International Practice of Improving Power System Flexibility and Its Enlightenment to China

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Abstract. With the rapid increase in the proportion of renewable energy in the power system, the volatility of renewable energy output has greatly increased the risk of power system operation and brought about the need for power system flexibility. A reasonable market mechanism in the electricity market can stimulate flexibility resources and fully exploit the flexibility of the system, which plays an important role in the efficient and safe operation of the power system. This paper studies several countries or regions that have a high share of renewable energy and have established relatively mature power markets, and then analyzes and compares the power system flexibility needs of these regions and the market mechanisms used to increase flexibility. Finally, the enlightenment of international practice to China based on the current situation is summarized.

1. Introduction
At present, climate warming is a crisis and challenge faced by all countries in the world. The clean transformation of power supply structure has become an inevitable trend for future development. As a signatory and advancing country of the Paris Agreement, China is also actively promoting the development of renewable energy. As of the first quarter of 2020, the cumulative installed capacity of renewable energy in China has reached 802 million kilowatts, and the installed capacity of wind power and photovoltaics has reached 213 million kilowatts and 208 million kilowatts, an increase of 12.4% and 15.6% year-on-year. The growth of renewable energy has brought about the need for power system flexibility, which has become a problem facing China's current further development. The growth of renewable energy has brought about the need for power system flexibility, which has become a problem for China's further development. With the publication of "Several Opinions on Further Deepening the Reform of the Electric Power System" (Zhongfa [2015] No. 9), China has begun a new round of power system reform. An important task in this power system reform is to establish the power market, which will become the main means of power resource allocation. It is now a critical stage in the construction of China's electricity market. Under the above background, how to increase the enthusiasm of adjustable resources and promote the flexibility of the power system through the market mechanism to ensure the implementation of the strategic goal of clean transformation of power supply structure is needed at this stage. Important issues to consider. Some countries and regions in the world have already explored and achieved some results on the flexibility of the power system. It is very meaningful to study the market mechanism of these regions, compare their similarities and differences, and analyze the practices that China can learn from.
2. Flexibility Definition and Flexibility Resource Classification

2.1. Definition of power system flexibility
Currently, there is no uniform definition of power system flexibility internationally. The North American Electric Reliability Commission (NERC) defines the power system flexibility as the ability to use system resources to meet load changes, mainly reflected in the flexibility of operation [1]. According to the International Energy Agency (IEA), flexibility of the power system means that the power system responds quickly to large fluctuations in supply or load (predictable or unpredictable changes and events) under economic operating conditions, thereby enabling Supply follows load increases or decreases accordingly [2]. Although various agencies have different definitions of power system flexibility, their core refers to the power system's ability to maintain a balance between supply and demand when supply and demand change, so as to achieve the purpose of safe and stable operation of the power grid.

2.2. Classification of power system flexibility resources
Resources that increase the flexibility of the power system can be divided into two categories:
(a) Physical flexibility resources, that is, objective physical resources for power systems to respond to changes in demand and power generation, including generation-side flexibility resources, demand-side flexibility resources, energy storage flexibility resources, grid flexibility resources.
(b) Mechanism flexibility resources, that is, mechanism designs that can make full use of the physical flexibility resources of the power system, including the design of the power market and power system regulation mechanisms.

In the power system, mechanism flexibility resources provide operation and management support for physical flexibility resources. On the one hand, mechanism flexibility resources call physical flexibility resources to meet the flexibility requirements to achieve real-time supply and demand balance of the power system. On the other hand, mechanism flexibility resources provide a reasonable path for adjusting resource recovery costs and providing flexibility services to obtain benefits. How to make full use of adjustability resources and give play to its characteristics and characteristics through mechanism design is the focus of this paper. The relationship between flexible resources is shown in the following figure 1.

3. International practice to increase flexibility

3.1. California
3.1.1. Overview of Power System and Power Market. In California, about 1/4 of the electricity is provided by renewable energy, of which photovoltaic is the main renewable energy source. In 2018, California wind power installed capacity accounted for approximately 7.5% of total installed capacity, and photovoltaics accounted for approximately 15%. In the next 20 years, California will continue to develop renewable energy. It is expected that by 2040, California renewable energy will account for 60% -70% of power generation. Most of the flexibility comes from the high proportion of gas-fired power generation and interconnection with other state grids.

