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Two-Part Tariff of Pumped Storage Power Plants for Wind Power Accommodation

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Abstract: Pumped storage power plants face many challenges in competing in the electricity market, and high pumping costs lead to high prices for their power generation, which is one of the important factors that has limited their development. To address this problem, this paper studies the pumped storage two-part tariff mechanism considering wind power accommodation and uses the peak-valley price difference of wind power to realize the rationality and economy of a pumped storage charging and discharging strategy. It can improve the competitiveness of pumped storage power plants participating in electricity market transactions. Then, by considering the economic advantages of "pumped storage + clean energy", a pumped storage and wind power joint optimal dispatching model was established based on the original pumped storage pricing method. This model takes the total system cost reduction after the introduction of pumped storage as the objective function to derive a reasonable pumped storage strategy. After which, the two-part tariff for pumped storage power plants was formulated based on the principle of reasonable revenue. Finally, a sensitivity analysis of various relevant parameters of the power plant was conducted through case studies to verify the effectiveness of the two-part tariff mechanism of pumped storage. It was found that the electricity tariff is lowest when the ratio of plant capacity to upper reservoir capacity is 1:6.37 (MW/million m^3).

Keywords: pumped storage power plant; wind power accommodation; electricity market; two-part tariff

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1. Introduction

At present, the construction of the new type of power system having new energy as the main body is an important direction for the power and energy industry [1]. Owing to the high penetration and large-scale integration of new energy, there is an urgent need to develop energy storage to enhance the flexible regulation capability and the electrical energy storage capacity of the power system [2,3]. As the most mature, safe, stable, and environmentally friendly energy storage method, pumped storage has great potential for further development [4,5]. However, at the same time, the development of pumped storage also faces many challenges, the most critical of which is the low enthusiasm of third-party investment and low economic competitiveness due to the imperfect tariff mechanism [6]. China is currently in the early stage of electricity market reform, and the two-part tariff, as the tariff policy mentioned by the National Development and Reform Commission on the vigorous development of pumped storage, is not only a favorable policy to promote the healthy development of pumped storage, but also a necessary means to extend the electricity market reform [7,8].

With the gradual emphasis on low-carbon emission reduction and the goal of "carbon peaking" and "carbon neutrality", new energy sources meeting emission reduction requirements are integrated into power systems on a large scale, and the reasonable and effective promotion of new energy consumption has become a promising research component of energy storage systems [9,10]. Since wind power has stochastic and intermittent characteristics, which results in power and frequency fluctuations, Yang et al. [11,12] proposed a temporary frequency-support scheme and adaptive droop control scheme for doubly fed induction generators that can help provide a promising power control solution for power systems with high wind power penetration levels. However, sometimes, the control of wind power itself cannot effectively smooth the power fluctuation. Sun et al. [13] analyzed the problems brought by large-scale wind power and photovoltaic grid connection to the power system and pointed out the main problems and trends facing the development of pumped storage power plants. Li et al. [14] proposed a new generation of pumped storage power plants combining variable speed unit technology, chemical energy storage systems, and multi-energy coupling of new energy systems such as wind and solar energy, taking the transformation of Langya Mountain pumped storage power plant in the Anhui power grid as an example. Rong et al. [15] aimed to develop a coordinated dispatching method that targets the maximum extra wind power consumed and the highest economic benefit of the hybrid energy system as the optimization objective to provide higher fuel savings and economic benefits. Xu et al. [16] established a hybrid power system model of solar-wind-hydro power generation, which provided a theoretical basis for the construction of pumped storage power plants integrated with hybrid power generation systems. Most of these studies are mainly from the perspective of enhancing the enthusiasm of energy storage systems to participate in new energy accommodation, but the energy level is relatively small and therefore does not provide sustained and long-lasting regulatory support.

Reasonable tariff mechanism and electricity market bidding models, applicable to pumped storage power plants, are of great significance for their participation in the electricity market competition. Many scholars have studied the operational strategies of various forms of energy storage systems to participate in the electricity market competition [17,18]. Many studies found that multi-level cooperative planning and control of energy storage systema reduced the investment cost of the system and realized the optimal configuration operation of energy storage equipment [19,20]. Wu et al. [21] provided joint participation of multiple wind power and pumped storage power plants in a spot market model, which considered the uncertainty of wind power real-time output, and proposed an optimal bidding strategy before a joint wind storage day. Heussen et al. [22] designed operating strategies for up to 100% RES power systems, explicitly considering non-dispatchable generation and storage capacity, as well as the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. Zhao et al. [23] investigated the economic feasibility of applying energy storage systems to wind farms in the electricity market environment in terms of levelized energy storage costs and analyzed the optimal business modes. The above studies tend to consider the maximization of energy storage participation in the electricity market revenue, while they seldom study the feasibility of energy storage in promoting new energy consumption while reducing the consumption of fossil energy.

Many scholars have also conducted numerical research studies on the pumped storage tariff mechanism and operation mode under the more mature domestic and international electricity markets [24]. Wu and Lin [25] assessed the value of energy storage in the power system based on the current situation of the domestic electricity market with provincial grid data. Newbery et al. [26] analyzed the market mechanism design issues that needed to be addressed to adapt to renewable energy supply in the European liberalized electricity market and reviewed the evolution of relevant policy mechanisms in the EU. The literature [27] discussed the energy system transformation schemes of 28 countries, including China, and analyzed the necessity of allocating investment to low-carbon technologies on the premise of affordability. At present, China is at the early stage of electricity market reform, and the auxiliary service and capacity markets are not yet fully established. Thus, the revenue of pumped storage power plants still focuses on electric energy revenue.

Considering the above problems, the main contributions of this paper are as follows:

1. Study the two-part tariff mechanism of pumped storage power plants considering the wind power accommodation scenario and realize the rationality and economy of pumped storage charging and discharging strategy by using the peak-valley price difference of wind power, so as to improve the competitiveness of pumped storage power plants to participate in electricity market transactions.
2. Determine the capacity tariff in the two-part pumped storage tariff through the approved operating period tariff method based on the principles of reasonable compensation of costs and reasonable determination of revenues and taxation in accordance with the law.
3. Considering the economic advantages of "pumped storage + clean energy", a pumped storage and wind power joint optimization scheduling model is to be established based on the original pumped storage pricing method. The pumped storage power electricity tariff is set on the basis of compensating variable costs through the optimal operation strategy obtained.
4. Analyze and illustrate the feasibility of pumped storage power plants to reduce fossil energy consumption in several scenarios.

