

Article

Cost Recovery for Variable-Speed Pumped Storage Power Plants in the Market Environment

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Abstract: As the construction of the new power system progresses, pumped storage plays an important role in the system as a typical regulating resource. However, the regulating capacity of traditional fixed-speed pumped storage units is limited and it is difficult to meet the increasing flexibility demands of system regulation. This paper studies the operation and cost recovery of pumped storage power stations based on doubly-fed variable-speed technology in the market environment. Using a combination of theoretical analysis and case study, the working principles and technical advantages of doubly-fed variable-speed pumped storage technology are first explained. We then develop a revenue model encompassing both the energy and ancillary service markets and analyze the impact of different pricing mechanisms on cost recovery for variable-speed pumped storage power stations within the current situation of China's electricity market. The research results indicate that under the combined effects of the electricity spot market and the ancillary service market, the flexibility value of variable-speed pumped storage power stations can be fully reflected, significantly increasing their revenues and enabling cost recovery and profitability. In the future, the pricing mechanisms of the electricity and ancillary service markets should be further improved, the functional positioning of pumped storage power stations should be optimized, and their support capabilities for the new power system should be enhanced.



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1. Introduction

To achieve the dual-carbon goals of carbon peaking and carbon neutrality, the proportion of new energy sources, primarily wind and solar, integrated into the new power system is gradually increasing [1]. However, due to the randomness, volatility, and uncertainty of new energy generation, the power system will face challenges in ensuring power supply security, accommodating new energy, and maintaining safe and stable operation. Therefore, flexible regulatory resources are particularly crucial for the construction and operation of new power systems [2].

As a typical regulatory power source, pumped storage is currently the most mature large-capacity energy storage technology, characterized by its operational flexibility, rapid response, large capacity, and long operational lifespan [3,4]. Compared to new energy storage technologies, pumped storage has unique advantages in terms of technological

development, economic efficiency, and construction scale, enabling it to play a greater regulatory role in new power system. Therefore, China has accelerated the construction of pumped storage in recent years: according to the Pumped Storage Industry Development Report 2022, by the end of 2022, China built 45.79 million kW of installed capacity of pumped storage, and according to the Medium and Long Term Development Plan for Pumped Storage (2021–2035): by 2025, the total operational scale of pumped storage will exceed 62 million kW; by 2030, this figure is expected to be approximately 120 million kW.

However, the currently operational pumped storage power stations in China are primarily composed of fixed-speed units with synchronous motors. Due to their control methods, their rotational speed remains constant and non-adjustable during the pumping mode, resulting in insufficient operational flexibility and limiting their role to peak shaving and valley filling [5,6]. As the proportion of new energy sources in the new power system continues to increase and the scale of pumped storage power stations expands, the characteristics of high-proportion new energy sending-end grids, characterized by “large-scale DC transmission, large-scale new energy, and weak AC systems”, become more prominent. Issues such as low system short-circuit capacity and instability in frequency and voltage become more acute. Consequently, the role of pumped storage power stations will evolve from merely being energy storage devices to becoming regulatory power sources with rapid system response speed, wide load power regulation capability, and high efficiency [7].

The application of variable-speed technology endows pumped storage units with the capability to operate at different rotational speeds. This characteristic greatly enhances the regulatory capacity of the units, making their operation more flexible, rapid, efficient, and reliable. Additionally, variable-speed technology allows the units to automatically adjust the motor speed and guide vane opening to maintain optimal operation under the given head and output requirements, resulting in lower mechanical wear and improved operational efficiency [2,8].

In recent years, with the increasing role of variable-speed pumped storage in power systems, research on variable-speed pumped storage has also been increasing. Apart from research on transient modeling and control, significant portions of studies focus on joint optimization with other power sources and operational strategies for participating in electricity markets. Variable-speed pumped storage power stations can coordinate with wind energy and achieve optimal energy management under the uncertainty of wind power forecast errors [9]. Additionally, pumped storage stations can operate in combination with wind, solar, and thermal energy, effectively mitigating the intermittency of wind and solar power generation while achieving cost savings and carbon emission reductions [10,11]. Pumped storage has even been applied to rural electrification, reducing the operational costs of distributed hybrid systems (wind-PV-diesel) and saving fuel [12,13]. The Western Electricity Coordinating Council (WECC) has conducted modeling tests on variable-speed pumped storage under different levels of renewable energy penetration [14]. Furthermore, there have been many comparative studies on the joint operation of fixed-speed and variable-speed pumped storage with renewable energy sources [8,14–16].

Research on the participation of variable-speed pumped storage in the electricity market can be divided into two parts: participation as an independent market entity and participation as part of a combined system with other renewable energy sources. In China, considering the development of the electricity market, most studies on pumped storage participation focus on institutional design, cost recovery under imperfect market mechanisms, and improving existing policies through full lifecycle benefit evaluation to facilitate the transition of pumped storage to an independent market entity [17]. Most studies are based on the mature development of the electricity markets and ancillary service markets. Some studies focus on pumped storage as a price taker for self-scheduling to

achieve operation. Many studies focus on the joint operation of pumped storage and wind power, optimizing management for reliable power supply, achieving profitability in the market, and reducing penalty costs [18]. Pumped storage combined with photovoltaic power generation in small agricultural activities can minimize electricity costs and reduce power consumption from the grid [13]. Additionally, pumped storage can be combined with wind, solar, and hydropower to form a multi-energy complementary system, enhancing the benefits of all entities in the system and achieving fair distribution of incremental benefits, promoting the integration of renewable energy. Furthermore, research on bidding strategies for pumped storage focuses on the different benefits brought by the risk due to uncertainty.

However, at present, the electricity price mode of pumped storage power stations adopts two-part electricity price, that is, electricity price and capacity price. The electricity price is arbitrage income from the peak and valley price difference: in the place where the power spot market operates, the pumped electricity price and the on-grid price of pumped storage power stations are settled according to the spot market price and rules; in the place where the power spot market has not yet operated, the pumped electricity price is executed at 75% of the base price of coal-fired power generation, and the on-grid electricity price is executed according to the base price of coal-fired power generation. The capacity electricity price is only verified by policy documents for each pumping and storage power station put into operation. These regulations bear on the development of China's power market, but they are not friendly to the operation and cost recovery of pumping and storage, and there are few studies on such issues, while the construction cost of variable-speed pumping and storage is higher, and it is urgent to study its cost recovery.

