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Capacity Allocation Method of Pumped-Storage Power Station for Multi-Level Market in New Power System

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Abstract: With the development of the electricity spot market, pumped-storage power stations are faced with the problem of realizing flexible adjustment capabilities and limited profit margins under the current two-part electricity price system. At the same time, the penetration rate of new energy has increased. Its uncertainty has brought great pressure to the operation of the power system. The ramp market and its market mechanism have emerged as the times require. To this end, this article proposes a bidding strategy for pumped-storage power stations to participate in multi-level markets such as the ramp market. Considering the demand calculation of ramping services, a two-layer model of pumped storage's participation in multiple markets is constructed. The upper level makes trading decisions with the goal of maximizing pumped-storage revenue; the lower level aims to minimize the total social cost and jointly clears the primary and auxiliary markets. The income from pumped storage participating in the main energy and ramp-up auxiliary markets at the same time is significantly higher than the income from the two-part electricity price system. Its flexible adjustment ability can be quantified, reducing dependence on capacity electricity charges and providing a theoretical reference for cost recovery and profitability of future pumped-storage power stations.

Keywords: pumped storage; ramp service; new ancillary services; market mechanism; two-part electricity price

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1. Introduction

At present, China is committed to building a high-proportion renewable energy power system. The proportion of new-energy power generation on the power supply side is becoming higher and higher. However, new-energy power generation is highly volatile and uncertain. New energy systems put forward higher requirements for the stable operation of power systems. Currently, market-based auxiliary services in various provinces in China—introduced to cope with a lack of flexible system adjustment capabilities—are subjected to frequency modulation and peak shaving [1–3], but the response time of frequency modulation is short, which requires high-frequency modulation performance from providers. However, peak modulation cannot be applied to address the lack of system flexibility. It is increasingly difficult for the existing ancillary service market to adapt to the flexible adjustment needs of the system. In recent years, ramp-up, as a new type of auxiliary service transaction, has attracted widespread attention from various countries. Its purpose is to encourage market members to reserve enough flexible adjustment service space for the system during a given period to ensure that adjustable outputs can meet load-changing requirements during subsequent time periods to ensure the real-time balance of the system. As pieces of large-scale energy storage equipment, pumped-storage power stations can play roles in peak shaving and valley filling, and they have the natural advantage of peak adjustment. At the same time, pumped storage can start quickly and has flexible ramping, and it can provide various auxiliary service functions such as frequency regulation and ramping for the system. It is an important way to improve the flexibility, economy, and safety of the power system [4].

Many scholars have studied and calculated the electricity price mechanism and benefits of pumped-storage power stations based on the two-part electricity price proposed in Document No. 633 and its corresponding settlement mechanism and cost-sharing method [5,6]. However, at this time, the power grid is responsible for the operation and dispatch of pumped-storage power stations, and the pumped-storage output curve is artificially controlled; thus, it cannot achieve coordinated operation and refined management with conventional units and is affected by the development of the spot market. Pumped-hydro-energy storage should be further promoted to participate in the market as an independent market entity to obtain benefits. The participation of pumped hydro-energy in the primary energy and ancillary service market has been studied in the literature. Reference [7] compared the frequency modulation performance of energy storage systems such as pumped storage and thermal power units and concluded that pumped-storage frequency modulation has the advantages of fast response and high stability. References [8,9] describe the cooperative optimization operation strategy of pumped-storage units participating in the electric energy market and different ancillary service markets. Reference [10] further studied an operation-planning model of variable-speed pumped-hydro-energy storage participating in the day-ahead energy market and frequency regulation market. Reference [11] established a risk–return model for pumped-storage power stations participating in the main energy market and backup auxiliary service market and analyzed power station income under different pricing mechanisms. Reference [12] summarizes the clearing mechanism of spot electric energy and frequency modulation ancillary service markets in current typical domestic and foreign markets. At the same time, a mathematical model including sequential clearing and joint clearing of the spot electric energy market and frequency regulation ancillary service market of pumped-storage power stations was also proposed. Reference [13] constructed a model in which multiple types of power sources, including wind, solar, water, and fire, participated in the frequency modulation market. It used the sequential bidding model and the marginal price-clearing method to analyze the impact of multiple types of power sources participating in frequency modulation on the frequency modulation performance of the system. Reference [14] points out that an energy storage method such as pumped storage has the advantages of fast charging and discharging speed, strong unit start–stop ability, and bidirectional adjustment. Pumped-storage units can be used as a flexible ramping resource and can be reasonably configured according to system needs. Reference [15] studied the flexibility advantages of five different pumped-storage units in a regional energy system, which can provide a reference for selecting pumped-storage units to enter the ramp-up auxiliary service market. References [16,17] studies the automatic power generation control strategy and clearing mechanism of energy storage participating in day-ahead and real-time markets. Right now, there are relatively few studies on the participation of pumped-storage units in the ramp-up auxiliary service market, and the issue of capacity allocation of pumped-storage units participating in the main energy and auxiliary service markets as independent markets needs to be studied.

