An Orderly Power Utilization Method for New Urban Power Grids Facing Severe Electricity Shortages

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Abstract—Due to the effects of windless and sunless weather, new power systems dominated by renewable energy sources experience power supply shortages, which lead to severe electricity shortages. Because of the insufficient proportion of controllable thermal power in these systems, this problem must be addressed from the load side. This study proposes an orderly power utilization (OPU) method with load as the primary dispatching object to address the problem of severe electricity shortages. The principles and architecture of the new urban power grid (NUPG) OPU are proposed to complete the load curtailment task and minimize the effects on social production and daily life. A flexible load baseline division method is proposed that considers the effects of factors such as gross domestic product, pollutant emission, and carbon emission to increase the flexibility and applicability of the proposed method. In addition, an NUPG OPU model based on the load baseline is proposed, in which the electric quantity balance aggregator (EQBA) serves as a regular participant in the OPU and eliminates the need for other user involvement within its capacity range. The electric quantity reserve aggregator (EQRA) functions as a supplementary participant in the OPU and primarily performs the remaining tasks of the EQBA. The electric power balance aggregator primarily offsets the power fluctuations of the OPU. Case studies demonstrate the effectiveness and superiority of the proposed model in ensuring the completion of the load curtailment task, enhancing the flexibility and fairness of OPUs, and improving the applicability of the proposed method.

Index Terms—Electric power balance, electric quantity balance, electricity shortage, orderly power utilization, new urban power grid.

NOMENCLATURE

A. Indices

i	Index of small- and medium-sized industrial, commercial, and entertainment users
j	Index of large industrial, commercial, and entertainment users
n	Index of energy storage

B. Parameters

α_1	Exchange coefficient of score
α_2	Exchange credit coefficient
γ	Multiple of the second-level baseline
τ	Multiple of the third-level baseline
η_i^{I}	Gross domestic product (GDP) index of industrial user
φ_i^{I}	Carbon emission of industrial user
φ_i^{IM}	Total carbon emission in the last month
ψ	Compensation factor for orderly power utilization (OPU)
ξ	Peak-shaving electricity price
∂_j^{I}	OPU instructions issued by electric quantity for industrial user balance aggregator (EQBA)
∂_j^{b}	Instructions issued to entertainment load
Ω_i^{I}	Electricity fees from exchange of industrial user
ε_i^{I}	Pollution index of industrial user
θ_i^{I}	Credit coefficient of industrial user
θ_i^{I1}	Remaining credit coefficient of industrial user
$\Delta\theta_i^{I}$	Amount of change in credit coefficient of industrial user
ΔP_K^{J}	Shortage of power balance tasks undertaken by EQAB K
ΔP_Z	Load that needs to be reduced
$\sum P_{w(i-1),1}^{I}$	Total load curtailment for the first $w(i-1)$ industrial users
c_x	Overall load curtailment ratio
f_n	Profit of independent energy storage
f_i^{IS}	Revenue of industrial user
$f_{w(i)}^{IS}$	Compensation for industrial user $w(i)$ from power supply
h_i^{IM}	GDP of industrial user in the last month
K	Number of residential users

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k_q	Coefficient of pollutant gas		ΔP^X	Fluctuating power
k_F	Coefficient of particulate matter		ΔP^G	Contribution load of EQRA
k_L	Conversion coefficient of green certificate		ΔP^C	Excess load of EQRA
k_s	Coefficient of wastewater		ΔP^y	Total grabbed load of EQRA
L	Number of independent energy storage		ΔP_i^{ly}	Grabbed load of industrial user
L_i^I	Total green certificate of industrial user in the last month		ΔP_i^{by}	Grabbed load of commercial user
M	Number of industrial users		ΔP_i^{ry}	Grabbed load of residential user
M_q	Amount of pollutant gases emitted		ΔP_i^{oy}	Grabbed load of public user
M_F	Amount of particulate matter emitted		ΔP_i^{IG}	Contribution load of industrial user
M_s	Amount of wastewater discharged		ΔP_i^{bG}	Contribution load of commercial user
N	Number of commercial users		ΔP_i^{rG}	Contribution load of residential user
N_I	Number of industrial users		ΔP_i^{OG}	Contribution load of public load
N_b	Number of entertainment loads		ΔP_i^{IC}	Excess load of industrial user
O	Number of public users		ΔP_i^{bC}	Excess load of commercial user
P_i^{IM}	Historical load of industrial user in the last month		ΔP_i^{rC}	Excess load of residential users
			ΔP_i^{Ix}	Required load reduction of industrial user
$\boldsymbol{P}_K^{F0}$	Score matrix formulated in previous round		ΔP_J^I	Total load reduction for industrial user
$P_{w(i)}^{IK}$	Total load curtailment of industrial user $w(i)$		ΔP_J^b	Total load reduction for entertainment load
$P_{w(i),\partial_{w(i)}^I}^{IK}$	Load curtailment limit of industrial user $w(i)$ under $\partial_{w(i)}^I$		B	Difference between P_N and P_S
			$\bar{B}$	Average value of B
$\boldsymbol{P}_{w(i)}^{IF0}$	Score matrix of industrial user $w(i)$		f^C	Total stage excess load cost of EQRA
$P_{w(i)}^{I1}$	Load plan of industrial user $w(i)$		$f_i^{IC}(t,\Delta t)$	Cost of industrial user
$P_{w(i)}^{IF2}$	Score to be paid by industrial user $w(i)$		$f_i^{bC}(t,\Delta t)$	Excess load cost of commercial user
$P_{w(i)}^{IF3}$	Final score paid by industrial user $w(i)$		$f_i^{rC}(t,\Delta t)$	Excess load cost of residential user
T_g	Contributed time		$f_i^{OC}(t,\Delta t)$	Excess load cost of public user
T_c	Excess time		ℓ	Total insurance load
t	Time		ℓ_i^I	Insurance load of industrial user
w_i^{IM}	Total pollutant emissions of industrial user in the last month		L	Number of independent energy storage
			P_a	Social welfare load
$\boldsymbol{W}$	Correlation matrix of user		P_C	Predicted power
$ZL_{w(i)}^I$	Instruction issued by EQBA for industrial user $w(i)$		P_i^I	Load baseline of industrial user
			P_i^b	Load baseline of commercial user
			P_i^r	Load baseline of residential user
C. Variables			P_i^{Ia}	Initial load baseline of industrial user
			P_i^{Ig}	Actual load of industrial user
$\beta(t,\Delta t)$	Total impact coefficient of electric quantity reserve aggregator (EQRA)		P_i^{IS}	Request load of industrial user
			P_i^{IX}	Issued load schedule of industrial user
$\beta_i^I(t,\Delta t)$	Impact coefficient of industrial user		P_j^b	Load baseline of entertainment load
$\beta_i^b(t,\Delta t)$	Impact coefficient of commercial user		P_j^{b1}	Historical load of entertainment user
$\beta_i^r(t,\Delta t)$	Impact coefficient of residential user		P_j^{I0}	Basic load of industrial user
$\beta_i^O(t,\Delta t)$	Impact coefficient of public user		P_j^{I1}	Historical load of industrial user
$\Delta\vartheta_i^I$	Load reduction coefficient of industrial user		P_m	Livelihood load
δ_i^I	Proportion of stage excess load of industrial user		P_n^s	Power provided by independent energy storage
			P_n'	Power baseline of independent energy storage
Δe_i^I	Excess load of industrial user		P_N	Historical load
ΔP^{up}	Upward adjustment power		P_S	Available power
ΔP^{dn}	Downward adjustment power		P_v	Public service load
ΔP_M^{up}	Upward adjustment power limit			
ΔP_M^{dn}	Downward adjustment power limit			

S_n Capacity of independent energy storage

I. INTRODUCTION

TO promote the development of clean energy and reduce greenhouse gas emissions [1], China has proposed the goals of carbon peaking and carbon neutrality, which aims to achieve a carbon peak by 2030 and carbon neutrality by 2060 [2], [3]. Therefore, the main power supply source of the new urban power grid (NUPG) will be renewable energy [4], which may lead to frequent and severe electricity shortages for the following reasons: ① renewable energy is mainly affected by weather [5], and the power of renewable energy will significantly decrease when no wind or sunlight is present in some areas [6]; and ② due to the reduced share of traditional thermal power and the absence of economically viable units to compensate for it, the generation side cannot provide sufficient power in the event of a shortage of renewable energy [7].

To address these problems of electricity shortage, some pioneering studies have focused mainly on two aspects: ① strengthening the construction of power systems to cope with uncertainties; and ② orderly load adjustment to address electricity shortages. To strengthen the construction of power systems, [8] and [9] focus on the effects of energy diversity and the risks of overreliance on a single source, respectively. The coupling between power and gas is enhanced in [10] to improve system flexibility [11], and the construction of reserve resources is strengthened in [12] to improve the short-term power balance capabilities. A high-voltage direct current (HVDC) system and pumped storage are constructed in [13] to ensure a stable power supply. The increased capacities of hydropower stations are presented in [14]. Reference [15] suggests that strengthening energy storage construction could address these problems. However, the lengthy construction and high costs of these methods cannot immediately address severe electricity shortages. Accordingly, this study chiefly addresses short- and long-term severe electricity shortages using an orderly power utilization (OPU) method, which does not incur high construction costs.

