Long Duration Flexibility Planning Challenges and Solutions for Power System With Ultra High Share of Renewable Energy

HAIBO LI (Member, IEEE), YISHA LIN (Student Member, IEEE), ZONGXIANG LU (Senior Member, IEEE), YING QIAO (Member, IEEE), JIANRU QIN, CHONGQING KANG (Fellow, IEEE), AND XI YE

Department of New Energy Power System Analysis and Optimization, Tsinghua Sichuan Energy Internet Institute, Chengdu 610213, China

Department of Electrical Engineering, Tsinghua University, Beijing 100084, China

Dispatching and control center, State Grid Sichuan Electric Power Company, Chengdu 610210, China

CORRESPONDING AUTHOR: Z. LU (luzongxiang98@tsinghua.edu.cn)

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ABSTRACT The uncertainty of wind/photovoltaics (PV) power generation and load fluctuations highlight the urgent need for flexible yet stable power resources. With the increasing in the share of renewable energy, the fluctuation presents a trend toward the longer periods, larger amplitudes, and more drastic changes. Therefore, research on the long duration flexible resources planning for the scenarios of the ultra high share of renewable power system (UHRPS) has become the focus. In this work, the main structural and operating characteristics of UHRPS are introduced and analyzed, which is followed by the flexibility requirements and flexibility planning challenges of UHRPS scenarios. Then, the current research trends in flexibility planning schemes of renewable energy power systems are reviewed. Finally, the key problems and solutions for research on the long duration flexible resources planning of UHRPS are proposed.

INDEX TERMS UHRPS, flexibility, supply and demand balance, power system planning.

I. INTRODUCTION Nowadays, human society is confronted by the challenges of energy security and climate change, given that the traditional energy development model cannot be sustained. It has become the common goal of all countries in their energy development plans to promote the transformation to the clean and low-carbon energy system. The extensive development of various types of renewable energy has become a global trend. By the end of 2020, the average global share of renewable energy has reached 29%[1], of which 27.3% in China, 20.9% in the United States [2], [3], and 38% in the European Union [4], respectively. In terms of the wind/photovoltaics (PV) power, the global generation accounts for about 9% of the total amount of renewable energy [1], of which 9.5% in China, 11.6% in the United States [2], [3] and 19.6% in the European Union [4], respectively. By the end of 2021, the amount equivalent to one billion kilowatts (kW) of renewable energy generation has been installed in China, in which the wind and the PV power generation account for more than 10% of the total electricity production. The above milestone indicates that China’s renewable energy power generation has entered a new stage of development. Under the strategic guidance of building a new type of society with the sustainable power system, China has set a target of increasing the total installed capacity of wind and solar power to over 1.2 billion kW by 2030.

As the ratio of renewable energy increasing, its role in the power system is changing [5]. In the low share stage (less than 15%), renewable energy is regarded as “negative load” to participate in the balance of the power system, and the traditional resources can meet the demand so that the problem of renewable energy curtailment rarely occurs [6]. In the medium share (15%-50%) stage, renewable energy has so-called “Semi-Controllable Characteristics” representing its participation in power system dispatch with a certain degree of confidence [7]. System flexibility becomes a key factor restricting the consumption of renewable energy. Flexible resources means that the resources can provide the adjustment capacity for power system to cope with the uncertainty. For example, the energy storage is one typical flexible resource. If the allocation of flexible resources is insufficient, there will be a serious phenomenon of renewable energy curtailment in which case the special flexibility expansion planning becomes necessary [8]. In the phase of high share stage (more than 50%), renewable energy becomes the main component of electricity. Therefore, a set of operational measures
similar to traditional power generators become essential. However, the overall output of renewable energy is largely affected by a number of natural factors, e.g., meteorological resources. On the one hand, the difficulty to maintain the balance between power supply and demand has increased sharply, on the other hand, the flexible resources within the power system will not be able to fully meet the demand, and the potential for flexibility demand to be tapped across the energy system [9]. The paper defines the “high share stage (more than 50%)” as the transitional stage of UHRPS, which refers to the power system in which the wind/PV power supply accounts for more than 50% of the gross generation of the system. It should be noted that, in order to fully describe the technical system of flexibility balance, this study focuses on the self-balancing system of energy supply and demand, that is, there is no large-scale power input or external transmission.

The generation of wind and solar power is strongly related with the meteorological process. The random fluctuation characteristics of wind speed and solar radiation can be directly transmitted to the power output characteristics. With the increasing share of wind power utilization, the coupling relation between meteorological factors and the power generation will gradually lead to the change of supply-demand balance, as well as flexibility planning method of power systems with the high share of renewable energy. It is clear that the operation characteristics of both supply and demand sides of power systems with the high share of renewable energy are deeply coupled with the meteorological process. From the supply side, with the continuous increase in the share of renewable energy such as centralized large-scale wind/PV power, the characteristics of the meteorological process dependence of the power supply are highlighted. Extreme weather without continuous wind will cause the low output of wind power to last for more than 50 hours (as shown in the Fig 5). At this time, the system needs flexible resources that last longer, so the system’s demand for long duration regulation of energy storage is also more prominent. The so-called long duration energy storage means that the energy storage charging time is longer, and the average charging and discharging frequency of the storage battery is low. But so far, the duration of long duration energy storage has not been clearly defined, and the U.S. Department of Energy classifies it as continuous discharge at rated power for 10 hours or more. However, it is meaningless to focus only on the charging and discharging time away from the application scene. The definition of long duration energy storage mentioned in this paper refers to the definition of literature [10], which can realize the energy storage system of charge-discharge cycle across the day, across the month, and even across the season.