Currently, scholars are conducting the following research on the relationship between the main energy market and the auxiliary service market and the clearing sequence: Reference [18] analyzes the impact of traditional unit combination models on flexible resource utilization efficiency, incorporates ramp variables into decision-making variables, and constructs a joint clearing model for the day-ahead market of electric energy and various ancillary services. It realizes the joint clearing of different trading varieties. Reference [19] points out that flexible ramping does not require quotations from market entities, and its price is essentially the opportunity cost lost by the unit in providing ramping services. A two-layer model for joint optimization of main energy and ramp-up was established. Reference [20] established a ramping demand curve calculation model with different demand elasticities and designed three ramping and electric energy market joint clearing models that consider different ramping demand elasticities. Literature [21] proposes a ramping capacity verification mechanism for coupling flexible ramping auxiliary services and the electric energy market, and builds a clearing model for joint operation of spot electric energy and auxiliary services. Literature [22] established a joint clearing model of the day-ahead electric energy market and the deep peaking service market. Literature [23] proposed a day-ahead electric energy-reserve joint clearing model with wind power participation. Literature [24] established a joint optimization model including primary frequency regulation services, and proposed a joint clearing and coordination mechanism between the spot electric energy market including energy storage and the primary frequency regulation auxiliary service market. Literature [25] considers the relationship between reserve and electric energy and the market development stage and establishes a clearing model for independent operation and joint operation of the reserve market. The above literature lacks research on the mechanism of pumped hydro energy storage participating in the joint clearing of primary energy and multiple ancillary service markets. With the gradual acceleration of the construction process of my country's electricity market, the varieties of ancillary service markets are becoming more and more abundant, and it is necessary to conduct research on the clearing model of pumped storage power stations as a variety of market entities.

This article starts from the electricity spot market mechanism that includes flexible adjustment of variety ramp-up auxiliary services, combined with the electricity price mechanism of pumped storage power stations. Conduct research on future market participation plans and profitability of pumped storage power stations, then a pumped storage power station is proposed as an independent entity to participate in the bidding and clearing settlement rules of the main energy market, ramping market, frequency regulation and backup market at the same time. Considering the demand calculation of the new auxiliary service of climbing, a two-layer model for pumped hydro energy storage to participate in multiple markets is constructed. The upper level makes trading decisions with the goal of maximizing pumped storage revenue, the lower level aims to minimize the total social cost and jointly clears the primary and auxiliary markets. The simulation results of the calculation example prove that the income of pumped hydro energy storage using the bidding strategy proposed in this article and participating in the main energy and auxiliary markets such as ramping is significantly higher than the income of the two-part electricity price. Its flexible adjustment ability can be quantified, reducing dependence on capacity electricity charges, and providing a theoretical reference for cost recovery and profitability of future pumped storage power stations.

2. Participate in the Design of the Capacity Allocation Framework of Pumped Storage Units in the Multi-Level Market

2.1. Pumped Storage Units Participate in Market Competition

The electricity price mechanism of pumped storage power stations has gone through several stages of reform and development, and now most of them adopt a two-part electricity price system. That is to say, the electricity participates in the market to obtain the electricity price, and the capacity part is compensated for the pumped storage energy according to the calculated capacity electricity price. Due to the inconsistent development level of the domestic spot market, there is no unified pricing mechanism for pumped storage power stations. Pumped storage power stations have not fully entered the market, and the services they provide are mostly in the form of compensation, which limits their role and cannot fully reflect their economic benefits. As the market develops and matures, the market mechanism will also change further. At the same time, complete market rules for ancillary services such as ramping, frequency modulation, and backup will be formulated. This article assumes that the market has developed to a certain stage and pumped storage power stations, as independent entities, participate in the competition in the primary and auxiliary markets to obtain benefits. Entities allowed to participate in the market include conventional thermal power units, pumped storage power stations and power users. When quoting, thermal power units make 24-h quotations based on power generation costs. Among them, the electric energy market adopts a full power bidding model. The power generation side reports the quotation, and the user side only reports the quantity. The load demand is matched with the power generation resources of the power generator, and a day-ahead electric energy trading plan is formed through clearing. The ramping market determines the daily ramping demand based on the net load curve. The power generation side declares ramping capacity based on its own willingness to provide ramping auxiliary services. The ramping price represents the opportunity cost paid by the unit to provide ramping services. The frequency regulation market obtains the bid-winning capacity of each unit based on the daily frequency regulation demand, clear the frequency regulation capacity electricity price and frequency regulation mileage electricity price. The former is the capacity price considering the opportunity cost, and the latter is the reflection of the frequency modulation effect, without considering the up and down frequency modulation. The spare market is cleared to obtain the unit's bid capacity and spare capacity price. When clearing the market, the electric energy market and the ramping, frequency regulation and reserve markets jointly optimize the clearing, and determine the schedule for the next day. The overall structure of pumped storage unit participation in the market is shown as Figure 1.

