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Discussion on the Development Path and Key Technology of New Power System under the Guidance of Double Carbon Target

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Abstract. Driven by the goal of "double carbon," the construction of a new power system with new energy as the main body has become the core task of China's energy transformation. This paper adopts a literature review to make a systematic compendium of key technologies, development trends, and challenges of new power systems. The construction of a new type of power system needs to focus on a high proportion of new energy consumption, multi-energy complementary synergies, digitalization and intelligent upgrading, and other directions, and rely on the source-network-load-storage integrated planning to achieve system optimization. New energy volatility problems, insufficient grid regulation capacity, the lack of a cost transmission mechanism, etc., still restrict its development, and thus, proposed through technological innovation, sound market mechanisms, and policy synergies to promote a new type of power system high-quality progress and the realization of the "dual-carbon" goals to play a supporting role.

Keywords: New power system, Level of new energy consumption, Source-network-load-storage synergy, electricity market

1. Introduction

Against the backdrop of global climate change, China has proposed the goal of "achieving peak carbon emissions by 2030 and carbon neutrality by 2060." As the world's largest energy consumer, China's power sector accounts for more than 40% of carbon emissions [1], and the power system, which used to be dominated by coal power, is facing great pressure to transform. The International Energy Agency (IEA) speculates that global electricity demand is expected to grow by 80 percent by 2050, with more than 90 percent of the new demand to be met by renewable energy. Against this backdrop, the construction of a new power system based on new energy sources, with high flexibility and resilience, has become an indispensable path to reach the "dual carbon" goal.

Existing research has been conducted across dimensions such as technological pathways, regional practices, and policy mechanisms. Research has comprehensively summarized the typical characteristics of the new power system, including a high proportion of renewable energy, multi-timescale energy storage, and digitalized control [2]. It proposes adopting a dual-path approach of "green electricity substitution + green hydrogen substitution," emphasizing the need to increase the share of non-fossil energy from 39% in 2025 to 95% by 2060 [3]. From the perspective of regional practice, taking the Guizhou Power Grid as an example, it is proposed that western energy bases should adopt a combined model of ultra-high voltage transmission and local consumption [4]. Focusing on the southern region, this study proposes a coordinated approach for offshore wind power and pumped storage hydroelectricity [5]. At the stage of policy mechanism research, a power market system aligned with new energy development should be established accordingly, incorporating approaches such as capacity compensation and green certificate trading [6].

The paper uses the method of systematic literature review and combines it with the empirical analysis of regional practical cases. It includes 42 pieces of Chinese and English literature and policies, looks into the three aspects of key technologies, development routes and challenge countermeasures, and investigates the improvement of the new power system. This study gives a theoretical basis for the new power system plan. It also provides references for policymakers, power grid companies and equipment manufacturers on technology choice, market promotion and investment decision-making.

2. Key technology framework for new power systems

2.1. High-ratio renewable energy grid integration technology

The core of the integration of renewable energy with high penetration is to solve the contradiction between the intermittent nature of renewable energy and the stability of the power grid. Flexible transmission technology realizes cross-regional power complementation and efficient power distribution through multi-terminal interconnection. Reduces output fluctuation, supports large-scale wind and solar integration [7]. Virtual Synchronous Generator (VSG) technology mimics the inertia and voltage regulation features of synchronous generators, it improves the dynamic stability of grid-connected renewable energy devices, and enhances frequency and voltage regulation. At the same time, combining smart inverters with dynamic reactive power compensation devices allows for real-time adjustments to power output and reactive compensation, reducing harmonic distortion and improving power quality. Integrating these technologies will lessen the influence of renewable energy on the power grid, facilitate the proper absorption of energy, and guarantee the stability and security of the system's operation.

2.2. Multi-time-scale energy storage technologies

Multi-time scale energy storage tech can make sure that renewable energy works well with the new power system, keeping the amount of power supplied and demanded balanced. Short cycle adjustments depend on the battery energy storage system to reach a millisecond response, which can stop the second wind and solar output fluctuations and cut down power waste. Pumped storage hydroelectricity is the main method for medium and long term regulation. It has a large capacity and a long discharge time, so it can provide stable support when the demand for electricity is at its peak or when there is not enough renewable energy available. Hydrogen storage for cross-seasonal demands through the "electricity-hydrogen-electricity" cycle, which enables long-term conversion and reuse of green electricity. Current development trend stresses diversification and cooperative integration: short cycle batteries combined with long cycle pumped storage and hydrogen energy systems can satisfy different requirements ranging from sub-second frequency control to seasonal energy storage. Deep coordination of multi-time scale energy storage turns the power system into "power generation following load" to "power generation and load interaction", so as to guarantee the flexibility, reliability and smooth integration of renewable energy [8].