Long duration flexibility supply-demand balance refers to the ability of the flexible resources of the system to meet the future electricity flexibility demand brought by a complete meteorological change process. The complete meteorological change process refers to a wind speed change process (refers to the wind speed increases from zero to the next zero period, which may last from several hours to several days) or the solar radiation may alternate day and night (the regularity is more obvious than wind power, but there may be periods of darkness caused by continuous rainy weather). According to historical meteorological data, the whole meteorological process has the characteristic of a variable period. Fig 1 shows the frequency distribution of the meteorological data cycle of a wind farm. It can be seen that the duration frequency of wind power is high regardless of the high output or low output. Long duration flexible resource allocation is of great significance to solve the power supply and consumption problem in the continuous multi-day scale of the UHRPS.

At present, the definition of power system flexibility only simply considers the randomness and uncertainty conditions caused by intermittent power sources, and only considers the problem of insufficient flexibility (wind and PV curtailment) in the local period presented in the stage of medium and low share of renewable energy. It ignores that in the future scenario of extremely high share of renewable energy power system, the power system will face large-scale and continuous power limitation (up to 1–15 days). Although, there are several challenges that already have been faced by several Independent System Operators (ISOS). For instance, the idea of coupling the planning/operation models with meteorological data has already been done, mostly in countries where the production of energy from variable sources is more than half of the daily production in several days during the year (i.e., Germany, Australia, Chile). Other point that is already been discussed by ISOs is the incorporation of long duration flexibility, either through ancillary services or by the incorporation of energy storage facilities (utility scale batteries, hydro pump storage, etc.). However, they are only the application of a single factor, and they have not solved the planning problem of comprehensively considering various long duration flexible resources. Therefore, it is necessary to build a theoretical and methodological system for flexibility planning of UHRPS, and increase the special work of long duration flexible resources planning in traditional planning stage. The contributions of this paper are as follows:

- A novel power system balance principle is proposed in this paper that transforming the traditional “power balance” analysis to the “flexibility balance” in the planning stage.
- Definition, evaluation system and planning framework of long duration flexibility of UHRPS are proposed.
Innovative models and methods in four key threads are proposed. A theoretical framework that can cope with various challenges and comprehensively consider various long duration flexible resource optimization planning that the future power system may face is proposed.

Existing research works have proposed that flexibility evaluation and planning should be paid attention to the power systems with high share of renewable energy [8], [9]. However, topics about long duration flexibility under the variable meteorological process are not sufficiently discussed. This paper focuses on the long duration flexibility planning of the UHRPS by analyzing the main structural characteristics and operation characteristics of UHRPS, and comparing with the previous development stage system that with low share of renewable energy. Besides, it also analyzes the flexibility challenges and flexibility planning requirements of the UHRPS. The present situation of power system flexibility planning methods in China and abroad is then summarized. Finally, the key problems and solutions of the research on the long duration flexible resource planning of UHRPS are proposed to provide support for the future power system planning.

II. CHARACTERISTICS OF UHRPS

A. STRUCTURAL FEATURES

1) SOURCE SIDE

Wind/PV power supply has a low capacity coefficient, and cannot provide stable output and auxiliary services like traditional thermal units. Other power sources complement each other and transform into flexible resources.

Wind/PV installed share is defined as the ratio of the wind/PV installed capacity to the total installed power generation capacity of the system. Wind/PV electricity share is the ratio of the wind/PV generation to the total generation of the system. Fig 2 shows the development of the average wind/PV installed share and the electricity share by different countries and the world from 2000 to 2018 (data from the US Energy Information Administration website). It can be seen from the Fig 2, the ratio of power generation/installed share of the wind/PV power sources in various countries is less than 1, and there is a gradual trend of increasing with the expansion of installed capacity.

2) POWER GRID SIDE

The characteristics of the reverse distribution of wind/PV power resources and load in China deeply affect the changes in the power grid structure with the continuous expansion of the installed scale of new energy.

From the perspective of source power grid, the centralized development mode of “new energy base + thermal power support + long-distance transmission” has greatly promoted the development of AC/DC power grid in China. On the one hand, the aggregation effect of renewable energy power sources leads to the amplification of its random and fluctuating characteristics; the deep integration of renewable energy multi-voltage hierarchical aggregation networks with local power grids affects power supply or leads to wind and PV abandonment. Local consumption and external output are combined to make the characteristics of high share of renewable energy power deeply coupled with the local load supply and inter-regional transmission function of the source power grid [12].

From the perspective of the receiving end power grid, the share of conventional power supply is gradually reduced, while distributed power generation is connected, accompanied by DC power grid, and the receiving end grid presents the characteristic of low inertia. The characteristics of power grid, such as heavy load evacuation and regulation ability, voltage supportability, power angle stability characteristic and dynamic stable oscillation damping ratio are reduced. The new changes of system security and stability should be considered in the planning and operation of the receiving end grid.

In addition, the rapid development of distributed new energy has greatly changed the structure of the distribution network. The development of offshore wind power also promotes the development of flexible DC network technology.