The remaining of this paper is as follows: Section 2 introduces the general structure of the two-part tariff system and several important factors influencing the tariff. Section 3 models the tariff formulation strategy, which is divided into two parts: the approved strategy for capacity tariff and the formulation strategy for electricity tariff. Section 4 covers case analyses, which analyze the effectiveness of the proposed modeling strategy with a typical case system, where four scenarios are set up to analyze the impact of wind power accommodation on the two-part tariff, and the variable cost analysis and price sensitivity analysis of pumped storage power plants. Finally, Section 5 concludes the paper.

2. Two-Part Tariff

2.1. General Structure of the Two-Part Tariff System

The two-part tariff is composed of two parts: capacity tariff and electricity tariff. The capacity tariff is mainly used to compensate the fixed cost of the power station, including power station investment, loan repayment, depreciation, and other economic factors, which can be calculated by transformer capacity or by maximum demand. Capacity tariffs are set by government pricing, market bidding, negotiation, and other methods. The electricity tariff is mainly used to compensate the variable cost of the power station and is closely related to the material cost and labor cost. The electricity tariff is calculated based on the actual electricity consumption. It can reflect a certain competitiveness of the power generation enterprises and is usually formed in market competition.

In the electricity market environment, the capacity tariff in the two-part tariff can compensate the capacity cost to a certain extent to ensure the construction investment cost recovery of pumped storage power plants and to protect the units from large losses. Thus, the capacity tariff of the same pumped storage power plant basically does not change. Without the burden of the capacity cost, the electricity tariff can reflect the marginal cost of pumped storage power plants more accurately. The competition in the market is fairer and more adequate, which is conducive to the stable operation of the electricity market. On this basis, the two-part tariff can further promote power generation enterprises to strengthen internal management, to improve operational efficiency, and to promote the smooth transition of the power generation side tariff mechanism to a fully competitive tariff. Thus, the implementation of the two-part tariff of pumped storage power plants at the initial stage of electricity market construction is a necessary means to extend the electricity market reform. In the early stage of China's electricity market reform, the two-part tariff system meets the requirements of reform and development. It has various advantages such as reducing the risk of pumped storage power plants participating in electricity market transactions, promoting fairness in power generation-side transactions, and giving full play to the resource allocation advantages of the market mechanism.

2.2. Influencing Factors of the Two-Part Tariff

There are many factors that affect the two-part tariff, including electric energy demand relationship factors, natural resource timing and seasonal factors, social and policy factors, etc. In this section, we focus on the electricity consumption and generation process of pumped storage power plants and discuss the influencing factors of the pumped storage two-part tariff.

2.2.1. Influence of Different Operating Strategies

The excellent auxiliary service capabilities of pumped storage power plants, such as peak and frequency regulation, standby and black start, are difficult to be compensated for in the electricity market, resulting in their often higher two-part tariffs. The pumping efficiency of conventional pumped storage power plants is around 75%, resulting in a significant portion of electricity being wasted in the storage process, and the implementation of the "high generation and low storage" strategy is severely limited based on the existing peak-to-valley price differences. The variable cost of pumped storage power plants mainly comes from the pumped power, and the upper and lower price limits of pumped power determine the range of variation of its electricity tariff. Compared with independent participation in the electricity market, pumped storage power plants generally operate in cooperation with wind power, nuclear power, and other clean energy systems. Through reasonable operation strategies, they can make full use of renewable energy and reduce the variable cost of pumped storage power plants so as to further optimize the electricity tariff structure.

2.2.2. Influence of Uncertainty of New Energy Output

In the process of pumped storage and new energy generation, the uncertainty of new energy output not only makes it more difficult to predict its day-ahead output, but also seriously affects the accuracy of tariff setting. Considering the superiority and stability of new energy accommodation and pumped storage in local accommodation of new energy, the tariff of pumped storage should be set according to the forecast of new energy day-ahead output to recover the corresponding variable cost. Under the premise of ensuring the safe operation of the power system, an appropriate balancing mechanism can be adopted to avoid large fluctuations in tariffs due to forecast errors.

2.2.3. Influence of Seasonal Storage Changes in Pumped Storage Power Plants

The influence of seasonal changes in available pumped storage water on electricity prices is mainly twofold: first, the loss of seasonal water evaporation and leakage will increase the variable cost of pumped storage power plants, resulting in a corresponding increase in electricity prices; second, the seasonal replenishment of natural water will increase the power generation capacity of pumped storage power plants, which will correspondingly reduce their energy storage potential and make the intra-day price fluctuations to a certain degree smaller. The selection of suitable sites and the establishment of water consumption indicators can appropriately mitigate the seasonal changes in the electricity tariff, so as to maintain the relative stability of the electricity tariff.

3. Modeling of a Two-Part Tariff Setting Strategy for Pumped Storage Power Plants

3.1. Methodology for Approving Capacity Tariffs

This paper determines the capacity tariff based on the operating period pricing method. It is based on the net present value (NPV) method of the dynamic economic evaluation methodology, which can be applied to the capacity tariff of pumped storage power plants. It is described as follows: First, a reasonable internal rate of return is determined with the investor, and the expected annual net cash inflow is calculated after the pumped storage power plant is put into operation based on the expected financial situation of the enterprise. Second, the sum of cash inflows for the entire operating period is calculated, taking into account the income from the sale of fixed assets at the end of the operating period, making it equal to the cash outflow during the construction period of the pumped storage power plant. Third, the annual electricity sales revenue is obtained, and then it subtracts the pumping costs, which takes 75% benchmark tariff of coal-fired units as the pumped stage price, to obtain the specific cash value of the reasonable capacity tariff. Finally, the result can be converted into a monthly capacity tariff per unit of installed capacity of the power station. In the model, the change of capital value over time during the construction period is ignored. After the pumped storage power plant is put into operation, the annual feed-in electricity amount, feed-in tariff, and operation and maintenance costs are set to remain basically the same. With one year as a calculation cycle, the loan repayment method is in the form of equal principal and interest, i.e., the total principal and interest repaid in each period remains the same. The straight-line depreciation method is used for depreciation of the fixed assets.