2.3. Smart grid and digital technology

Smart power grids and digital tech can make the new power system work well and change easily. Digital twin tech allows virtual models to mirror the power grid's operation in real time, improving fault forecast and repair efficiency. Take the high voltage substation digital twin system as an example, it has reached the leading fault diagnosis accuracy in the industry [8]. Blockchain has made a transparent and trustworthy system for green power trading, which is good for using lots of renewable energy. AI and big data analysis improved the scheduling of the system. The AI system of Guowang Jiangsu Company has reduced the prediction error rate of renewable energy from 15% to 7% [9]. IoT technology can enable wide-ranging perception and cooperative management of dispersed energy devices, allowing them to be linked up and put into use immediately with smart reactions. Together they create the smart center of today's power system, making it stronger, less costly to run, and giving us a way to reach our goal of no more carbon by using information.

2.4. Demand-side response technology

Demand response technology adjusts user power consumption according to changes in power supply and demand to balance the two sides, which is one of the important parts of a flexible power system. It depends on price signals and incentives to make people want to take part; for instance, the time-based pricing approach tells companies that use lots of energy to move their work times to when there's not as much need for electricity, so it helps ease the big rush of people using power at once [10]. Virtual power plants (VPP) incorporate dispersed energy storage and adjustable loads into the power grid to improve its flexibility [11]. Smart electricity meters and Internet of Things technology help users get real-time information, AI algorithms can help them save electricity, and they can also work together with the power grid. These technologies lessen the pressure on frequency regulation brought about by intermittent renewable energy, and foster a low-carbon and cost-effective operating mode through the reduction of reliance on traditional peak-cutting sources.

3. Development pathways for new power systems

3.1. Phased construction goals phased development goals

New power systems need to develop step by step according to the rule of slow development so that it can smoothly change from old energy to clean energy. At the beginning stage, it's important to improve the function location of coal-fired power generation, gradually increase the installed capacity and acceptance capacity of new energy, and promote the flexibility of the power grid and the construction of energy storage facilities. As the transition moves into the middle phase, the system will turn its attention to the new energy-powered power supply method. Technological innovation and market mechanism reform will be used to speed up the change in how coal-fired power plants are used, and make it easier for big amounts of hydrogen energy and capturing carbon dioxide to be used on a large scale. After entering the long term stage, non-fossil energy will become the main force in the power system to achieve deep decarbonization of energy supply and consumption. And then it will lead to the wide use of green hydrogen energy in industry, transportation and other areas. This strategy of phases makes sure that the switch is stable, and there's still space for technology to keep changing and industries to get better.

3.2. Regional differentiation pathways

There are significant differences in resource endowment and energy demand in various regions of China, so it is necessary to formulate development strategies adapted to local conditions. The western region has abundant natural landscape resources, which requires strengthening the construction of cross-regional power transmission channels. The use of ultra-high-voltage technology can realize the large-scale outward transmission of clean energy, and also enhance local consumption capacity to alleviate the problem of insufficient power supply. The Eastern Load Center should give priority to the clustered development of distributed energy and offshore wind power generation, and encourage the adoption of intelligent microgrid and virtual power plant technology to enhance the resilience of urban power grids [12]. The southern region has obvious complementarity in terms of water, wind and solar energy resources, and seasonal power balance can be achieved through multi-energy coordination systems, like the flexible integration of hydropower and pumped storage. Islands and remote areas must use digital technology to build integrated systems covering power generation, transmission, consumption and storage. This approach maximizes the use of local renewable energy resources and reduces dependence on external energy. The core of regional differences lies in the reasonable coordination of resource endowment and demand characteristics, and to abandon the one-size-fits-all development model.

