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The Semi-Scheduling Mode of Multi-Energy System Considering Risk–Utility in Day-Ahead Market

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Abstract: The large-scale development of renewable energy has an urgent demand for an adjustable power supply. For a multi-energy system with multiple types of heterogeneous power sources, including wind power, photovoltaic (PV) power, hydropower, thermal power and pumped storage, a novel semi-scheduling mode and a solution method were proposed in this paper. Firstly, based on the load and the reserve demand during the peak load period, the semi-scheduling mode was adopted to determine the start-up combination of thermal power units. Furthermore, by predicting the generating/pumping power, the working state of pumped storage units was determined to realize the independent solution of discrete integer variables. Secondly, the risk–utility function was constructed to quantify the attitude of pumped storage towards the uncertainty of renewable energy output, which completed the quotation and clearing of the pumped storage in the ancillary service market. Finally, by taking the minimum total quotation cost as the objective, the wind–solar–hydro-thermal-pumped storage coordinated (WSHTPC) model was built in the day-ahead market. The feasibility and effectiveness of the proposed model were verified through the simulation of a typical day with different renewable energy penetration rates.

Keywords: multi-energy system; semi-scheduling mode; pumped storage; ancillary service market; risk–utility

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1. Introduction

At present, China is in a critical period of low-carbon energy transformation. With the large-scale development of renewable energy, the anti-peak shaving characteristics of wind power and the strong randomness of PV power lead to the frequent deep peak shaving of thermal power units [1–3]. Furthermore, the thermal power units may even be forced to shut down in the low net load period. However, once the thermal power unit is shut down, it takes 8–10 h to restart. In a power system dominated by thermal power, the quick-adjusting capacity of the system is obviously insufficient, resulting in a serious energy abandonment problem [4–6]. Therefore, in order to enhance the consumption of renewable energy and improve energy utilization efficiency, it is an effective measure to fully exploit the system reserve space [7,8]. In existing studies, pumped storage is often used as an independent peak-shaving resource [9]. However, pumped storage also has excellent frequency regulation ability and rotating reserve ability [10–12]. Thus, the allocation of pumped storage's reserve capacity is a problem worthy of discussion. On the one hand, if the reserve capacity is too small to stabilize the fluctuation of renewable energy, the purpose of promoting the consumption of renewable energy cannot be achieved [13]. On the other hand, too much reserve capacity decreases the opportunity cost for pumped storage to make profits in the real-time market [14].

With the diversified development of power source structure, the joint scheduling of multiple heterogeneous power sources becomes the focus to promote the healthy and sustainable development of power systems [15,16]. In order to increase the amount of clean energy consumption and avoid deep peak shaving of thermal power units, the pumped storage is usually bundled with wind power, PV power or thermal power. Generally, the economy and stability operation of thermal power [17,18], the minimum energy abandonment of clean energy [19,20] and the minimum load fluctuation [21] are often taken as objectives, and a large number of scheduling models have been built [22], which ignore the benefits of pumped storage. However, if considered an independent market entity [23], pumped storage operators have the right to determine the scheduling mode by themselves to safeguard their own benefits.

The outline of the paper is described as follows. Section 2 includes ancillary service and semi-scheduling mechanism of pumped storage units. Section 3 outlines the semi-scheduling model. Section 4 highlights the risk–utility function used in the ancillary service market decision-making model. WSHTPC's mathematical model of the day-ahead market is built in Section 5. The case study and the results are discussed in Section 6. To conclude the work, a conclusion in Section 7 was given.