After the pumped storage plant is completed and put into operation, the annual net cash flow is M_n in the first year to year $N-1$; at the end of year N, the annual net cash inflow includes income from the salvage sale of fixed assets.

$$M_{n(n=1,\,2,\,\ldots,\,N-1)} = I' - C_{om} - A_r - T \tag{1}$$

$$M_{n(n=N)} = I' - C_{om} - A_r - T + (1-\rho_{cin})C_s \tag{2}$$

where, N is the operating and service life of the pumped storage plant; I' is the annual sales revenue including tax; C_{om} is the annual operation and maintenance fee; A_r is the annual loan repayment; T is the total annual tax payment; C_s is the income from salvage sale of fixed assets; and ρ_{cin} is the corporate income tax rate.

Tax-inclusive annual revenue from electricity sales consists of VAT fees and non-tax-inclusive annual revenue from electricity sales.

$$I' = I + T_{vat} \tag{3}$$

where, I is the annual sales revenue without taxes; and T_{vat} is the value added tax (VAT) fee.

The total annual tax payment consists of VAT, sales tax, and corporate income tax, while each type of tax is calculated from the corresponding tax rate.

$$T = T_{vat} + T_{sal} + T_{cin} \tag{4}$$

$$T_{vat} = \rho_{vat} I \tag{5}$$

$$T_{sal} = \rho_{sal} I \tag{6}$$

$$T_{cin} = \rho_{cin}(I - C_{om} - A_r - T_{sal} - C_d) \tag{7}$$

where, ρ_{vat} is the VAT rate; ρ_{sal} is the sales tax rate; T_{sal} is the sales tax fee; and T_{cin} is the corporate income tax fee.

The cash outflow during the construction period of a pumped storage power plant is the difference between the total dynamic investment and the loan amount during the construction period, and the cash outflow during the construction period is equal to the total cash inflow during the operation years:

$$(1+i)NO = \sum_{n=1}^{N} M_n \tag{8}$$

$$NO = C - L \tag{9}$$

where, NO is the cash outflow during the construction period; i is the internal reasonable rate of return; C is the total dynamic investment; and L is the total loan amount.

The final capacity tariff per unit of installed capacity is obtained as P_c (CNY/month/MW).

$$P_c = \frac{M - I + C_c}{12V} \tag{10}$$

where, C_c is the annual pumping cost; Q is the total annual power generation; V is the installed capacity. The annual pumping cost, total annual generation, and tax-inclusive annual electricity sales revenue are calculated in the following section, and the specific solution process is shown in Figure 1.

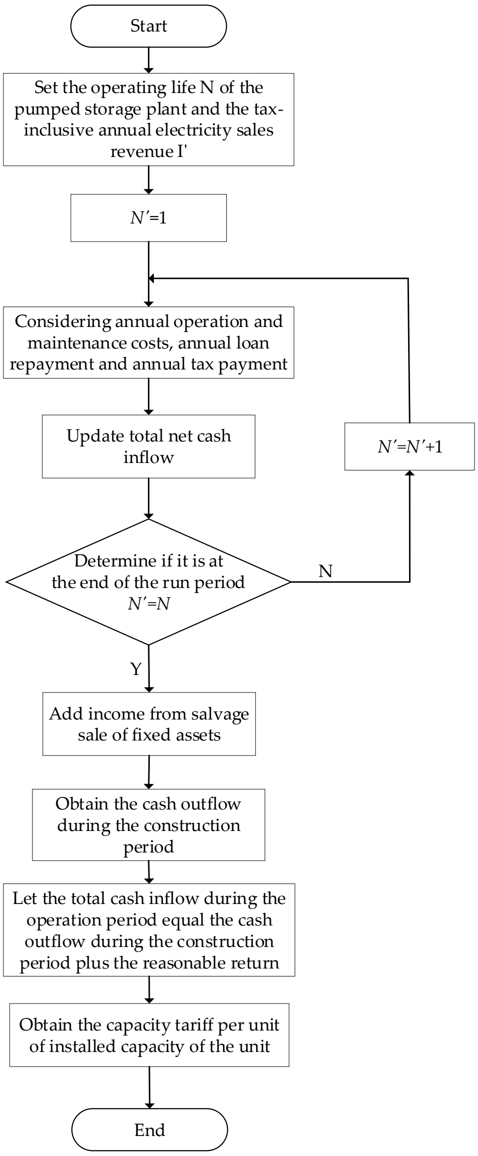


Figure 1. Flow chart of capacity tariff solving.

3.2. Modeling the Strategy for Setting Electricity Tariffs

3.2.1. Background

The main influencing factor of the electricity price of pumped storage power plants is the pumping cost. The joint operation mode of "pumped storage + clean energy" can take advantage of the peak-valley price difference caused by the uncertainty of clean energy output, thus reducing the pumping cost of pumped storage power plants, and effectively improving their competitiveness in the electricity market. The operation mode of "pumped storage + clean energy" mainly includes "integrated" operation mode, "joint" operation mode, and "independent" operation mode. Compared to the other two models, the "joint" operation mode can retain the independence of the clean energy power plant and the pumped storage power plant, while making better use of the production capacity and energy storage of both, as shown in Figure 2.

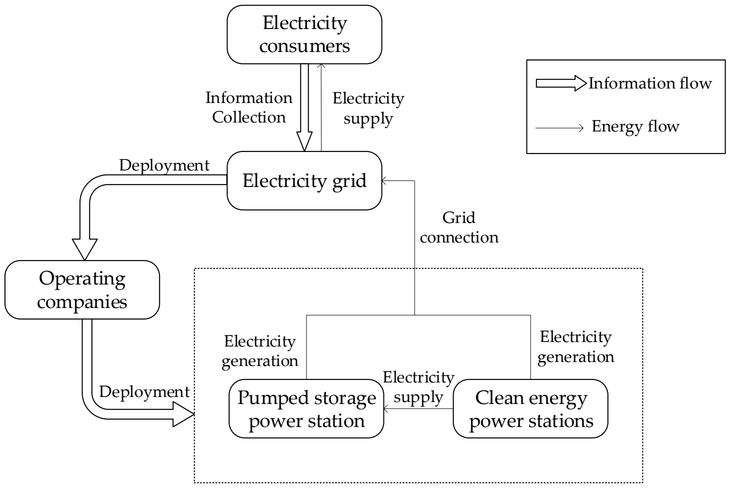


Figure 2. Combined operation mode of wind power and pumped storage.