Therefore, this paper investigates the operational model and cost recovery mechanism of variable-speed pumped storage power stations against the backdrop of the gradual advancement of China's spot market and the establishment and improvement of the ancillary services market. First, the structure of mainstream variable-speed power stations is analyzed, and the working principles and technical characteristics of doubly-fed variable-speed pumped storage technology are deeply examined. Based on this, a mathematical model for doubly-fed variable-speed pumped storage power stations considering wide load and high efficiency characteristics is established. A clearing model for doubly-fed variable-speed pumped storage power stations considering the reserve market is proposed. Finally, based on a case study in a specific region of China, the impact of different factors on the cost recovery of the power station is analyzed. Furthermore, the functional positioning of pumped storage power stations in the power system under different cost recovery methods is discussed.

The main contributions of this paper are as follows:

- (1) Under the background of large-scale development of pumped storage and the gradual application of technologies such as doubly-fed variable-speed, this paper clearly elaborates on the three major operational characteristics of doubly-fed variable-speed pumped storage power stations compared to conventional pumped storage, based on technical principles. These characteristics are: wide load operating capability, variable efficiency operating characteristics, and highly flexible operating strategies. The corresponding operational advantages are also explained.
- (2) A mathematical model of a doubly-fed pumped storage power station that considers wide load and variable efficiency operating characteristics is proposed. Innovatively, a linearization method for the variable efficiency operation of doubly-fed pumped storage power stations is introduced, solving the non-linear problem caused by the multiplication of power and efficiency variables.
- (3) Considering the development of spot markets in different regions of China, a grid and electricity pricing model composed of benchmark and floating prices is proposed.

Case analysis is conducted based on Chinese policy documents, and the impact of prices, markets, and other factors on the cost recovery of doubly-fed variable-speed pumped storage power stations is analyzed from multiple perspectives, taking into account the functional positioning of pumped storage in the power system.

2. Overview of the Principles and Technical Characteristics of Doubly-Fed Variable-Speed Pumped Storage Power Stations

2.1. The Principle of Doubly-Fed Variable-Speed

Currently, operational variable-speed pumped storage units can be classified into two types based on speed variation principles: doubly-fed and full-power. Doubly-fed variable-speed pumped storage units consist of a pump turbine and a doubly-fed induction motor. Their main structure is similar to that of fixed-speed pumped storage units, but with the difference that the rotor of the induction motor is connected to the grid through a converter. Speed variation in pump mode is achieved through coordinated control by the converter and the governor. This type can be used for large-capacity variable-speed pumped storage units, such as the Hebei Fengning Pumped Storage Power Station [19].

On the other hand, full-power variable-speed pumped storage units differ from fixed-speed units by having a full-power frequency converter between the stator and the grid. The principle of speed variation is similar to that of integrating new energy sources into the grid via power electronic devices [20]. Consequently, this technology is mainly applied to small-capacity variable-speed pumped storage stations, such as the Sichuan Chunchangba Pumped Storage Power Station. The specific structures of the three types of pumped storage power stations are shown in Figure 1.

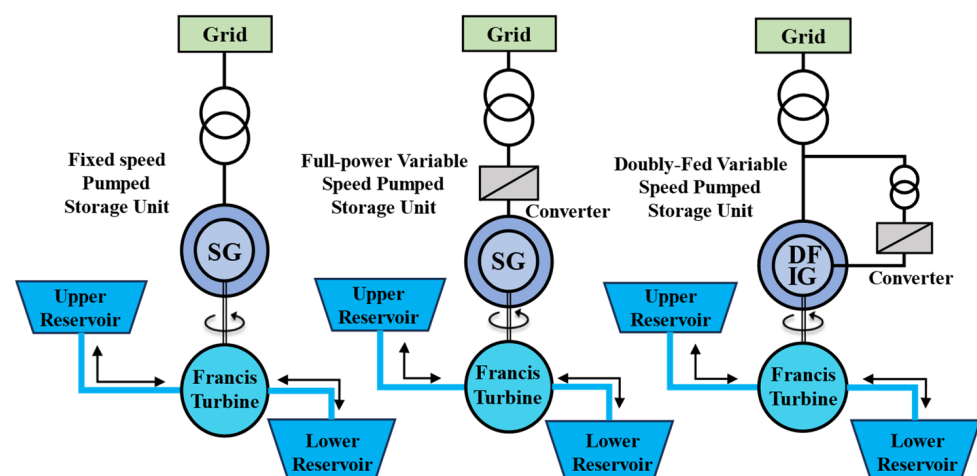


Figure 1. The specific structure of three kinds of pumped storage power plants.

The principle of full-power variable-speed technology is simple, its application scale is small, and it cannot flexibly meet system regulation needs. In contrast, the doubly-fed variable-speed pumped storage unit uses a three-phase symmetrically distributed excitation winding on the rotor, which is supplied with excitation current by a frequency converter with adjustable amplitude, frequency, phase, and phase sequence. This creates a rotating AC magnetic field. Compared to full-power variable-speed pumped storage units, the rotor winding power is determined by the slip power, which means the capacity of the converter only needs to match a portion of the motor capacity, significantly reducing the cost of the converter. Therefore, this paper primarily focuses on doubly-fed variable-speed pumped storage units.

Taking a standard wound-rotor induction motor as an example, the stator winding is supplied with AC power at a frequency of f_1 , generating a rotating magnetomotive force ($\dot{F}_1$). The speed n_1 of ($\dot{F}_1$) is synchronous speed, which is given by [21]:

$$n_1 = \frac{60f_1}{p} \quad (1)$$

In this formula, p is the number of pole pairs of the winding.

The short-circuited rotor winding generates a current through induction, and the energized rotor accelerates under the action of the air-gap magnetic field. When stable, the frequency of the induced current is f_2 , generating an excitation magnetomotive force ($\dot{F}_2$) at the speed of n_2 . The relationship between n_2 and f_2 is given by [21]:

$$n_2 = \frac{60f_2}{p} \quad (2)$$

The slip ratio s is defined as [21]:

$$s = \frac{n_1 - n_2}{n_1} \quad (3)$$

To ensure continuous and stable power output, the speed difference between the stator and rotor magnetomotive force must be sufficiently small. The typical operational slip ratio s for asynchronous motors ranges from 0.01 to 0.05. In the context of variable-speed pumped storage units operating in pump mode, this adjustment range is very small and can be negligible.