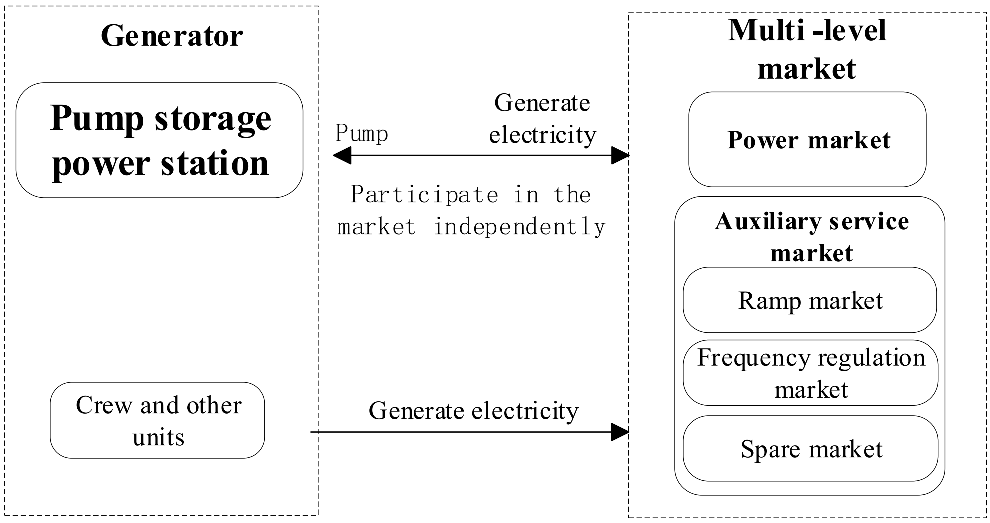

Figure 1. Overall structure of pumped storage unit participation in the market.

2.2. Double-Layer Model Structure of Pumped Storage Unit Capacity Allocation

In a competitive market, the decisions of various market entities restrict each other and affect the formation of market clearing results. Market entities focus on their own benefits and use appropriate bidding strategies to maximize their own returns. This article studies how pumped storage power stations can participate in the market and make profits. The quotation of pumped storage units must take into account the quotation strategies of other units and the results of market clearing by the trading center. When the market clears, the dispatch results are determined based on the response of each unit to maximize social welfare.

This creates a two-layer model, as shown in Figure 2. First of all, it is necessary to calculate the demand for ramping capacity in the ramping market, including deterministic demand and uncertain demand. Then, consider the market demand to allocate capacity to pumped hydro energy storage. Among them, the upper model is the transaction decision-making model of pumped storage units, allocate capacity to pumped storage power stations with the goal of maximizing profits. Consider the marginal cost of generating electricity or providing ancillary services and the trading strategy for mobile phone sets, quote and participate in the main and auxiliary markets, and implement optimization analysis based on the clearing price predictions of the main and auxiliary markets. The lower-level model is a joint clearing model of the primary and auxiliary markets based on market member quotations, with the goal of minimizing the total social cost. Implement optimal clearing based on market member quotes considering security constraints. Achieve market equilibrium through repeated iterations between upper and lower models.

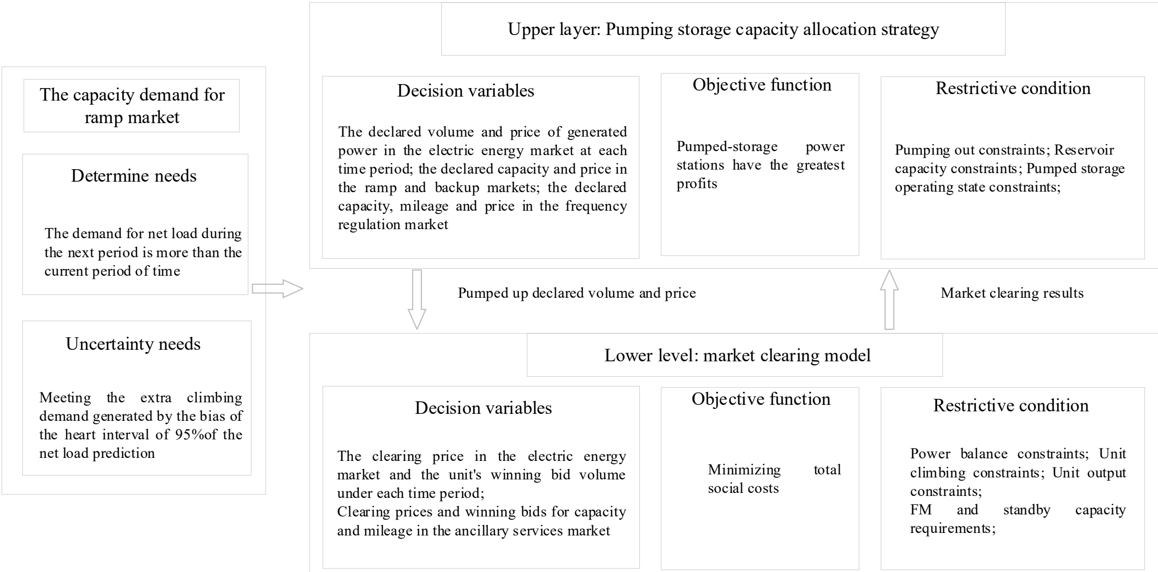

Figure 2. Bi-level model structure for pumping capacity allocation.