To adjust the load and address electricity shortages orderly, existing methods have mainly focused on balancing real-time power fluctuations [16]. These methods include adjustments to peak-valley differences [17], the conduct of economic dispatch [18], participation in demand response [19], optimization of electric vehicle charging/discharging [20], OPUs of air conditioning systems [21], coordination of distributed energy storage [22], management of interruptible load OPUs [23], and management of combined battery/vehicle [24]. These methods are effective in addressing general electricity shortages. However, due to limited load participation types, numbers, and depth, addressing severe electricity shortages is difficult. Moreover, these methods rely solely on a single-load baseline in which users are provided with only one load baseline and no other options, resulting in a lack of flexibility in the OPUs. If users fail to follow instructions because of limited grid interaction, the effectiveness of the OPU is compromised. Therefore, this study builds an NUPG OPU model to dispatch all the adjustable loads of NUPGs to provide sufficient load adjustment capacity. A flexible load baseline and interactive mechanism based on the "Online State Grid" APP (OSGA) are established to enhance OPU flexibility.

Notably, if a user cannot complete the OPU instructions, the dispatch pressure and operating costs of the NUPG increase significantly. Reference [25] considers both user value and the willingness to rank users for an OPU. Users can interact with the power grid, ensuring the fairness and flexibility of the OPU, which provides a significant reference for this study. References [26] and [27] determine the participation order of OPUs by ranking users based on node loss, mixed attributes, and grid loss. However, due to the lack of effective assessments of user performance, incomplete tasks are eventually transferred to the power grid. In addition, the lack of correlation between different rounds of OPUs results in the same user ranking, leading to an unfair selection of users in each round. Thus, scores and credit coefficients are introduced in this study to evaluate OPU performance of the user and establishes a correlation mechanism between different rounds of the OPUs to ensure effectiveness and fairness.

The factors affecting social development should be considered in the OPU process. Reference [28] also considers the effects of electricity prices on OPUs. References [29] - [31] consider factors such as the economy and pollutant emissions in OPUs. However, these methods do not consider carbon emissions and have difficulty in meeting the requirements of the goals of carbon peaking and carbon neutrality. Therefore, in this study, gross domestic product (GDP), pollutant emission, carbon emission, green certificate, and credit coefficient in OPUs are comprehensively considered to fully meet the demand of social development.

For frequently occurring OPUs, minimizing their effects on the overall societal power consumption is crucial. Thus, we set up primary and auxiliary users participating in the OPU. The OPU tasks are firstly assigned to primary users and then auxiliary users are involved. Ultimately, we propose a method for addressing the severe electricity shortages from the load side. The comparative technical features of similar research works, as shown in Table I, are as follows.

1) A novel OPU method for NUPGs is proposed to address severe electricity shortages and further reduce the effects on the overall societal power consumption compared with the method presented in [23].

2) Through the introduction of historical scores, credit coefficient, and insured power, a two-stage self-adaptive OPU method based on an adjustable load baseline is proposed. The proposed method improves the flexibility and fairness of the OPU compared with the traditional methods presented in [26] and [27].

3) Compared with [29] and [30], which focused only on economy, pollutant emission, carbon emission, credit coefficient, and green certificate, the insured power is further incorporated into the load baseline division method. Through this method, the effectiveness and applicability of the OPU are effectively enhanced.

TABLE I
COMPARATIVE TECHNICAL FEATURES OF SIMILAR RESEARCHES

Reference	Load adjustability	Number of baselines	Severe scenario	Interaction to grid	Factor					
					Economy	Pollutant emission	Carbon emission	Green certificate	Credit coefficient	Insured power
[16]-[19], [22]	×	1	×	×	√	×	×	×	×	×
[21], [25]	√	1	×	√	√	×	×	×	×	×
[23], [24], [26], [27]	×	1	×	√	√	×	×	×	×	×
[28]-[31]	×	1	×	×	√	√	×	×	×	×
This study	√	3	√	√	√	√	√	√	√	√

Note: √ and × indicate whether this item has been considered or not.

The remainder of this paper is organized as follows. Section II describes OPU principles and OPU architecture. Section III describes the load baseline division method for OPU. Section IV presents the NUPG OPU model based on load baseline. Section V discusses the case studies, and Section VI concludes the study.

II. OPU PRINCIPLES AND OPU ARCHITECTURE

We first present OPU principles with load as the main dispatch object and further propose an OPU architecture.

A. OPU Principles

In this study, a severe electricity shortage scenario refers to a power curtailment of more than 20% in the NUPG, as shown in Fig. 1, where EQBA, EQRA, and EPBA are short for electric quantity balance aggregator, electric quantity reserve aggregator, and electric power balance aggregator.
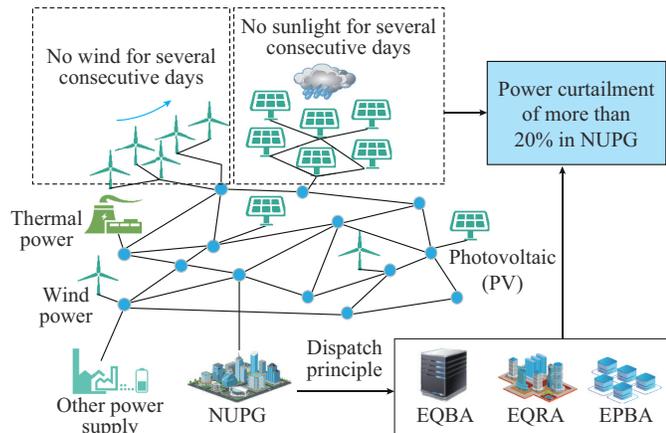

Fig. 1. Severe electricity shortage scenario.

The proposed OPU principles are summarized as follows.

Principle 1: large users are selected as primary participants in routine OPU. When these users complete a task, other users can refrain from participating to minimize their effects on social production and daily life.

Principle 2: small- and medium-sized users are selected as auxiliary participants in OPU and are responsible for completing the tasks that large users cannot perform.

Principle 3: power supply is ensured for critical civilian needs and public services essential for societal operations. Strict limitations are simultaneously imposed on the power consumption of certain commercial and entertainment loads during this specific period or under specific circumstances.

Principle 4: based on the public utility nature of public electric resources and the need to safeguard the electricity usage rights of all users, when OPU tasks for auxiliary users are determined, incorporating assessments of historical power usage behavior is advisable. In general, for auxiliary users with high historical load consumption and poor behavioral performance, they are recommended to take on a proportionately greater share of OPU tasks.

Electricity has significant effects on various aspects of societal production and daily life, particularly during severe electricity shortages.

First, to minimize the effects on societal production and daily life as much as possible, users with relatively higher loads are selected as primary participants (where the loads of these users are several times those of other users) to undertake regular OPU tasks. Within their capacity, other users do not need to participate, thereby reducing the number of households affected by electricity shortages. Therefore, Principle 1 is proposed.

Second, when primary participants are unable to fully complete the tasks, some users must assist them in completing the OPU tasks. Therefore, Principle 2 is proposed.

Third, during severe electricity shortages, the limited power supply should prioritize the electricity demands of essential users, including residential loads and public services crucial for societal operations, while restricting commercial and entertainment loads. Therefore, Principle 3 is proposed.

Fourth, based on the historical power usage behaviors of different users and the fact that electric power is a public resource, the limited power should be distributed based on the equal usage rights of various types of users. Auxiliary users with a history of higher power consumption and poor behavioral assessments must perform more tasks as deemed appropriate. Therefore, Principle 4 is proposed.

B. OPU Architecture

Deviating from the existing methods which focus on general electricity shortages, this study proposes an OPU architecture suitable for severe electricity shortages, as shown in

Supplementary Material A Fig. SA1. When a severe electricity shortage occurs on the power side, the large-scale power grid issues a load curtailment task to the NUPG dispatch and control center. First, the NUPG conducts independent energy storage for an OPU. Second, the EQBA is activated to undertake the remaining task. If the EQBA can complete the task, the EQRA does not need to participate. Third, if the EQBA cannot complete the task, the remaining tasks are performed using the EQRA. Fourth, the power fluctuations of the OPU are reduced using the EPBA. The contents of the EQBA, EQRA, and EPBA are as follows: ① the EQBA aggregates primary industrial and commercial users, whose loads account for a significant proportion but whose numbers are relatively small. The EQBA dispatches these users for routine participation in the OPU through a score mechanism and a multilevel load baseline; ② the EQRA aggregates auxiliary users whose load is lower but whose numbers are greater, excluding resident and guaranteed loads. The EQRA dispatches these users to participate in the OPU through the OSGA; and ③ the EPBA primarily controls flexible users, including electric vehicles and air conditioning units, to mitigate power fluctuations generated by the OPU through incentive pricing.

III. Load Baseline Division Method for OPU

We next propose flexible load baselines for the EQBA to improve OPU flexibility. The EQRA load baselines meet the requirements of goals of carbon peaking and carbon neutrality by considering the factors such as GDP, pollutant emission, carbon emissions, credit coefficient, and insured power.

A. Flexible Load Baselines of EQBA

1) Load Baseline for Independent Energy Storage

In the event of electricity shortages, EQBA prioritizes scheduling independent energy storage to participate in OPUs to mitigate the intermittency of renewable energy sources. The power provided by the independent energy storage is primarily used during periods of severe electricity shortage relative to the historical load, thereby mitigating the effects of renewable energy intermittency, as shown in regions A and B in Fig. 2. The available power can be determined for the user based on the predicted power and the power supplied by independent energy storage.
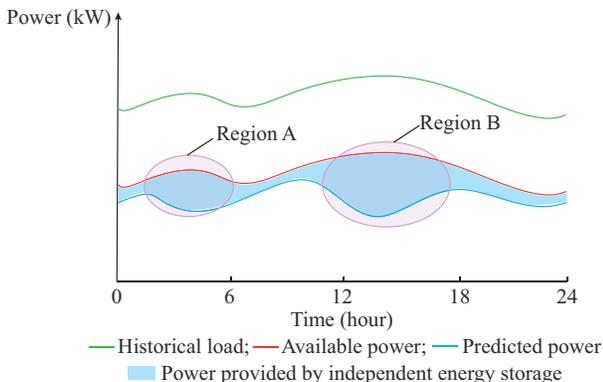

Fig. 2.   Principle of independent energy storage participating in OPU.