To enhance the adjustable range of pumped storage units under pump mode and meet the regulation needs of modern power systems, the rotor winding of doubly-fed asynchronous motors is supplied with AC power at a frequency f_s , generating a magnetomotive force $\dot{F}_s$ at the speed of n_s . This setup ensures that the composite formed by the magnetomotive force generated by rotor rotation $\dot{F}_2$ and the AC excitation magnetomotive force $\dot{F}_s$ rotates synchronously with $\dot{F}_1$. This can be expressed as [22]:

$$n_2 \pm n_s = n_1 \quad (4)$$

In this way, supplying power through the converter allows for both generating and motoring in super-synchronous and sub-synchronous states, achieving variable-speed constant frequency operation. This breaks the strong dependency between rotor speed and grid frequency, expanding the adjustable range of pumped storage units under pump mode. The T-S diagram of the doubly-fed asynchronous motor is shown in Figure 2.

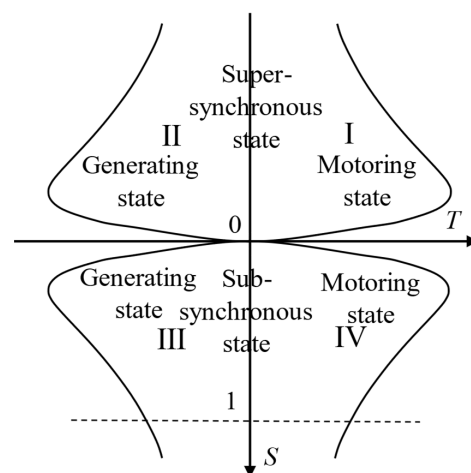


Figure 2. T-S diagram of doubly-fed induction motor.

2.2. Technical Characteristics of Doubly-Fed Variable-Speed Pumped Storage Power Stations

2.2.1. Wide Load Operating Capability

The minimum output of a conventional fixed-rate pumped storage unit in the generation mode is usually set to 50% P_N , and non-adjustable power in the pumping mode, with a minimum input of 100% P_N . In contrast, the rotor of doubly-fed variable-speed units utilizes AC excitation technology to partially decouple power from hydraulic input. This allows the minimum output in the generation mode to be reduced to 30~40% P_N , and the input range in the pumping mode to be adjusted to 70~100% P_N .

2.2.2. High Efficiency Operating Characteristics

Whether conventional fixed-speed or doubly-fed variable-speed pumped storage units, their operating efficiency is not constant. For fixed-speed pumped storage units, the power in the pumping mode is constant. In this case, the operating efficiency fluctuates slightly due to hydraulic factors, which can be neglected from a planning and operational perspective. In the generation mode, although the power of fixed-speed pumped storage units can vary within a certain range, due to the small scale and low utilization hours of pumped storage in traditional power systems, the efficiency of these units in partial load conditions has a negligible impact on system operation. Combining this with practical operating experience, the “pump four generate three” principle can cover most operational scenarios, making it scientifically valid to set the operating efficiency of fixed-speed pumped storage units at a fixed value of 75%. However, when doubly-fed variable-speed technology is applied to pumped storage units, the units can achieve the highest efficiency under current conditions by automatically adjusting the speed and guide vane opening through the governor and guide vane servo mechanism, while meeting the corresponding head and output requirements. Comparing the efficiency of fixed-speed and variable-speed pumped storage units, it is evident that the energy conversion efficiency of variable-speed units is higher than that of fixed-speed units in most power dispatch scenarios, especially when the units operate under partial load conditions.

2.2.3. Highly Flexible Operating Strategy

The functional positioning of pumped storage units in the system requires them to have high flexibility. Compared to fixed-speed pumped storage, the response speed and transition time between operating conditions of doubly-fed variable-speed pumped storage units are significantly reduced. The four-quadrant operational capability broadens the operating conditions of variable-speed pumped storage. The operating conditions of doubly-fed variable-speed pumped storage units can be categorized into three types: stable, temporary, and special conditions. Stable conditions include shutdown, idling, no-load, generation, generation with phase shifting, pumping with phase shifting, and pumping states. Temporary conditions include intermediate shutdown and rotational states. Special conditions refer to black start states. The rapid response characteristics of doubly-fed variable-speed pumped storage units endow them with the ability to flexibly switch between multiple operating conditions, providing more options for operational decision making and allowing for optimal operation based on revenue and dispatch requirements.

3. Clearing Model for Doubly-Fed Variable-Speed Pumped Storage Power Stations Considering Wide Load and High Efficiency Characteristics

3.1. High Efficiency Operation Principle of Variable-Speed Unit Considering Mechanical Factors

3.1.1. Derivation of the Power–Speed–Flow Relationship

Based on the description of the characteristics of variable-speed units in practical centrifugal pumps [22], the relationship between power and speed is derived [22]:

$$\frac{P_1}{P_N} = \left(\frac{N_1}{N_N} \right)^3 \quad (5)$$

where P_1 is the power at different times, P_N is the rated power, N_1 is the speed at different times, and N_N is the rated speed.

By applying an equivalent mathematical expression to (5), the relationship between power and rotational speed can be expressed as [22]:

$$N(P) = \sqrt[3]{P}, \quad P_{\min} \leq P \leq P_{\max} \quad (6)$$

Since the relationship between P and N in the above equation is non-linear, it needs to be piecewise linearized using mathematical methods.

According to the required computational accuracy, $n + 1$ segmentation points $[a_1, a_2, \dots, a_{n+1}]$ are selected, dividing the original function into n intervals, transforming (6) into (7)–(9) [23].

$$N(P) = \begin{cases} k_1 P + c_1, & a_1 \leq P < a_2 \\ k_2 P + c_2, & a_2 \leq P < a_3 \\ \vdots & \vdots \\ k_n P + c_n, & a_{n-1} \leq P \leq a_n \end{cases} \quad (7)$$

$$k_m = \frac{N(P_{m+1}) - N(P_m)}{P_{m+1} - P_m} \quad (8)$$

$$c_m = N(P_m) - \frac{N(P_{m+1}) - N(P_m)}{P_{m+1} - P_m} P_m \quad (9)$$

Introducing $n + 1$ continuous auxiliary variables $[b_1, b_2, \dots, b_{n+1}]$ and n binary auxiliary variables $[d_1, d_2, \dots, d_n]$, such that they satisfy (10)–(15).

$$b_j \geq 0 \quad (10)$$

$$b_1 \leq d_1 \quad (11)$$

$$b_{n+1} \leq d_n \quad (12)$$

$$b_j \leq d_{j-1} + d_j \quad (13)$$

$$\sum_{j=1}^{n+1} b_j = 1 \quad (14)$$

$$\sum_{j=1}^n d_j = 1 \quad (15)$$

By introducing these variables, (17) can be transformed into (24).

$$\begin{cases} P = \sum_{j=1}^{n+1} d_j a_j \\ N = \sum_{j=1}^{n+1} d_j N(a_j) \end{cases} \quad (16)$$

Since speed and flow rate among the adjustable parameters play a decisive role in the efficiency of the variable-speed unit's pump operation, the expression of the flow rate varying with speed is deduced through the coupling adjustment relationship between speed and flow rate:

$$q(N) = eN + f \quad (17)$$

where N is the input speed, q is the output flow rate, e is the fitting slope, and f is the fitting intercept, as detailed in Table 1.