2.3. Calculation of Ramping Demand

The calculation of ramp demand mainly includes two parts: deterministic ramp demand and uncertain ramp demand. Deterministic ramping demand refers to the change in net load of the system in the next period compared with the current period. Uncertain ramping demand refers to the additional ramping demand generated in order to meet the deviation of a certain confidence interval (such as 95%) of the system net load forecast. The components of the ramping requirements are shown in Equations (1) and (2) respectively.

$$D_t^{Ra_{up}} = D_t^{Ra_{up,D}} + D_t^{Ra_{up,U}} \tag{1}$$

$$D_t^{Ra_d} = D_t^{Ra_{d,D}} + D_t^{Ra_{d,U}} \tag{2}$$

In the formula, t is the current period, and the period length is 1 h; $D_t^{Ra_{up}}$ and $D_t^{Ra_d}$ are the total uphill and downhill demands of the system respectively; $D_t^{Ra_{up,D}}$ and $D_t^{Ra_{d,D}}$ are the determined uphill and downhill demands respectively; $D_t^{Ra_{up,U}}$ and $D_t^{Ra_{d,U}}$ are the uncertain uphill and downhill requirements respectively.

Next, consider the deterministic climbing requirements of the system, and the calculations are as shown in Equations (3)–(5).

$$\Delta Q_t = Q_{t+1} - Q_t \tag{3}$$

$$D_t^{Ra_{up,D}} = max(0, \Delta Q_t) \tag{4}$$

$$D_t^{Ra_{d,D}} = min(0, \Delta Q_t) \tag{5}$$

In the formula, Q_t and Q_{t+1} are the system net load forecast values of the current time period t and time period t + 1 respectively; ΔQ_t is the system net load forecast change value between time periods.

The error value of system net load prediction is closely related to typical days (holidays, working days) and specific time periods. Therefore, a fixed system net load forecast deviation rate interval is used to count the frequency of occurrence within the net load forecast deviation rate interval range of each system on the same typical day and in the same time period. This frequency is used as a probability. Multiply the system net load forecast deviation rate by the net load forecast value in period t to obtain the probability density distribution function of the load forecast error in that period.

The uncertainty ramp requirement calculation is as follows. Equations (6)–(8) represent the uncertain uphill climb requirements, and Equations (9)–(11) represent the uncertain downhill climb requirements.

$$D_t^{Ra_{up,U}} = max\left(0, P_{up,p,t} + D_t^{Ra_{d,D}}\right) \tag{6}$$

$$P_{up,p,t} = max\left(0, P_{up,t}\right) \tag{7}$$

$$\int_{-\infty}^{P_{up,t}} p_t(e)de = \lambda_U \tag{8}$$

$$D_t^{Ra_{d,U}} = min\left(0, P_{d,n,t} + D_t^{Ra_{up,D}}\right) \tag{9}$$

$$P_{d,n,t} = min(0, P_{d,t}) \tag{10}$$

$$\int_{-\infty}^{P_{d,t}} p_t(e)de = \lambda_D \tag{11}$$

In the formula: $p_t(e)$ is the probability density distribution function of the system net load forecast error based on the probability histogram, λ_U is the value of the probability density distribution function integrated from negative infinity to $P_{up,t}$, which is the upper limit of the confidence interval, λ_D is the value of the probability density distribution function integrated from negative infinity to $P_{d,t}$, which is the lower limit of the confidence interval. For example, in the 95% confidence interval, λ_U, λ_D are 97.5% and 2.5% respectively, $P_{up,t}$ and $P_{d,t}$ are respectively the upper and lower bounds of the net load prediction at the corresponding confidence level. The two are absolutely controlled to generate $P_{up,p,t}$ greater than or equal to 0 and $P_{d,n,t}$ less than or equal to 0.

3. Bidding Model for Pumped Storage Units in Multiple Markets

3.1. Upper-Level Transaction Decision-Making Mode

3.1.1. Objective Function

The total revenue obtained by a pumped storage power station is the sum of the revenue from participating in the main and auxiliary markets. Pumped storage power stations participate in the electric energy market and ancillary service market. In this article, the ancillary service market includes three markets: ramping, frequency regulation and backup.

The upper-level objective function with the goal of maximizing the total revenue obtained by the pumped storage power station is shown in Equation (12).

$$R = max\sum_{t}^{T}(R_{\mathrm{E},t} + R_{\mathrm{Ra},t} + R_{\mathrm{F},t} + R_{\mathrm{R},t} - C) \tag{12}$$

$$R_{E,t} = \pi_{\mathrm{da},t}\left(P_{\mathrm{E.t}}^{e} - P_{\mathrm{E.t}}^{p}\right) \tag{13}$$

$$R_{F,t} = \pi_{\mathrm{F,cap}}P_{F,t} + \alpha_{\mathrm{mile}}\pi_{\mathrm{mile},t}P_{F,t} \tag{14}$$

$$R_{R,t} = \pi_{\mathrm{R,cap}}P_{R,t} + \beta_R\pi_{R,t}P_{R,t} \tag{15}$$

$$R_{\mathrm{Ra},t} = \pi_{\mathrm{Ra,up,t}}P_{\mathrm{Ra,up,t}} + \pi_{\mathrm{Ra,d,t}}P_{\mathrm{Ra,d,t}} \tag{16}$$