Accordingly, the load baseline model for independent energy storage is established in (1)-(4). This model minimizes the variance of B as the objective function in (1). The time interval is 15 min with 96 time slots. Equation (3) is a constraint [32] according to (1)-(3). $P'_n(t)$ for independent energy storage is computed in (4). In addition, n can arrange a power schedule based on $P'_n(t)$ to participate in the OPU, which can mitigate the intermittency of renewable energy sources.

$$\min \sum_{t=1}^{96}(B(t)-\bar{B})^2 \tag{1}$$

$$B(t)=P_N(t)-P_S(t) \tag{2}$$

$$\sum_{t=1}^{96}(P_S(t)-P_C(t))=\sum_{n=1}^{L}S_n \tag{3}$$

$$P'_n(t)=(P_S(t)-P_C(t))S_n\bigg/\sum_{n=1}^{L}S_n \tag{4}$$

EQBA then calculates the load baselines for large users based on the available power.

2) Flexible Load Baseline for Large Users

In contrast to the existing single-load-baseline method, this study establishes a flexible load baseline for users to adjust their load tasks. Taking industrial users as an example, the flexible load baseline of the EQBA is expressed by (5). The first-level load baseline is determined using $P_j^{I0}(t)$ to maintain user operations. The second-level load baseline is determined using the $P_j^{I0}(t)$, $P_j^{I1}(t)$, and γ, as indicated in (5). Similarly, the third-level load baseline is calculated using $P_j^{I0}(t)$, $P_j^{I1}(t)$, and τ, as expressed in (5). According to Principle 3, EQBA issues the command $\partial_j^b=1$ to entertainment loads during electricity shortages, and $P_j^b(t)$ for this type of user is zero, as expressed by (6).

$$P_j^I(t)=\begin{cases} P_j^{I0}(t) & \partial_j^I=1 \\ P_j^{I0}(t)+P_j^{I1}(t)\gamma & \partial_j^I=2 \\ P_j^{I0}(t)+P_j^{I1}(t)\tau & \partial_j^I=3 \\ 0<\gamma<\tau<1 \end{cases} \tag{5}$$

$$\begin{cases} P_j^b(t)=0 \\ \partial_j^b=1 \end{cases} \tag{6}$$

B. Load Baselines of EQRA

According to Principle 2, the load baselines of EQRA must be determined based on the remaining load curtailment tasks $\Delta P_J^I+\Delta P_J^b-P_S(t)$ of EQBA, as shown in Fig. 3.

$$P_i^{Ia}(t)=P_i^{I1}(t)-\Delta P_i^{Ix}(t) \tag{7}$$

$$\Delta P_i^{Ix}(t)=\Delta\vartheta_i^I(t)P_i^{I1}(t) \tag{8}$$

$$\Delta\vartheta_i^I(t)=c_x(P_i^{I1}(t)-P_i^{I0}(t))\bigg/\sum(P_i^{I1}(t)-P_i^{I0}(t)) \tag{9}$$

$$c_x=1-\frac{P_S(t)-P_a(t)}{P_N(t)-\Delta P_J^I-\sum_{j=1}^{N_l}P_j^{b1}(t)-P_a(t)} \tag{10}$$

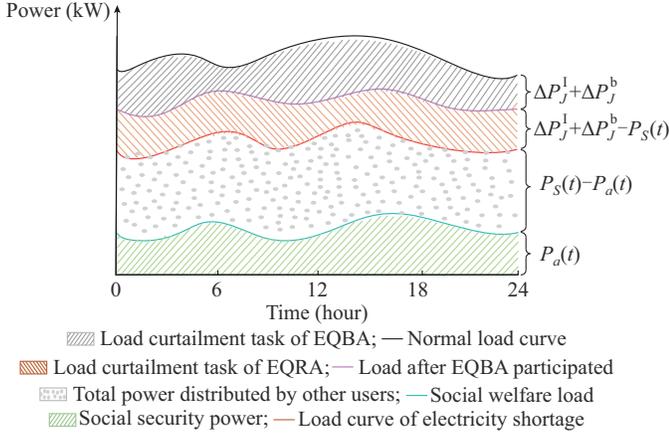Fig. 3.   OPU task allocation mechanism of NUPG.

$$\Delta P_J^I = \sum_{j=1}^{N_1} (P_j^{I1}(t) - P_j^I(t)) \tag{11}$$

$$\Delta P_J^b = \sum_{j=1}^{N_b} P_j^{b1}(t) \tag{12}$$

$$P_a(t) = P_v(t) + P_m(t) + \ell(t) \tag{13}$$

The greater the gap between $P_i^{I1}(t)$ and the guaranteed load $P_i^{I0}(t)$, the larger is the reduction coefficient. c_x in the EQRA is expressed by (10), which is calculated based on the tasks $\Delta P_J^I + \Delta P_J^b$ undertaken by the EQBA as well as the remaining total allocated load $P_S(t) - P_a(t)$ and $P_N(t)$. Equations (11) and (12) represent the total load reduction for ΔP_J^I and ΔP_J^b in the EQBA, respectively. The entertainment load can be segregated using user tags. $P_a(t)$ is calculated by (13).

Figure 4 can be used to illustrate the rationale behind Principles 3 and 4. After the EQBA participates in the OPU, if a 40% reduction in power is necessary, an EQRA should be dispatched to participate in the OPU. The livelihood load is 50 kW.
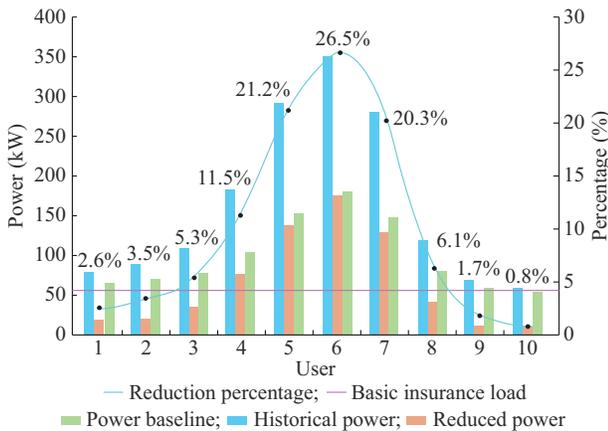

Fig. 4.   Load reduction ratio of each user.

First, users 1, 2, and 10 are used to justify Principle 3. The historical loads of users 1 and 10 are 30 kW and 45 kW, respectively, which are both less than the livelihood load of 50 kW. User 2 represents the public service load. Therefore, users 1, 2, and 10 do not need to undertake the load reduction task.

Second, users 6 and 9 are used to justify Principle 4, where their historical loads are 350 kW and 70 kW, respectively. According to (7)‑(13), the load reduction ratios are 26.5% and 1.7%, respectively. Given that the historical load of user 6 exceeds that of user 9, user 6 is assigned with more load reduction tasks.

1) OPU Allocation Principle of EQRA

According to Principles 2 and 4, several factors should be considered when assigning OPU tasks to EQRA auxiliary users [29], including economic, low-carbon, and environmental requirements. Therefore, to further refine Principles 2 and 4, this study establishes OPU rules that comprehensively consider GDP, pollutant emission, carbon emission, and credit coefficient.

Rule 1: more power is allocated to users with a higher GDP per unit of energy consumption to support economic development with a limited electricity supply.

Rule 2: more power is allocated to users with lower carbon emissions per unit of energy consumption to encourage green certificate purchases and to reduce carbon emissions.

Rule 3: more power is allocated to users with lower pollution indices per unit of energy consumption to promote electricity usage of renewable energy.

Rule 4: more power is allocated to users with higher credit coefficients to encourage them to abide by the load baseline, thereby reducing the balancing pressure on the NUPG.

2) EQRA Load Baseline Considering Social Factors

Based on the initial load baseline in (7) and combined with rules 1-4, we next propose an EQRA load baseline calculation method while considering social factors and calculate the load baselines for industrial, commercial, and residential users. $P_i^I(t)$ is calculated by (14), which considers η_i^I, φ_i^I, ε_i^I, θ_i^I, and $\ell_i^I(t)$. Insurance load refers to the load acquired by purchasing insurance. This parameter is designed to enhance OPU flexibility and ensure an uninterrupted power supply for users. Users can safeguard their power supply in the situations of electricity shortages by pre-purchasing insurance. The GDP index is calculated by (15). Carbon emissions are calculated by (16) according to the φ_i^{IM} and L_i^I of the previous month. Equation (17) calculates the pollution index, which is determined by w_i^{IM} in the previous month. w_i^{IM} is calculated by (18).

$$P_i^I(t) = P_i^{Ia}(t)\eta_i^I \varphi_i^I \varepsilon_i^I \theta_i^I + \ell_i^I(t) \tag{14}$$

$$\eta_i^I = 1 + (h_i^{IM}/P_i^{IM}) \Big/ \sum_{i=1}^M (h_i^{IM}/P_i^{IM}) - \frac{1}{M} \tag{15}$$

$$\varphi_i^I = 1 + \frac{1}{M} - \frac{(\varphi_i^{IM} - L_i^I k_L)/P_i^{IM}}{\sum_{i=1}^M [(\varphi_i^{IM} - L_i^I k_L)/P_i^{IM}]} \tag{16}$$

$$\varepsilon_i^I = 1 + \frac{1}{M} - (w_i^{IM}/P_i^{IM}) \Big/ \sum_{i=1}^M (w_i^{IM}/P_i^{IM}) \tag{17}$$

$$w_i^{IM} = k_q M_q + k_F M_F + k_s M_s \tag{18}$$

The calculation principles for $P_i^b(t)$ and $P_i^r(t)$ are similar to those for industrial users. The relevant research is beyond

the scope of this study but is a further research direction for future work.

