Pathway toward carbon-neutral power systems in China

Xinyu Chen, Yaxing Liu and Yuxin Zhang

At the General Debate of the United Nations General Assembly conducted in September 2020, President Xi Jinping proposed that China will strive to achieve carbon neutrality before 2060. A recent study using high-resolution modeling pioneered in issuing optimized pathways for achieving carbon-neutral electrical systems in China by mid-century with negative CO_2 abatement costs[1].

As the world's largest energy producer and consumer, China requires a total investment of over one hundred trillion fixed assets to realize carbon neutrality, which will become an important engine for the green recovery of the global economy in the post-pandemic era. Presently, however, China's national top-level plan for the transition pathway toward a carbon-neutral electrical system remains unclear and the local goals and plans of emission reduction lack coordination. Designing a reliable and cost-effective transition pathway to establish carbon neutrality and ensure a secure energy supply is required urgently.

In a recent study published in *Joule*, Chen et al.[1] developed a cross-sector, high-resolution assessment model to quantify the optimal energy structures on a provincial basis for different years. Based on comprehensive grid data, hourly power system simulations for all provinces for a full year were incorporated into the assessment model to quantify the renewable balancing cost. To elucidate the transition pathway of China's electrical energy system, an 8760-hour simulation with ~60 scenarios of different low-carbon targets and research scopes in different targeted years were simulated to design a cost-effective roadmap. The transition pathway proposed by Chen et al. is not only technically feasible but also more cost-competitive than the conventional energy system powered by fossil fuels. Compared with the province-based balancing scenarios, the nationwide balancing scenario can reduce the total transition cost by 1.2 trillion *yuan* annually, which is roughly 2/3 of China's annual financial budget for public health.

Chen et al. analyzed the investment and operation costs for national and provincial planning with the target of realizing 80% renewable energy penetration, emphasizing the importance of coordinating the transmission line network and strengthening the connections among the provincial electrical systems. The results show that with coordinated optimization, 1.2 trillion *yuan* can be saved in the annual investment and operation costs per year, amounting to 5% of China's total fiscal expenditure in 2020. For the nationwide planning, increasing the investment in cross-sector grids can effectively promote the integration of renewable energy, substantially replace the installed capacity for energy storage by benefiting from a large power balancing scale to weaken the volatility of renewable energy, and largely alleviate the extreme imbalance in the distribution of load and resources in China.

Chen et al. summarized the provincial power generation mix and inter-provincial transmission network across China in 2050 required to achieve an 80% renewable standard portfolio. From

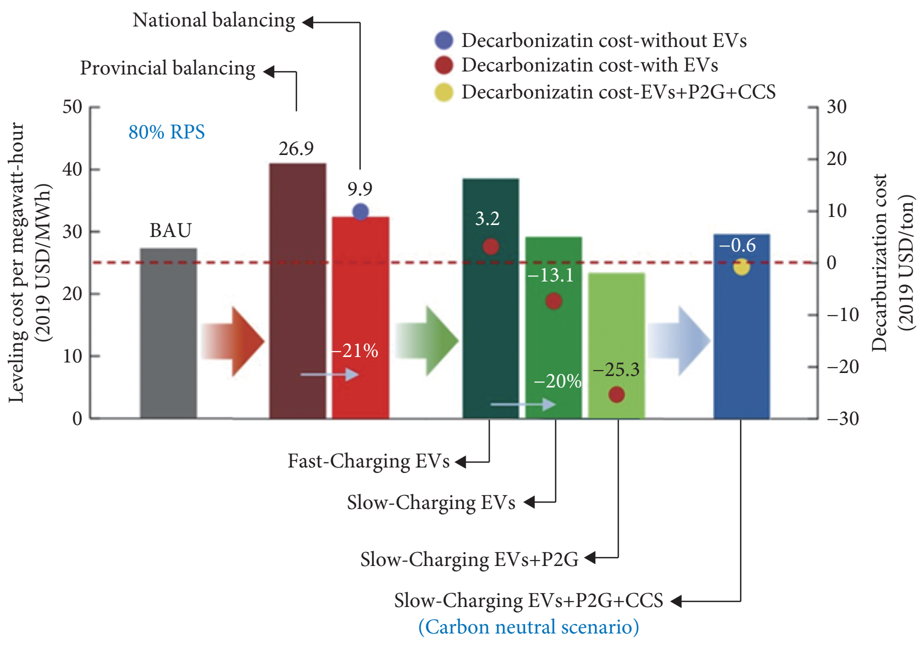

Fig. 1 Decarbonization costs across different scenarios for China in 2050 at 80% renewable energy penetration (reprinted with permission from ref. [1], © 2021 Elsevier Inc.).