In California, the electricity wholesale market includes the bilateral trading market and the spot market, where the spot market includes the day-ahead market, the hourly market, and the real-time market. Various types of flexible resources can participate in spot transactions at different stages according to their own output characteristics or load characteristics to enhance the flexibility of the power system.

3.1.2. Flexibility needs analysis. California's daily power generation curves and demand curve are shown in the figure 2 [3]. In the picture, the net load curve after deducting renewable energy presents the famous "duck curve". California's high proportion of photovoltaic power generation is one of the important reasons for the formation of the "duck curve". In addition, the "duck curve" reflects the time mismatch between the peak demand of the system and the production of renewable energy. For example, in California, the peak demand occurs after the sunset of solar power outages. These factors have brought greater climbing and intra-day regulation needs to the California power system. As the proportion of renewable energy increases in the future, the peak-to-valley difference in net load and the rate of change of net load in the figure may become larger, and the demand for flexibility will also increase.

Gas-fired power generation and hydropower generation (especially pumped storage) can provide flexible services on multiple time scales due to their faster climbing speed, shorter response time and more flexible adjustment functions. As can be seen from the figure below, during the period of rapid changes in net load demand, California can meet the flexibility needs of the system mainly due to two aspects: (1) high proportion of gas power generation and hydropower generation; (2) electricity imports.

![California daily power generation accumulation curves and demand curve](image)

Figure 2. California daily power generation accumulation curves and demand curve

3.1.3. Mechanisms to increase flexibility. Energy Imbalance Market (EIM): The CAISO Energy Imbalance Market is formed by expanding its real-time market and real-time economic dispatch to the balanced responsibility area in charge of the Western Electric Power Coordination Committee [4]. The Energy Imbalance Market establishes a trading platform for geographically independent and balanced responsibility areas, while retaining its scheduling autonomy. The entities in the zone can voluntarily participate in the Energy Imbalance Market. Among them, the entities that choose to participate need to submit incremental or decrement quotations, and the non-participants need to submit their self-scheduling plan. After receiving the imbalance information, the market adopts a security-constrained economic scheduling algorithm to clear the market and send updated scheduling instructions to the members in the area. The scheduling instructions of the non-participants are the same as their self-scheduling plans. Finally, the increase and decrease of the unbalanced electric energy are paid and
refunded to the market according to the node marginal electricity price of the corresponding market. In the Energy Imbalance Market, the dispatch center of each balance responsibility area can grasp the information of the surrounding power grid in real time, and each balance responsibility area can share peak shaving resources, use abandoned power, and reduce the overall volatility of renewable energy power sources. By expanding the scope of balance, CAISO has realized the surplus and deficiency between regions, promoted the consumption of new energy as a whole, and increased the flexibility of the system. Operational logic diagram of Energy Imbalance Market is shown in the following figure 3.

![Operational logic diagram of Energy Imbalance Market](image)

**Figure 3.** Operational logic diagram of Energy Imbalance Market

*Flexible Ramping Products:* As California's net load change range and speed continue to increase, the system needs greater climbing capacity to maintain power balance. In 2016, CAISO introduced a variety of auxiliary services called Flexible Ramping Products in the real-time market [5]. Unlike traditional ancillary service products, the requirements and specifications of such products are not based on the state of the system at a certain moment, but on the changes at two points in time. CAISO uses historical data to estimate the probability of power imbalance under a certain amount of FRP, and multiplies it by the value of load loss to obtain the FRP elastic demand curve, which determines the capacity of purchasing flexible climbing products. With the lowest cost as the goal, CAISO optimizes this demand curve along with other demand for energy and service products and the supply curve formed by the bidding of power plants to determine the market price and quantity of each product. Finally, the settlement is based on the opportunity cost of the capacity of the flexible climbing product. This ancillary service guides units with better performance to provide climbing through price incentives, which alleviates the challenges brought by the changes in wind power and solar energy to the power system to some extent.