In order to explain the regional differences more specifically, this article selects Jiangsu, Guangdong and Sichuan as research subjects. These three provinces show obvious gradient differences in resource endowment, energy transformation path and policy and technology application. This paper analyzes their significant differences in key indicators such as renewable energy absorption rate, energy storage allocation ratio and fault response time.

As shown in Figure 1, Jiangsu Province has the highest absorption rate of renewable energy, which is closely related to the high proportion of energy storage facilities in the province and the promotion of virtual power plant (VPP) pilot projects. The absorption rate of renewable energy in Guangdong Province ranks second, and the proportion of energy storage and deployment is increasing year by year. However, rapid load growth and significant peak-to-trough differences make it particularly necessary to further strengthen the distributed energy storage and demand-side response mechanism. The absorption rate of renewable energy in Sichuan Province is relatively low, the proportion of energy storage deployment is the lowest, and the fault response time is the longest. This reflects its relative lag in intelligent scheduling and digital technology application, especially in areas where there is a need to strengthen power grid coverage and multi-energy collaborative control capabilities in mountainous areas.

These three provinces have shown obvious differences in the development of new power systems. For example, Jiangsu is in a leading position in technology deployment and has strong policy support, performing better in renewable energy integration and system resilience. In contrast, Sichuan relies on the traditional energy structure, and the progress of intelligent upgrading is slow, facing major challenges. Therefore, in the future, it is necessary to promote the development of energy storage deployment, intelligent upgrading and market mechanism in a differentiated manner according to the resource endowment and development stage of each region, so as to realize the coordinated development of the national new power system.

Table 1. Key indicators comparison among Jiangsu, Guangdong, and Sichuan provinces (2022-2024)

Indicator	Province	2022	2023	2024
Renewable Energy Integration Rate	Jiangsu	92.3%	94.7%	96.1%
Energy Storage Configuration Ratio	Guangdong	6.8%	9.5%	12.3%
Fault Response Time	Sichuan	120s	105s	92s

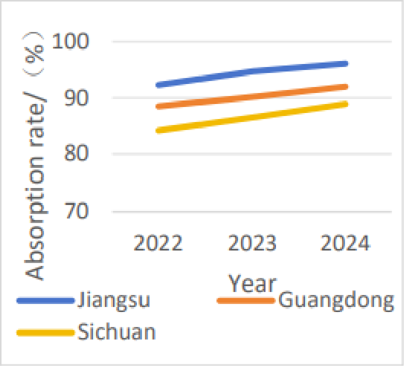

Figure 1. Changes in renewable energy absorption rates in Jiangsu, Guangdong, and Sichuan provinces

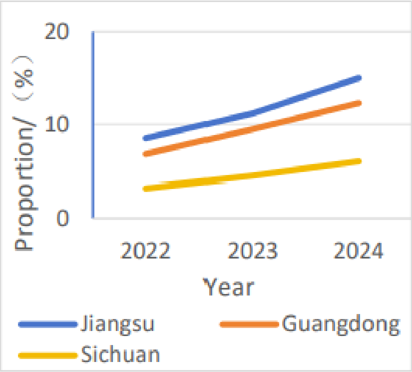

Figure 2. Changes in energy storage configuration ratios across Jiangsu, Guangdong, and Sichuan provinces

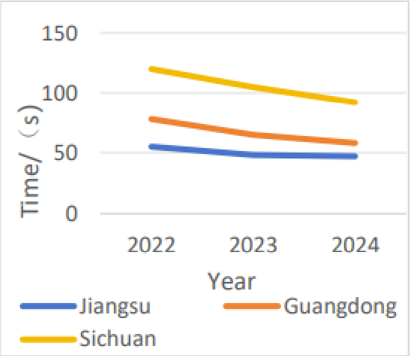

Figure 3. Changes in fault response times across Jiangsu, Guangdong, and Sichuan provinces

Figure 1 shows the absorption rate of renewable energy in Jiangsu, Guangdong and Sichuan from 2022 to 2024. The absorption rate of renewable energy in the three provinces is increasing, with Jiangsu performing especially well.

Figure 2 is about how much the amount of energy storage used by Jiangsu, Guangdong, and Sichuan changes from 2022 to 2024. In these three provinces, the proportion of energy storage deployment is increasing, and Jiangsu has always been at the forefront.