IV. NUPG OPU MODEL BASED ON LOAD BASELINE

To minimize the effects on industrial production and daily lives of residents, this study establishes an EQBA to undertake routine OPU tasks, where an EQRA assists in handling the remaining tasks of EQBA, and an EPBA is used to smooth out the power fluctuations generated by OPU.

A. EQBA OPU Model Based on Scores

1) EQBA OPU Model for Independent Energy Storage

Independent energy storage that participates in OPU has a profit f_n calculated by (19).

$$f_n = \psi \int_0^{96} P_n^s(t)\mathrm{d}t - \xi \int_0^{96} (P_n'(t) - P_n^s(t))\mathrm{d}t \tag{19}$$

2) EQBA OPU Model for Large Users

We next construct an EQBA OPU model based on scores, which updates user ranking according to user performance scores from each OPU round. This prevents users from being selected after each round, thereby ensuring fairness.

When the primary user participates in OPU, it is ordered by the score matrix $\boldsymbol{P}_K^{F0}$. In this study, users with lower scores are selected as the initial loads to participate in OPU. Equation (20) calculates W between different OPU rounds, and (21) calculates the $\boldsymbol{P}_K^{F0}$ formulated in the previous round, where *ascend* denotes the matrix-sorting instruction from the smallest to the largest. The score matrix of the previous round is given by (21). Constraint (22) indicates that when the EQBA sends $ZL_{w(i)}^I$ to users, $P_{w(i)}^{IK}$ of the users must be greater than the task ΔP_K^J of EQBA k. $P_{w(i)}^{IK}$ is calculated by (23). The scores obtained at different load baseline levels are expressed by (24). Users can adjust the level to $\partial_{w(i)}^{I1}$ if they are unable to execute the instruction, and $P_{w(i)}^{IF2}$ is calculated by (25). To guarantee the performance of the loads in accomplishing the OPU task in the EQBA, this study stipulates that the first $ks/4$ users should not be allowed to adjust the load level, as shown in (25). $P_{w(i)}^{IF3}$ is calculated using (26) after the load level is adjusted. To enhance the OPU flexibility, users can exchange Ω_i^I by removing the score exchanged by user $w(i)$, $\Delta P_{w(i)}^{IF}$, according to (27). Following the exchange, the score is calculated using (28). $\boldsymbol{P}_{w(i)}^{IF0}$ is updated according to (29). Finally, due to the failure to provide power according to $P_{w(i)}^{I1}(t)$, the power supply should compensate $w(i)$ with $f_{w(i)}^{IS}$ according to (30).

$$W = sort(P_K^{F0}, 2, ascend) \tag{20}$$

$$\boldsymbol{P}_K^{F0} = [P_1^{IF0}, P_2^{IF0}, \ldots, P_{ks}^{IF0}] \tag{21}$$

$$\begin{cases} ZL_{w(i)}^I = \partial_{w(i)}^I \\ P_{w(i)}^{IK} \geq \Delta P_K^J \end{cases} \tag{22}$$

$$P_{w(i)}^{IK} = P_{w(i), \partial_{w(i)}^I}^{IK} + \sum P_{w(i-1), 1}^I \tag{23}$$

$$P_{w(i)}^{IF1} = \begin{cases} 3 & \partial_{w(i)}^I = 1 \\ 2 & \partial_{w(i)}^I = 2 \\ 1 & \partial_{w(i)}^I = 3 \end{cases} \tag{24}$$

$$P_{w(i)}^{IF2} = \partial_{w(i)}^I - \partial_{w(i)}^{I1} \quad i > ks/4 \tag{25}$$

$$P_{w(i)}^{IF3} = P_{w(i)}^{IF1} + P_{w(i)}^{IF2} \tag{26}$$

$$\Omega_i^I = \alpha_1 \Delta P_{w(i)}^{IF} \tag{27}$$

$$P_{w(i)}^{IF} = P_{w(i)}^{IF3} - \Delta P_{w(i)}^{IF} \tag{28}$$

$$P_{w(i)}^{IF0} = P_{w(i)}^{IF0} + P_{w(i)}^{IF} \tag{29}$$

$$f_{w(i)}^{IS} = \psi \int_0^{24} (P_{w(i)}^{I1}(t) - P_{w(i), \partial_{w(i)}^I}^I(t))\mathrm{d}t \tag{30}$$

B. EQRA OPU Model

We next construct an EQRA OPU model based on the OS-GA, which includes three parts: ① the interaction mechanism of the EQRA load baseline, in which the EQRA interacts with users through the OSGA and uniformly adjusts the load baseline levels of users to ensure the completion of the total task; ② the OPU trading model, in which EQRA calculates user benefits and costs based on user behavior; and ③ the OPU assessment mechanism, which involves constructing a credit coefficient to evaluate user performance and prevent user load from exceeding the load baseline.

1) Interaction Mechanism of EQRA Load Baseline

First, the EQRA assigns an initial load to the auxiliary users based on the remaining task and historical loads, as shown in Fig. 5. Second, users can request to adjust their loads if they cannot complete the task. Third, EQBA calculates the user baseline according to the contribution and stage excess loads, as expressed by (31)-(34).
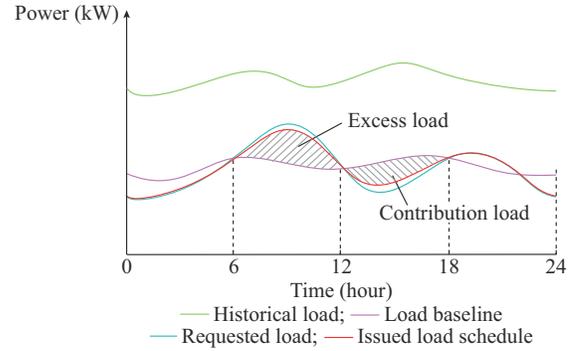

Fig. 5. Interaction process of OPU in EQRA.

$$\Delta P_i^{IG}(t) = P_i^I(t) - P_i^{IS}(t) \quad P_i^{IS}(t) \leq P_i^I(t) \tag{31}$$

$$\Delta P_i^{IC}(t) = P_i^{IS}(t) - P_i^I(t) \quad P_i^{IS}(t) > P_i^I(t) \tag{32}$$

$$\Delta P^G(t) = \sum_{i=1}^M \Delta P_i^{IG}(t) + \sum_{i=1}^N \Delta P_i^{bG}(t) + \sum_{i=1}^K \Delta P_i^{rG}(t) + \sum_{i=1}^O \Delta P_i^{OG}(t) \tag{33}$$

$$\Delta P^C(t) = \sum_{i=1}^M \Delta P_i^{IC}(t) + \sum_{i=1}^N \Delta P_i^{bC}(t) + \sum_{i=1}^K \Delta P_i^{rC}(t) \tag{34}$$

Taking industrial users as an example, users are regarded as having $\Delta P_i^{IG}(t)$ when $P_i^{IS}(t)$ is less than the load baseline, which is calculated by (31). Otherwise, users are regarded as having $\Delta P_i^{IC}(t)$, which is calculated by (32). $\Delta P^G(t)$ of the EQRA is calculated by (33). $\Delta P^C(t)$ of the EQRA is calculated by (34).

The EQRA uniformly allocates load schedules based on the calculation results of (33) and (34) and issues them to the users' OSGAs. The specific process is as follows: ① when $\Delta P^G(t) \leq \Delta P^C(t)$ and $P_i^{IS}(t) \geq P_i^I(t)$, the issued load schedule $P_i^{IX}(t)$ is calculated by (35), which allocates $\Delta P^G(t)$ according to the proportion of each user's excess volume; ② when $\Delta P^G(t) \leq \Delta P^C(t)$ and $P_i^{IS}(t) < P_i^I(t)$, $P_i^{IX}(t)$ is calculated by (36); ③ when $\Delta P^G(t) > \Delta P^C(t)$ and $P_i^{IS}(t) \geq P_i^I(t)$, the total contribution load is sufficient, and the EQRA releases the remaining load on the OSGA for users to obtain $\Delta P_i^{ly}(t)$, where the issued load schedule is calculated by (37); ④ when $\Delta P^G(t) > \Delta P^C(t)$ and $P_i^{IS}(t) < P_i^I(t)$, the $P_i^{IX}(t)$ is calculated by (38) for the purpose of effectively allocating $\Delta P^S(t)$ as calculated by (39). $\Delta P^y(t)$ in the EQRA is calculated by (40).

$$P_i^{IX}(t) = \Delta P^G(t) \cdot \Delta P_i^{IC}(t)/\Delta P^C(t) + P_i^I(t) \tag{35}$$

$$P_i^{IX}(t) = P_i^{IS}(t) \tag{36}$$

$$P_i^{IX}(t) = P_i^{IS}(t) + \Delta P_i^{ly}(t) \tag{37}$$

$$P_i^{IX}(t) = \Delta P^S(t) \Delta P_i^{IG}(t)/\Delta P^G(t) + P_i^{IS}(t) \tag{38}$$

$$\Delta P^S(t) = \Delta P^G(t) - \Delta P^C(t) - \Delta P^y(t) \tag{39}$$

$$\Delta P^y(t) = \sum_{i=1}^{M} \Delta P_i^{ly}(t) + \sum_{i=1}^{N} \Delta P_i^{by}(t) + \sum_{i=1}^{K} \Delta P_i^{ry}(t) + \sum_{i=1}^{O} \Delta P_i^{oy}(t) \tag{40}$$

2) OPU Trading Model

We next propose an OPU trading model to calculate the revenue from users' contribution load and the stage excess load cost. The model is composed of the stage excess load cost model and contribution load revenue model.