In the formula, $R_{E,t}$, $R_{F,t}$, $R_{R,t}$, $R_{\mathrm{Ra,up},t}$ and $R_{\mathrm{Ra,d},t}$ are the income of the pumped storage power station in the electric energy market, frequency regulation market, reserve market and ramping market at time *t*, respectively, *C* represents the operating cost per unit time of the pumped storage power station; $\pi_{\mathrm{da},t}$, $\pi_{\mathrm{F,cap}}$, $\pi_{\mathrm{mile},t}$, $\pi_{\mathrm{R,cap}}$ and $\pi_{\mathrm{Ra},t}$ respectively represent the day-ahead electricity price, frequency regulation capacity electricity price, frequency regulation mileage electricity price, reserve electricity price and up and down ramp prices of market clearing at time *t*, $\pi_{R,t}$ represents the compensation price for increased power generation when the reserve capacity of the pumped storage power station is called; $P^e_{\mathrm{E.t}}$, $P^p_{\mathrm{E.t}}$, $P_{F,t}$, $P_{R,t}$, $P_{\mathrm{Ra,up,t}}$ and $P_{\mathrm{Ra,d,t}}$ respectively represent the power generation, pumping capacity, frequency regulation capacity, reserve capacity, and up and down ramping capacity of the pumped storage power station that won the bid at time t. α_{mile} is the mileage-capacity ratio; β_R is the reserve call rate.

3.1.2. Constraints

(1) Output constraints

$$P_{min} \leq P_{\lambda,t} \leq P_{max}, \lambda = 1,2,3,4,5, t \in T \tag{17}$$

$$P_{min} \leq P_{2,t} + P_{3,t} + P_4 + P_5 \leq P_{max}, t \in T \tag{18}$$

In the formula, P_{min} is the minimum allowable power generation divided by the pumping power in each period, P_{max} is the maximum allowable power generation divided by the pumping power in each period; $P_{\lambda,t}$ represents the power generation divided by the pumping quantity at t under different states of the pumped storage power station. When λ = 1, it is the pumping power, when λ = 2, it is the power generation and grid power, λ = 3 is the capacity to participate in the frequency regulation market, λ = 4 is the capacity to participate in the reserve market, λ = 5 is the capacity to participate in the ramping market.

(2) Reservoir capacity constraints

Equation (19) indicates that at the beginning and end of the optimization cycle, the reservoir storage capacity of pumped hydro storage is equal; Equation (20) indicates the upper and lower limits of the reservoir storage capacity; Equation (21) indicates the constraint on the relationship between reservoir storage capacity and power.

$$V_0 = V_T \tag{19}$$

$$V_{min} \leq V_t \leq V_{max} \tag{20}$$

$$V_t = V_{t-1} - \alpha\left(P^e_{E,t} + P^e_{R,t} + 0.5P_{F,t}\right)/\eta + \alpha\left(P^p_{E,t} + P^p_{R,t}\right) \tag{21}$$

In the formula, V_t is the reservoir storage capacity of the pumped storage power station at time t; V_{min} is the lower limit of storage capacity, V_{max} is the upper limit of storage capacity; $P^e_{R,t}$ and $P^p_{R,t}$ are the bid-winning reserve capacity during power generation and water pumping respectively; α is the conversion coefficient between electric power and storage capacity; η is the power generation efficiency of pumped storage power station.

(3) Working condition state transition constraint

Equation (22) indicates that pumped hydropower storage cannot be in the working state of water pumping and power generation at the same time; Equations (23) and (24) represent the conversion relationship of pumped hydropower storage working status.

$$y^e_t + y^p_t \leq 1 \tag{22}$$

$$s^e_t = max\left\{y^e_t - y^e_{t-1}, 0\right\} \tag{23}$$

$$s^p_t = max\left\{y^p_t - y^p_{t-1}, 0\right\},\ t \in T \tag{24}$$

In the formula, y^e_t and y^p_t respectively represent that the pumped storage unit is in the power generation and pumping state at time t; s^e_t and s^p_t are the number of starts and stops of the pumped storage unit under power generation and pumping conditions respectively.

(4) Constraints on the maximum number of starts and stops of the unit

Equations (25) and (26) represent the constraints on the maximum number of starts and stops of pumped hydro storage.

$$\sum_{t=1}^{T} s^e_t \leq N^e_t \tag{25}$$

$$\sum_{t=1}^{T} s_t^p \leq N_t^p \tag{26}$$

In the formula, N_t^{e} and N_t^{p} are the maximum number of starts and stops of pumped storage under power generation and pumping conditions respectively.

3.2. Lower Market Joint Clearing Model

Objective Function

After the market develops to a certain stage, the clearing method will gradually transform from sequential clearing to joint clearing, thereby better allocating market product resources among market entities and further maximizing social welfare. Therefore, a clearing method is adopted that combines the electric energy market with the ramping, frequency regulation, and backup ancillary service markets. Allowing high-level services to substitute low-level services, a clearing calculation can obtain the clearing results and prices in each market. The clearing model aims to minimize the total social cost. As shown in Equation (27).