2. Ancillary Service and Semi-Scheduling Mechanism of Pumped Storage Units

2.1. Demand Analysis of Reserve Capacity

In order to prompt the low-carbon development of the multi-energy system, the proportion of renewable energy access has been greatly improved, resulting in insufficient system adequacy. Thus, the difficulties of scheduling have become prominent. As shown in Figure 1, when renewable energy accesses the system, the demand for peak shaving, frequency regulation and rotating reserve of the net load curve increase significantly. In September 2021, the state issued the medium- and long-term development plan for pumped storage (2021–2035), which stated that as a low-carbon and adjustable power supply, pumped storage could quickly respond to market signals and has a good cooperation effect with wind power, PV power and thermal power [24]. When combined with China's energy resource conditions, pumped storage is the key way to meet the regulation demand of power systems at present and in the future. It plays an important role in ensuring the security of power systems and promoting the large-scale development and consumption of renewable energy [25].

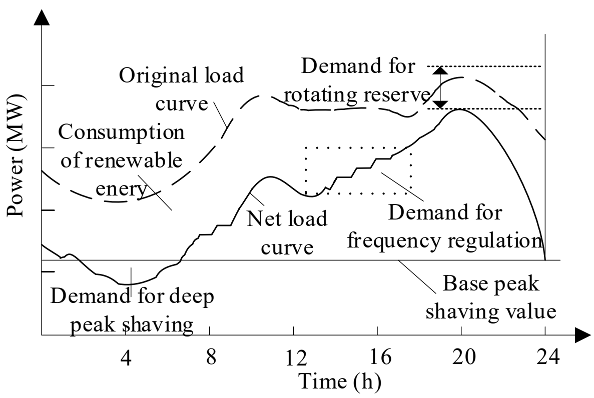


Figure 1. Schematic diagram of regulating demand of power systems.

2.2. Scheduling Mode of Pumped Storage

Affected by power market reform and policy factors, it will be a new normal for pumped storage to participate in power market transactions as an independent market entity and obtain corresponding benefits. In the current power market environment in the United States, there are mainly three kinds of scheduling modes for pumped storage [26]. The characteristics of the three scheduling modes are shown in Table 1 [27].

Table 1. Comparison of Pumped Storage Scheduling Mode.

Scheduling Mode	Declared Data	Optimized Objective	Joint [1]?	Technical Difficulty	Advantage	Disadvantage
Self-scheduling	Day-ahead output curve	Maximum operators benefit	No	Lower	Rapid clearing speed	High demand for electricity price forecast
Full-scheduling	Operating parameters	Maximum social benefit	Yes	Higher	Less system cost	Long simulation time
Semi-scheduling	Generating/pumping window and quotation	Minimum total quoted cost	Yes	Medium	Not considering the working state	Unable to reflect the real cost

[1] Joint is whether the pumped storage units are jointly scheduled with conventional units.

In the self-scheduling mode, the output curve of pumped storage units, as the boundary condition of day-ahead market clearing, could be determined by the operators in advance. Thus, its obvious advantage is rapid clearing speed. However, it requires high accuracy of electricity price forecast. Pumped storage operators could make a profit with an accurate electricity price forecast. On the contrary, they may suffer great economic loss.

In the full-scheduling mode, pumped storage operators only need to provide the operating parameters. Additionally, pumped storage units are jointly scheduled with other units to maximize the social benefit. Thus, the pumped storage plays an important role in regulating the effect under this mode. However, it needs a long simulation time. The simulation time, in particular, is multiplied if there are a number of pumped storage units.

The semi-scheduling mode, being widely used in all independent system operators (ISO) except PJM, is a compromise between the self-scheduling mode and the full-scheduling mode. In the semi-scheduling mode, the pumped storage operators declared the generating/pumping window and quotation according to the price signals. Generally, the generating/pumping quotation, including electric energy quotation, frequency regulation quotation and rotating reserve quotation, reflects the unit generating/pumping cost value. Then, the pumped storage units and conventional units are jointly scheduled to achieve the goal of minimizing the total quotation cost [28,29].

Compared with the self-scheduling mode, the semi-scheduling mode can correct the unreasonable output results caused by the operator's prediction error of the electricity price, which brings greater benefits to the operator and the whole system. Compared with the full-scheduling mode, under the semi-scheduling mode, the pumped storage operators are profitable, and the working state of pumped storage units could be determined in advance, which could speed up the clearing process. Thus, considering the pumped storage operator's benefits and the whole system's benefits comprehensively, as well as the clearing process, the pumped storage semi-scheduling mode is a more appropriate choice for the initial power market.