3) LOAD SIDE

It is sensible to ask where the surplus of wind/PV power goes. To address this issue, load becomes a key part of the system regulation. For a UHRPS stage, it is necessary to consider power-to-gas (P2G), power-to-heat (P2H), power-to-cooling (P2C), power-to-vehicle (P2V) and other P2X (Power-to-X) technologies [13], [14], [15]. These approaches achieve a coupling balance between the power sector and other energy sectors.

The input power of many P2X devices can be flexibly adjusted under energy demand constraints. TABLE 1 summarizes the allowable input power fluctuation range and energy regulation constraints of some P2X devices [16].

With the introduction of P2X technology, more flexible loads will occur in UHRPS, where the input power of the load is allowed to fluctuate over a wide range of time without affecting terminal power consumption. According to the
length of elastic adjustable time scale, it can be divided into low elastic load with flexible and adjustable intraday power and high elastic load with longer time scale freely adjustable. Together with rigid loads whose power demands must be met in real time in the traditional sense, they form the total load in UHRPS.

4) STORAGE SIDE

Energy storage is designed to provide flexible balancing capabilities and is an essential component in UHRPS. However, considering the balance of the total cost of the system, the energy storage capacity should not be too large. For the scenario of 100% renewable energy power system, the energy storage capacity is roughly within 30% of the total power generation [16], [23]. In addition, there are evidences that if the short duration energy storage is completely relied upon, the required lithium battery manufacturing materials will exceed the existing proven total developable amount [24].

Considering the process of technological maturity and the downward trend of the cost, electrochemical energy storage will still be a foreseeable short duration energy storage body. Many studies have pointed out that extending the storage duration of electrochemical energy storage can be technically and economically beneficial, which will sustain the long duration use of the electrochemical energy storage [25], [26]. In addition, pumped storage power stations and compressed air energy storage are also important components of long duration energy storage. The seasonal energy storage is mainly realized by thermal storage and chemical storage, corresponding to heat storage tank heat storage and gas storage using salt caves or aquifers [27]. In recent years, some new energy storage concepts also have been put forward by some scholars, such as pumped storage in buildings [28]. The energy storage role of electric vehicles is realized by combining P2V and V2G(Vehicle-to-grid) [29]. The energy storage with hydrogen energy as the carrier is realized by electric hydrogen production-hydrogen storage-hydrogen combustion power generation [30].

**TABLE 1.** Allowable input power fluctuation range and energy regulation constraints for different P2X devices.

| P2X                                      | Allowable fluctuation of input power | Energy regulation constraint  |
|------------------------------------------|-------------------------------------|--------------------------------|
| Alkaline electrolysed water              | 10% - 110%                          | Hydrogen production demand    |
| Proton exchange membrane electrolyzed water | 0-160%                              | Hydrogen production demand    |
| Solid oxide electrolyzed water           | 20-100%                             | Hydrogen production demand    |
| Heat pump                                | 10-100%                             | Temperature regulation range  |
| The electric boiler                      | 20-100%                             | Temperature regulation range  |
| Air conditioner                          | 30%-100%                            | Refrigeration temperature regulation range |

**FIGURE 3.** Sequential and duration curves of net load in UHRPS.

**B. OPERATION CHARACTERISTICS**

1) THE FLEXIBILITY DEMAND GREATLY INCREASES BY THE FLUCTUATION CHARACTERISTICS OF WIND/PV POWER

In UHRPS, the system operation is dominated by the characteristics of wind/PV power. Flexibility is a new concern of the UHRPS [31], [32], and the rapid growth demand for flexibility will be the key contradiction of the UHRPS. Based on the capacity planning data in 2060 [11], the net load sequential and duration curves of the UHRPS for China State Grid can be obtained as shown in Fig 3.

Accordingly, the power and energy flexibility requirements of positive/negative net load when the wind/PV electricity share reaches different levels are estimated. Firstly, the net load can be written as follows:

\[ P_N = P_L - P_W - P_S \]  \hspace{1cm} (1)
\[ P_N^+ = \max \{P_N, 0\}, \quad P_N^- = \min \{P_N, 0\} \]  \hspace{1cm} (2)

where, \( P_N \) is considered as net load, \( P_L \) and \( P_W \) are load and wind power, respectively. \( P_S \) represents solar power. \( P_N^+ \) and \( P_N^- \) are the part with positive and negative net load, respectively. Positive and negative net load power regulation requirements can be written as follows:

\[ \alpha_{D,i}^P = \Delta P_D^P / P_L D \in \{+,-\} \]  \hspace{1cm} (3)
\[ \Delta P_i^+ = P_{N,max,i} - P_{N,min,i} \]  \hspace{1cm} (4)
\[ \Delta P_i^- = \max \{0, P_{N,max,i}^+ - \min \{P_S, 0\} \} \]  \hspace{1cm} (5)
\[ \alpha_{D,i}^P = \sum_i \alpha_{D,i}^P / nD \in \{+,-\} \]  \hspace{1cm} (6)

where, subscript \( i \) indicates the day, and \( n \) represents the total number of days. \( D \) indicates the case where the net load is positive (+) or negative (−). \( \alpha_{D}^P \) and \( \Delta P_D^P \) represents the daily power flexibility demand and daily maximum power flexibility demand under scenario \( D \), respectively. \( P_L \) is the annual average load and \( P_C \) is the installed capacity of other power sources. \( \eta \) is the adjustment range coefficient of other power sources. \( P_{N,max,i} \) and \( P_{N,min,i} \) are the maximum and minimum net load in case \( D \) on day \( i \), respectively.