Table 1. Fitting coefficient between flow rate and rotational speed.

Parameter	Value
e	3.197492067
f	2.039914169

By linear fitting the data, the reverse derivation from power to speed and then to flow rate is achieved.

3.1.2. Relationship Between Efficiency, Flow, and Speed

Based on efficiency data of variable-speed pumped storage units under different flow rates and speeds, a second-order cone model of efficiency as a function of flow rate and speed is fitted, expressed as follows:

$$\eta(q, N) = Aq^2 + BN^2 + CqN + Dq + EN + F \quad (18)$$

$$\eta(N) = (Ae^2 + B + Ce)N^2 + (2Aef + Cf + De + E)N + Af^2 + Df + F \quad (19)$$

where $\eta(q, N)$ is the efficiency determined by speed and flow rate, q is the flow rate, N is the speed, and A to F are the fitting coefficients, as detailed in Table 2.

Table 2. Fitting coefficient of efficiency with respect to flow rate and rotational speed.

Parameter	Value	Parameter	Value
A	−1.09820	D	13.810658
B	60.42876	E	94.941557
C	17.358743	F	36.328550

3.2. Model of Doubly-Fed Variable-Speed Pumped Storage Power Stations

Currently, most power plants with variable-speed pumped storage units consist of a certain proportion of both fixed-speed and variable-speed units. However, as pumped storage continues to develop on a larger scale, the proportion of variable-speed units will gradually increase. Therefore, this study assumes a doubly-fed variable-speed pumped storage power plant composed of multiple doubly-fed variable-speed units, sharing a common upper and lower reservoir. It is assumed that the maximum power output of each unit is the same in both pumping and generating modes. By ignoring the impact of shared pipelines among multiple units, the plant's multiple units can be combined into a single

larger capacity unit for analysis. Considering the fast power response capability of variable-speed pumped storage units, output ramp constraints are temporarily not considered. Compared to conventional pumped storage power plants, variable-speed pumped storage power plants have a stronger ability to handle power system load fluctuations, enabling them to respond more quickly in peak shaving and valley filling, increasing their dispatch frequency. Additionally, variable-speed pumped storage power plants also undertake tasks such as frequency regulation and phase shifting, resulting in frequent condition transitions. Therefore, the daily start–stop constraint for variable-speed pumped storage power plants is not considered.

3.2.1. Output Constraints

- The pumping mode

In the pumping mode, compared to full-power and fixed-speed pumped storage, doubly-fed variable-speed pumped storage has a wider operational adjustment range. The output constraint is expressed as follows:

$$y_t^p P_{min}^{pum} \leq P_t^{pum} \leq y_t^p P_{max}^{pum}, t \in \Gamma_t \quad (20)$$

where P_t^{pum} is the pumping power exchanged between the pumped storage power plant and the grid at time period t , P_{min}^{pum} and P_{max}^{pum} are the minimum and maximum allowable pumping powers, respectively, y_t^p denotes the pumping operational state during period, and t, Γ_t represents the set of operational times for the station.

The output constraint for fixed-speed pumped storage units is expressed as follows:

$$P_t^{pum} = y_t^p P_{max}^{pum}, t \in \Gamma_t \quad (21)$$

- The generation mode

The output constraint of a doubly-fed variable-speed pumped storage power plant in the generation mode can be described as follows:

$$x_t^g P_{min}^{gen} \leq P_t^{gen} + P_t^{spi} \leq x_t^g P_{max}^{gen}, t \in \Gamma_t \quad (22)$$

where P_t^{gen} and P_t^{spi} are the generating power and spinning reserve power exchanged between the pumped storage power plant and the grid at time period t , P_{min}^{gen} and P_{max}^{gen} are the minimum and maximum allowable generating power per time period, respectively, both constrained by the structure of the pump-turbine, and x_t^g is the generating operation state at time period t .

3.2.2. Operational State Constraints

Similar to conventional storage power plants, a variable-speed pumped storage power plant can only operate in one mode at any given time—generation, pumping, or shutdown. The operational state constraint is expressed as follows:

$$x_t^g + y_t^p + z_t^s = 1 t \in \Gamma_t \quad (23)$$

where z_t^s is the shutdown state at time period t .

3.2.3. Reservoir Capacity and Continuity Constraints

The output constraint of a doubly-fed variable-speed pumped storage power plant in the generation mode can be described as follows [24]:

$$E_{min} \leq E_t \leq E_{max} \quad t \in \Gamma_t \quad (24)$$

$$E_t = E_{t-1} + y_t^p P_t^{pum} \eta^{pum} - x_t^g P_t^{gen} / \eta^{gen} - \lambda P_t^{spi}, \quad t \in \Gamma_t \cap \{t | t \geq 2\} \quad (25)$$

where E_t represents the converted power generation from the reservoir capacity during time period t , E_{max} is the equivalent power generation of the maximum upper reservoir capacity, and E_{min} is the equivalent power generation of the minimum upper reservoir capacity. η_t^{pum} is the efficiency of the plant in the pumping mode at time period t , η^{gen} is the efficiency in generating mode, and λ represents the head loss of the pumped storage unit in spinning reserve mode.

3.2.4. Maximum Continuous Pumping and Generating Time Constraints

The single-mode duration constraints for a doubly-fed variable-speed pumped storage power plant are as follows:

$$\sum_{t=k}^{k+T_{max}^{gen}-1} x_t^g \leq T_{max}^{gen}, \quad k \in \{1, 2, \dots, 25 - T_{max}^{gen}\} \quad (26)$$

$$\sum_{t=k}^{k+T_{max}^{pum}-1} y_t^p \leq T_{max}^{pum}, \quad k \in \{1, 2, \dots, 25 - T_{max}^{pum}\} \quad (27)$$

where T_{max}^{pum} and T_{max}^{gen} are the maximum allowable continuous pumping time and maximum allowable continuous generating time, respectively.