As China's power market is still in its infancy, the market mechanism is imperfect, and the regulation pressure of the power system is huge, so we can not completely copy the semi-scheduling mode abroad. In order to achieve the win–win goal of pumped storage and power system, a novel semi-scheduling mode of pumped storage needs to be built on the basis of a stable power supply in China.

3. Semi-Scheduling Mode

3.1. Semi-Scheduling Flow

Based on the energy complementation, the process of semi-scheduling mode is shown in Figure 2. Firstly, based on the predicted information, including the curve of wind power, PV power, load and external electricity the next day, considering the system demand of frequency regulation and rotating reserve, the start-up combination of thermal power units was determined. Furthermore, considering that the pumped storage units generate electricity at the peak load period and pump water at the low load period, the working state of the pumped storage units is determined by predicting its generating/pumping power. Finally, the start-up combination of thermal power units, the working state of the pumped storage units, and the quotation of pumped storage operators are transmitted into the WSHTPC mathematical model as inputs.

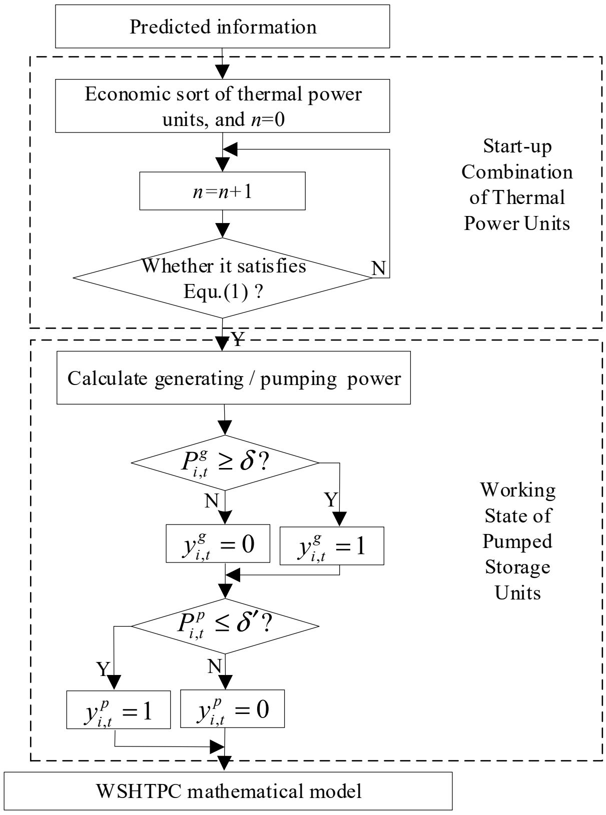


Figure 2. Semi-scheduling Flow Chart.

3.2. Start-Up Combination of Thermal Power Units

The large-scale access to renewable energy will lead to the redundancy of thermal power installed capacity in the power system. In order to avoid the imbalance between the power supply and the load demand, it is necessary to determine the start-up combination of thermal power units in advance. The specific steps are as follows:

S1: Economic sort of thermal power units according to the minimum specific consumption;

S2: On the premise that all wind power and PV power are consumed, and the hydropower and pumped storage units are fully generated, the maximum start-up combination of thermal power units is determined at the moment of maximum load. The start-up combination of thermal power units meets the following requirement:

$$\sum_{i=1}^{n-1} P_{i,\max}^{Th} < D_{e,\max} - P_{\max}^{E} - \sum_{i \in W} P_{i,\max}^{W} - \sum_{i \in S} P_{i,\max}^{S} - \sum_{i \in H} P_{i,\max}^{H} - C_p \cdot N_P + D_r + D_s \leq \sum_{i=1}^{n} P_{i,\max}^{Th} \tag{1}$$