3.2.2. Model

In this paper, considering the pumped storage power generation tariff when the pumped storage power plant and wind power jointly participate in the electricity market, the maximum reduction of the total cost of power generation in the new system after the introduction of pumped storage power plant in the original power system (Equation (11)) and the minimum pumping cost of pumped storage power plant (Equation (12)) are the two optimization objectives. After obtaining the daily optimal power generation strategy, the pumped storage power generation tariff is formulated according to the principle of reasonable recovery of the variable costs storage's time-of-use tariff.

$$\max(F_1 + F_2 - F_3 - F_4) \tag{11}$$

$$\min(F_3 + F_5) \tag{12}$$

where, F_1 is the reduction in the generation cost of coal-fired units; F_2 is the wind abandonment penalty of the original generation system; F_3 is the start-up and shutdown cost of pumped storage units; F_4 is the incremental energy cost of pumped storage losses; and F_5 is the pumping cost of pumped storage plants.

$$F_1 = \sum_{t \in T} \rho_t^h \times t \times \sum_{g \in G} (P_{g,t}^{h_0} - P_{g,t}^h) \tag{13}$$

$$F_2 = \sum_{t \in T} \sum_{g \in G} \delta \times (P_{g,t}^w - P_{g,t}^{w_0}) \tag{14}$$

$$F_3 = \sum_{g \in G} c_{start} \times \max\{(U_{g,t} - U_{g,t-1}), 0\} \tag{15}$$

$$F_4 = (1 - \eta) \times \Delta t \times \sum_{t \in T} \sum_{g \in G} (\rho_t^w \times P_{g,t}^c) \tag{16}$$

$$F_5 = \Delta t \times \sum_{t \in T} \sum_{g \in G} (\rho_t^w \times P_{g,t}^c) \tag{17}$$

where, $P_{g,t}^{h_0}$ is the actual power generated by the gth pumped turbine of the original power generation system at moment t; $P_{g,t}^{h}$ is the actual power generated by each coal-fired unit of the new system with the introduction of pumped storage; δ is the wind abandonment penalty factor; $P_{g,t}^{w}$ is the actual power generated by each wind turbine of the new system; $P_{g,t}^{w_0}$ is the actual power generated by each wind turbine in the original system; η is the energy conversion efficiency of pumped storage units; ρ_t^w is the feed-in tariff for each wind power period; ρ_t^h is the feed-in tariff for thermal power; c_{start} is the start/stop cost of the pumped storage unit; and $U_{g,t}$ is the operating state of the gth pumped turbine at moment t.

3.2.3. Constraints

The constraints of the model are mainly composed of the power balance and operating characteristics of pumped storage units, coal-fired units, and wind turbines. It includes all of the following:

The pumped-storage power station's pumping power constraints (Equations (18) and (19)).

$$0 \le P_{g,t}^{f} \le U_{g,t}^{f} P_{\max}^{f} \tag{18}$$

$$0 \le P_{g,t}^{c} \le U_{g,t}^{c} P_{\max}^{c} \tag{19}$$

where, $P_{g,t}^{f}$ and $P_{g,t}^{c}$ are the power generation and pumping power of pumped storage power plant units; $U_{g,t}^{f}$ and $U_{g,t}^{c}$ are the power generation and pumping status of pumped power plant units; $P_{\max}^{f}$ and $P_{\max}^{c}$ are the power generation and pumping power limits of pumped power plants.

The pumping power balance constraints (Equation (20)) and the pumping state constraints (Equation (21)).

$$\sum_{t \in T} P_t^f = \eta \times \sum_{t \in T} P_t^c \tag{20}$$

$$U_{g,t}^{f} + U_{g,t}^{c} \le 1 \tag{21}$$

where, P_t^f and P_t^c are the total power generation and total pumping power of pumped storage power plant units.

The storage capacity of the power station with the lower storage capacity constraints (Equations (22) and (23)).

$$0 \le V_1 - E_{nt}^{f} + E_{nt}^{c} \le V_{1\max} \tag{22}$$

$$0 \le V_2 - E_{nt}^{c} + E_{nt}^{f} \le V_{2\max} \tag{23}$$

where, $V_{1\max}$ and $V_{2\max}$ are the upper and lower reservoir capacity of the pumping station; V_1 and V_2 are the initial daily upper and lower reservoir capacity; E_{nt}^{f} and E_{nt}^{c} are the amount of water generated and pumped up to moment t.

Power generation and pumping power constraints (Equations (24) and (25)).

$$E_{nt}^{f} = n \times \Delta t \times R_w \times \sum_{g \in G} \sum_{t \in nt} (U_{g,t}^{f} \times P_{g,t}^{f}) \tag{24}$$

$$E_{nt}^{c} = n \times \Delta t \times R_w \times \sum_{g \in G} \sum_{t \in nt} (U_{g,t}^{c} \times P_{g,t}^{c}) \tag{25}$$

where, n is the number of time periods; Δt is the time interval; and R_w is the average water consumption rate of hydropower units.

The price of pumped electricity is the same as that of wind power (Equation (26)).

$$\rho_t^w = \rho_t^c \tag{26}$$

where, ρ_t^c is the pumping tariff.

The wind turbine output constraints (Equation (27)), coal-fired unit output constraints (Equation (28)).

$$0 \leq P^{w}_{g,t} \leq P^{w}_{\max} \tag{27}$$

$$0 \leq P^{h}_{g,t} \leq P^{h}_{\max} \tag{28}$$

where, $P^{w}_{\max}$ and $P^{h}_{\max}$ are the upper limits of output of wind turbines and coal-fired units.

The unit climbing constraints (Equations (29) and (30)).

$$P_{g,t} - P_{g,t-1} \leq P^{up}_{g} \tag{29}$$

$$P_{g,t-1} - P_{g,t} \leq P^{down}_{g} \tag{30}$$

where, P^{up}_{g} and P^{down}_{g} are the upper and lower limits of unit output.

The system power balance constraints (Equations (31) and (32)).

$$P^{u}_{t} = \sum_{g \in G} (P^{w_0}_{g,t} + P^{h_0}_{g,t}) \tag{31}$$

$$P^{u}_{t} = \sum_{g \in G} (P^{w}_{g,t} - P^{c}_{g,t} + P^{h}_{g,t} + P^{f}_{g,t}) \tag{32}$$

where, P^{u}_{t} is the load of electricity consumers by time.