Positive/negative net load energy flexibility demand can be written as follows:

\[ \alpha_{E,i}^P = P_{N,i} / P_L \]  \hspace{1cm} (7)
where, $\alpha_P$ represents the daily energy flexibility demand, and $\overline{P}_N$ represents the average net load power under scenario $D$.

The estimated results under different share of electric conditions are shown in Fig 4. The time sequence constraints are ignored in this estimation and indicators are 0 when the wind/PV electric share is lower than 40%. With the development of wind/PV electricity share from midium to ultra-high, both power and energy flexibility requirements are increased, and the demand for flexible regulation in negative net load period are gradually increased to the same or even higher level than that in positive net load period.

The increased frequency of negative net loads is an important feature of the system compared to the previous phase, where wind/PV power and energy fluctuations are responded by large elastic loads, and P2X becomes a key means of cross-sector balancing. P2V and temperature-controlled loads (P2H and P2C) were mainly considered to study the demand side response in the past [33]. In recent years, P2G, which mainly refers to electric hydrogen production, has attracted attention to realize the tracking of load to power fluctuation. Electric hydrogen production load is considered to be an important resource to follow the drastic fluctuation of photovoltaic power generation [34]. In the literature [35], it is considered that electric hydrogen production is an indispensable response resource for future system operation in terms of either power or energy regulation volume.

2) THE CONTRADICTION BETWEEN LONG DURATION AND SEASONAL BALANCE IS PROMINENT

The energy shift time index is calculated based on the data in Fig 3. An ideal storage with unlimited storage capacity and no energy dissipation is assumed to calculate the index, which can deposit excess wind/PV power at any time and release wind/PV power whenever needed. The longest time required by the ideal energy storage to complete a complete energy shift process (the ideal energy storage starts from the initial state with storage value as zero and eventually returns to the initial state) is used to represent the energy shift time required by the system to make full use of surplus wind/PV generation. The formula is as follows.

$$E_{S,t} = - \sum_{\tau=t_0}^{t_{end}} P_{N,\tau}$$ (10)

where, $d$ represents the energy shift time; $E_{S,t}$ and $t_0$ represent the energy value and starting time of the $t$-th energy shift process at time $t$, respectively. The defining conditions are $E_{S,t}^k < 0$ and $E_{S,t}^k = 0$; $\tau_{end}$ represents the end time of the $k$-th energy shift process, and its defining conditions are $E_{S,t}^k > 0$ and $E_{S,t}^k = 0$.

The estimated results are also shown in Fig 4. In terms of absolute value, the energy shift time requirement increased from 8 hours (40% share) to 6938 hours (100% share), and the long duration and seasonal energy shift demand became prominent.

Similarly, research institutions such as IEA [36] and New Climate Institute [37] have pointed out that the balance problem at the monthly to annual scale will be the main contradiction when the share of wind/PV electricity reaches a high level. Extensive simulation analysis has also found that increasing the energy storage duration is important to further increase the share of wind/PV power generation [38], [39].

3) METEOROLOGICAL ELEMENTS BECOME IMPORTANT PARAMETERS OF SYSTEM OPERATION

For the operation of UHRPS, the boundary of flexible supply-demand balance will be greatly changed by the uncertainty of meteorological conditions, and meteorological factors will become the important parameters affecting the flexibility balance.

Meteorological factors are sensitive factors on both sides of supply and demand in UHRPS. From the source side, load supply capacity of the system is impacted by continuous weather conditions of “Dunkelflaute” [40] without wind, solar and extreme weather such as low temperature cold wave [41]. However, the system’s ability to absorb excessive power is challenged by windy and sunny weather [42]. From the load side, the share of urban load increases, especially the share of temperature control load, resulting in a great increase in the temperature sensitivity of load. For instance, residential heating in France relies heavily on electric boilers, which results in a temperature sensitivity of 2300 MW/°C [43] for the electricity load in France, compared to an average load level of about 3.5%/°C.
C. FLEXIBILITY METRICS OF UHRPS

Referring to the idea of reliability evaluation index definition, this paper selects the Loss of Flexibility Probability (LOFP), the Loss of Flexibility Duration (LOFD) and the Loss of Flexibility Expectation (LOFE) as the evaluation indexes of system flexibility. Its physical meaning is shown in Fig 5.

When the probability distribution function \( P(A) = P(\psi = \psi_i), i = 1, 2, \ldots \) of the system operation state and the component flexibility supply are determined, the flexibility index of the system can be calculated by convolution method, and the calculation of the above indexes is given by (12) ~ (14).

\[
\text{LOFP}^A_{\nu, \tau} = \sum_{\psi_i \in \Psi} P(\psi = \psi_i) P(Y^A_{\nu} = y \mid \psi = \psi_i, \tau) \\
\times I \left( \sum_{i \in S} x^A_{\nu, i} (\psi_i) < y \right) \tag{12}
\]

\[
\text{LOFD}^A_{\nu, \tau} = T \times \text{LOFP}^A_{\nu, \tau} \tag{13}
\]

\[
\text{LOFE}^A_{\nu, \tau} = \sum_{\psi_i \in \Psi} P(\psi = \psi_i) P(Y^A_{\nu} = y \mid \psi = \psi_i) \\
\times \left[ y - \sum_{i \in S} x^A_{\nu, i} (\psi_i) \right]^+ \tag{14}
\]

where, \( \text{LOFP}^A_{\nu, \tau}, \text{LOFD}^A_{\nu, \tau}, \text{LOFE}^A_{\nu, \tau} \) is the direction \( A \) dimension of \( \nu \) system flexibility index under time scale \( \tau \); \( [\alpha]^+ = \max(\alpha, 0) \); \( I \) is the indicator function. If \( \sum x^A_{\nu, i} (\psi_i) < y \) is used, then \( I \left( \sum x^A_{\nu, i} (\psi_i) < y \right) = 1 \), and vice versa \( I \left( \sum x^A_{\nu, i} (\psi_i) < y \right) = 0 \).