3.3. Considering the Electricity Pricing Settings in the Context of China's Market Environment

Currently, there are clear policies regarding the electricity pricing for pumped storage power stations in China: In regions where the electricity spot market is operating, the water pumping price and the on-grid electricity price of the power station are settled according to the spot market. In regions where the electricity spot market is not yet operating, the on-grid electricity price of the power station follows the benchmark price for coal-fired power generation, and the water pumping price is executed at 75% of the benchmark price for coal-fired power generation.

Based on the spot market prices in regions where the electricity spot market is operating and the benchmark prices in regions where the electricity spot market is not yet operating, this paper assumes that the on-grid electricity price satisfies:

$$p_t = p_b + p_f \quad (28)$$

where p_t is the on-grid electricity price in period t ; p_b is the benchmark on-grid electricity price in period t ; and p_f is the floating on-grid electricity price in period t , which follows a normal distribution, i.e.,

$$p_f \sim N(\mu_t, \sigma_t^2) \quad (29)$$

where t is the period identifier; μ_t is the expected value of the floating on-grid electricity price in period t ; σ_t^2 is the variance of the floating on-grid electricity price in period t , reflecting different pricing mechanisms through different variances.

To facilitate the operation of pumped storage power stations as independent market entities in the power grid, when the pumped storage power station is in the pumping mode, it needs to purchase electricity from the grid like other industrial electricity facilities. Considering the transmission and distribution fees, the electricity price for pumped storage power stations in the same period should be higher than the on-grid electricity price. Therefore, this paper assumes the electricity price for pumping as $p_t^p = (1 + k)p_t$.

3.4. Operational Modelling of a Doubly-Fed Variable-Speed Pumped Storage Plant Considering the Standby Market

3.4.1. Objective Function

The model aims to maximize the net revenue of a pumped storage power plant in the current electricity market environment. The revenue includes the peak–valley price difference in the electricity market over a cycle, the revenue from unused spinning reserve capacity, and the revenue from the energy called upon within the reserve capacity.

Objective function:

$$\max W = \sum_{t=1}^{24} (P_t^{gen} p_t - P_t^{pum} p_t^p + P_t^{spi} p_t^{spi} + P_t^{spin} p_t^{spin}) \quad (30)$$

where P_t^{spin} is the spinning reserve power called upon at time t ; p_t , p_t^p , p_t^{spi} , and p_t^{spin} are the electricity prices for generation, pumping, spinning reserve capacity, and the energy called upon within the spinning reserve at time t , respectively.

3.4.2. Constraints

This section integrates the doubly-fed variable-speed pumped storage power plant model into the system operation. The system's reserve capacity demand includes both system load reserve constraints and system contingency reserve constraints. This paper does not distinguish between these two types of reserves and assumes that the variable-speed pumped storage power plant can self-schedule to allocate reserve and generation power, as shown in the following:

$$P_t^{spin} = k_{spin} P_t^{spi} \quad t \in \Gamma_t \quad (31)$$

$$p_t^{spin} = k_{sp} p_t \quad t \in \Gamma_t \quad (32)$$

Considering the uncertainties in load and renewable energy output, it is assumed that the energy called upon within the spinning reserve constitutes a proportion k_{spin} of the total reserve energy, with this proportion being less than 1. The coefficient k_{sp} defines the price factor for energy called upon within the spinning reserve market, generally greater than 1, indicating that energy called upon from spinning reserve is more expensive than normal electricity purchases, reflecting the value of ancillary services.

The overall system constraints include the constraints of the doubly-fed variable-speed pumped storage power station model (20) to (27) and the system reserve constraints (31) to (32).

4. Results and Discussion

4.1. Parameter Settings

The parameters of the pumped storage power plant example are shown in Table 3. According to the Appendix of Document No. 633, "Method for Determining the Capacity Electricity Price of Pumped Storage Power Plants", the capacity electricity price is determined based on a 40-year operation period, a 6.5% internal rate of return on capital, total project investment, capital investment, loan interest rate, and operation and maintenance

rate, among other parameters. The unit cost of the power plant is calculated at 971.43 USD/kW, based on the average unit cost of a pumped storage power plant under construction in a certain region of China, where the cost level is higher than other regions in the country. Based on a 40-year operation period and a 6.5% internal rate of return on capital, the capacity electricity price is 64.49 USD/kW, which translates to a daily capacity revenue of USD 636.0 k.

Table 3. Calculation parameters of pumped storage power plant.

Parameter	Unit	Value
Maximum reservoir capacity converted to equivalent electricity generation E_{max}	MWh	36,000
Minimum reservoir capacity converted to equivalent electricity generation E_{min}	MWh	0
Maximum allowable continuous generation time T_{max}^{gen}	h	12
Maximum allowable continuous pumping time T_{max}^{pum}	h	10
Maximum allowable generation/pumping power P_{max}	MW	3600
Minimum allowable generation power P_{min}^{gen}	MW	1440
Minimum allowable pumping power P_{min}^{pum}	MW	2160
Initial reservoir capacity converted to equivalent electricity generation E_0	MWh	0
Comprehensive efficiency of variable-speed pumped storage η_{cs}	%	81
Comprehensive efficiency of conventional pumped storage η_{cs}	%	76.5
Rotating reserve consumption loss of the pumped storage unit λ	%	7

4.2. Doubly-Fed Variable-Speed Pumped Storage Plant Participates in Energy Market Bidding

In the case study of this section, the benchmark grid price adopts a time-of-use pricing system with peak and off-peak periods, and the pumping price is set at $k = 0.13$. Considering the characteristics of new energy output and user electricity consumption patterns, the generation side is divided into peak and off-peak periods as follows: peak period: 8:00–12:00, 16:00–20:00; normal period: 6:00–8:00, 12:00–16:00, 20:00–22:00; off-peak period: 0:00–6:00, 22:00–24:00. The off-peak price adopts the unit cost of coal-fired power in the region at 0.035 USD/kWh, the normal period price adopts the benchmark coal-fired price in the region at 0.051 USD/kWh, and the peak price is set at 0.075 USD/kWh. The pricing complies with the “Notice on Further Improving the Time-of-Use Pricing Mechanism” by the National Development and Reform Commission.

The fluctuating grid price p_t in different periods follows a normal distribution. Since the fluctuating grid price is related to the pricing mechanism, the mean value of the normal distribution is set to 0. The greater the uncertainty in the power system, the more active the spot market, and the larger the variance. Meanwhile, it is assumed that the power market is large enough that the pumped storage power station, as a price taker in the market, does not affect the grid price when participating in the market.