3.2.4. Algorithm and Solving Process

In this paper, the NSGA-II algorithm proposed on the basis of the genetic algorithm is used to solve the multi-objective optimization problem, including selection, crossover, mutation and other genetic operations, non-dominated sorting strategy, crowding degree comparison operator and elite retention strategy which are added to the selection operation. Finally the Pareto optimal decision-making scheme is obtained. The algorithm obtains the Pareto optimal solution of the original objective, i.e., the solution with the best quality. A solution method for the effective objective function obtained by the Monte Carlo integration method can obtain a solution with compromise between optimality and robustness. However, the model has a limited amount of disturbance, and the quality of the solution is more critical, so the NSGA-II algorithm can meet the requirements for solving the model. The basic process of solving is shown in Figure 3.

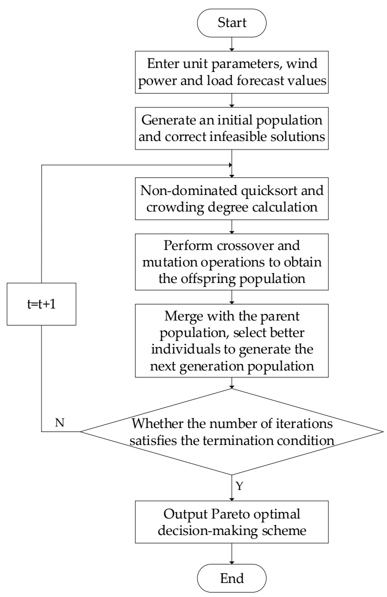


Figure 3. Flow chart of electricity price solution.

After the daily optimal power generation strategy is obtained according to the model, the electricity purchase cost of the pumped storage period is recovered in the power generation period of the day. Then the electricity tariff is determined according to the supply and demand relationship between the load demand and the electricity tariff. In this way, users are guided to purchase electricity during the load valley period, thus increasing the wind power accommodation and reducing the energy storage costs. The price-demand relationship is approximated as a linear function. The minimum electricity price is set to 200 CNY/MWh, i.e., k_1 = 200, and k_2 can be calculated according to Equations (33) and (34). Thus, the electricity tariff can be obtained during the power generation period.

$$F_5 = \sum_{\mathrm{t} \in T} \rho_t P_t^u \tag{33}$$

$$\rho_{\mathrm{t}} = k_1 + k_2 P_t^u \tag{34}$$

where, F_5 is the daily pumping cost of the pumped storage plant; P_t^u is the time-of-day electricity load of the electricity users; k_1 and k_2 are price demand factors; and ρ_t is the time-of-day electricity tariff.

In the pumping period of pumped storage, the joint system of "pumped storage + wind" gives priority to wind power supply, followed by thermal power supply, and the electricity tariff is set with the main purpose of compensating the variable cost. In summary, the expression of the pumped storage electricity tariff is shown in Equation (35).

$$\rho_{\mathrm{t}} = \begin{cases} k_1 + k_2 P_t^u, & U_{g,t} = 1 \\ \frac{\sum\limits_{g \in G} (\rho_t^w P_{g,t}^w + \rho_t^h P_{g,t}^h)}{P_t^u}, & U_{g,t} \neq 1 \end{cases} \tag{35}$$

4. Case Study and Discussion

4.1. Result Analysis

The following example system is used: The installed capacity of pumped storage is 300 MW; the upper and lower reservoir capacity is capped at 30 million m^3; the initial reservoir volume is 50% of the capacity limit; the average energy conversion efficiency is 75%; and the average water consumption rate of hydroelectric units is 4000 m^3/MWh; the installed capacity of wind power is 1200 MW; the wind speed and power generation are measured by a domestic wind farm; the installed capacity of thermal power is 2000 MW; the time scale is set at 1 h; the wind power theoretical output and load forecasting power data etc., refer to the relevant research in the literature [28]. The NSGA-II algorithm is used to solve this multi-objective optimization problem, and the simulations are performed in Python 3.8 to obtain the results.

As shown in Figure 4, the main pumping time of the pumped storage power plant is concentrated at 1–7 and 13–15 h, and the maximum pumping power is reached at 1–7 h; while the main power generation time is concentrated at 9–11 and 18–22 h, while the maximum power generation is reached at 9–11 and 18–21 h. The pumped storage units are in standby mode at 11–13, 15–18, and 22–23 h. After obtaining a reasonable pumping strategy for pumped storage, the amount of water pumping and the amount of electricity generated for a day can be obtained. Then, according to the principle of ensuring the pumping cost of pumped storage power plants is reasonably covered, the expected total revenue of power generation in a day can be calculated.

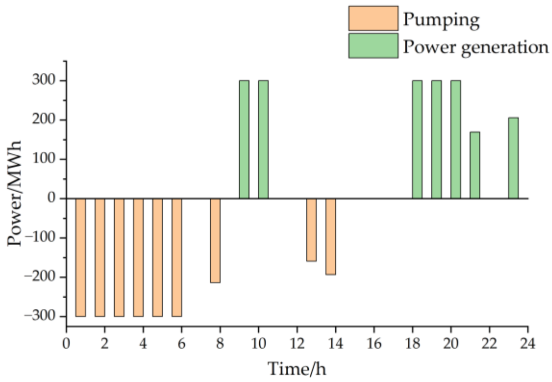


Figure 4. Pumping strategy of pumped storage power station.

According to the capacity tariff approval method in Section 3.1, substitute into Equations (1)–(10). The operating life of the pumped storage power plant is set to 20 years; the cash outflow during the construction period is set to 2 billion CNY; the installed capacity is 300 MW; the annual operation and maintenance fee is 70,000 CNY/year/MW; the reasonable rate of return is 8%, and the tax rate is all calculated according to the relevant national standards. The capacity electricity fee is charged in the form of a contract in units of years or months and can also be divided into unit hours to obtain the corresponding capacity tariff. The calculated capacity tariff of the pumped storage unit is 27,900 CNY/month/MW. Then, according to the actual operating capacity and pumped power generation of the pumped storage unit, the capacity tariff per unit of electricity is obtained. The time-of-use tariff and the capacity average tariff are summed in the unit dispatching period, and finally the two-part tariff in the unit dispatching period is obtained, as shown in Figure 5.