The above flexibility index has a clear physical meaning. The LOFP index reflects the possibility of insufficient flexibility, while the LOFD index represents the total duration of insufficient flexibility. LOFE index can be connected with the system load loss and renewable energy limit. Taking the power-based flexibility index as an example, the mathematical derivations are shown in Formulas (15) ~ (16). It can be seen that the system load loss and renewable energy limit have a simple linear relationship with the flexibility index.

\[
E_{\text{LS}} = \sum_{t} P_{\text{LS}, t} I_t = T \sum_{t} P_{\text{LS}, t} \frac{I_t}{T} = T \times \text{LOFE}^+_{\rho, \tau} \tag{15}
\]

\[
E_{\text{REC}} = \sum_{t} P_{\text{REC}, t} I_t = T \sum_{t} P_{\text{REC}, t} \frac{I_t}{T} = T \times \text{LOFE}^+_{\rho, \tau} \tag{16}
\]

where, \( E_{\text{LS}} \) and \( E_{\text{REC}} \) represent load loss and renewable energy limit respectively.

III. FLEXIBILITY CHALLENGES AND FLEXIBILITY PLANNING NEEDS FOR UHRPS

A. FLEXIBILITY CHALLENGES FOR UHRPS

1) COMPLEX SYSTEM FLEXIBILITY REQUIREMENTS WITH LONGER PERIODS, LARGER AMPLITUDES, AND MORE DRAMATIC CHANGES ARE CAUSED BY DEEP COUPLING OF METEOROLOGICAL AND ELECTRICAL FACTORS

In UHRPS, the power output of wind/PV is affected by meteorological factors, continuous extreme weather without wind and solar will lead to insufficient load supply capacity of new energy system. Conversely, windy/sunny weather puts forward higher requirements for the system’s surplus power consumption capacity. A sequential output of a cluster wind farm is shown in Fig 6, which shows that the rapid fluctuation of wind power output makes it even exceeds the load to become the main body of the system flexibility demand, and there is a continuous ultra-low output period of 50 hours or even longer, which requires flexible resources which can provide flexibility with longer duration period and greater adjustment frequency.

2) THE DIFFICULTY OF POWER BALANCE IS EXACERBATED BY THE MISMATCH BETWEEN LOAD DEMAND AND NEW ENERGY OUTPUT CHARACTERISTICS

The user’s electricity consumption habits cause the load curve to show the characteristics of peaks during the day and troughs at night. However, the wind power output is low during the day and high at night, which does not match the load characteristics and has obvious anti-peak characteristics. The photovoltaic output is high at noon during the day, which does not match the load curve of the grid is a typical “duck curve”, as shown in Fig 7. In the net load curve, the electricity load changes rapidly during the morning and evening peak hours, while the
curve is concave and valley-shaped during the noon and off-peak hours, which increases the difficulty of power balance undoubtedly in the power system. It also puts forward higher requirements for the flexible adjustment and fast adaptability of the system.

3) SPATIAL CORRELATION PROPERTIES SHOULD BE CONSIDERED IN FLEXIBLE BALANCE OF SUPPLY AND DEMAND DUE TO THE WIDE AREA DISTRIBUTION CHARACTERISTICS OF NEW ENERGY

Considering the spatial distribution of wind and solar power sources featured with a widespread and enormous number of locations, requirements are also put forward for the balance of power and electricity on the spatial scale of the system. Different from the traditional centralized power generation, the new energy station has the characteristics of small installed capacity and large number, which is connected to the power system in a hierarchical structure, as shown in Fig 8. This structure leads to the fact that the power generation of adjacent wind/PV units is not independent, but is geographically dependent. The Fig 9 shows the probability distribution of wind power output under different new energy share in a certain region of China. It can be seen from figure (a) that when the wind power share is low, the wind power output has a greater probability that the output is 0, and the probability decreases with the increase of output value. It can be seen from figure (b) that when the wind power share is high, the probability distribution of wind power output also shows the law that the probability decreases with the increase of the output value, but the probability of the minimum output value is lower, indicating that the complementarity between wind farms in the space with high wind power share is stronger. Therefore, in the future, the UHRPS may also need to consider the power balance on the spatial scale.

B. THE NEED FOR FLEXIBILITY PLANNING OF AN UHRPS

From the analysis of the aforementioned challenges, it can be seen that resources, weather and environment have become the key influencing factors on both sides of power supply and demand under the new scenario. In terms of power supply, wind speed, wind direction, solar irradiance, temperature, pressure, etc., are the meteorological parameters that affect the output of wind/PV energy. There are differences and spatial correlations on the meteorological parameters involving short, medium and long time scales, which is reflected in the random changes in output caused by short duration changes in wind speed or solar irradiance, and the seasonal differences in output caused by climates in different seasons. The load efficiency of the power system is also strongly correlated with meteorological parameters such as temperature, humidity, and wind speed, existing uncertainties and spatial correlations.