$$F = min\sum_{t}^{T}\sum_{i}^{I}\left[\pi_{i,t}^{\mathrm{da}}P_{i,t}^{E} + \left(\pi_{i,t}^{\mathrm{F,cap}} + \alpha_{\mathrm{mile}}\pi_{i,t}^{\mathrm{mile}}\right)P_{i,t}^{F} + \left(\pi_{i,t}^{\mathrm{R,cap}} + \beta_R\pi_{i,t}^{R}\right)P_{i,t}^{R} + \pi_i^{Ra}P_{i,t}^{Ra} + C_{i,t}^{U}\right] \tag{27}$$

$$C_{i,t}^{U} = u_{i,t}(1 - u_{i,t})C_i \tag{28}$$

In the formula, F is the total social cost; T is the number of dispatching period periods; I is the number of units participating in dispatching in the system. $\pi_{i,t}^{\mathrm{da}}$, $\pi_{i,t}^{\mathrm{F,cap}}$, $\pi_{i,t}^{\mathrm{mile}}$, $\pi_{i,t}^{\mathrm{R,cap}}$, and π_i^{Ra} are the electric energy, frequency regulation capacity, frequency regulation mileage, reserve and climbing market winning prices of unit i at time t, respectively. $\pi_{i,t}^{R}$ is the reserve capacity price of unit i called at time t. $P_{i,t}^{E}$, $P_{i,t}^{F}$, $P_{i,t}^{R}$ and $P_{i,t}^{Ra}$ are respectively the electric energy, frequency modulation, reserve, and climbing scalars of unit i at time t. $C_{i,t}^{U}$ is the startup cost of unit i at time t. $u_{i,t}$ is a 0–1 variable indicating the start and stop status of unit i at time t. C_i is the start-up cost of unit i at time t. C_i is the start-up cost of unit i.

$$\sum_{i}^{I} P_{i,t}^{E} = P_t^{D} \tag{29}$$

$$P_{i,t}^{E} - P_{i,t-1}^{E} \leq P_i^{\mathrm{ramp}} \tag{30}$$

$$u_{i,t}P_{i,t}^{\mathrm{E,min}} \leq P_{i,t}^{E} \leq u_{i,t}P_{i,t}^{\mathrm{E,max}} \tag{31}$$

In the formula, P_t^{D} is the system load at time t; P_i^{ramp} is the climbing ability of unit i in adjacent periods; $P_{i,t}^{\mathrm{E,max}}$ and $P_{i,t}^{\mathrm{E,min}}$ are respectively the upper and lower limits of the output of unit i at time t.

Equations (32) and (34) can prevent price deficits from occurring when the market clears. Equation (32) indicates that the frequency regulation capacity provided by all winning units must be greater than or equal to the market demand. Equations (33) and (34) represent the substitutability of high-quality ancillary services for low-quality ancillary services, that is, the frequency regulation, reserve and ramping capacity provided by the winning unit shall not be less than the sum of the three demands.

$$\sum_{i}^{I} P_{i,t}^{F} \geq D_t^{F}, \forall t \in T \tag{32}$$

$$\sum_{i}^{I} P_{i,t}^{F} + \sum_{i}^{I} P_{i,t}^{R} \geq D_t^{F} + D_t^{R}, \forall t \in T \tag{33}$$

$$\sum_{i}^{I} P_{i,t}^{Ra} + \sum_{i}^{I} P_{i,t}^{F} + \sum_{i}^{I} P_{i,t}^{R} \geq D_t^{Ra_{up}} + D_t^{Ra_d} + D_t^{F} + D_t^{R}, \quad \forall t \in T \tag{34}$$

In the formula, D_t^{F}, D_t^{R}, $D_t^{Ra_{up}}$, and $D_t^{Ra_d}$ represent the market demand for frequency modulation, backup, and up and down ramps respectively.

4. Example Analysis

4.1. Parameter Settings

This chapter verifies the validity of the model through arithmetic simulation. The above optimization model can adopt iterative interactive optimization between the unified upper and lower layers. In the MATLAB interface, call the YALMIP toolbox to program variables, constraints and optimization objectives, and use the CPLEX solver to solve it. The parameters of each generating unit, the frequency modulation mileage multiplier and the reserve calling coefficient are shown in Appendix A Table A1; the quotation of the unit in the auxiliary market is shown in Appendix A Table A2; the user load curve in the system is shown in Figure 3; Under the two-part electricity price system, the on-grid electricity price is based on the benchmark electricity price of 350 yuan/MWh, and the pumped water electricity price is 250 yuan/MWh.

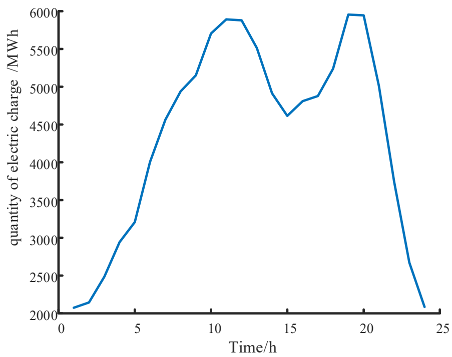

Figure 3. User load forecast curve.

4.2. Analysis of Pumped Storage Capacity Allocation Results

(1) Market clearing price results

The clearing prices in each market are shown in Figure 4.

