is below 10%, the integration of new energy has a limited impact on the power system. However, as VRE penetration increases, several challenges emerge, including limited flexibility due to the intermittency of VRE[12], diverse operating scenarios resulting from the stochastic nature of VRE[13], and the low inertia issue arising from high shares of power electronics[14]. The effects of these challenges on the power system are noticeable across various time scales and gradually shift from being localized to becoming a systemic challenge as VRE penetration increases. In response to these challenges, various industrial and academic solutions have been proposed. These solutions can be broadly classified into four main groups: inertial stabilization control[15], temporal power balancing[16], spatial power balancing[17], and introducing diversified power sources[18,19]. These techniques vary in terms of principles, economic costs, and development prospects. Each key technology can only address a specific portion of the problems. Therefore, the application of these technologies should comprehensively consider their technical performance, cost-effectiveness, and complementarity with other technologies.

2 Power system transition analysis tool towards decarbonization goal

China's power system transition is a complex long-term planning

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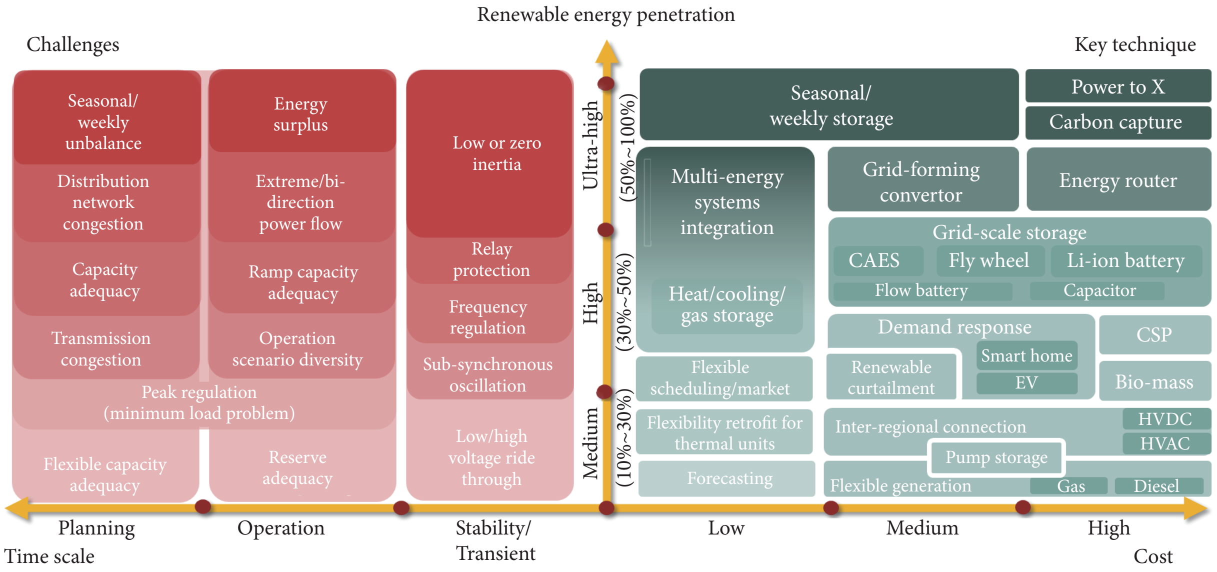

Figure 1 Challenges and key techniques of power system transition.

issue, with high demands for the effective coordination of the three targets: security and reliability, economic efficiency, and environmental sustainability. This requires fully exploiting the development potential of the entire power system. In response to this practical demand, a coordinated generation-grid-load-storage optimization planning model has been established based on Grid Optimal Planning Tool (GOPT) software platform developed by Tsinghua University. The model considers multiple secure and policy constraints, such as reserve requirements, minimum inertia limits, and carbon emission restrictions. Based on actual data collection of China's power system, the provincial VRE potential, supply curves, thirteen types of generation units, AC/DC transmission lines, and three types of demand response resources are considered and coordinated in the model. The GOPT can be applied to optimize the morphology and decarbonization pathway for China's power systems.