To guarantee the performance of the loads in accomplishing the OPU task in EQRA, an additional stage load purchase cost model is built to limit the additional high load and reduce the dispatch pressure on NUPG, as shown in (41)-(44).

$$f_i^{IC}(t, \Delta t) = \begin{cases} \xi \Delta t \Delta e_i^I(t) & 0 < \delta_i^I(t) \leq 10\% \\ \xi \Delta t \int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t \times 10\% + 1.5\xi \Delta t \left(\Delta e_i^I(t) - \right. \\ \left. 10\% \times \int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t \right) & 10\% < \delta_i^I(t) \leq 20\% \\ 2.5\xi \Delta t \int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t \times 10\% + 2\xi \Delta t \left(\Delta e_i^I(t) - \right. \\ \left. 20\% \times \int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t \right) & 20\% < \delta_i^I(t) \leq 30\% \\ 0 & \delta_i^I(t) > 30\% \end{cases} \tag{41}$$

$$\delta_i^I(t) = \int_t^{t+\Delta t} (P_i^{IX}(t) - P_i^I(t))\mathrm{d}t \bigg/ \int_t^{t+\Delta t} P_i^I(t)\,\mathrm{d}t \tag{42}$$

$$\Delta e_i^I(t) = \int_t^{t+\Delta t} (P_i^{IX}(t) - P_i^I(t))\mathrm{d}t \tag{43}$$

$$f^C(t) = \sum_{i=1}^{M} f_i^{IC}(t, \Delta t) + \sum_{i=1}^{N} f_i^{bC}(t, \Delta t) + \sum_{i=1}^{K} f_i^{rC}(t, \Delta t) + \sum_{i=1}^{O} f_i^{OC}(t, \Delta t) \tag{44}$$

The peak-shaving electricity price increases with an increase in the excess electricity. When the proportion of excess electricity exceeds 30%, the user enters the load restriction stage and is forced to reduce the load, as shown in Fig. 6.
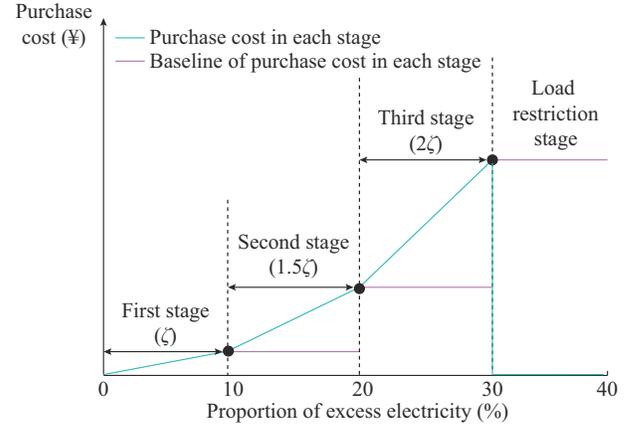

Fig. 6. Purchase cost of user.

$f_i^{IC}(t, \Delta t)$ is expressed by (41), which generates different costs according to the different proportions of $\delta_i^I(t)$, as calculated by (42). For example, when $10\% < \delta_i^I(t) \leq 20\%$, the peak-shaving electricity price is 1.5ξ. When $\delta_i^I(t) > 30\%$, it enters the load restriction stage, and the load is reduced. $\Delta e_i^I(t)$ is expressed by (43). $f^C(t)$ of EQRA is expressed by (44).

The contribution load revenue model based on various impact factors is expressed by (45)-(47). Due to the different loads of various users, the impact on users differs when the same load is applied. Thus, we construct $\beta_i^I(t, \Delta t)$ instead of the absolute contribution amount to calculate the revenue. The impact factor of industrial user i at time $(t, t+\Delta t)$ is calculated by (45). f_i^{IS} is calculated by (46). $\beta(t, \Delta t)$ of EQRA is expressed by (47).

$$\beta_i^I(t, \Delta t) = \frac{\Delta t \left(\int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t - \int_t^{t+\Delta t} P_i^{IS}(t)\mathrm{d}t \right)}{\int_t^{t+\Delta t} P_i^I(t)\mathrm{d}t} \tag{45}$$

$$f_i^{IS} = \sum \frac{\beta_i^I(t, \Delta t)}{\beta(t, \Delta t)} f^C(t) + \xi \int_0^{24} (P_i^{I1}(t) - P_i^{IX}(t))\mathrm{d}t \tag{46}$$

$$\beta(t, \Delta t) = \sum_{i=1}^{M} \beta_i^I(t, \Delta t) + \sum_{i=1}^{N} \beta_i^b(t, \Delta t) + \sum_{i=1}^{K} \beta_i^r(t, \Delta t) + \sum_{i=1}^{O} \beta_i^O(t, \Delta t) \tag{47}$$

3) OPU Assessment Mechanism

We next construct the credit coefficient θ_i^I to guarantee the performances of the auxiliary users and encourage the user to comply with the load schedule. Here, θ_i^I is calculated by (48), which is determined by the contribution load and T_g and by the stage excess load and T_c. When $P_i^{Ig}(t) > P_i^{IX}(t)$, the user is considered uncreditworthy. The greater the values of T_c and $P_i^{Ig}(t)$, the smaller the values of θ_i^I, while θ_i^I further reduces the load baseline of the user in the next OPU. Therefore, θ_i^I guarantees the performance of the auxiliary us-
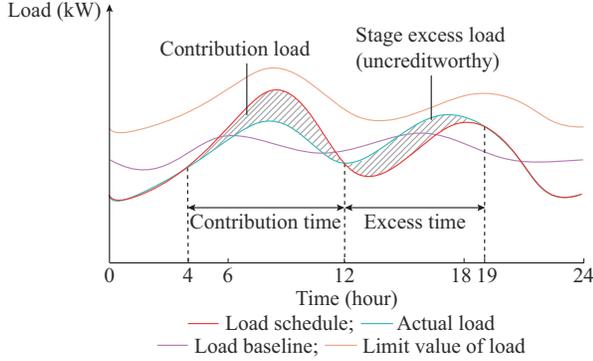
er, as shown in Fig. 7.

Fig. 7.   Actual contribution and stage excess loads of users.

To improve the OPU flexibility, users can exchange $\Delta\theta_i^{\mathrm{I}}$ for Ω_i^{I} according to (49) and (50).

$$\theta_i^{\mathrm{I}} = 1 - \frac{1}{2}\left(\frac{T_c - T_g}{96} + \frac{\int_0^{96} P_i^{\mathrm{Ig}}(t) - P_i^{\mathrm{IX}}(t)\mathrm{d}t}{\int_0^{96} P_i^{\mathrm{IX}}(t)\mathrm{d}t} \right) \tag{48}$$

$$\Omega_i^{\mathrm{I}} = \alpha_2 \Delta\theta_i^{\mathrm{I}} \tag{49}$$

$$\theta_i^{\mathrm{II}} = \theta_i^{\mathrm{I}} - \Delta\theta_i^{\mathrm{I}} \tag{50}$$

C. EPBA OPU Model

The EPBA primarily mitigates power fluctuations derived from untrustworthy users or inaccuracies in renewable energy forecasts during OPU. The EPBA OPU model is expressed as:

$$\Delta P^{\mathrm{up}}(t) = \begin{cases} \Delta P^{\mathrm{X}}(t) & 0 < \Delta P^{\mathrm{X}}(t) < \Delta P_{\mathrm{M}}^{\mathrm{up}}(t) \\ \Delta P_{\mathrm{M}}^{\mathrm{up}}(t) & \Delta P^{\mathrm{X}}(t) \geq \Delta P_{\mathrm{M}}^{\mathrm{up}}(t) \end{cases} \tag{51}$$

$$\Delta P^{\mathrm{dn}}(t) = \begin{cases} \Delta P^{\mathrm{X}}(t) & \Delta P_{\mathrm{M}}^{\mathrm{dn}}(t) < \Delta P^{\mathrm{X}}(t) < 0 \\ \Delta P_{\mathrm{M}}^{\mathrm{dn}}(t) & \Delta P^{\mathrm{X}}(t) \leq \Delta P_{\mathrm{M}}^{\mathrm{dn}}(t) \end{cases} \tag{52}$$

D. OPU Process in NUPG

In practical implementation of the proposed method, EQBA contracts with primary users and dispatches them through a score mechanism and multilevel load baseline. EQRA dispatches auxiliary users through OSGA, and EPBA dispatches users such as electric vehicles through incentive prices to ensure that OPU is effectively implemented in practice. NUPG allocates load curtailment tasks to each aggregator as follows.

1) After independent energy storage participates in OPU, NUPG issues OPU tasks to EQBA.

2) When the OPU task is beyond the scope of EQBA, NUPG assigns the remaining load curtailment tasks to EQRA. EQRA calculates the load curtailment tasks of auxiliary users based on the credit coefficient, exchange of electricity, pollution coefficient, GDP, and insurance load. The credit coefficient is calculated based on user behavior in the last OPU. Then, EQRA determines the load baseline of auxiliary users through the following setps: ① the initial load baseline is issued to auxiliary users; ② auxiliary users re-

quest an adjusted load from EQRA through the OSGA if they cannot complete the OPU task; and ③ EQRA comprehensively adjusts the load baseline through the interaction mechanism and then issues the load schedule to the auxiliary users' OSGA.

3) According to the actual load information from the smart meter, EQRA assesses the load behavior of auxiliary users using (41)-(44). If the total load of one auxiliary user exceeds the load limit, EQRA issues a command to the user's smart meter.

4) With the trading model, the actual contribution load, stage excess load, and credit coefficient of users are calculated, and the transaction results are issued to the OSGA.

5) The power fluctuations generated during the load curtailment process are smoothed out by the EPBA, as shown in Supplementary Material A Fig. SA2.