3.2. Germany

3.2.1. Overview of Power System and Power Market. The proportion of renewable energy in Germany is very high. In 2019, the installed capacity of renewable energy in Germany exceeded half of the total installed capacity, reaching 52.1%, of which wind power accounted for the highest, at 26.6%. In the "Renewable Energy Act", a higher target for renewable energy in 2030 was set: the proportion of power generation reached 65%. In addition, in recent years, the proportion of Germany’s traditional energy sources, led by coal and nuclear power, has fallen rapidly. Its nuclear phase-out target is scheduled to be completed by 2022, which further increases the demand for flexibility in the power system.

In Germany, the spot market can be divided into the pre-market and the intra-day market, which are the main tools to adapt to the fluctuations of wind power and solar power. The day-ahead market covers the largest amount of information in the entire market, bidding at noon every day, and trading one day in advance to subdivide electric energy products every hour. In the intra-day market, market entities have the opportunity to correct the deviation between the previous day and the intra-day forecast, allowing market entities within the jurisdiction of the German grid operator to submit 15 minutes of electrical energy products 30 minutes before delivery.
3.2.2. Flexibility needs analysis. Renewable energy in Germany is mainly composed of wind power. Germany daily power generation accumulation chart and demand curve are shown in the figure 4 [6]. As can be seen from the power generation accumulation chart, wind power generation accounts for about half of the total power generation in Germany at all times. In contrast, the system net load change caused by solar power generation is relatively small. Germany's maximum net load demand appears around 8:00 am and 18:00 pm. At present, it is mainly through market price incentives to guide traditional energy and pumped storage to meet its climbing needs.

Unlike California, Germany 's main flexibility need is not how to deal with large changes in the system ’s net load in a short period of time, but the peak shaving problem caused by the large-scale renewable energy at night. German renewable energy is dominated by wind power. Due to the windy climate in Germany at night, it is complementary to the solar energy generated during the day to a certain extent, and the total output of renewable energy is relatively stable. In contrast, Germany's day and night load demands vary greatly, and oversupply often occurs at night. In addition to the high proportion of renewable energy, the low performance of traditional energy regulation and insufficient system adjustable resources are also one of the important reasons for this flexibility demand.

![Figure 4](image)

**Figure 4.** Germany daily power generation accumulation curves and demand curve

3.2.3. Mechanisms to increase flexibility. Unified European Electricity Market: Unified European Electricity Market has been officially operational since February 2014 [7]. The regions that are currently participating in the unified clearing of the market include the Midwest power market, the United Kingdom, the Nordic power market, the Baltic power market, the southwestern power market, and the central and southern power market. In the south-central power market, Germany has established grid interconnections with 9 countries including Austria, Switzerland, and Poland. In the intra-day market, market entities have the opportunity to correct the deviation between the previous day and the intra-day forecast. Transactions between European countries allow market entities to submit 15 minutes of electrical energy products 60 minutes before delivery (Transactions within the jurisdiction of German domestic grid operators are 30 minutes before delivery). The establishment of a unified European electricity market helps large-scale renewable energy power generation (marginal cost is almost zero). The electrical energy in enriched areas will flow to areas with a high proportion of thermal power generation (high marginal cost), making renewable energy power generation more adequate. And extensive use, overall improve the ability to consume renewable energy. The unified European electricity market has expanded the market scope of German electricity resources, realized the optimized allocation of electricity resources in Germany and neighboring countries, helped Germany to absorb a large amount of surplus wind power at night. While improving the flexibility of the power system, it also improves the efficiency and economy of energy use.

Negative electricity price: In the spot market, when the system demand is low and a large number of inflexible units have to continue to generate electricity, negative electricity prices will appear. Inflexible traditional generating units have certain climbing constraints during operation, and due to high shutdown and start-up costs, such generators will submit negative quotations (that is, bid for opportunity costs) to avoid unit start-up and shutdown costs. In addition, cogeneration units with heating obligations will also
submit negative quotations because they cannot shut down. The emergence of negative electricity prices indicates that the system lacks flexibility, but its existence provides flexibility incentives for the supply and demand sides. On the one hand, it encourages generators to invest in better and more flexible technologies. On the other hand, it guides the load to shift from periods of high demand to periods of lower demand, thereby reducing the possibility of negative electricity prices. In addition, negative electricity prices have also driven market design adjustments, such as redesigning the balance market and reducing the proportion of Betfair units to achieve power balance.