3 Power system decarbonization pathway of China

We conducted an analysis on the pathway of China's power system towards the dual carbon goals using real-life data[20,21] (see Figure 2). The key findings are as follows.

3.1 Generation side

The dual carbon goals primarily influence the installed capacity of coal power and VRE in China. Under the carbon neutral goal, the energy penetration rate of VRE is expected to reach more than 70% by 2060, with wind power and PV having installed capacities of more than 3500 GW and 2200 GW, respectively. Coal power plants are scheduled to start retiring from 2040, while their produced energy will start to reduce from 2030. Energy storage systems (ESSs) and concentrated solar power (CSP) are expected to play a critical role as flexible generation sources.

In terms of the timeline, the period from 2030 to 2040 is crucial for China's power system transition. The average annual incremental installed capacity for wind power and PV exceeds 80 GW and 110 GW, respectively. Additionally, the annual addition of ESS installed capacity exceeds 30 GW. During this period, the installed capacity of coal power is expected to decrease by approximately 60%.

Different types of VRE vary in spatial distribution. Large-scale onshore wind power units are mainly located in Northwest, North, and Northeast China. Offshore wind power is located in the three coastal load centers. PV units contribute significantly to the generation mix in most provinces in the country, especially in high-altitude provinces. CSP units are mainly located in Northwest China and Inner Mongolia where high-quality solar energy resources are abundant.

3.2 Transmission side

High renewable penetration also increases the demand for long-distance transmission lines, requiring more intensive grid interconnection to cope with the generation-load imbalance. Under the neutrality scenario, inter-provincial electricity exchange in 2060 is projected to reach 3.6 times the current level in 2020. The grid capacity needed for such exchanges estimated to be 2.6 times the current capacity in 2020. The capacity of newly constructed inter-provincial grid interconnection is approximately 780 GW, comprising around 370 GW for AC transmission and about 410 GW for DC transmission. The inter-regional transmission network maintains a "strong DC and weak AC" configuration. The power transmission direction retains the current basic mode of "West to East" and "North to South". Central China and East China regions remain the primary sources of electricity input, with the annual imported electricity exceeding 800 TWh. Moreover, the inter-provincial grid interconnection must gradually evolve from a simple power transmission channel to a platform supporting bidirectional energy sharing between regions with different generation resources.

3.3 Demand side

Under the carbon neutrality target, flexibility resources on the demand side will become crucial factors for supporting power balance. The total capacity demand for various types of resources is expected to increase rapidly after carbon peaking, reaching more than 25% of the maximum load. Electric vehicle (EV) groups and Power-to-Hydrogen (P2H) resources are expected to dominate the flexible resources on the demand side of the future power system.