In view of the randomness and uncertainty on both sides of supply and demand due to resources, meteorological and environmental factors, the demand for flexibility in the power system has expanded. For instance, the intermittent nature of wind/PV output has expanded the power system’s ability to long duration flexibility. Long duration flexibility of supply-demand balance refers to the ability of the flexible resources of the system to meet the future electricity flexibility demand brought by a complete meteorological change process, which refers to a wind speed change process. In order to adapt to the development of a UHRPS in the future, it is imminent to leverage the potential of various flexible resources and promote the coordination of “source-grid-load-storage” in terms of developing the flexibility of resources.

Regarding the status quo, it is necessary to build a theory for long duration flexibility planning of UHRPS, and to add it in the traditional planning process. From a planning point of view, under the new energy scenario, the main issue for power system planning is that resources cannot match the...
growing demand for flexibility, meanwhile, it usually needs a relatively long time to satisfy the demand for system flexibility, which also needs to be adapted to the changes across the day. Therefore, a flexibility evaluation index needs to be established to quantify the flexibility of the system, using the potential of system flexibility resources. At the same time, a flexible resource allocation method is required to realize the coordination and unification of flexible resources of source-network-load-storage.

IV. STATUS OF METHODS FOR POWER SYSTEM FLEXIBILITY PLANNING

Through the efforts of experts and research institutions, planning software tools such as WASP, GESP, GASP, JASP have been formed [44], and the technology of traditional power system planning has become relatively mature. In UHRPS, the planning concept needs to be changed from “power balance” to “flexibility balance”. At present, a power planning model considering flexibility balance constraints has been proposed [45]. This work presents the application status of the existing flexibility planning methods from the points of view of the generation, transmission, and distribution flexibility planning of power generation.

The main issue of traditional generation planning is the balance and reliability of power. Most research aims to minimize the cost during the planning period by evaluating the planning scheme from an economic perspective [46]. However, with the gradually increasing share of wind/PV renewable energy, the flexibility of the power system has become an urgent problem to be solved. The 14th Five-Year Plan of China points out that it is necessary to promote the flexible transformation of coal-fired power, to accelerate the construction of pumped storage power stations and the large-scale application of renewable energy storage technologies, and to comprehensively improve the flexibility of the UHRPS [47].

Literature [48] evaluated the flexibility of the system and combined long duration investment and short duration operating costs to determine the optimal combination of flexible generator sets. Literature [49] proposed a criterion for evaluating the flexibility of power generation systems and established a power planning algorithm that considered uncertainty. Literature [50] studied the indicators for measuring the flexibility of power systems and proposed a method that combines existing planning techniques with flexibility assessment to study optimal power expansion decisions. Literature [51] proposed an optimization model to design flexible systems that softened the system uncertainty into the flexibility planning of future systems. Literature [52] proposed a two-layer low-carbon expansion power generation planning method considering the uncertainty of renewable energy on multiple time scales. The flexibility of peak shaving and 15-minutes scales allowed for optimal scheduling of the system. Literature [53] proposed a long duration capacity planning approach that incorporated short duration operational characteristics within an hour into long duration capacity planning, using historical phase planes of capacity and slope to bridge the gap between long duration capacity planning and short duration hourly flexibility. Literature [54] proposed a long duration capacity expansion model by more accurately representing the flexibility requirements of the power system in the long duration scope of considering investment decisions.

A. FLEXIBILITY PLANNING OF TRANSMISSION GRID

Many solutions to the transmission network planning problem have been proposed considering uncertain factors in UHRPS [55], [60]. Literature [55] constructed uncertainty sets for daily demand, wind power, and dynamic thermal rating (DTR) systems. While DTR systems, energy storage systems, and optimal line switching operations were considered as the system flexibility resources. Literature [56] proposed a multi-stage power transmission expansion method with a multi-objective optimization framework based on internal scenario analysis by defining multiple scenarios to account for system uncertainty. Literature [57] proposed an adaptive robust optimization model for the planning problem of power generation and transmission expansion and designed an uncertainty set to represent the uncertainty of load and renewable energy as well as short duration operation uncertainty. Literature [58] constructed the hourly net load ramp uncertainty set to describe the change of hourly net load, including wind power generation and the uncertainty set of the annual curve of the net load to describe the uncertainty of the normal annual net load duration curve.

The system flexibility in transmission network planning is concerned in literatures [61], [62], [63], [64], [65], [66]. Literature [61] proposed a coordinated network expansion planning method based on the optimal power flow equation and planning constraints of different equipment. The planning of the wind farm were coordinated through the energy storage system to improve the flexibility of the system. Literature [62] discussed the problem of transmission expansion planning when the database size available for evaluating reliability indicators and investment budgets for building new equipment was limited. Literature [63] proposed a safety-constrained multi-stage power transmission expansion planning model considering variable series of reactors, which realized the reliability and economy of network planning. Literature [65] increased the flexibility of the transmission and generation capacity expansion planning by introducing Transmission Switching (TS), which decomposed the planning problem into a main problem, and two sub-problems in terms of performance and economy. In contrast, the main problem considered the role of TS in enhancing expansion plans. Literature [66] established a “storage-transmission” joint planning model considering flexibility and realized the optimal configuration of energy storage and transmission line expansion.