V. CASE STUDIES

To verify the effectiveness of this study in practical applications, an IEEE 39-bus system is modified to simulate the operating environment of the NUPG, with the proportion of renewable energy set to be 90%. Practical data from BY, SG, and SS wind farms in China are connected to Buses 32, 35, and 37, respectively. Buses 30, 33, 36, and 38 are converted into distributed wind and PV units [33]. To control all users connected to the buses, the loads are modified into load aggregators, as illustrated in Fig. 8. Load aggregators such as the EQBA, EQRA, and EPBA are grouped into commercial, industrial, residential, and public loads.
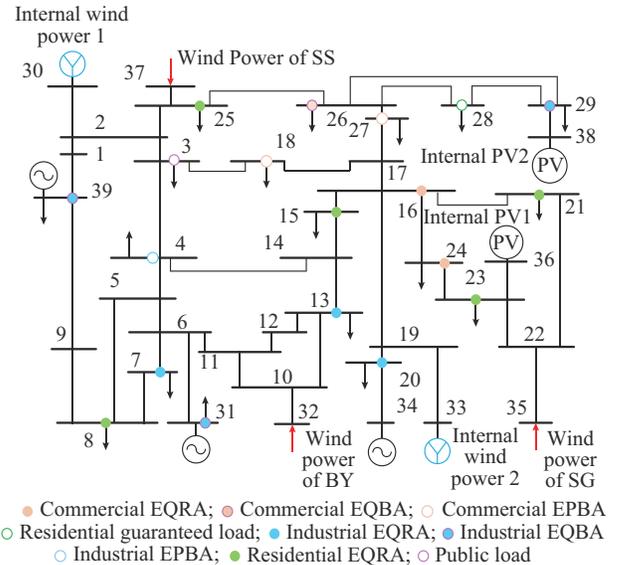

Fig. 8.   Modified IEEE 39-bus system.

Three simulation scenarios are defined to analyze the performance of the OPU method. Accordingly, scenario 1 assumes a 20% electricity shortage. The EQBA has an adequate load curtailment capacity, and the EQRA does not need to participate in the OPU. Thus, the task of electricity shortage is accomplished mainly by the EQBA OPU model based on the scores calculated by (24). To validate the effectiveness of the EQRA OPU model, a 40% electricity short-

age is assumed for scenario 2. The load curtailment capacity of the EQBA can complete only some of the OPU tasks, with the remaining tasks undertaken by the EQRA OPU model. To ensure the stable operation of the NUPG, scenario 3 smooths out the power fluctuations generated in scenario 2.

A. Scenario 1: 20% Electricity Shortage

The fairness of the score-based EQBA OPU model and the effectiveness of the flexible EQBA load baseline are verified. First, the effectiveness of the model in reducing the impact on societal power consumption is verified.

In this scenario, the EQBA first activates independent energy storage using (1)-(4), where the capacities and profits of the independent energy storage are listed in Table II.

TABLE II
CAPACITY AND PROFITS OF INDEPENDENT ENERGY STORAGE

Energy storage No.	Capacity (GWh)	Profit (¥)
1	3.10	1240000
2	3.53	1412000
3	2.81	1124000
4	3.01	1204000
5	2.68	1072000

Figure 9(a) shows the allocation of the independent energy storage capacities, where the maximum electricity shortage is reduced from 20% to 10.4%, effectively mitigating the effects of renewable energy intermittency. Figure 9(b) shows the power baselines for each independent energy storage. When the compensation is 400 ¥/MWh, the profits of each independent energy storage are calculated by (41), with the results listed in Table II.
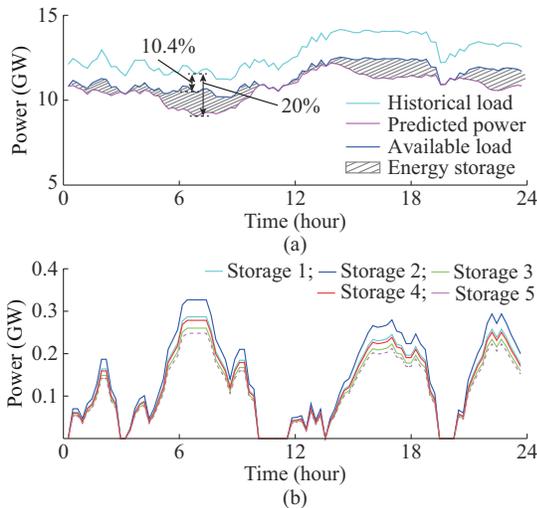

Fig. 9. Power of energy storage. (a) Allocation of energy storage capacity. (b) Power baseline for each independent energy storage.

Then, using the available load data, the NUPG allocates load curtailment tasks to each EQBA according to their loads. The NUPG contains EQBAs 26, 29, 31, and 39. Taking EQBA 31 as an example, the load curtailment task is allocated by (53). EQBA 31 controls eight industrial users.

The flexible load baselines for user 2 are shown in Fig. 10(a). When a user cannot complete the task as scheduled at point D, the task can be adjusted to the maximum of point B, resulting in an increase of 40% in task flexibility. By contrast, traditional methods have only one load baseline and cannot adjust tasks.
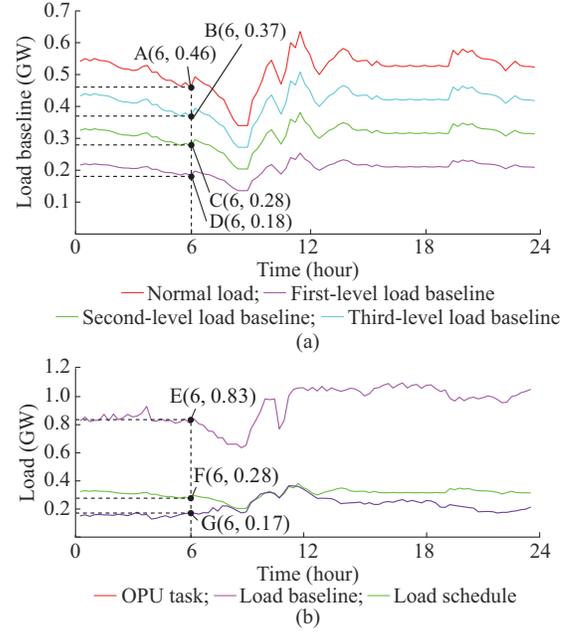

Fig. 10. Load of user 2. (a) Flexible load baseline. (b) Load curtailment task.

$$\Delta P_{31}^{J}(t) = \frac{P_{31}^{J}(t)}{P_{26}^{J}(t) + P_{29}^{J}(t) + P_{31}^{J}(t) + P_{39}^{J}(t)} \Delta P_{Z} \quad (53)$$

EQBA 31 arranges the eight industrial users in ascending order of their historical scores and issues initial instructions, as listed in Table III.

TABLE III
LOAD CURTAILMENT INSTRUCTION AND SCORE OF EACH USER

User No.	Instruction			Score		
	Traditional	Initial	Final	Historical	Current	Cumulative
8	2	1	1	1	3	4
2	2	1	1	2	3	5
7	2	1	1	3	3	6
4	2	1	2	6	1	7
5	2	1	3	8	2	10
6	2	0	0	9	0	9
1	2	0	0	10	0	10
3	2	0	0	11	0	11

According to the EQBA OPU model, if user 4 cannot meet baseline levels and requests adjustments, EQBA 31 modifies the baseline of user 5 to ensure that the task can be completed, where the final instructions are presented in Table III. Consequently, user 4 loses a score and user 5 gains one, where user scores for this round are listed in Table III. Users 4 and 7 have a 66.67% difference in scores in this round, reflecting their performance in the OPU and enhanc-

ing the OPU fairness. Based on the historical and round scores, the cumulative scores can be calculated to provide a basis for the next OPU, as shown in Table III. The final load curtailment task for user 2 is shown in Fig. 10(b).

When $k_1 = 100$ MWh, user 5 can trade 10 scores for 1000 MWh of power using (27), further enhancing the OPU flexibility.

Based on Table III, traditional methods issue instructions to all eight industrial users under EQBA 31, whereas this study provides instructions to only five industrial users according to Principle 1, as indicated in Table IV. Regarding the number of aggregators, the traditional methods require the participation of all 17 load aggregators, excluding resident guaranteed and public loads, as shown in Fig. 8. However, only four EQBAs are included in this study, as shown in Table IV. As Fig. 8 shows, the NUPG has 19 aggregators. The load impact of this study is 21.1% according to Principle 1, which is lower than those of traditional methods [23], demonstrating the rationality and effectiveness of Principle 1, as indicated in Table IV.

TABLE IV
IMPACT COEFFICIENT OF DIFFERENT METHODS

Method	Number of users in EQBA 31	Number of aggregators in NUPG	Impact coefficient (%)
Traditional	8	17	89.5
Proposed	5	4	21.1

B. Scenario 2: 40% Electricity Shortage

Under a 40% electricity shortage, the EQBA cannot undertake the full task due to its limited load curtailment capacity, and the EQRA takes on the remaining tasks. The NUPG allocates the remaining tasks to each EQRA in proportion to their respective loads by employing a principle similar to that in (53). The superiority of various methods proposed in the EQRA OPU model is validated.

1) Superiority of Load Baseline Interaction Mechanism

The effectiveness of the load baseline interaction mechanism and the effects of social factors on the EQRA load baseline are studied through the following five cases.

Case 1: the load baselines of each user in EQRA 20 are calculated by comprehensively considering GDP, pollutant emission, carbon emission, green certificate, credit coefficient, and insured power.

Case 2: the same as Case 1 but without GDP, pollutant emission, or carbon emission.

Case 3: the same as Case 1 but without green certificates.