Figure 3 shows the changes of fault response time in Jiangsu, Guangdong and Sichuan province from 2022 to 2024. In general, these three provinces have made continuous progress in terms of fault response efficiency. Jiangsu always keeps the shortest response time, then comes Guangdong, and Sichuan is just a little bit behind them.

3.3. Technology-economy-policy synergy pathway

Building a new power system needs to take technology innovation as the driving force, market mechanism as the connection, and policy protection as the support, so that the effect of three-way synergy can be achieved. Technologically speaking, we need to build a complete innovation ecosystem along the whole chain from basic research to engineering application. Focus on the breakthroughs in key areas such as long duration energy storage and flexible grids, and then use demonstrations to push for commercialization. Economic mechanisms have to be restructured at the same time, using market methods such as green electricity premiums and capacity compensation to realize the worth of flexible resources. It will lead private capital into long term, high risk energy storage and hydrogen facilities which solves the problem of mismatched investment return cycle.

Policy areas need better dynamic coordination between high-level designs and local implementations. On the one hand, unified technical standards and planning approval procedures need to be utilized so as to avoid regional development fragmentation. On the other hand, financial inducements and legal protections should be applied for improving cross-provincial energy collaboration and coordination. Some places have made it necessary to pair "new energy plus energy storage", which makes these systems technically and economically feasible, and promotes the rational use of resources by means of inter-regional power mutual assistance rules. It is only through the concerted efforts of technology, markets and policies that we will be able to tackle the intricate issues involved in transforming our systems and move forward towards an efficient, low carbon, sustainable power system.

4. Achieving breakthroughs in development bottlenecks and establishing a collaborative optimization mechanism for new power systems

4.1. Multidimensional bottleneck analysis of new power systems

The development of new power systems faces complex challenges at the technical, economic and institutional levels. The high volatility and randomness of renewable energy power generation bring great challenges to the real-time power grid balance. Output changes greatly make the frequency regulation under pressure, and no long-term energy storage tech restricts the season's energy adjustment ability, so it is hard to fit the seasonal features of renewable energy. Security risk caused by too much dependence on digital technology is becoming more and more obvious, and power monitoring systems are also threatened by data leakage and network attacks [13]. The current cost transfer mechanism fails to cover the auxiliary service costs needed to incorporate new energy, further increasing the burden on power grid operators. Also, the investment return cycle of infrastructure such as long-term energy storage differs greatly from that expected by social capital, dampening their willingness to enter the market. The installation growth rate of new energy facilities is slower than the planning and building of the power grid, causing some areas to have a power grid integration capacity that is behind schedule. There are different standards for connecting to the grid among different places when it comes to distributed energy, which makes it harder to work together and plan things out between those places [14]. All these various bottlenecks are interwoven, reducing the flexibility and resilience of the new power system. We have to find ways to get over these obstacles using a system coordination mechanism.

4.2. Cooperative optimization pathways for new power systems

In order to solve the various problems of developing new power systems, we need to set up a cooperation framework which can make technology, market force and policy work together. This will help the system go from just being good at one thing to being good at everything.

4.2.1. Technology innovation as the driving force: building a resilient technology system

Improving the flexibility and safety of the new power system should be given top priority so that the new power system can achieve technological breakthroughs. Flexible power grid technology field, hybrid cascade flexible DC power transmission technology with modular multi-level converter to limit the fluctuations of renewable energy in the local power grid area, and realize stable cross-regional power transmission. It decreases our reliance on traditional synchronous power grids and gives a physical foundation for power grid structures that have a lot of renewable energy. Take the Zhangbei project as an example, it has used flexible DC transmission technology to solve the problem of voltage fluctuations during long-distance transmission of wind and solar energy, setting a precedent for cross-regional energy supplementation.

Innovation of long-term energy storage tech is necessary to deal with seasonal changes in renewable energy production. Compressed air energy storage and liquid flow battery technology can be commercially applied to solve the current shortage of short-term energy storage, thus maintaining a long-term equilibrium between supply and demand in the power system. The Jiangsu Jintan compressed air energy storage project utilizes underground salt caverns for storing gas, achieving low-cost storage of large amounts of electricity and providing a practical solution for the extensive use of long-term energy storage technology. Scheduling instruction transmission uses quantum encryption technology to prevent network attacks on power monitoring systems. From the pilot test of Zhuhai Digital Station, it can be seen that this technology greatly improves the safety of data at key points.