B. FLEXIBILITY PLANNING OF DISTRIBUTION NETWORK

In the scenario of UHRPS, the volatility, intermittency and unpredictability of wind/PV renewable energy aggravate the volatility of the net load of the distribution network when a
high share of distributed new energy, so higher requirements are put forward for the planning of the distribution network. In recent years, scholars have coupled flexible resources to distribution network planning and researched on demand response and energy storage allocation in order to further improve the flexibility of distribution network systems.

Literature [67] established a flexibility clearing house (FLECH) in the distribution network system to improve the flexibility of the system and reduce the network congestion of the distribution system through distributed power sources. Literature [68] analyzed the impact of distributed energy and demand-side response on active distribution network planning, considered the uncertainty of load demand response and distributed generation, and discussed the future research direction of flexibility planning of active power distribution system. Literature [69] studied the impact of flexible resources such as adjustable thermal units, energy storage, and hourly demand response on the operation of the random day-ahead market. It proposed a random day-ahead scheduling model with flexible resources selection. Literature [70] analyzed the supply and demand relationship of distribution network flexibility. It proposed a two-layer optimal allocation model for flexible resources. Literature [71] studied the flexibility assessment problem of the distribution system considering the interaction between electric vehicles and power grid.

In summary, the current research on flexible resources planning mainly has the following problems: 1) In terms of flexible resources objects, the existing researches focus more on the generation side to improve the flexibility of the generation side, and less on long duration energy storage, especially new energy storage such as hydrogen storage. 2) In terms of the model, the existing research model framework basically adopts the bi-level programming, but in terms of the internal production simulation model, it mainly focuses on the consideration of time scales such as intra-day peak shaving and ramping, and lacks the consideration of the inter-day flexibility supply and demand balance constraint of meteorological variable cycle process matching. 3) There is little research on multi-type long duration flexible resources co-ordination optimization planning, and it is unable to answer the optimal alternative order problem of various types of long duration flexible resources in the gradual retirement process of traditional thermal power units.

V. KEY ISSUES AND SOLUTIONS FOR LONG DURATION FLEXIBLE RESOURCE PLANNING FOR UHRPS

Based on the basic process of classical flexibility planning, this paper proposes innovative models and methods in four key threads. Namely, the demand probability model for the inter-day flexibility considering both supply and demand, the optimization method for the flexibility of multi-type, inter-day adjustment of resources and capability analysis, the long duration flexibility supply and demand balance principle, and the multi-type, long duration flexible resources bi-level optimization planning. The exploration of the inter-day flexibility planning and its application is conducted by considering the coupling characteristics of the meteorology and electricity. The general idea of this paper is shown in Fig 10.
A. KEY PROBLEM 1: PROBABILISTIC DEMAND MODELING FOR INTER-DAY ADJUSTMENT FLEXIBILITY ON BOTH SIDES OF SUPPLY AND DEMAND CONSIDERING THE COUPLING CHARACTERISTICS OF METEOROLOGY AND ELECTRICITY

Both the supply and demand sides of a UHRPS have significant interdependence characteristics of meteorological factors. Meteorological data has strong uncertainty, which brings in corresponding uncertainty in the characteristic curve and flexibility demand in the supply and demand sides of the power system. It is necessary to use probabilistic modeling methods to characterize the long duration uncertainty characteristics of meteorological factors which have a common-mode effect on the supply and demand sides of UHRPS.

The solution to problem 1 can be shown in Fig 11. Firstly, according to the reconstruction curve of meteorological historical data for many years, the spatial correlation and spatial aggregation complementary characteristics of renewable energy output, the spatial correlation and spatial aggregation complementary characteristics of renewable energy output in different spatial locations are analyzed, and the probability distribution function model of joint output of multiple stations is constructed by using the Copula function and other probability correlation modeling theory. In particular, the probability of occurrence of low probability and high consequence (HILP) events (extreme high temperature, low temperature, strong wind, no wind, etc.) is considered, and the probabilistic modeling method of multiple uncertainties on both sides of supply and demand is formed, which covers various possible scenarios of UHRPS. Secondly, combined with the full-cycle features identified in meteorology and the renewable energy output, and by using the correlation analysis such as multiple regression, information entropy, and decision tree, a time sequential reconstruction method for abnormal and missing meteorological data is proposed. Then, the probabilistic correlation between the renewable energy output and multiple types of meteorological factors are analyzed by taking into account the key factors of the renewable energy output. A time-varying probability model of renewable energy output based on the uncertainty of meteorological data is established. Finally, the main components of meteorological factors affecting the supply and demand sides of UHRPS are identified, by using the dependence of the renewable energy output and the meteorological factors. The definition of long duration flexibility and the evaluation index of supply and demand are used to analyze the demand for inter-day adjustment flexibility on both sides of the supply and demand of UHRPS considering the meteorological factors.

B. KEY PROBLEM 2: OPTIMIZATION METHOD FOR THE FLEXIBILITY OF MULTI-TYPE, INTER-DAY ADJUSTMENT OF RESOURCES AND CAPABILITY ANALYSIS

The long duration flexible resource and equipment model presents heterogeneous coupling characteristics. According to the definition and evaluation indicators of long duration flexibility, a multi-type, long duration flexible resource supply and its probability distribution model should be established. The supply capacity of flexible resources has a strong correlation with the operating state of the power plant. It is an important yet difficult topic as to establish a unified long duration flexible supply assessment method and its probability distribution model for multi-type heterogeneous flexible resources and the flexibility balance principle.