3.3. Texas

3.3.1. Overview of Power System and Power Market. The Texas Electric Reliability Commission (ERCOT) is an independent system operator in most parts of Texas. Gas-fired power generation is ERCOT’s largest power generation resource, with installed capacity accounting for about half of the total capacity. In 2019, Texas wind power accounted for 27% of the installed capacity, which is the main renewable energy generation, while the solar power installed capacity is relatively small, only 3.5%. At present, the ERCOT power grid is not interconnected with other power grids, and it must maintain a balance between its own power generation and load.

In the Texas electricity market, more than 95% of the electrical energy transactions are completed by bilateral transactions, and less than 5% of the electrical energy transactions are completed by the spot market and the auxiliary service market. The operation of its electricity market is divided into three stages: the day before, adjustment and real-time operation stage. The main trading varieties in the day-ahead stage are capacity trading, energy trading, day-to-day reliability unit combination service and auxiliary service transaction. The adjustment phase is from 18:00 the previous day to 1 hour before the real-time operation. The main transaction types are the reliability unit combination service transaction and the supplementary auxiliary service transaction before the hour. The real-time operation phase includes 1 hour before real-time operation and real-time operation hours. Every 15 minutes is a settlement cycle, which mainly performs real-time energy balance and guarantees the stability and reliability of the system.

3.3.2. Flexibility needs analysis. Texas has vigorously developed wind power in recent years, and has become the state with the largest wind power generation in the United States. The rapid development of wind power brings many benefits to Texas, but also brings some challenges to the flexibility of the power system. Daily power generation curves in Texas are shown in the figure 5 [8], the load change in Texas is not large, and the peak-valley difference is relatively small. The wind power output is extremely uneven, with large randomness and volatility, which greatly increases the uncertainty of the change of the net load and expands the demand for system flexibility. As an isolated power grid, ERCOT can satisfy the real-time balance of the load, thanks to its high proportion of gas power generation. As shown in the following figure, gas power generation is the main adjustment method of ERCOT. In addition, coal power also plays a certain adjustment role.

Figure 5. Texas daily power generation accumulation curve
3.3.3. Mechanisms to increase flexibility. **Unified European Electricity Market**: ERCOT has only a single energy market and no capacity market. The cost of power plant construction for power plants must be recovered from the benefits of power generation and auxiliary services. To encourage investment in the construction of new power plants, ERCOT has developed a series of scarce pricing mechanisms [9-10]. Increase the price of electricity in the case of scarce spares. Unlike other electricity markets in the United States, ERCOT’s real-time market does not have a combination of electricity and auxiliary services cleared, and real-time reserve price increments are introduced to reflect the value of reserve scarcity. It is calculated every 15 minutes and is related to node marginal electricity prices and reliability deployment prices. The increment constitutes the final real-time settlement price. When the reserve level is lower than the minimum tolerance level, the probability of loss of load defaults to 1, and the real-time settlement price will soar up to the price limit (currently $9000/MWh). Under a certain degree of scarcity, that is, a certain probability of loss of load, if the energy price is too low to reflect the scarcity situation, then the incremental value of the reserve price will increase to supplement the scarcity signal; on the contrary, if the energy price is high enough to reflect the scarcity signal, then the corresponding real-time standby price increment value is zero. The system energy price and the real-time reserve price increment jointly reflect the scarcity of the power system and can convey the signal of the system energy scarcity to the market subject in real time. It intuitively reflects the supply and demand in the market, and encourages units with better regulation performance to generate electricity at the peak of the load, thereby improving the flexibility of the system.

3.4. United Kingdom

3.4.1. Overview of Power System and Power Market. In 2018, the total installed capacity of the United Kingdom was 82932MW, of which natural gas installed capacity accounted for 38.9%, coal power installed capacity accounted for 18.9%, renewable energy installed capacity accounted for approximately 23%, wind power accounted for 11.3%, and photovoltaic power generation accounted for 2.7%. The UK plans to provide 50% of its electricity generation in 2030 by wind and solar energy.

In the UK, the wholesale electricity market is composed of bilateral transactions and a spot balance market, which is different from the US spot market classification (pre-market, hourly market/intra-day market, and real-time market). The UK power market uses a rolling balance method. That is, 1 hour before the actual power generation, the wholesale market is closed and the equilibrium market is opened. Various flexible resources can participate in the balanced market by submitting buyer bids or seller bids. In the balanced market, the imbalances that occur during real-time operation are settled according to the system electricity purchase price and the system electricity sale price, respectively. The purpose is to encourage generators and users to strive to minimize unbalanced electricity.