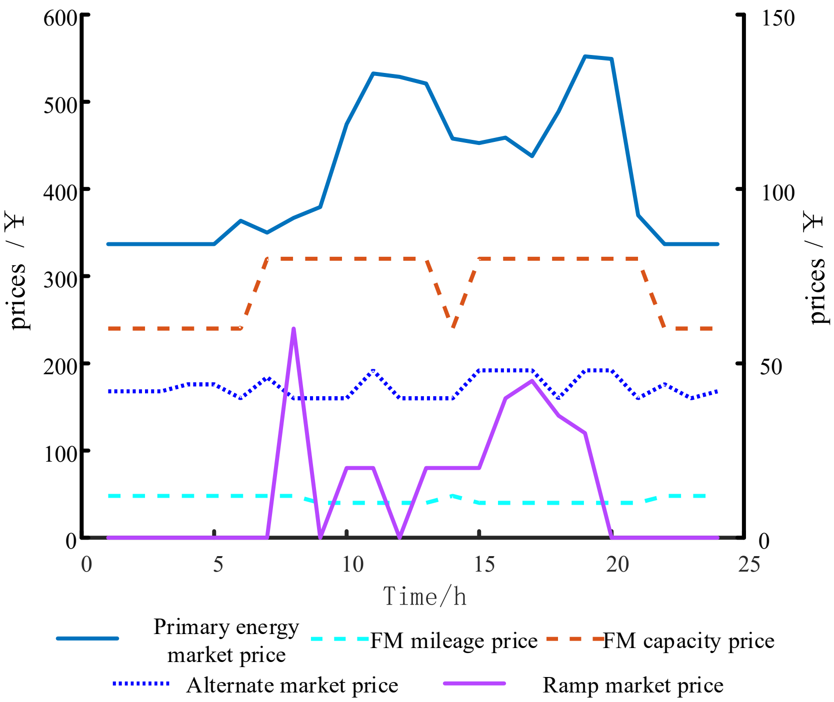

Figure 4. Market clearing price.

It can be seen from the electric energy market clearing price in Figure 2 that the electric energy market clearing price has a similar trend with the electricity load curve. The peak electricity prices between 11:00–12:00 and 19:00–20:00 are due to the large demand for electricity at this time and the increased pressure on the system's power supply. The power supply of thermal power companies has also increased, thus increasing the quotations of power companies. The clearing price from 19:00–20:00 is higher than the price from 11:00–12:00, but the electricity consumption from 11:00–12:00 is higher. This is because during the peak period of electricity consumption at noon, new energy supplies more electricity, causing the thermal power companies that mainly set prices to win less electricity and lower their quotations. Therefore, the electricity price at this time is lower than that of the peak electricity period in the evening. At the same time, a certain amount of climbing demand will be generated. Due to the different willingness and conditions of different units to participate in the ancillary market, the gap in the clearing prices of the ancillary service market at different times is small. The clearing prices in the frequency regulation market and the reserve market do not change with the load curve trend, and generally show a trend of being higher during the day and lower at night, ramp market prices are related to net load changes.

(2) The output of each unit in the energy market

The bid winning amounts of different generating units in each period of time in the electric energy market are shown in Figure 5. As can be seen from Figure 3, in the electric energy market, each unit will participate in market transactions, but the three thermal power units G1, G2, and G3 occupy most of the market share due to their high power generation capacity and low quotation levels. Pumped storage units use different strategies to trade in the energy market according to changes in market prices. The main trend is to generate electricity during peak periods and pump water during trough periods to obtain more revenue.

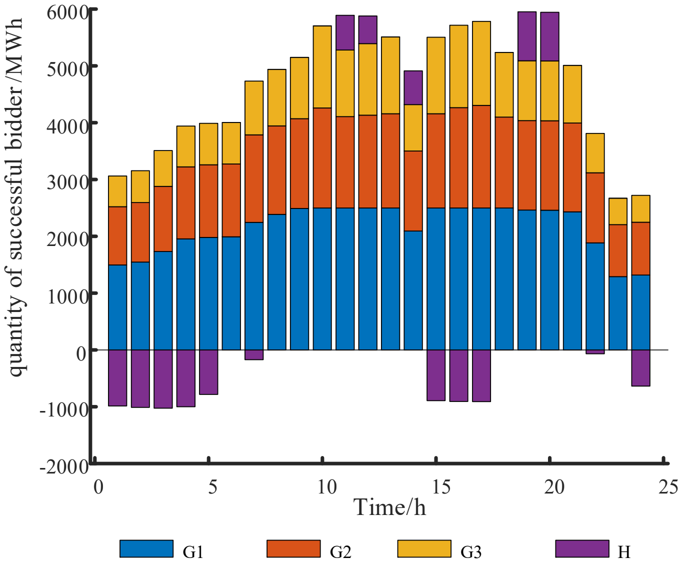

Figure 5. Winning bids for generator sets in energy market.

(3) Bid winning status of pumped storage power stations in multiple markets at various times

The output of pumped storage power stations in different markets at each moment is shown in Figure 6.

Figure 6 shows that pumped storage units pump a large amount of water when electricity prices are low, thus having enough power generation to provide the market. When pumping water, pumped storage units tend to participate in the energy market and frequency regulation market, have higher backup costs, and cannot fully meet the demand for pumped storage power generation. At this time, pumped storage units do not participate in the reserve market. When generating electricity, pumped storage units are more willing to participate in the auxiliary service market, and the income from the auxiliary market will be greater than the energy market. Pumped hydro energy storage only participates in the electric energy market during peak electricity price periods. Driven by price signals, pumped hydro energy storage participates in different market transactions through pumping to obtain maximum returns.