where n is the number of start-up combinations of the thermal power units; W, S and H are the set of wind power units, PV power units and hydropower units, respectively; the superscript of Th, W, S, H and E represent thermal power, wind power, PV power, hydropower and external electricity, respectively; $P_{i,\max}$ is the maximum output of unit i; $D_{e,\max}$ is the maximum load; $P_{\max}^{E}$ is the external electricity at the moment of maximum load; C_p and N_P are the installed capacity and the number of pumped storage units; D_r and D_s are the demand of frequency regulation and rotating reserve in the power system.

Generally speaking, the more thermal power units are started, the more frequency regulation and rotating reserve are provided. However, it should be noted that if the minimum technical output of thermal power units cannot be met during the low load period, the dispatcher should choose to shut down one thermal power unit or abandon some renewable energy according to the actual situation.

3.3. Working State of Pumped Storage Units

The application of pumped storage can effectively lighten the peaking shaving task of thermal power units, and the thermal power units can undertake more base load and waist load of the power system to reduce their coal consumption. Thus, based on the determined start-up combination of thermal power units, considering that the pumped storage units generate electricity at the peak load period and pump water at the low load period, the working state of the pumped storage units is determined by predicting the generating/pumping power.

At the peak load period, the thermal power units generally operate at 100% installed capacity. By assuming that wind power, PV power and hydropower are consumed completely, the generating power of the pumped storage unit can be calculated according to Equation (2). If the generating power is greater than the threshold value, it indicates that the power supply is insufficient, and the pumped storage unit should be in the generating window to shave the load, as shown in Equation (4).

At the low load period, the thermal power unit generally operates at low load or is shut down directly. Considering that the basic peak shaving benchmark of the thermal power unit is 50% installed capacity when the basic peak shaving cannot meet the peak shaving demand, the pumped storage unit is usually in the pumping state. By assuming that wind power, PV power and hydropower are consumed completely and all thermal power units operate at 50% installed capacity, the pumping power of the pumped storage unit can be calculated according to Equation (3). If the pumping power is less than the threshold value, it indicates that the power supply is redundant, and the pumped storage unit should be in the pumping window to fill the load, as shown in Equation (5).

$$P_{i,t}^{g} = D_{e,t} - P_t^E - \sum_{i \in G} P_{i,\max}^{Th} - \sum_{i \in W} P_{i,t}^{W} - \sum_{i \in S} P_{i,t}^{S} \tag{2}$$

$$P_{i,t}^{p} = D_{e,t} - P_t^E - 0.5 \times \sum_{i \in G} P_{i,\max}^{Th} - \sum_{i \in W} P_{i,t}^{W} - \sum_{i \in S} P_{i,t}^{S} \tag{3}$$

$$y_{i,t}^{g} = \begin{cases} 1, & P_{i,t}^{g} \geq \delta \\ 0, & P_{i,t}^{g} < \delta \end{cases} \tag{4}$$

$$y_{i,t}^{p} = \begin{cases} 1, & P_{i,t}^{p} \leq \delta' \\ 0, & P_{i,t}^{p} > \delta' \end{cases} \tag{5}$$

where G is the set of thermal power units; the superscript of g and p represent generating window and pumping window of pumped storage; $P_{i,t}^{g}$ and $P_{i,t}^{p}$ are the generating power and pumping power at time t; $D_{e,t}$ and P_t^E are the load and the external electricity at time t; $P_{i,t}^{W}$ and $P_{i,t}^{S}$ are the output of wind power and PV power at time t; $y_{i,t}$ is the state variable of unit i at time t; δ and δ' are power threshold values, which are set according to the system conditions and the installed capacity of pumped storage units.