3.4 Storage side

With the increasing penetration of VRE, the development of

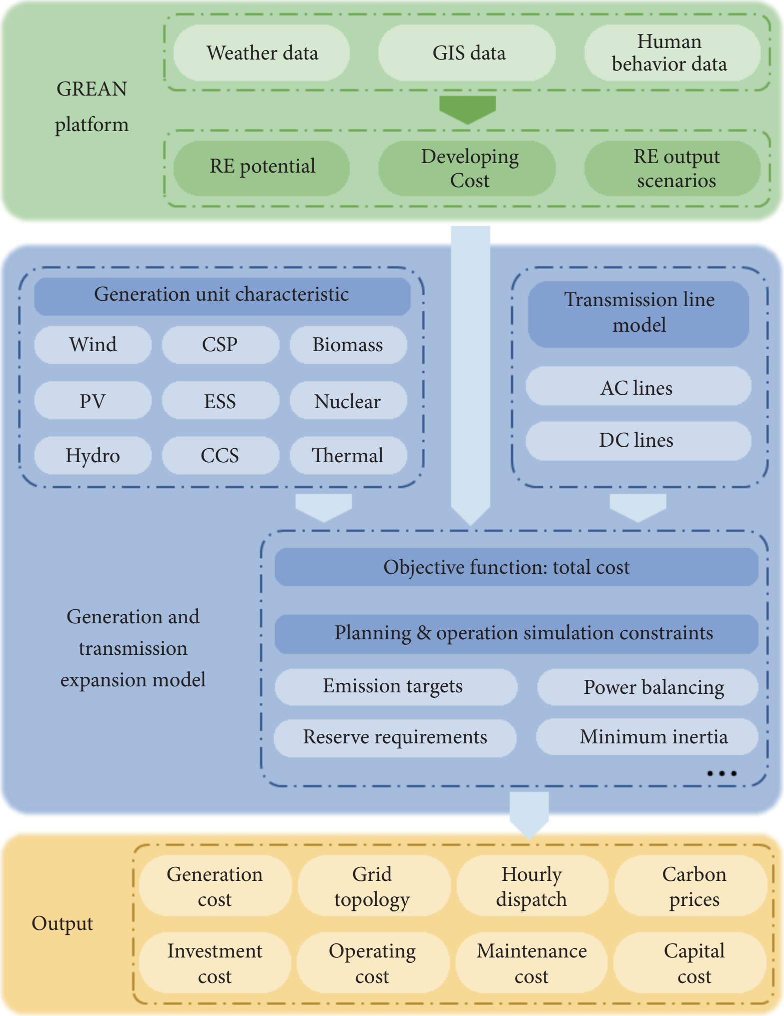

Figure 2 **Power system planning platform for achieving decarbonization goal.**

energy storage technology has attracted wide attention. By the end of 2022, the installed capacity of ESS in China was 55 GW, comprising 46 GW of pumped storage and 9 GW of new energy storage techniques such as batteries and compressed air energy storage. Over the next forty years, the installed capacity of ESS is expected to significantly increase in response to the growing demand for flexibility in the new-type power system. By 2030, pumped storage is projected to reach 200 GW, while new energy storage is expected to exceed 100 GW. Under the carbon neutrality scenario, the capacity of ESS is expected to double further, with pumped storage reaching 400 GW and new energy storage techniques exceeding 200 GW.

4 Discussion

The aforementioned results highlight significant differences between the new-type power system and the current one in terms of generation, transmission, distribution, and storage. However, until now, no single balancing power system has been able to accommodate over 50% VRE penetration, leading to a lack of consensus on the paradigm for future power system. Challenges related to reliability, flexibility, and stability are anticipated in the future power system. Moreover, numerous emerging technologies may influence its transition pathway. These challenges and new changes warrant further analysis and in-depth research. In this regard, we would like to share our perspectives here.

4.1 How do renewables contribute to the adequacy of the new-type power system?

As VRE continuously replaces fossil fuel within the power system, the role of conventional power sources is expected to gradually shift from energy support to flexibility support, while VRE will take on the primary responsibility for fulfilling load demand. Additional capacity investments are essential during the planning stage to enhance the system reliability and mitigate the risk of demand loss. The contribution of conventional power sources to reliability can be quantified by the concept of capacity credit which considers varying forced outage rate. However, the effective load capacity of VRE is unclear due to its intermittent and stochastic nature. The extension of capacity credit to renewable energy has attracted attention in the academic community but has not yet yielded a convincing conclusion[22]. The following issues require further study. Confidence capacity based on the equivalent reliability principle cannot effectively address issues such as insufficient power supply from VRE during extreme weather conditions of consecutive days without wind and sunlight. The unclear principle of aggregating capacity credit of different units hinders the effective utilization of meteorological conditions and output complementarity between wind and PV to optimize the capacity and spatial layout of VRE units. Further research is needed on the impact of energy-limited resources such as ESS on the capacity credit of VRE.

4.2 How much flexibility from the demand side should contribute to balancing the new-type power system?

The current power system heavily relies on fossil fuel units to compensate for load fluctuations and accommodate VRE. However, fossil fuel units will struggle to fully meet the rigid load demands in the future new-type power system, despite some of them will be retained for flexibility support. Meanwhile, with the integration of new types of loads and the improvement of market mechanisms, the foundation for bidirectional interaction between supply and demand is gradually being established. Unlike the centralized generation side, the load side consists mostly of distribution resources which vary in type, are dispersed in location, and exhibit high uncertainty. Virtual power plant (VPP) technology emerges as a promising research field to control the massive distributed resources[23]. The aggregation of distributed resources can operate cooperatively as a power station for providing flexibility support. However, future power system planning will simultaneously consider multiple forms of flexibility requirements, such as fluctuation smoothing, peak shaving, frequency regulation, which may be further subdivided. There are two technical issues that require further investigation. The first is how much flexibility support should the allocated to the demand side at the planning stage. The second is how to coordinate heterogeneous resources at the control stage to fulfill the various flexibility requirements.