the prospect of a nationwide power system, ~900 GW offshore wind power, ~1700 GW land wind power, and ~1350 GW photovoltaic power are required to serve 80% of the electricity demand by 2050. Regionally, it is recommended that over 700 GW of offshore wind power installations are deployed in eastern coastal China, 1500 GW of onshore wind power are deployed in mainly Northeast China, Northwest China, and North China, and 950 GW of photovoltaic power installations are distributed in Northwest China (200 GW), North China (500 GW), and East China (250 GW). In 2050, in the context of high-penetration renewable energy, the national transmission line paradigm must undergo structural changes, with the overall transmission framework shifting from the current "West-East transmission structure" to a "peripheral to central" alternative due to the uneven distribution of renewable energy potential.

The research also analyzes the change in the role of thermal power units in its transition to carbon-neutral electrical systems. The result shows that the total installed capacity of thermal power units will still exceed 1,000 GW at 80% renewable energy penetration; however, the annual full load hours of these thermal power units would only be 1,400 h (equivalent to 16% utilization ratio), thus decoupling the installed capacity and electricity generation of the thermal power units. With elevated renewable energy accommodated by the electrical systems, thermal power units will transform from electricity supply to vital support for capacity and flexibility adjustment, which requires regulation in the formation of on-grid thermal power tariffs accordingly.

Moreover, the study analyzes the crucial role that the decline in energy storage prices and the deployment of power-to-gas (P2G) technologies play in realizing carbon neutrality of the electrical systems. The results demonstrate that for every 10% decrease in the electrochemical energy storage prices in 2050, about 280 billion *yuan* can be saved for the total annual system operation cost. The decreased storage prices would increase the ratio of storage to renewable capacity, enhancing the capability of the electrical systems to integrate renewable energy. The P2G technologies enable the electrical systems to operate much more flexibly. With an extremely high ratio of renewable energy, the large amount of surplus electric power generated from renewable sources can be harnessed to produce hydrogen and improve the overall benefits of carbon-neutral electrical systems.

Additionally, the study optimizes the grid-connected charging strategy of electric vehicles under the carbon-neutral scenario and analyzes the impact of charging behavior on the operation of the power system, which serves as a key guidance for the joint decarbonization of electrical and transportation systems. The study optimizes the charging strategy of electric vehicles, demonstrating that the slow-charging strategy can effectively harness solar photovoltaic power to reduce the curtailment rate and peak load during charging periods. In the case of slow charging, there are shifts in charging times, from the evening rush to the afternoon, and charging sites, from residential areas to destinations (work locations or shopping malls), compared with the current situation. The results provide important insights into planning the installation of charging stations for electric vehicles and enacting policies on charging prices.

Based on the findings and insights, there are some takeaway messages for the formulation of subsequent policies related to the carbon-neutral transition. First, it is necessary to strengthen the scientific top-level design of the transition pathway toward electrical energy systems. The lack of scientific planning will bring challenges to the secure and stable operation of energy systems and cause economic losses in trillions of RMB. Second, it is necessary to further boost investment and research and development into offshore wind power. Offshore wind power will become the largest source of low-cost decarbonization of load centers on China's southeast coast in the long term. Third, it is necessary to coordinately optimize interprovincial grids across China and attach importance to changes in the national grid paradigm during the carbon-neutral transition. Developing intraregional and interregional ultrahigh-voltage transmission technology can sharply reduce the total investment of China. Fourth, it is necessary to optimize the layout of the charging infrastructure of electric vehicles. Presently, charging piles are mainly installed in residential areas. With high renewable energy penetration in 2050, office spaces, shopping malls, and other destinations will become mainstream charging sites. Therefore, attention should be paid to the construction of charging piles in these areas.

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https://doi.org/10.23919/IEN.2022.0013

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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.