4. Ancillary Service Market Decision-Making Model

Generally speaking, it is the obligation for pumped storage to stabilize the uncertainty of renewable energy output. The greater the uncertainty of renewable energy output, the more reserve capacity the pumped storage units need to provide, pumped storage units could make profits in the ancillary service market by providing reserve capacity, if pumped storage units sell too much reserve capacity, their opportunity cost of making profits in the real-time market will be affected. Thus, the allocation of reserve capacity for pumped storage units is a decision-making problem that needs to consider risks.

4.1. Risk–Utility Model of Pumped Storage Units

The risk attitudes of pumped storage units were divided into risk aversion and risk preference in this paper. Additionally, the risk attitude closely connects to the form of a utility function. Furthermore, the exponential function is a typical convex function, indicating that y is sensitive to the increase in x, and the logarithmic function is a typical concave function, indicating that y is slow to the increase in x. The two are the common analytic expression to express the utility curve by computing. Thus, the corresponding risk–utility functions can also be divided into the concave utility function and the convex utility function.

For risk-averse pumped storage units, with the increase in renewable energy output, the willingness of pumped storage units to provide reserve capacity decreases, which means the proportion of pumped storage units providing reserve capacity decreases. Then, the pumped storage unit is regarded as risk-averse, and its risk–utility function is constructed as the concave, the general form of logarithmic function [30], as shown in Equation (6).

$$U(x_t) = c_1 + a_1 \log(c_3 x_t + c_2) \tag{6}$$

where x_t is the predicted output value of renewable energy at time t; $U(x_t)$ is the utility value of the pumped storage unit providing reserve capacity, called utility capacity; and a_1, a_2, c_1, c_2 and c_3 are parameters of the function.

For risk-preference pumped storage units, with the increase in renewable energy output, the willingness of the pumped storage unit to provide reserve capacity increases, which means the proportion of the pumped storage unit providing reserve capacity increases. Then, the pumped storage unit is regarded as a risk preference, and its risk–utility function is constructed as the convex, the general form of the exponential function, as shown in Equation (7).

$$U(x_t) = c_1 + a_1 \cdot e^{a_2 x_t + c_2} \tag{7}$$

4.2. Clearing Calculation

The clearing calculation process is shown in Figure 3. In the ancillary service market decision-making model, based on the predicted output values of renewable energy, including wind power and PV power the next day, assuming that the error of the actual output values of the renewable energy follows the normal distribution, a large number of actual output data are generated by Monte Carlo sampling method. Then, the output deviation is calculated between the actual value and the predicted value according to Equation (8), and generate the "output-deviation" scatter diagram. Furthermore, the risk attitude of the pumped storage unit is constructed according to Equations (6) and (7), and call *curve_fit* function on the Python platform to fit the risk–utility function. Finally, the declared capacity of reserve capacity is decided as shown in Equations (9)–(11).

$$\Delta P_{t,i} = |P_{t,i} - x_t| \tag{8}$$

where $\Delta P_{t,i}$ is the renewable energy output deviation i at time t.

$$\overline{P}^{g}_{i,t} = \lambda \frac{U(x_t)}{N_P} \tag{9}$$

$$\overline{P}^{g}_{r,i,t} = \lambda_1 \cdot \overline{P}^{g}_{i,t} \tag{10}$$

$$\overline{P}^{g}_{s,i,t} = \lambda_2 \cdot \overline{P}^{g}_{i,t} \tag{11}$$

where $\overline{P}^{g}_{i,t}$ is the declared capacity of reserve capacity for the pumped storage unit i at time t; $\overline{P}^{g}_{r,i,t}$ and $\overline{P}^{g}_{s,i,t}$ are declared capacity of frequency regulation and rotating reserve, respectively; λ, λ_1 and λ_2 are the capacity coefficients, which are set according to the output deviation of renewable energy and the installed capacity of pumped storage units.