4.2.2. Market mechanism restructuring: unlocking the value of flexible resources

Market mechanism design should strive to unlock the potential of flexible resources. Introducing a capacity compensation mechanism can ease the conflict between traditional power sources and renewable energy. By offering financial rewards to reserve units, the system guarantees adequate regulatory capacity during changes in renewable energy output. Jiangsu's pilot program uses capacity payments to make sure that coal-fired power plants have a role during the changeover period, giving a dependable backup for adding new energy sources.

Expanding the auxiliary service market is one of the measures that can encourage distributed resources to participate in system regulation. Virtual power plants combine various distributed resources including energy storage and controllable loads to create massive peak capacity. Market-based operation makes the system more flexible, and it also brings economic benefits to the user-side resources. Shanghai virtual power plant success indicates that the efficient allocation of social resources can be realized by incentivizing users to engage in frequency regulation services via price signals. The green power premium mechanism combined with the carbon market [15] creates a path for turning environmental worth into economic worth. Companies buying green electricity not only cuts down on how much they have to pay for carbon permits, but also helps their brand get more value from the market, which makes a good circle of green development.

4.2.3. Policy coordination support and safeguards: strengthening top-level design and local implementation

To make the policies stronger, we need to have both big plans from above and little changes happening down below. In the planning phase, if we adopt a simultaneous approval system for new energy projects along with power grids and energy storage facilities, it will avoid the wind and solar curtailment due to the delay of infrastructure construction. Nationwide integration of grid connection technical standards for distributed power sources would lower the difficulty of dispatch brought about by regional variations, thus removing roadblocks to the extensive development of multi-energy complementary systems. Incorporate renewable energy consumption targets into local government performance evaluations and enhance cross-regional power support [16]. The Yangtze River Delta area has accomplished a reasonable distribution of inter-provincial power resources through legislation that defines the proportion of peak-shaving resources, which provides important experience for larger-scale coordinated growth among regions. Local implementation and top-level design work together to maintain regional-specific flexibility and promote the national objective of constructing a new power system.

4.3. Collaborative optimization effect evaluation

To quantitatively evaluate the influence of synergy among technology, market, and policy on the performance of new power systems, we can set up a multiple linear regression model to examine the relationship between important elements and crucial system performance measures (such as the degree of renewable energy incorporation):

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \epsilon_i \tag{1}$$

where Y_i denotes the renewable energy absorption rate for the i-th province; X_{1i} represents the energy storage configuration ratio; X_{2i} serves as an indicator reflecting the level of grid intelligence (such as the number of sensors per unit area or the proportion of digital investment); X_{3i} represents the level of policy support (such as the scale of green electricity transactions or dedicated fiscal subsidies); β_0 is the constant term; β_1, β_2, and β_3 are regression coefficients; and ϵ_i is the random error term.

The collaborative optimization mechanism has greatly improved the overall efficiency of the new power system through deep integration of technological breakthroughs, market restructuring and policy guarantees. Taking the practices of Jiangsu, Guangdong, and Sichuan provinces as examples, the differences in their renewable energy absorption rates (Y)can be well explained by this model: Jiangsu's high absorption rate stems from its significant energy storage deployment (X_1), advanced smart grid infrastructure (X_2), and effective VPP promotion policies (X_3); whereas the relative backwardness of Sichuan reflects the shortcomings of these three indicators. This shows that the elements of science and technology, intelligence and policy covered by the model are indeed the core variables that affect the efficiency of the system.

Table 2. Key indicators comparison for Jiangsu, Guangdong, and Sichuan provinces in 2024

Province	Renewable Energy Integration Rate	Energy Storage Configuration Ratio	Intelligence Level Index (Max: 10)	Policy Support Intensity
Jiangsu	96.1%	15%	8.5	High
Guangdong	92%	12.3%	9.2	Extremely high
Sichuan	88.9%	6%	7.8	mid-to-high

The data in Table 2 indicates that energy storage configuration (X_1) and smart grid level (X_2) exhibit a significant positive correlation with renewable energy absorption rate (Y), consistent with the model's predictions.