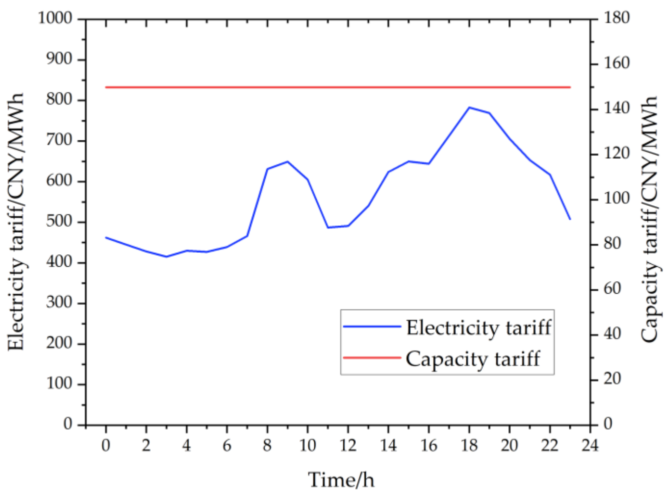


Figure 5. Two-part tariff for pumped storage.

As shown in Figure 5, the pumped storage power plant mainly generates electricity when the user's electricity load and the tariff of other power generation units is high. The peak electricity consumption of the day is reached in the evening time, and its pumped storage electricity tariff is correspondingly higher. The overall daily electricity tariff curve has two peaks at 8–10 and 18–20 h, respectively. In other phases, customer's electricity demand and pumped storage generation decrease, and electricity tariff is correspondingly lower, with the daily power tariff generally at a low point at 2–4 and 11–12 h. Based on the solved daily capacity tariff results, the capacity tariff per unit of electricity can be determined by the daily operating hours of the pumped storage unit and the total amount of pumped generation. Ultimately, the total daily capacity tariff revenue is guaranteed to compensate the capacity cost. The capacity tariff component and the electricity tariff component together form the two-part tariff for pumped storage plants.

4.2. Analysis of Two-Part Tariff

4.2.1. Setting of the Scenarios

In this example system, the fundamental factor affecting the electricity price of pumped storage plants is the pumping cost. The pumping cost is determined by the wind power tariff and the amount of wind power accommodation. In order to study the relationship between the pumped storage tariff and the amount of wind power accommodation, this section compares the impact of wind power accommodation on the pumped storage two-part tariff by setting up four example scenarios, which are shown in Table 1. The sign " × " means there are no such units in the scenario, and the sign "√" means there are such units in the scenario.

Table 1. Setting of the algorithm scenarios.

Example Scenarios	Pumped Storage Units	Wind Turbine	Thermal Power Unit	Source of the Two-Part Tariff
1	×	√	√ (100%)	—
2	√	×	√ (100%)	pumped storage
3	√	√	√ (100%)	pumped storage + wind energy
4	√	√	√ (80%)	pumped storage + wind energy

In scenario 1, there is no pumped storage unit involved in power supply, and the power generated by wind power and the user load do not match. Thus, there is a large amount of curtailed wind power, resulting in a large waste of energy. In this scenario there is no pumped storage unit involved in power supply. Instead, the corresponding pumping cost expectation can be calculated by the cost of wind power generation at the same generation capacity.

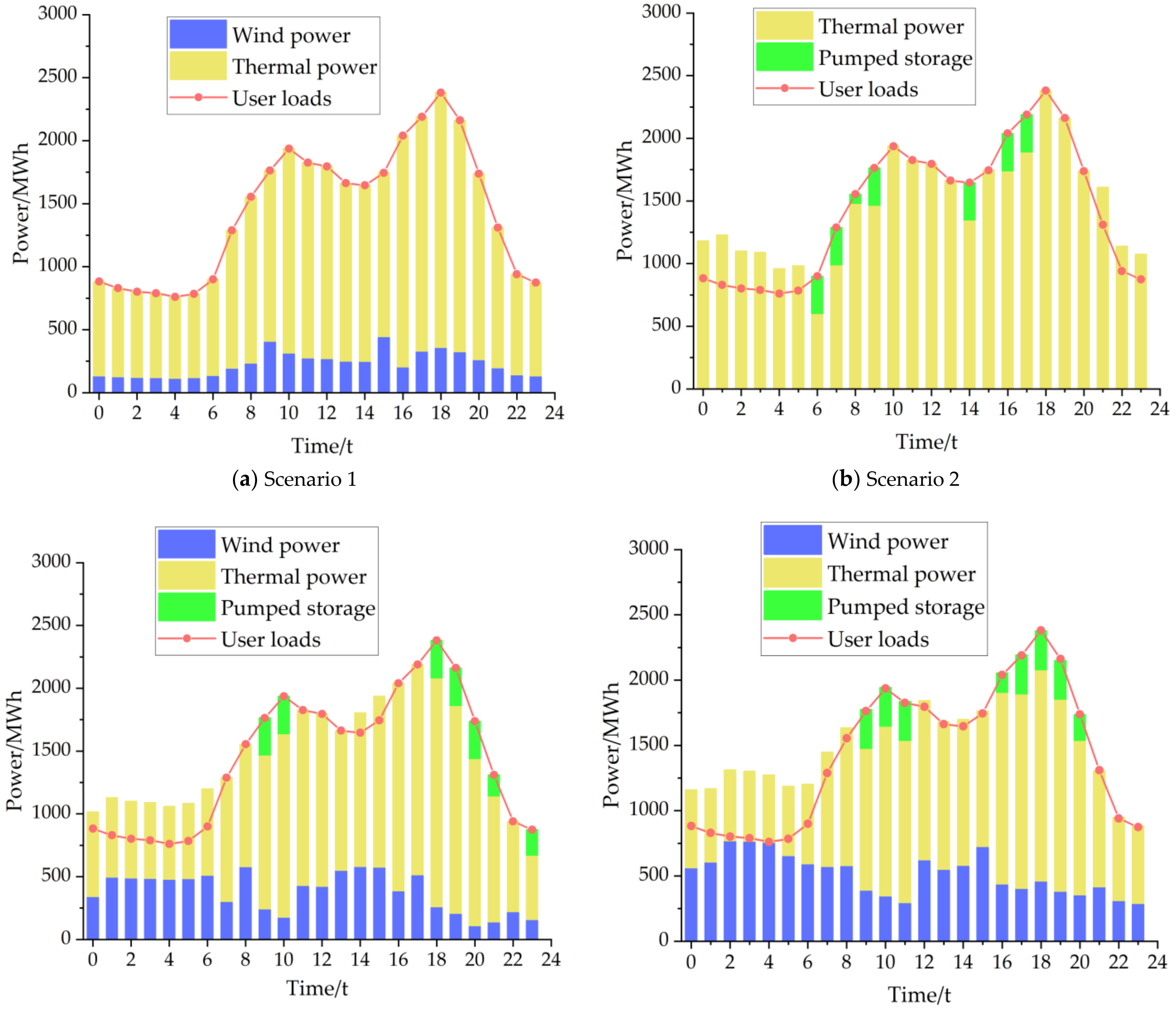
Scenario 2 includes pumped storage without wind turbines, and there may be a problem of low utilization of pumped storage units. The price fluctuation of thermal power is much less than that of wind power, and pumped storage can only use the excess generation capacity of thermal power for storage.