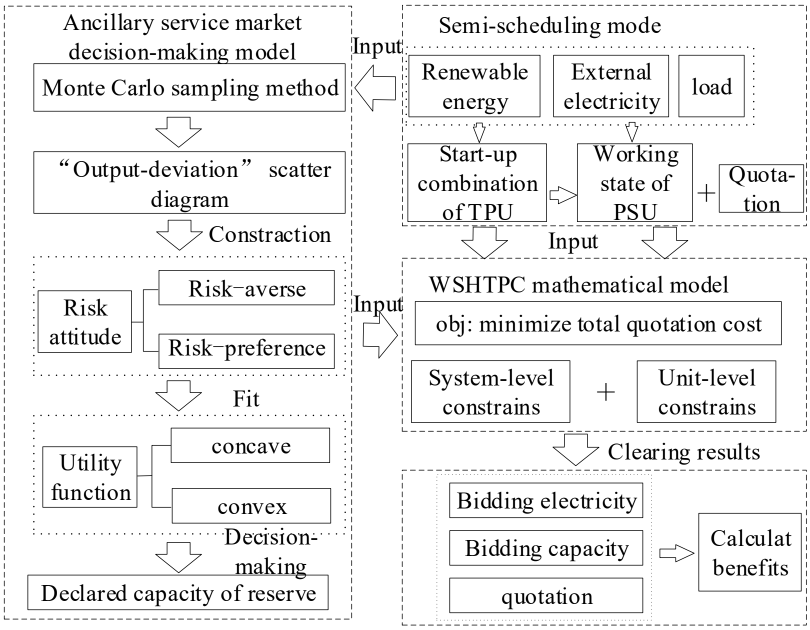


Figure 3. Framework of WSHTPC Model.

5. WSHTPC Mathematical Model of Day-Ahead Market

The overall framework of the WSHTPC model in the day-ahead market is shown in Figure 3, including the semi-scheduling mode, ancillary service market decision-making model and WSHTPC mathematical model. Firstly, the inputs were transmitted, including the start-up combination of thermal power units n, the working state of pumped storage units $y^{g}_{i,t}$ and $y^{p}_{i,t}$ in the semi-scheduling model, and the declared reserve capacity of pumped storage $\overline{P}^{g}_{r,i,t}$ and $\overline{P}^{g}_{s,i,t}$ in the ancillary service market decision-making model, into the WSHTPC mathematical model. Then, by taking the minimum total quotation cost as the objective, the clearing results of units were optimized by calling Gurobi Optimizer in the Python platform. Finally, the benefits in combination with the unit quotation were calculated.

5.1. Objective Function

Based on the quotation data and operating parameters of the units, according to Equations (13), (15) and (17), the quotation cost of the thermal power units, hydropower units and pumped storage units were calculated, respectively; Equation (14) represents the electricity generation cost function of thermal power units; Equation (16) represents the dynamic characteristic of hydropower units. Then, by taking the minimum total quotation cost as the objective as Equation (12), the clearing results in the day-ahead market were optimized, as shown below.

$$\min CTP + CHP + CPS \tag{12}$$

where CTP, CHP and CPS are quotation costs of thermal power units, hydropower units and pumped storage units, respectively.

$$CTP = \sum_{i\in G}\sum_{t\in T}\left(f_i(P^{Th}_{i,t})\cdot y^{Th}_{i,t} + C^{Th}_{r,i,t}\cdot P^{Th}_{r,i,t} + C^{Th}_{s,i,t}\cdot P^{Th}_{s,i,t}\right) \tag{13}$$

$$f_i\left(P^{Th}_{i,t}\right) = a_i\cdot\left(P^{Th}_{i,t}\right)^2 + b_i\cdot P^{Th}_{i,t} + c_i \tag{14}$$

$$CHP = \sum_{i\in H}\sum_{t\in T}\left(C^{g}_{i,t}\cdot P^{H}_{i,t}\cdot y^{H}_{i,t} + C^{g}_{r,i,t}\cdot P^{H}_{r,i,t} + C^{g}_{s,i,t}\cdot P^{H}_{s,i,t}\right) \tag{15}$$