4.3 How can security and stability issues be effectively considered in the planning of the new-type power system?

Security and stability are essential for the normal operation of the system, particularly with the integration of high penetration VRE. In traditional planning models, ensuring security and stability relies on the combination of pre-checks, where simple empirical security rules are established in advance, and post-checks, which involve adjusting planning schemes based on simulations of critical scenarios. However, the changes in stability mechanisms present significant challenges to the above paradigm. On the one hand, high shares of power electronics profoundly affect the dynamics of new-type power system, even prompting IEEE to introduce two new types of stability: resonance stability and converter-driven stability[24]. More complex stability mechanisms cannot be adequately captured by simple empirical constraints, rendering pre-checks ineffective in mitigating insecurity and instability. On the other hand, diverse operational patterns resulting from the uncertainty of VRE make it difficult to identify the critical scenarios, adding considerable complexity to adjustments and simulations in post-checks. Given these limitations, there is a growing need to directly incorporate security and stability analysis into the planning model. However, this presents technical challenges, as dynamic processes are often described by complex physical laws while the planning model needs efficient solvability. Data-driven security and stability rules may offer a promising solution but there are still a series of technical challenges that need to be addressed before they can be applied to planning models[25]. The first challenge stems from the generation of the database because the accuracy and generalization of the security and stability rules relies on an accurate depiction of the operation pattern space which is difficult to achieve prior to planning. The second challenge lies in the effective embedding of security and stability rules into planning models because a large number of binary variables will be introduced when converting the rules obtained by machine learning methods into embeddable constraints, which may result in the intractability of planning models. The third challenge is to collaboratively consider multiple types of security and stability constraints, which is necessary because future power systems may face multiple security and stability issues simultaneously, but greatly increasing the complexity of the planning models.

4.4 How do various long-term uncertainty factors affect the transition pathway of the new-type power system?

Power systems planning towards carbon neutrality is a typical decision-making problem with long-term uncertainty. The deep decarbonization of the power system requires the coordinated integration of VRE and various emerging technologies, such as new energy storage and carbon capture and storage (CCS). Given that these emerging technologies are still in the early stages of development, their technological maturity and cost-effectiveness may change significantly during power system transitions[26]. It is challenging for us to accurately predict the future pathway of China's power system at the current stage. Consequently, it is critical to obtain more information than a specific optimal planning scheme from planning models. Planners and policy makers will commonly have two types of needs. When the planning model is feasible, they need to explain the optimal planning scheme, such as ranking the impacts of different uncertainty factors on transition pathway or identifying bottlenecks in the decarbonization of power systems. When the planning model is infeasible, they need to adjust the parameters reflecting uncertainty factors to make the model feasible, which can serve as a guideline for future energy policy formulation. As the transition pathway of China's power system is influenced by various long-term uncertainty factors, a simple comparison of schemes will no longer be able to fulfill the above demands. These two types of demands can be formulated as a quantitative attribution problem for the power system, but the related modeling methods and efficient algorithms are still in the early stages of development[27].

5 Conclusions

Carbon neutrality is the ultimate target of energy transition, while the power system will become the backbone of a carbon-neutral energy system. Ensuring rapid growth of wind power and PV is critical to decarbonizing the power sector. The integration of VRE presents substantial challenges to power system stability, control, dispatch operations, and planning decisions. Addressing these challenges in the power system transition requires a comprehensive consideration of different technologies in terms of technical performance, cost-effectiveness, and their complementarity. As a systematic, and urgent problem, China's power system transition is a long-term planning process that should consider the energy-economy-environment targets. Sufficient coordination between generation, transmission, load, and storage is crucial for constructing China's new-type power system. With the advancement of decarbonization, there are still a series of issues, such as reliability, flexibility and stability, that need to be studied in depth for constructing the new-type power system.

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Additional information

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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