3.4.2. Flexibility needs analysis. The daily load curve in the UK and its power generation accumulation curves are shown in the figure 6 [11]. Compared with other regions mentioned above, the UK’s renewable energy output is relatively stable. On the one hand, this is due to the relatively high proportion of biomass power generation in renewable energy. On the other hand, the United Kingdom has a temperate maritime climate with uniform wind speed throughout the day and little change in cold and heat throughout the four seasons, making wind power output that is usually volatile relatively uniform. On the whole, the change in net load in the UK is similar to the change in load, and the demand for load balancing caused by renewable energy is smaller than in other regions. When the system load changes, the natural gas units with a relatively high proportion in the United Kingdom meet the flexibility requirements for climbing up and down the power system. Power imports and pump-storage stations also play a role in this process.
3.4.3. Mechanisms to increase flexibility. Capacity Market: The United Kingdom introduced the capacity market in 2014 to guide power investment by correcting market failures and capacity prices, avoiding the cyclical excess and shortage cycles of installed power generation capacity, and ensuring safe and stable power supply in the most cost-effective manner [12]. The UK capacity market is conducted in the form of auctions. The subject matter is the power generation capacity required by the capacity delivery annual system. Market operations can be divided into six stages: capacity quota, prequalification, auction, transaction, delivery and payment. Capacity quota is the process by which the system operation department analyzes the capacity demand and decides the total auction capacity. The central auction is held 4 years before delivery to determine the capacity price and signing eligibility, which includes the primary market and the secondary market: the primary market allocates capacity first; when the primary capacity market allocates capacity resources, the secondary market Conduct secondary transactions on remaining capacity to achieve capacity adjustment and risk avoidance. The traded capacity is acquired by the State Grid Corporation of England on behalf of the electricity sales company, and the cost of the capacity contract is borne by the electricity sales company, and is settled based on its share of the electricity market in the year of delivery. The winning capacity must ensure that power can be provided when the system needs it, or face penalties. At present, all existing and newly built capacity in the UK is eligible to participate in the auction of the capacity market, including most power plants, energy storage, demand-side response capacity and projects that can provide long-term reductions in power demand, which is conducive to promoting flexible resources resource construction and investment. Flow chart of the operation of the UK capacity market is shown in the figure 7.

![Flow chart of the operation of the UK capacity market](image_url)
3.5. Summary of mechanisms to increase flexibility

3.5.1. Electric energy market mechanism. From a common point of view, in order to enhance the flexibility of the power system, the regional power markets have established a spot market with centralized bidding that uses time-sharing power (electricity) as the transaction target, and allows certain adjustments before real-time operation. From the perspective of their respective characteristics, there are certain differences in the regional power market market's division of the spot market stage, spot settlement cycle, pricing and settlement mechanism. Construction and investment. Comparison of spot market mechanisms is shown in the table 1 below.

Table 1. Comparison of spot market mechanisms

|                  | ERCOT                  | CAISO                  | United Kingdom             | Germany               |
|------------------|------------------------|------------------------|----------------------------|-----------------------|
| Spot market model| Day-ahead market +     | Day-ahead market +     | Day-ahead market +         | Day-ahead market +    |
| Adjustment phase | +                      | +                      | + Intra-day balance        | + Intra-day market    |
| Real-time market |                        |                        |                           |                       |
| Day-ahead market trading target period | 1 hour                | 1 hour                 | 1\0.5 hour                | 1 hour               |
| Intra-day adjustment measures | You can submit or change your own | Adjustments can be made to the previous trading plan in Hour-ahead market | Quotes can be made every 30 minutes for the real-time stage in the balanced market | Market entities can submit 15-minute quotations 30 minutes before the real-time operation phase |

Key factors to improve the flexibility of the power system:

a) Day-ahead market segmentation of the trading target time period and intra-day adjustment mechanism: The subdivision of the target time period makes the system's predicted curve and actual load curve closer when the load is predicted. Thereby reducing the deviation of the day-to-day trading curve and the real-time transaction curve, reducing the adjustment deviation of the system in the real-time phase and the demand for flexibility resources. The essence of the intra-day adjustment mechanism of each regional market is to adjust the previous trading plan, making the decision close to real-time, thereby further reducing the adjustment deviation and flexibility resource requirements of the system in the real-time stage, and improving the power system flexibility.