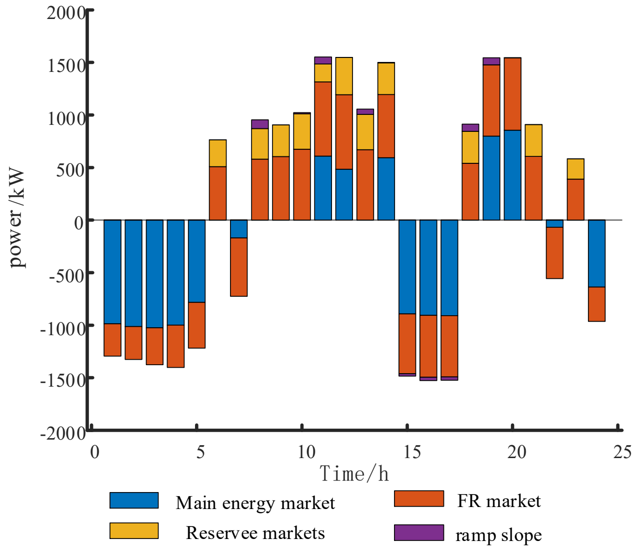

Figure 6. Pumped storage output in the energy market and ancillary service market at 1–24 h.

4.3. Analysis of Income from Pumped Hydro Energy Storage

The comparison of the economic benefits of pumped storage energy participating in the market and the income under the two-part electricity price is shown in Table 1. It can be seen from the table that under the conditions set in this article, the daily income of pumped storage units when participating in the market is 2.6517 million yuan, which is 145,200 yuan more than the daily income under the two-part electricity price, and the annual income is 967.8705 million yuan. Calculated based on a 40-year operating period, it can create an economic value of 38.715 billion yuan. The main source of revenue comes from participating in the ancillary service market to provide ancillary services such as frequency regulation, backup, and ramping. When comparing the two-part electricity price, the average daily income is 2.5065 million yuan, of which capacity electricity fee is the main source of income. It can be seen that in the income composition of pumped storage units, electricity charges account for a low proportion, about 4%. The income from participating in the ancillary service market can cover the capacity electricity fee, ensure the cost recovery and further profitability of the pumped storage power station, and cope with the risk of capacity fee reduction.

Table 1. Comparison of gains from pumping participation in the market with gains from the two-part system.

Participation in the Market	Incomes/Ten Thousand Yuan	Two-Part Tariff	Incomes/Ten Thousand Yuan
electricity purchase	−223.54	Electricity quantity and cost	10.6
generate electricity	201.69	volumetric electricity tariff	240.05
FM market	214.3		
rotating spare	45.14		
ramp market	27.58		
total daily profit	265.17	total daily profit	250.65
total profit for the year	96,787.05	total profit for the year	91,487.25
profit growth for the year	5.79%		

5. Conclusions

In the context of a large number of renewable energy being connected to the grid and a lack of flexible adjustment services for system operation, ramp-up auxiliary services have emerged and become a hot research topic. This paper studies the bidding and joint clearing of pumped hydro energy storage in the electric energy, ramping, frequency regulation, and reserve markets, and draws the following conclusions:

(1) In the two-part electricity price system proposed in Document No. 633, pumped storage power stations mainly rely on capacity electricity charges to make profits. Part of the income from electricity is reflected through the peak and valley electricity prices in the spot market. After pumped storage entered the market, it competed as an independent operating entity. The daily income increased by 5% compared with the two-part electricity price. It no longer needs to rely on capacity electricity charges to achieve profitability.

(2) The markets that pumped storage units tend to participate in at different points in time are different, driven by price signals, pumped hydro energy storage participates in different markets by arranging pumping plans to obtain higher returns, which places higher requirements on the bidding and trading strategies of pumped hydro storage units in different markets.

(3) The profit share of pumped storage units from participating in the auxiliary service market such as ramping is much higher than the profit from participating in the electric energy market, This can increase the enthusiasm of pumped storage units to participate in the ancillary service market such as ramping, and quantify the value of the flexible adjustment capabilities of pumped storage units. In the context of large-scale new energy grid integration, pumped hydro storage units actively provide auxiliary services, which is conducive to maintaining the safe and stable operation of the power system.

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Appendix A

Table A1. Parameters of generator sets.

	a/¥	b/ yuan·MW^{-1}	c/ yuan·MW^{-2}	Maximum Output/MW	Minimum Output/MW	The Frequency Modulation Mileage Multiplier	The Reserve Calling Coefficient
G1	3933.99	181.64	0.09	1500	450	7	0.2
G2	3628.17	183.53	0.11	1300	350	8	0.2
G3	5249.99	201.98	0.19	1100	250	7	0.2
H	201	0	0	1500	0	10	0.2

Table A2. Generator sets quoted in ancillary markets.

	Frequency Modulation Capacity Price/(yuan/MW)	Frequency Regulation Mileage Quotes/(yuan/MW)	Reserve Offer/(yuan/MW)
G1	60	12	48
G2	65	14	46
G3	70	15	44
H	95	10	40

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