The above empirical analysis shows that the collaborative optimization mechanism has effectively improved the overall efficiency of the new power system through the deep integration of technological breakthroughs, market restructuring and policy guarantees. From a technical point of view, the iterative development of flexible power grid technology and the progress of long-term energy storage technology have enhanced the system's ability to adapt to the fluctuations of renewable energy power generation. At the same time, the improvement of the digital security protection system has successfully reduced the risk of network attacks, thus laying a stable foundation for the integration of a large number of renewable energy. In terms of market mechanism, capacity compensation, expansion of auxiliary services and the transmission of green power premiums have stimulated the vitality of the flexible resource market. Therefore, it promotes dynamic stability of supply and demand and eradicates imbalance of traditional cost transmission. Policy coordination strengthens the cross-region and cross-department coordination capabilities through overall planning and standardized integration methods, in order not to lead to resource mismatch and duplicate construction. While the multi-dimensional synergy greatly promoted the economic efficiency and the economic and environmental benefits of this system, it also promoted industry transformation and improved employment structure at the social level, and created a favourable environment for the low-carbon transformation of the energy system. Technology and mechanism innovation will be continuously deepened. The coordinated mechanism will be further developed to unleash the potential of the new power system, to attain a more sophisticated dynamic balance and guarantee energy security and promote sustainable development.

5. Conclusion

Against the backdrop of the dual carbon goals, building a new power system has become the core driving force behind the profound transformation of China's energy system. This paper comprehensively analyzes comparative data across Jiangsu, Guangdong, and Sichuan provinces regarding key indicators such as renewable energy absorption rates, energy storage configuration ratios, and fault response times. It provides a systematic interpretation of the technical architecture, evolutionary pathways, and coordination mechanisms for new power systems. Establishing a technical framework anchored by flexible transmission networks as the physical backbone, multi-temporal and spatial energy storage clusters as the regulatory hub, and digital intelligent technologies as the decision-making core is fundamental to achieving efficient integration of renewable energy. The regression analysis results in this paper also confirm that there is a significant positive correlation between the proportion of energy storage deployment and the level of system intelligence, on the one hand, and the renewable energy absorption rate, on the other. Regional development should be based on differences in resource endowments, coordinating the improvement of ultra-high voltage cross-regional power transmission, distributed energy aggregation, and multi-energy complementarity. The current system transition faces dual obstacles of insufficient flexible resources and sluggish market mechanisms, urgently requiring a three-dimensional approach integrating technology, markets, and policies to resolve challenges in cost transmission and security resilience. Future efforts should deepen research on user-side interaction mechanisms, extreme climate adaptation capabilities, and green hydrogen-carbon capture coupling technologies. Accelerating the engineering application of frontier technologies like perovskite photovoltaics and superconducting power transmission will provide a systematic solution for the global carbon neutrality process.

Although this paper provides a systematic review and empirical analysis of the key technologies, development pathways, and coordination mechanisms for new power systems under the dual carbon goals, certain limitations remain that warrant further refinement and enhancement in future research. First, the data coverage is limited. This paper primarily uses Jiangsu, Guangdong, and Sichuan provinces as examples for regional comparative analysis. While these three provinces to some extent represent the developmental disparities between eastern, southern, and western regions, they still do not comprehensively cover all types of energy regions nationwide. The representativeness and universality of the sample thus have room for improvement. Second, there is a lack of analysis regarding the system's adaptability to extreme weather events and emergencies. The resilience and recovery capabilities of the new power system when confronting sudden events such as extreme weather or cyberattacks have not been included within the scope of this study. Yet these represent critical issues that cannot be overlooked in future systems featuring high proportions of renewable energy. Subsequent research may enhance the comprehensive analysis of system resilience, security protection, and emergency response mechanisms.

Looking ahead, research on new power systems should place greater emphasis on multidisciplinary integration and multidimensional collaboration, particularly by intensifying exploration in cutting-edge technological fields such as user-side interaction mechanisms, green electricity-green hydrogen-carbon capture coupling systems, and superconducting power transmission. At the same time, we should promote the deep integration of industry, academia, research, and application to accelerate the transformation of scientific and technological achievements into practical applications and engineering demonstrations. This will provide more actionable and forward-looking solutions for the low-carbon energy transition in China and globally.

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