The solution to problem 2 can be shown in Fig 12. Firstly, in terms of the flexibility conversion characteristics of primary and secondary energy, considering the energy demand characteristics of electric vehicle terminal, the power-energy flexible adjustable characteristics of P2X implementation technology, the technical parameters requirements of the conversion process and the energy efficiency and economic performance are analyzed. At the same time, in terms of the storage characteristics of electric vehicles,
the energy dissipation characteristics of charging, discharging and dynamic storage process are studied. From the two dimensions of power and energy balance, the necessity and potential of UHRPS elastic load depth response to wind/PV random fluctuations are evaluated, and the interactive participants of source-load depth interaction, the interactive characteristics of each participant and the cooperation mode of multi-elastic load joint response are analyzed. Secondly, different types of long duration energy storage are considered. Their inter-day regulation ability is analyzed. Long duration flexible supply probability model for inter-day regulation of energy storage and flexibility regulation of thermal power resources is established. Then, a multi-type, long-period flexible resource regulation model is proposed, analyzing the impact of factors such as meteorology, states, and resources on long duration flexible resources such as pumped storage, solar thermal, etc. A comprehensive evaluation model for future inter-day and long duration flexible resource supply capacity is established. The complementary characteristics of flexible resource supply capacity matching the time scale of the whole process of variable-period meteorology is analyzed. Based on the analysis, a synergistic optimization method of multi-type, long-period flexible resources inter-day regulation ability based on weather-state-resource dependence is proposed.

C. KEY PROBLEM 3: THE PRINCIPLE OF LONG DURATION FLEXIBILITY TO BALANCE SUPPLY AND DEMAND

The long duration flexibility supply and demand balance is strongly coupled with factors such as meteorological conditions, system operating status, and flexible resource parameters. The current time sequential model with a limited time duration cannot well match the characteristics of the meteorological process. If the simulation period is not sufficiently long to capture the underlying characteristics of the meteorological data, it may lead to analysis deviation caused by the “truncation” of the calculation time.

The solution to problem 3 can be shown in Fig 13. Firstly, wind/PV new energy output model is established to analyze the time scale distribution of meteorological processes. The load-side response model of electric vehicles is established to tap its potential to provide flexibility, reveal the spatiotemporal evolution characteristics of new loads such as electric vehicles and establish its description method. The long duration flexibility in the supply and demand balance criterion and balance mechanism of new electric vehicle load are studied. The long duration flexibility in the supply and demand balance criterion are studied, and a long duration flexibility balance principle based on the coupling characteristics of meteorological and electricity is proposed. Secondly, a probabilistic modeling method with multiple uncertainties on both sides of supply and demand is formed, considering the flexibility requirements caused by wind/PV and new loads. A probabilistic model considering the coupling of inter-day balance and intra-day balance is proposed. Finally, the periodic characteristics of renewable energy with continuous high output and low output are identified, and the periodic distribution of renewable energy output data dependent on meteorological resources is analyzed. A fast algorithm of variable step sizes for production simulation based on the meteorological data is proposed.

D. KEY PROBLEM 4: TWO-LAYER OPTIMIZATION PLANNING FOR MULTI-TYPE LONG DURATION FLEXIBLE RESOURCES

The purpose of long duration flexible resource planning is to find the resource combination that meets the needs of the system’s inter-day adjustment flexibility in an economically optimal way. Although single resource planning can also solve the problem of long duration flexible resources in the system, the complementary characteristics of multiple types of resources cannot be fully exploited, the global optimization of multiple types of resources in a unified framework cannot be realized, and the optimal replacement order of traditional coal power resources cannot be answered.

The solution to problem 4 can be shown in Fig 14. Firstly, a sampling method in uncertainty scenarios for price factors is proposed, considering the future price trend of new flexible resources. Secondly, a multi-type, long-period and flexible resource optimization planning model with stochastic time series simulation and investment decision nesting is proposed. Finally, several typical scenarios of UHRPS are extracted. Considering the future renewable energy development goals and load evolution trends under the resource endowment of each typical scenario, the application of the long duration flexible resource optimization planning model is carried out, and the long duration flexible resource planning
principles and typical parameters for different typical regions are refined.

VI. CONCLUSION

Under the background of climate change, the power system will evolve to a UHRPS with wind/PV power sources as the main power, possibly in the next few decades. The random fluctuation characteristics of wind/PV power generation will drive for changes in the composition and operation mode of UHRPS. However, there is still a lack of technical analysis system for the long duration flexible resource planning that is compatible with UHRPS. This paper aims to make a preliminary response to this question based on the current research on the future power system and the engineering operation experience, in order to provide directions for future research and analysis.

In this work, the characteristics of UHRPS is analyzed. On the source side, wind/PV power sources with the low capacity factor become the main component, and other power sources are transformed into flexible resources. On the grid side, the network functions of the source grid, with multi-voltage levels, are coupled, and the power grid appears low inertia characteristic. On the load side, elastic load demand response becomes the norm, and P2X offers the potential for coupling between electricity and other energy sectors. On the storage side, multiple types of energy storage can achieve flexible balance on multiple time scales. In addition, the challenges of flexibility balance faced by the UHRPS are analyzed from three perspectives, i.e., meteorological-electric coupling, mismatch between supply and demand characteristics, and wide spatial distribution of new energy. By fully investigating the research status of power system flexibility planning, four key issues and solutions for long duration flexible resource planning for UHRPS are proposed.

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