Case 4: the same as Case 1 but without credit coefficient.

Case 5: the same as Case 1 but without insured power.

Table V lists the parameters for each user in EQRA 20. Cases 1 and 2 calculate the total GDP, pollutant emission, and carbon emission of EQRA 20 based on load baselines, where the results are listed in Table VI. Under Case 1, the GDP increases by 19.05%, pollutant emission decreases by 18.78%, and carbon emission decreases by 17.2% as compared with those under Case 2, thus validating the superiority and effectiveness of this study.

TABLE V
PARAMETERS FOR EACH USER IN EQRA 20

User No.	GDP (¥)	Pollutant emission (g)	Carbon emission (g)	Green certificate (g)	Credit coefficient	Insured power (MW)
1	13.2	3.44	0.92	20	0.70	10
2	19.9	3.39	0.91	30	1.00	0
3	23.4	0.94	0.86	0	0.85	10
4	25.1	3.76	0.88	40	0.91	0
5	27.4	1.64	0.83	10	1.00	10
6	28.2	3.38	0.78	0	0.95	10

TABLE VI
PARAMETERS UNDER DIFFERENT LOAD BASELINES

Baseline	GDP (¥)	Pollutant emission (kg)	Carbon emission (kg)
Case 1	218700	20880	6690
Case 2	183700	25710	8077

Under Cases 3-5, the load baseline of user 1 is shown in Fig. 11. User 1 purchases 20 g of green certificates under Case 1, resulting in a higher load baseline than that under Case 3. Under Case 4, the constraints of credit coefficient are ignored, resulting in a better outcome than that under Case 1 and hindering the completion of the OPU task. Under Case 5, the insured power is ignored, but under Case 1, 10 MW of insured power is purchased, resulting in a higher baseline power than that under Case 5. As demonstrated in Cases 3-5, the proposed method enables users to adjust their load baselines by purchasing green certificates and insured power while complying with credit coefficient, further enhancing the OPU flexibility.
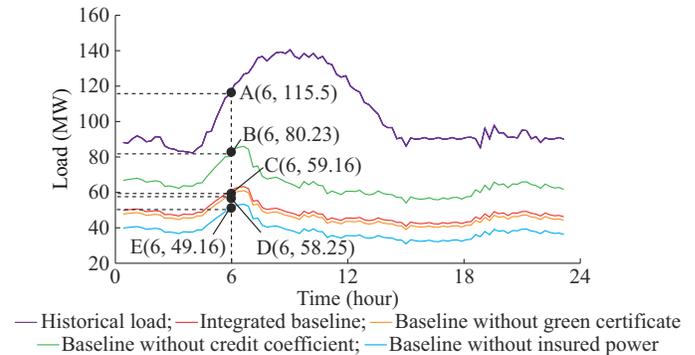

Fig. 11. Influence of different factors on load baseline of EQRA.

To further illustrate the flexibility and effectiveness of the load baseline interaction mechanism, the formation process of the load schedule in EQRA 20 is analyzed, as shown in Fig. 12. As $\Delta P^G(t) > \Delta P^C(t)$ at the 6th hour, users can compete for power based on their unique situations. User 1 purchases 10 MW of power, which changes the load baseline from 63 MW to 73 MW, and the load baseline increases by 15.87%, as shown in Table VII. This further enhances the OPU flexibility.
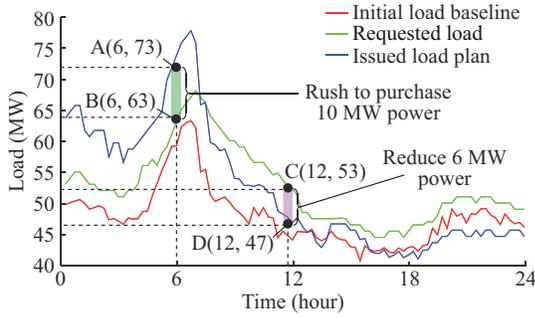
Fig. 12.　Formation process of load schedule in EQRA 20.

ty of the OPU trading model.

Fig. 13.　Actual power consumption curve of user 1.

As $\Delta P^G(t) \leq \Delta P^C(t)$ at the 12th hour, EQRA 20 must redistribute power, and the load baselines for users 1, 3, and 4 are reduced by 6 MW, 7.6 MW, and 6.8 MW, respectively, according to (35) and (36), as shown in Table VIII. This effectively guarantees that the EQRA completes its tasks.

TABLE VII
SCHEDULING WHEN CONTRIBUTION LOAD EXCEEDS STAGE EXCESS LOAD

User No.	Requested load (MW)	Purchased load (MW)	Load schedule (MW)
1	63.0	10.0	73.0
2	49.8	0.0	49.8
3	85.2	4.8	90.0
4	65.4	0.0	65.4
5	100.0	0.0	100.0
6	112.0	7.0	119.0

TABLE VIII
SCHEDULING THE CONTRIBUTION LOAD IS LESS THAN STAGE EXCESS LOAD

User No.	Initial baseline (MW)	Requested load (MW)	Reduced load (MW)	Load schedule (MW)
1	44.8	52.6	6.0	46.6
2	59.3	39.3	0.0	39.3
3	57.9	68.4	7.6	60.8
4	47.5	61.3	6.8	54.5
5	71.2	71.2	0.0	71.2
6	64.3	64.3	0.0	64.3

2) Superiority of OPU Trading Model

Taking EQRA 20 as an example, the actual load of user 1 in EQRA 20 is shown in Fig. 13. Based on the assumption that $\psi = 600$ ¥/MW, users 1 and 4 exceed their loads by 2 MW and 6.62 MW at the 6th hour, resulting in excess load costs of ¥300 and ¥900, as calculated by (41). Users 2 and 6 contribute 2.8 MW and 4 MW of power at the 6th hour, and their benefits are derived from the excess load costs of users 1 and 4, as shown in Table IV. Assume that the industrial electricity cost and power compensation fee are 1000 ¥/MW and 400 ¥/MW, respectively. Accordingly, the daily total costs and benefits for EQRA 20 are calculated (Case A) without tiered excess load costs or contribution load revenue (Case B), as shown in Table X. The electricity cost in Case A is less than that in Case B, with the maximum electricity cost savings reaching 87%, thus demonstrating the superiori-

TABLE IV
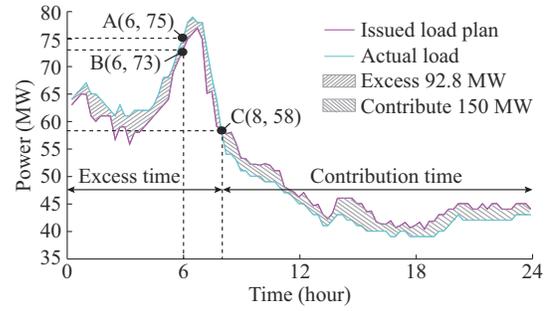EXCESS LOAD COST AND POWER SAVING INCOME OF USERS AT THE 6TH HOUR

User No.	Excess load (MW)	Average cost (¥)	Affected coefficient	Income (¥)
1	2.00	300	0	0
2	−2.80	0	0.056	813
3	0.00	0	0	0
4	6.62	999	0	0
5	0.00	0	0	0
6	−4.00	0	0.034	486

TABLE X
TOTAL ELECTRICITY COST AND INCOME OF EACH USER

User No.	Total stage excess load cost (10^4¥)	Total income (10^4¥)	Total power compensation fee (10^4¥)	Electricity cost for Case A (10^4¥)	Electricity cost for Case B (10^4¥)
1	1.4	2.8	50.6	71.0	123
2	1.4	3.4	82.6	12.4	97
3	1.3	1.6	23.1	134.6	158
4	7.3	1.7	39.6	125.0	159
5	3.9	0.1	26.0	185.8	208
6	0.8	6.5	38.4	138.9	183

3) Effectiveness of OPU Assessment Mechanism

Take EQRA 20 as an example, the credit coefficients for each user are calculated using (48) and are listed in Table XI. Users 1-3 and 6 comply with the credit guidelines and receive credit coefficients, whereas users 4 and 5 do not adhere to the credit rules and loose their credit coefficients. The composite credit coefficients for users 4 and 6 differ by a maximum of 41.7%. User performance in the OPU is quantified using composite credit coefficients to determine the next OPU load baseline, demonstrating the fairness and effectiveness of Principle 4. In addition, this mechanism can encourage users to comply with credit and prevent excessive power usage, thus validating the effectiveness of this study.

Users can trade credit coefficients for a certain amount of electricity. For example, when $k_2 = 1000$ MWh, user 6 can trade 0.2 credit coefficients for 500 MWh of electricity through (49). This further enhances the OPU flexibility.

TABLE XI
CREDIT COEFFICIENT OF EACH USER IN OPU

User No.	Time credit	Electricity credit	Comprehensive credit
1	0.33	0.01	1.170
2	0.19	0.01	1.100
3	0.19	0.01	1.100
4	−0.51	−0.05	0.720
5	−0.42	−0.03	0.775
6	0.41	0.06	1.235

4) Less Impact on User Power Consumption

The impact of user power consumption is calculated based on the load curtailment and historical load. The results for the user in EQRA 20 are listed, as shown in Table XII. The impact of the average allocation method is 46%, and the average impact of this study is 28.3% according to Principle 2. This study has a smaller impact on users as compared with the traditional method, demonstrating the rationality and effectiveness of Principle 2.