Scenario 3 includes pumped storage units and wind turbines. Pumped storage can store energy during the time when wind power discards a large amount of wind and generates electricity during the time when the electricity load is high, successfully dissipating part of the discarded wind power.

In scenario 4, thermal power output is reduced by 20%, and the amount of curtailed wind that energy storage can participate in dissipating increases. However, there may be a situation where the pumped storage capacity is insufficient to meet the load demand. At this time the pumped storage capacity can be increased appropriately, and the pumping cost is indirectly reflected by comparing the average electricity tariff of pumped storage generation.

4.2.2. Analysis of Unit Output

Before setting the tariff, in order to discuss the feasibility of pumped storage power plants for promoting the efficiency of wind power consumption and reducing fossil energy consumption, the output of each unit in four arithmetic scenarios is listed and analyzed, as shown in Figure 6.



(**a**) Scenario 1 (**b**) Scenario 2 (**c**) Scenario 3 (**d**) Scenario 4

Figure 6. Output of different units in four scenarios.

In scenario 1, without the participation of the pumped storage plant, wind power accommodation is low, and thermal power is involved in supplying power as the main output unit due to its price advantage.

In scenario 2, without the participation of wind turbines, the pumped storage plant pumps water when the thermal price is low and generates electricity when the thermal price is high, ensuring the economic operation of the plant.

In scenario 3, due to the peak-to-valley price difference of wind power, the pumped storage plant is more willing to consume wind power when it is low and to generate power during peak customer load periods, reducing thermal power output as well as fossil fuel consumption.

In scenario 4, the reduction of thermal power output further increases wind power accommodation during low load hours, reflecting the high efficiency of pumped storage plants in promoting wind power accommodation and the feasibility of reducing fossil fuel consumption. Compared to scenario 3, the generation periods of pumped storage plants are more concentrated during peak load hours, because the reduction of the thermal power output amplifies the peaking capacity of the pumped storage, making it necessary to meet the load demand while considering the economics.

4.2.3. Analysis of Cost and Tariff

In order to compare the differences between the two-part tariff pricing mechanisms for pumped storage independent participation and joint participation with wind power in the electricity market, the pumped storage capacity tariff and electricity tariff for scenarios 2, 3, and 4, as well as the thermal power and wind power tariff are presented, as shown in Figure 7.

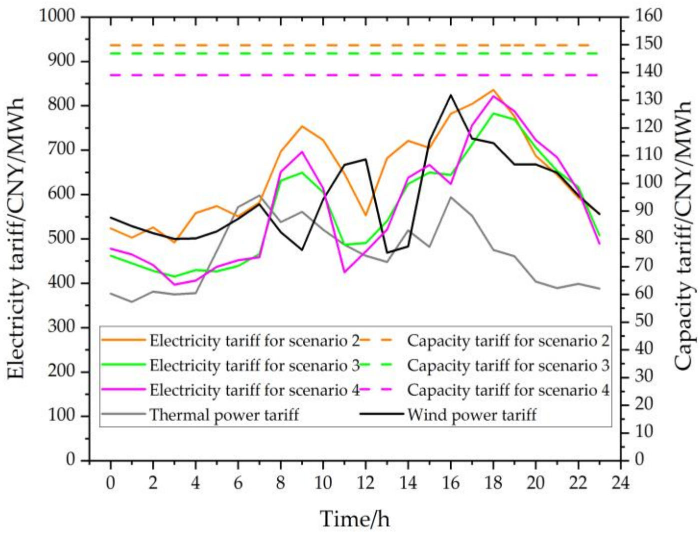


Figure 7. Two-part tariff for each scenario.

In scenario 2, the pumped power of pumped storage mostly comes from thermal power units, with higher pumping costs, resulting in a relatively high overall power tariff. Because of the small peak-to-valley price difference (344 CNY/MWh) for thermal power, the peak-to-valley price difference for pumped storage power is small. The capacity tariff calculated according to the capacity tariff is the highest compared to other scenarios due to the high cost of pumping water in pumped storage power plants without the participation of wind turbines, mainly from thermal power units.

In scenario 3, the pumped storage units and wind turbines participate in electric energy dispatch at the same time, and the pricing mechanism of the capacity tariff does not change because it is mainly used to compensate the fixed costs such as the construction investment of pumped storage power plants. However, the pricing mechanism of the electricity tariff changes significantly compared to scenario 2, due to the fact that the sources of pumped storage power plants' pumped electricity are wind turbines and thermal power units respectively. This results in different pumping and generation strategies in the two scenarios. In this scenario, pumped storage can pump water during the time when the wind power tariff is low, which greatly reduces the pumping cost, and its capacity tariff and the electricity tariff are reduced compared with scenario 2. Moreover, pumped power is mainly provided by wind power, which has a high fluctuation in electricity tariff. The peak-valley difference of the electricity tariff increases (368 CNY/MWh). Thus, pumped storage power plants combined with wind power plants can reduce the capacity tariff and electricity tariff to a certain extent, which improves their competitiveness to participate in the electricity market.

In scenario 4, the thermal unit output decreases and the output requirement of pumped storage increases. Compared with scenario 3, the peak-valley difference of the pumped storage electricity tariff further increases to 425 CNY/MWh, and the peak electricity tariff reaches a maximum of 822 CNY/MWh. The capacity tariff has a small decrease compared with scenario 3. To further analyze the relationship between pumping cost and two-part tariff under different scenarios, the pumped electricity, pumping cost expectation, average capacity tariff, and average electricity tariff under four scenarios are presented in Table 2.

Table 2. Comparison of pumping costs and two-part tariff for each scenario.

Scenario	Daily Pumping Power/MWh	Daily Pumping Cost/$\times 10^4$CNY	Average Pumping Cost/CNY/MWh	Average Electricity Tariff/CNY/MWh	Average Capacity Tariff/CNY/MWh
1	—	118.62	632.64	645.29	—
2	2500	115.54	462.16	624.21	149.81
3	2500	102.93	411.72	559.94	146.83
4	2700	111.46	412.81	561.43	139.11

As shown in Table 2, in the generation side system without pumped storage in scenario 1, the cost of wind power is significantly higher than the other three scenarios for the same amount of pumped power, and the average pumped cost (632.64 MWh) and average electricity tariff (645.29 MWh) are the highest when losses are taken into account. This is the scenario which focuses on the benefits of wind farms as the main study [23].