b) Inspire regulate high-performance resources to provide flexibility: Emphasize the difference in the regulation performance of the generator set, and use the price incentive method to guide the units with good regulation performance to send more at the peak load time, less or not in the trough period and compensate their corresponding opportunity cost, which is conducive to fully tap the potential flexibility of the system And guide the market’s investment in flexible generators.

c) Expand the scope of power balance: Establish cross-regional (or national) electricity markets or develop electricity trade with neighboring systems (or countries) to expand the scope of electricity balance, and help the large-scale renewable energy power generation enrichment areas to flow to areas with a high proportion of thermal power generation. It makes the renewable energy power generation more fully and widely used to achieve the optimal allocation of resources and complement each other.
3.5.2. Ancillary services market mechanism. At present, Texas, California, the United Kingdom and Germany have established relatively mature auxiliary service markets as supplements and cooperation for the electric energy market. Judging from the classification of ancillary services, the ancillary service markets in various regions mainly focus on the acquisition and transaction mechanism of various active services. Although the specific technical requirements are different, they all follow the principle of classification according to response time, and in order from fast to slow, active services are divided into three frequency adjustment services such as primary frequency modulation (frequency maintenance), secondary frequency modulation (frequency recovery) and tertiary frequency modulation (alternative reserve under the principle of economic dispatch). From the point of view of the way of obtaining standby resources, the various types of operating standby resources defined by it are generally obtained through the spot market or various types of standby markets established separately. For example, California has introduced Flexible Ramping Products for ramping needs. Flexible resources with different response capabilities, ramping speeds, and adjustment capacities will also choose to provide different types of flexible services and submit quotations according to their actual conditions.

3.5.3. Capacity compensation mechanism. In the electricity market studied in this chapter, only the UK has established a capacity market mechanism. Its main goal is to ensure the sufficient long-term system capacity in the future while achieving its low-carbon energy strategy. The capacity market forms capacity prices in the form of market competition to realize the cost recovery of power generation capacity, which is an organic component of the competitive power market. The UK allows and encourages existing and new capacity to participate in auctions in the capacity market, which is conducive to the cost recovery of various flexible resources including energy storage and demand-side response. In addition, Texas, which has only an energy market and no capacity market, has formulated a series of scarce pricing mechanisms for capacity compensation to increase the price of electricity in the case of system power and backup scarcity. It guides the unit to provide flexible services through price incentives, which provides more guarantee for the safe and stable operation of the power system.

4. Conclusions
Combining the research content of this article and the current situation of China's development, several key points to improve the flexibility of China's power system can be summarized.

a) Speed up the construction of the spot market: China's natural resource endowment is unevenly distributed, and new energy is developing rapidly. Objectively, there is a need for a large-scale optimization of resource allocation and full utilization and consumption of new energy. In the regions and countries discussed in this article, the electric power spot market's subdivision of the trading target time period and the adjustment mechanism for the declared power are helpful to reduce the deviation of the forecast from the real-time transaction curve, and are an effective means of absorbing clean energy and renewable energy. In addition, accelerating the construction of the power spot market is conducive to the system through price incentives to guide units with good regulation performance to fully provide flexibility.

b) Power generation capacity recovery cost mechanism: The practice of power market construction in most countries and regions in the world shows that, In the process of establishing a competitive electricity wholesale market, the capacity mechanism can give a relatively stable expectation of investment in generating capacity investment, and plays an important role in ensuring the smooth operation of the electricity spot market and the normal development of medium-term and long-term transactions. The capacity market mechanism, scarcity pricing mechanism and capacity compensation mechanism have different applicable conditions, and China needs to actively explore and explore suitable capacity cost recovery mechanisms and methods at all stages of its development.

c) Emphasize the construction of peak shaving market: At present, my country's power market trading products mainly focus on medium-term and long-term electric energy. In the transition period of building the power market, it is necessary to strengthen the construction of the peak shaving market,
through market means to enable flexible resources to recover costs, obtain benefits, and improve power system flexibility.

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