Considering the different development levels of power spot markets in different regions of China, different scenarios are set by changing the variance of the fluctuating price following a normal distribution: 0, 0.03, and 0.05, resulting in grid price curves under three scenarios as shown in Figure 3. Three price scenarios corresponding to three pricing mechanisms. The operating conditions of the variable-speed pumped storage power station under different pricing mechanisms are compared with those of the constant-speed pumped storage power station.

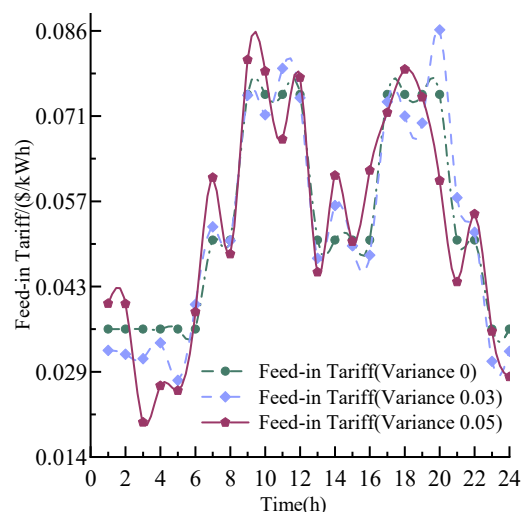


Figure 3. Three price scenarios corresponding to three pricing mechanisms.

Scenario 1: Variance is 0. The power spot market is not yet operational, adopting the time-of-use pricing system with the grid price being the benchmark price in the region.

Scenario 2: Variance is 0.03. The power spot market is relatively active, adopting real-time spot market prices, with the grid price being the real-time price.

Scenario 3: Variance is 0.05. The power spot market is active, adopting real-time spot market prices, with a larger peak-to-valley difference than Scenario 2.

The operating conditions of the variable-speed and constant-speed pumped storage power stations participating in the energy market under three pricing scenarios are shown in Table 4. The optimal daily operation mode of the variable-speed pumped storage power station in Scenario 1 is shown in Figure 4.

Table 4. Operating conditions of pumped storage power stations participating in the energy market under three pricing scenarios.

Scenario	Peak-to-Valley Price Ratio	Variable-Speed Pumped Storage Revenue (USD 10 k)	Constant-Speed Pumped Storage Revenue (USD 10 k)
1	2.1016	387.5	314.6
2	3.1654	602.5	505.3
3	4.0229	630.8	543.0

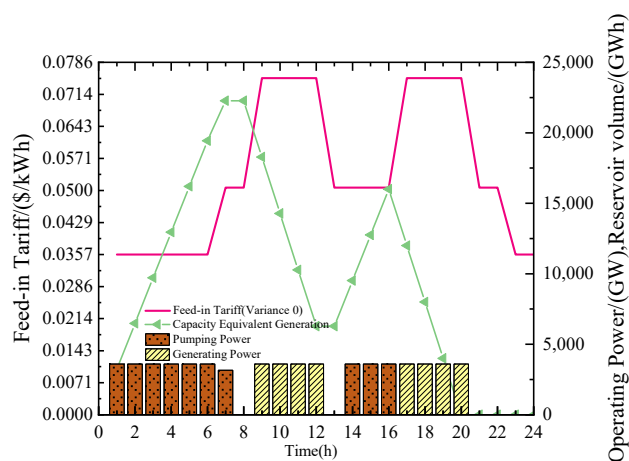


Figure 4. Optimal daily operation mode of the variable-speed pumped storage power station in Scenario 1.

As shown in Figure 4, the equivalent power generation of the reservoir capacity is closely related to the price. During the high-load peak period, when the price is highest, the variable-speed pumped storage station is fully generating, and during the low-load off-peak period, when the price is lowest, the variable-speed pumped storage station is fully pumping. During the normal period, the pumped storage station determines the pumping and generating states and power levels based on the load forecast for the next period, which aligns with the operation mechanism of pumped storage. This model can provide a reference for maximizing the revenue of pumped storage power stations in the energy market before the ancillary services market is perfected.

As shown in Table 4, the more active the power spot market is, the greater the peak-to-valley price ratio, and the more revenue the pumped storage power station can earn through low-price purchase and high-price sale. The variable-speed pumped storage power station, with its flexible adjustment characteristics and high efficiency, can achieve higher revenue compared to the constant-speed pumped storage power station. However, even if the fluctuating price variance is 0.05 and the peak-to-valley price ratio is expanded to 4.0229, the highest energy revenue of the variable-speed pumped storage power station is still less than USD 636.0 k, unable to meet the cost guidance according to the policy document's capital internal rate of return. Moreover, most of the power stations in the current system are constant-speed pumped storage stations, making cost guidance more difficult. Therefore, it is difficult for pumped storage power stations to achieve cost guidance by only participating in the energy market. Capacity compensation in the current market environment is indispensable for pumped storage power stations. A mature power market environment should provide a way for pumped storage power stations to reflect their value as a product transfer facility, i.e., the ancillary services market.

4.3. Participation of Doubly-Fed Variable-Speed Pumped Storage Plants in Both the Energy Market and the Ancillary Services Market

In this section's case study, the price parameters are taken from Scenario 2 in Section 4.2. The pumping price k is set at 0.13, the call proportion k_{spin} is set at 0.1, the spinning reserve price p_{spin} is set at 0.0171 USD/kWh, and the call price coefficient k_{sp} is set at 1.5. The optimal daily operation mode of the variable-speed pumped storage power station in this scenario is shown in Figure 5.

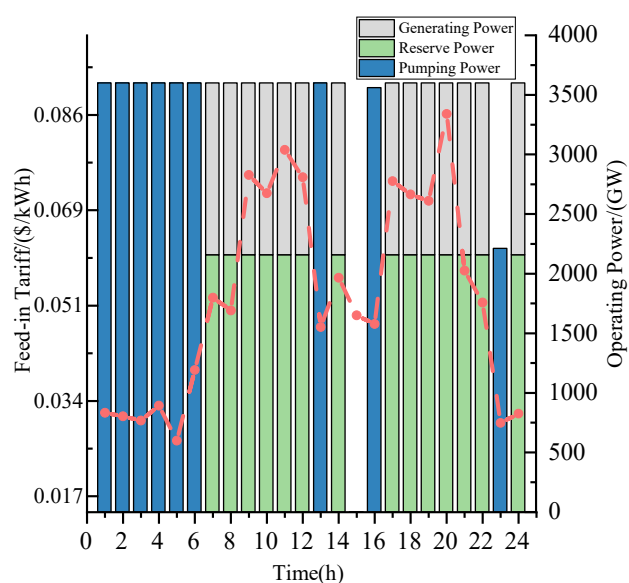


Figure 5. Optimal daily operation mode of the variable-speed pumped storage power station participating in the energy market and spinning reserve ancillary services market.