TABLE XII
IMPACT ON USER POWER CONSUMPTION

User No.	User power consumption	
	Average allocation method (%)	This study (%)
1	46	35
2	46	70
3	46	1
4	46	22
5	46	18
6	46	24

C. Scenario 3: Smooth Power Fluctuations in Severe Electricity Shortages

We next verify the effectiveness of the EPBA OPU model in mitigating power fluctuations in a 40% electricity shortage. EPBAs 4, 18, and 27 address fluctuations derived from user defaults or prediction errors using (51) and (52), as shown in Fig. 14. The EPBA model reduces fluctuations from −270 MW and 285 MW to −42 MW and 32 MW, which greatly alleviates the power balancing pressure on the NUPG and illustrates the effectiveness of the EPBA OPU model.
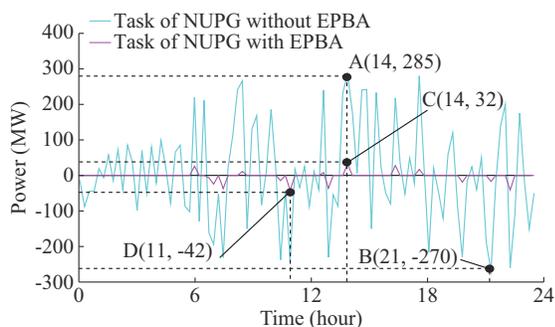

Fig. 14. Power balance tasks of NUPG.

VI. CONCLUSION

This study proposes a novel OPU method for an NUPG to address severe electricity shortages. The proposed method can minimize the effects on users while improving the flexibility, effectiveness, and fairness of OPU. The main conclusions of this study are summarized as follows.

1) The proposed method can reduce the effects on social production and daily life. The results indicate that the EQBA OPU model can decrease the effects from 89.5% to 21.5%, whereas the EQRA OPU model can reduce the effects from 46% to 28.3%.

2) The flexible load baselines of the EQBA provide multiple baselines for users to adjust their loads, and the maximum load adjustment increases by 40%. The EQRA OPU model enables users to adjust their power consumption schedules, and the adjustable power consumption increases by 15.87%.

3) The EQBA OPU model maintains fairness through score-based user participation adjustments, whereas the EQRA updates the next load baseline through credit, ensuring fairness. Therefore, addressing these disparities in terms of fairness is crucial.

4) The EQRA load baseline, which considers social factors and enhances the effectiveness of OPU. The results indicate that this study can increase GDP by 19.05% and reduce pollutant and carbon emissions by 18.78% and 17.2%, respectively.

Due to the high cost of energy storage and insufficient suitable energy to offset declining thermal power, load management has become a vital solution for large power systems. With the development of technology and new resources, more solutions will become available to address the problem of electricity shortages. In a future work, we will consider emergencies involving electricity shortages and study the effects of electricity shortages on transmission networks to improve the effectiveness of OPUs.

REFERENCES

[1] B. Lin and Z. Li, "Towards world's low carbon development: the role of clean energy," *Applied Energy*, vol. 307, no. 1, p. 118160, Feb. 2022.

[2] Y. Zhang, Y. Han, D. Liu *et al.*, "Low-carbon economic dispatch of electricity-heat-gas integrated energy systems based on deep reinforcement learning," *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 6, pp. 1827-1841, Nov. 2023.

[3] S. Mallapaty, "How China could be carbon neutral by mid-century," *Nature*, vol. 586, pp. 482-483, Oct. 2020.

[4] R. Zhang and J. Yu, "Capacity evaluation of electric bus load participating in peak shaving of new urban power grid," *Proceedings of the CSEE*, vol. 42, no. S1, pp. 82-94, Aug. 2022.

[5] Q. Wang, C. Miao, and Y. Tang, "Power shortage support strategies considering unified gas-thermal inertia in an integrated energy system," *Applied Energy*, vol. 328, no. 15, p. 120229, Dec. 2022.

[6] S. Lain and P. Stefan, "The increasing impact of weather on electricity supply and demand," *Energy*, vol. 145, no. 15, pp. 65-78, Feb. 2018.

[7] Z. Ni, Y. Li, L. Dong *et al.*, "Evaluation of the exit sequence of thermal power in the transformation of full clean energy generation," in *Proceedings of 2020 4th International Conference on HVDC*, Xi'an, China, Dec. 2020, pp. 398-403.

[8] S. Kosai and H. Unesaki, "Short-term vs long-term reliance: development of a novel approach for diversity of fuels for electricity in energy security," *Applied Energy*, vol. 262, no. 15, p. 114520, Mar. 2020.

[9] M. A. Paim, A. R. Dalmarco, C. H. Yang *et al.*, "Evaluating regulatory strategies for mitigating hydrological risk in Brazil through diversifi-

cation of its electricity mix," *Energy Policy*, vol. 128, pp. 393-401, May 2019.

[10] J. Li, G. Li, S. Ma *et al*., "Modeling and simulation of hydrogen energy storage system for power-to-gas and gas-to-power systems," *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 3, pp. 885-895, May 2023.

[11] A. R. A and L. Hughes, "Energy security and the diversity of energy flows in an energy system," *Energy*, vol. 73, no. 14, pp. 137-144, Aug. 2014.

[12] Y. Chen, "Addressing uncertainties through improved reserve product design," *IEEE Transactions on Power Systems*, vol. 38, no. 4, pp. 3911-3923, Jul. 2023.

[13] A. Blakers, B. Lu, and M. Stocks, "100% renewable electricity in Australia," *Energy*, vol. 133, no. 15, pp. 471-482, Aug. 2017.

[14] Y. Liu, Q. Ma, Z. Wang *et al*., "Cogitation on power and electricity balance dispatching in new power system," *Proceedings of the CSEE*, vol. 43, no. 5, pp. 1694-1705, Mar. 2023.

[15] H. C. Gils, Y. Scholz, T. Pregger *et al*., "Integrated modelling of variable renewable energy-based power supply in Europe," *Energy*, vol. 123, no. 15, pp. 173-188, Mar. 2017.

[16] S. Li, C. Gu, X. Zeng *et al*., "Vehicle-to-grid management for multi-time scale grid power balancing," *Energy*, vol. 234, no. 1, p. 121201, Nov. 2021.

[17] Y. Tao, M. Huang, Y. Chen *et al*., "Orderly charging strategy of battery electric vehicle driven by real-world driving data," *Energy*, vol. 193, no. 15, p. 116806, Feb. 2020.

[18] H. Hou, M. Xue, Y. Xu *et al*., "Multi-objective economic dispatch of a microgrid considering electric vehicle and transferable load," *Applied Energy*, vol. 262, no. 15, p. 114489, Mar. 2020.

[19] M. Yu and S. Hong, "Supply-demand balancing for power management in smart grid: a Stackelberg game approach," *Applied Energy*, vol. 164, no. 15, pp. 702-710, Feb. 2016.

[20] W. Zou, Y. Sun, D. Gao *et al*., "A review on integration of surging plug-in electric vehicles charging in energy-flexible buildings: impacts analysis, collaborative management technologies, and future perspective," *Applied Energy*, vol. 331, no. 1, p. 120393, Feb. 2023.

[21] R. Zhang, J. Yu, Y. Tang *et al*., "Capacity evaluation of central air conditioning load participating in peak shaving of renewable dominated power systems," *IET Generation, Transmission & Distribution*, vol. 17, no.1, pp. 181-199, Jan. 2022.

[22] A. Clerjon and F. Perdu, "Matching intermittent electricity supply and demand with electricity storage-an optimization based on a time scale analysis," *Energy*, vol. 241, no. 15, p. 122799, Feb. 2022.

[23] Q. Chen, X. Shan, J. Luo *et al*., "Source-grid-load coordinated control strategy and its application under UHVDC faults," *Automation of Electric Power Systems*, vol. 41, no. 5, pp. 147-152, Mar. 2017.

[24] H. Liu, C. Wang, P. Ju *et al*., "A bi-level coordinated dispatch strategy for enhancing resilience of electricity-gas system considering virtual power plants," *International Journal of Electrical Power & Energy Systems*, vol. 147, p. 108787, May 2023.

[25] Y. Wang, J. Ding, S. Tian *et al*., "An orderly power utilization mode based on intelligent multi-agent apanage management system," *Power System Technology*, vol. 43, no. 5, pp. 1802-1809, May 2019.

[26] Q. Yan, X. Tong, N. Zhang *et al*., "A dynamic multi-level temporal and spatial coordination method for orderly power utilization based on customer load curtailment cost characteristics," *Power System Technology*, vol. 40, no. 2, pp. 425-432, Feb. 2016.

[27] H. Zhong, Q. Xia, M. Huang *et al*., "A pattern and method of orderly power utilization considering transmission loss reduction and congestion elimination," *Power System Technology*, vol. 37, no. 7, pp. 1915-1921, Jul. 2013.

[28] Z. Ye, "Research on orderly power consumption method of power users based on demand side management," M. S. thesis, Department of Electronic Engineering, Nanchang University, Nanchang, China, 2022.

[29] Q. Xu, Y. Ding, Q. Yan *et al*., "Research on evaluation of scheduling potentials and values on large consumers," *Proceedings of the CSEE*, vol. 37, no. 23, pp. 6791-6800, Dec. 2017.

[30] W. Wang, "Power supply enterprise for electricity power limitation of sequence optimization research," M. S. thesis, Department of Business Administration, North China Electric Power University, Beijing, China, 2009.

[31] W. Zhang, "The study of orderly power utility analysis, evaluation and optimization model of electricity customers," Ph. D. dissertation, Department of Economics and Management, North China Electric Power University, Beijing, China, 2016.

[32] V. Dao, H. Ishii, Y. Takenobu *et al*., "Intensive quadratic programming approach for home energy management systems with power utility requirements," *International Journal of Electrical Power & Energy Systems*, vol. 115, p.105473, Aug. 2020.

[33] R. Zhang and J. Yu, "External tie line power fluctuations smoothing strategy of new urban power grid," *International Journal of Electrical Power & Energy Systems*, vol. 153, p. 109289, Jun. 2023.

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