In scenario 2, due to the low fluctuation of thermal power prices, it is difficult for the pumped storage units to realize the operation strategy of "low price pumping and high price discharging", resulting in a total daily pumping cost 126,100 CNY higher than that of scenario 3. The average power price and average capacity price are 64.27 CNY/MWh and 2.98 CNY/MWh larger, respectively.

In scenario 3, compared to scenario 1, the participation of pumped storage plants optimizes wind power accommodation, and the combined system reduces costs by 34.9% and increases revenues by 13.2% compared to wind turbines alone. In addition, the economy of pumped storage is better than that of scenario 2, because it pumps and stores electricity when the wind power price is low and generates electricity when the electricity load is high. The total pumping cost, average pumping cost, average electricity tariff, and average capacity tariff are all better than those of scenario 2, showing that pumped storage combined with wind power can significantly improve the economy of the system.

Compared to scenario 3, wind storage combined system power supply increases in scenario 4, which requires an appropriate increase of the installed capacity of pumped storage. In the case of increased pumped power, the total daily pumping cost increases by 85,300 CNY. The average power tariff also has a small increase by 1.49 CNY/MWh. However, due to the increase in total power generation, the capacity tariff to compensate for the fixed costs compared to scenario 3 is reduced by 7.72 CNY/MWh. It is apparent that the installed capacity of a pumped storage power plant has an impact on the pumping cost, from which its own factors such as installed capacity, upper reservoir capacity, initial daily storage capacity, and pumping efficiency may also have an impact on the pumping cost.

4.3. Sensitivity Analysis of Two-Part Tariff for Pumped Storage

From Section 4.2, the factors of pumped storage power plants may have an impact on the pumping cost and thus on the generation price. Thus, the sensitivities of the factors are analyzed in this section.

4.3.1. Impact of Installed Capacity of Pumped Storage Units on Two-Part Tariff

As shown in Table 3, the pumping cost decreases with the increase of installed capacity. This is because in the same period, power plants with large installed capacity can store more electricity for power generation when the wind power tariff is low, which can better absorb the curtailed wind power. They can also reduce their own pumping cost, as well as reduce the electricity tariff part of the two-part tariff. However, the installed capacity cannot be increased infinitely due to technology, while the capacity of the domestic pumped storage single unit is generally 200 MW or 300 MW. Thus, the installed capacity can be 300 MW.

Table 3. Pumping costs at different installed capacities.

Installed Capacities	200	250	300	400
Pumping Costs	106.41	104.07	102.93	101.68

4.3.2. Impact of Pumped Storage Plant Storage Capacity on Two-Part Tariff

The maximum reservoir capacity and the initial daily capacity of pumped storage plants have an impact on the pumping cost. The reason is that pumped storage power plants cannot pump infinitely when pumping water, due to the limitation of the lower reservoir volume and the remaining capacity of the upper reservoir, and similarly when generating electricity. The maximum reservoir capacity also has limitations on the amount of water pumped and generated. The installed capacity of the pumping units is set at 300 MW.

The optimal storage size for different energy storage costs is considered in the literature [23]. Similarly, the optimal storage size and the capacity of pumped storage power plants are discussed here based on a method to improve the economics of pumped storage and provide the basis for the construction and operation of pumped storage power plants.

As shown in Table 4, in this example system, when the upper limit of the reservoir capacity is 20–30 million m^3, the cost of pumping water is the lowest, and the corresponding electricity tariff is also the lowest. Moreover, the unused part of the reservoir capacity is very large at this time, and the excess capacity is wasted. When it is reduced to 19.1 million m^3, the pumping cost can still remain at 1,029,300, and the capacity-to-capacity ratio is 1:6.37 (MW/10,000 m^3). The lowest pumping cost and the lowest electricity tariff component of the two-part tariff is achieved when the upper and lower initial storage capacity ratios are 1:1. Because their ability to cope with both pumping and generation is stronger when the upper and lower storage capacities are relatively close to each other, they can adapt to changes in a variety of load conditions. In contrast, when the capacity ceiling is small or the difference between the upper and lower initial reservoirs is large, a feasible pumping and generation strategy is not available because it cannot meet the customer load requirements.

Table 4. Pumping costs of power plants with different parameters.

Upper and Lower Storage Capacity Ratio \ Storage Capacity Limit /$\times 10^4$ m^3	3000	2500	2000	1500	500
4:1	105.86	107.39	109.75	—	—
2:1	102.93	103.39	104.21	105.94	109.75
1:1	102.93	102.93	102.93	103.60	105.86
1:2	103.27	103.60	104.58	106.26	109.75
1:4	105.86	107.39	109.75	—	—

5. Conclusions

This paper studies the two-part tariff for pumped storage combined with wind power to participate in the electricity market. An optimal dispatching model for pumped storage power plants and wind farms to jointly participate in the electricity market is established to find the optimal pumping and generation strategy for pumped storage and to calculate its capacity tariff and electricity tariff. The strategy is verified through case studies. The impact of the installed capacity and reservoir capacity of pumped storage power plants on the power generation tariff is also studied. The following conclusions were obtained.

1. Pumped storage power plants combined with wind power plants to participate in the electricity market can increase the amount of wind power accommodation, reduce fossil energy consumption, and significantly improve the economy of the joint operation system.
2. The electricity tariff of a pumped storage power plant is mainly determined by the pumping cost and the capacity electricity price is mainly determined by the capital investment and total generation capacity during the construction period. The electricity tariff and the capacity tariff are 560 CNY/MWh on average and 146.83 CNY/MWh, respectively, in the example.
3. The electricity tariff of pumped storage power plants decreases as the installed capacity increases. The lowest electricity tariff is achieved when the appropriate reservoir capacity is selected, and the upper and lower initial reservoir capacity ratios are 1:1. The electricity tariff of a pumped storage power plant is lowest when the ratio of the capacity to the upper reservoir capacity is 1:6.37 (MW/million m^3).

Pumped storage plants can also improve wind power accommodation by participating in the auxiliary service market, including the electricity capacity market and the rotating standby market, further improving the economy of their operation. The subsequent research studies can be continued in future work.

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