From Figure 5, it can be seen that with price fluctuations, the pumped storage power station can maximize its revenue by reasonably arranging the pumping and generating states and adjusting the ratio of power generation to reserve. Compared with Figure 4, the annual utilization hours of the pumped storage power station increase, making the station more active. This indicates that when the value of the services provided by pumped storage is reflected in the system, the pumped storage power station will be called upon more frequently.

Both constant-speed and variable-speed pumped storage units can provide spinning reserve ancillary services while supplying power. The difference lies in whether the power of the unit can be adjusted during the pumping condition. The pumping power of the constant-speed unit cannot be adjusted, while the variable-speed unit's pumping power can be adjusted widely. Thanks to the flexibility of the variable-speed unit, its speed and other parameters automatically adjust according to the operating conditions, resulting in higher operational efficiency. Therefore, the flexibility value of the variable-speed pumped storage station is higher than that of the constant-speed station, allowing it to earn more revenue from the ancillary services market, compensating for its higher construction costs. The revenue situation of both types of stations participating in the energy market and the spinning reserve market based on Scenario 2 prices is shown in Table 5.

Table 5. Revenue situation of two types of stations participating in the energy market and spinning reserve market.

Revenue \ Type	Constant-Speed Pumped Storage Station	Variable-Speed Pumped Storage Station
Energy Market Revenue (USD 10 k)	54.17	45.24
Ancillary Services Market Revenue (USD 10 k)	724.97	849.14
Total Revenue (USD 10 k)	779.07	894.39

From Table 5, it can be seen that the revenue of both the variable-speed and constant-speed pumped storage stations in the energy market is less than the revenue when only participating in the energy market. This indicates that the flexibility value of pumped storage stations is greater than the peak–valley price difference arbitrage. The total revenue of the variable-speed pumped storage station is higher than that of the constant-speed pumped storage station, but the revenue sources differ significantly. The energy market revenue of the variable-speed pumped storage station is lower than that of the constant-speed station, while its ancillary services market revenue is higher, indicating that the flexibility value of the variable-speed pumped storage station is higher, making it more inclined to earn revenue in the ancillary services market. This model can provide a reference for the development and improvement of the ancillary services market in China, and offer insights for cost guidance for pumped storage power stations in the electricity market.

4.4. Impact of Pricing Mechanisms in the Energy Market on Doubly-Fed Variable-Speed Pumped Storage Plants in a Market Environment

Assuming the on-grid electricity price is fixed, the coefficient k determines the revenue of the variable-speed pumped storage power station in the energy market and the ancillary services market. The ratio of the pumping price to the on-grid price is $k + 1$. The pumping price significantly affects the operating state and power of the variable-speed pumped storage power station. To study the pricing mechanism in the market environment, the value range of k is set from 0.01 to 0.20, with a step size of 0.01. Other parameters are the

same as in Section 4.3. The revenue situation of the variable-speed pumped storage power station under different values of coefficient k is shown in Figure 6.

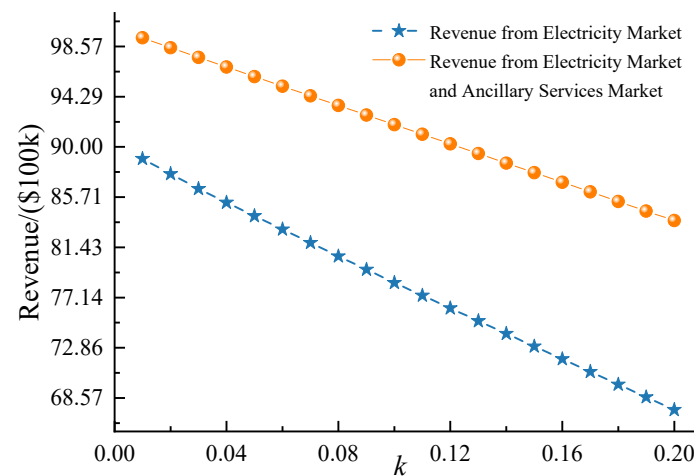


Figure 6. Revenue situation of the variable-speed pumped storage power station under different values of coefficient k .

From Figure 6, it can be seen that compared to participating only in the energy market, the revenue of the variable-speed pumped storage power station in both markets is less sensitive to the coefficient k , and the difference in revenue gradually widens as k increases. However, even when the value of k is 0.20, the revenue from only participating in the energy market is still higher than the daily capacity cost of USD 636.0 k that needs to be guided. This shows that the implementation of peak–valley electricity prices is very important for the cost guidance of the variable-speed pumped storage power station.

4.5. Implications of Pricing Mechanisms in the Ancillary Services Market for Doubly-Fed Variable-Speed Pumped Storage Plants in a Market Environment

Regarding the pricing mechanism of the ancillary services market, take the spinning reserve market as an example. When the proportion of the called reserve power to the total reserve power in the spinning reserve market is a fixed value, the revenue of the power station in the spinning reserve market is mainly affected by two factors: the pricing of reserve capacity and the coefficient of the called reserve price. Based on these two variables, this paper analyzes the revenue situation of the spinning reserve market and proposes corresponding pricing suggestions. Taking the reserve capacity price in a certain region of China as a reference, the price range of reserve capacity is set from 0.0143 USD/kWh to 0.0214 USD/kWh, with an incremental step of 0.0014 USD; the value range of the called reserve price coefficient is from 1 to 2, with an incremental step of 0.1; other parameters are consistent with those in Section 4.2. The revenue situation of the variable-speed pumped storage power station under different coefficient settings is shown in Figure 7.

From Figure 7, it can be seen that the revenue of the variable-speed pumped storage power station gradually increases with the increase in the reserve price and the called reserve price coefficient, from the lowest revenue of participating in the two markets, which is difficult to cover costs, to the highest revenue of 1.024 million USD. Within the different value ranges of the two variables, the cost guidance of the variable-speed pumped storage power station is relatively simple. In Section 4.1, the average construction cost per unit of the pumped storage is 971.43 USD/kW, corresponding to the construction cost of pumped storage in this region of China; in this region, the proportion of completed feasibility studies and pre-feasibility studies with unit construction costs above 1142.86 USD/kW is 28%, and above 1000 USD/kW is 92%. The figures of 66.286 and 75.714 in the figure correspond to

the costs of pumped storage power stations with unit construction costs of 1000 USD/kW and 1142.86 USD/kW, respectively. It is evident that when the pricing of ancillary services is reasonable, the variable-speed pumped storage power station can effectively cover costs and achieve profitability in the electricity market, which will be conducive to the construction and development of pumped storage power stations in China.

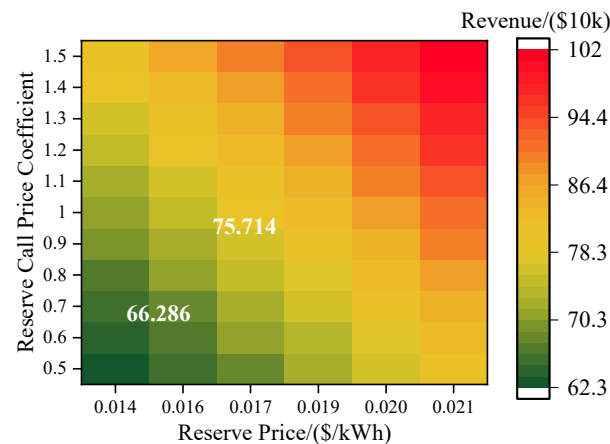


Figure 7. Revenue situation of the variable-speed pumped storage power station under different reserve capacity prices and reserve called price coefficients.

4.6. The Impact of Pricing in the Energy and Ancillary Services Markets on the Operational Decision Making and Functionality of Doubly-Fed Variable-Speed Pumped Storage Plants in a Market Environment

Existing pumped storage power stations operate under two modes: unified management by the power grid and leasing management by the power grid. However, regardless of the mode, their utilization rates remain low. This is primarily due to the underdeveloped ancillary services market in China, which limits the ability of pumped storage power stations to reflect their flexibility value through the market. Consequently, it is challenging to determine their decision making and functional positioning as independent market entities.

The operational decisions for variable-speed pumped storage power stations include pumping, shutting down, generating power, and providing reserve. And IV.C analyzed the impact of price on the states of pumping, shutting down, and generating power. This section focuses on the impact of price signals on the allocation of reserve power and generated power, thereby determining the functional positioning of variable-speed pumped storage power stations within the grid. In a power market environment, price signals can directly influence the decisions and positioning of variable-speed pumped storage power stations. In this section, the reserve call price coefficient is assumed to be fixed, with the price coefficient k ranging from 0 to 0.5 in increments of 0.05. The reserve capacity price ranges from 0.007 USD/kWh to 0.0214 USD/kWh in increments of 0.0014 USD/kWh. Other parameters remain consistent with those in Section 4.3. The daily reserve/generation power of variable-speed pumped storage power stations under different values of the price coefficient k and reserve capacity prices are shown in Figure 8.

As shown in Figure 8, when the reserve capacity price is relatively high and the price coefficient is low, variable-speed pumped storage power stations are more active, with high daily generation and spinning reserve power. Across the range of the two variables, daily reserve power generally exceeds daily generation power, indicating that the role of variable-speed pumped storage power stations in the grid leans more towards that of a regulating power source. However, when both the reserve capacity price and the price coefficient are low, daily generation power exceeds reserve power, suggesting that the variable-speed pumped storage power station in this scenario gains more profit from

arbitrage in the energy market than from spinning reserve. Therefore, price signals play a crucial role in the operational decisions and functional positioning of variable-speed pumped storage power stations. Through reasonable market pricing, these stations can cover costs and generate profits while leveraging their flexibility value, thereby addressing uncertainties in the power system and maintaining the safe and stable operation of the grid.

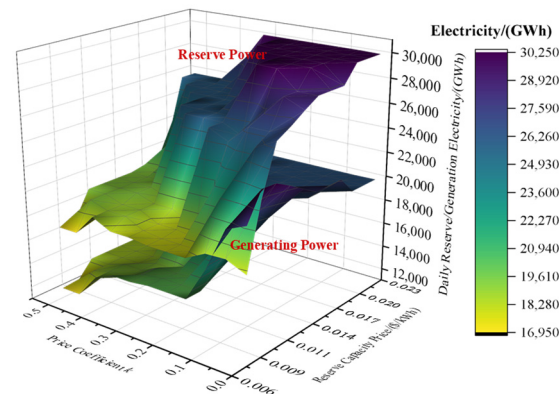


Figure 8. Daily reserve/generating power of variable-speed pumped storage power stations under different values of the price coefficient k and reserve capacity price.

5. Conclusions

Starting from the background of the rapid development of variable-speed pumped storage in the new power system under the dual-carbon goals, this paper addresses issues such as the strong public attributes of pumped storage power stations in China and the challenges of cost allocation. Based on the operating principles of doubly-fed variable-speed pumped storage, it analyzes the advantages brought by variable-speed technology to the operation of pumped storage stations and establishes a mathematical model for the power station. Further, considering the construction of China's electricity market, the revenue model of variable-speed pumped storage power plant participating in the electricity market and auxiliary service market is established, and the pricing mechanism of China's electricity market and auxiliary service market is studied. Validation and analysis are conducted based on a case study in a specific region of China, and the main conclusions of this study are as follows:

- When variable-speed pumped storage power stations participate in the day-ahead energy market, their revenue is closely related to the activity level of the regional electricity spot market. Even with the peak-to-valley price ratio increasing to 4.0229, the revenue remains insufficient to cover costs, highlighting the critical role of the ancillary service market in the economic viability of variable-speed pumped storage power stations. Additionally, when the power stations participate in both the day-ahead energy market and the ancillary service market, their utilization rates and revenues significantly improve, enabling both fixed-speed and variable-speed pumped storage power stations to recover costs and generate profits. Among them, variable-speed pumped storage power stations are more inclined to achieve higher revenues through the ancillary service market.
- Electricity and ancillary services market pricing directly affect the operational decisions of variable-speed pumped storage power stations, thereby influencing their revenue. Different operational decisions correspond to different functional roles within the grid. For example, when reserve prices and electricity prices are both low, the storage function of variable-speed pumped storage power stations is emphasized, while their regulatory function is weakened. Conversely, when reserve prices are high, the reserve capacity increases, positioning the stations as regulatory power sources.

- The cost recovery of pumping and storage power stations is largely influenced by policy. Compared with the current pumping and storage cost recovery policy, the mechanism described in this paper suggests that market construction should continue to improve the activity, promote the peak–valley price difference to further expand, create more profit space for variable-speed pumped storage power stations, and optimize the auxiliary service market pricing mechanism to encourage the active participation of power stations.

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