$$P^{H}_{i,t} = 9.81 y^{H}_{i,t}\eta^{H}_{i} q_{i,t} h_{i,t} \tag{16}$$

$$CPS = \sum_{i \in P} \sum_{t \in T_{g,i}} \left(C_{i,t}^{g} \cdot P_{i,t}^{g} \cdot y_{i,t}^{g} + C_{r,i,t}^{g} \cdot P_{r,i,t}^{g} + C_{s,i,t}^{g} \cdot P_{s,i,t}^{g} \right) + \sum_{i \in P} \sum_{t \in T_{p,i}} \left(-C_{i,t}^{p} \cdot P_{i,t}^{p} \cdot y_{i,t}^{p} + C_{r,i,t}^{p} \cdot P_{r,i,t}^{p} + C_{s,i,t}^{p} \cdot P_{s,i,t}^{p} \right) \quad (17)$$

where P is the set of pumped storage units; T is the scheduling time set; $P_{i,t}$ is the bidding electricity of unit i at time t; $f_i(\cdot)$ is the electricity generation cost function of unit i, and a_i, b_i and c_i are power generation cost coefficient; $C_{r,i,t}$ and $P_{r,i,t}$ are quotation and bidding capacity of frequency regulation of unit i at time t; $C_{s,i,t}$ and $P_{s,i,t}$ are quotation and bidding capacity of rotating reserve of unit i at time t; $C_{i,t}$ is the quotation of electricity generation cost of unit i at time t; η_i^H is the efficiency of hydropower unit i.

5.2. Constraint Condition

5.2.1. System-Level Constraints

Equation (18) represents the load balance constraint; Equation (19) represents the constraint of system demand of frequency regulation; Equation (20) represents the constraint of system demand of reserve capacity.

$$\sum_{i \in G} P_{i,t}^{Th} + \sum_{i \in H} P_{i,t}^{H} + \sum_{i \in P} P_{i,t}^{g} + \sum_{i \in W} P_{i,t}^{W} + \sum_{i \in S} P_{i,t}^{S} + P_t^E = D_{e,t} + \sum_{i \in P} P_{i,t}^{p} + \sum_{i \in W} W_{i.t}^{W} + \sum_{i \in S} W_{i.t}^{S} \quad (18)$$

$$\sum_{i \in G} P_{r,i,t}^{Th} + \sum_{i \in H} P_{r,i,t}^{H} + \sum_{i \in P} \left(P_{r,i,t}^{g} + P_{r,i,t}^{p} \right) \geq D_r \quad (19)$$

$$\sum_{i \in G} (P_{r,i,t}^{Th} + P_{s,i,t}^{Th}) + \sum_{i \in H} (P_{r,i,t}^{H} + P_{s,i,t}^{H}) + \sum_{i \in P} (P_{r,i,t}^{g} + P_{r,i,t}^{p} + P_{s,i,t}^{g} + P_{s,i,t}^{p}) \geq D_r + D_s \quad (20)$$

where $W_{i,t}$ is the energy curtailment of unit i at time t.

5.2.2. Unit-Level Constraints

(1) Constraints of thermal power units, hydropower units and pumped storage units

Equations (21)–(24) represent the upper and lower limits constraints of bidding capacity of reserve capacity for thermal power units, hydropower units and pumped storage units. Equations (25) and (26) represent the climbing constraint of the above units.

$$0 \leq P_{r,i,t} \leq \overline{P}_{r,i,t} \quad (21)$$

$$0 \leq P_{s,i,t} \leq \overline{P}_{s,i,t} \quad (22)$$

$$P_{i,t} - P_{r,i,t} \geq y_{i,t} \cdot P_{i,\min} \quad (23)$$

$$P_{i,t} + P_{r,i,t} + P_{s,i,t} \leq y_{i,t} \cdot P_{i,\max} \quad (24)$$

$$P_{i,t} - P_{i,t-1} \leq r_{u,i} \quad (25)$$

$$P_{i,t-1} - P_{i,t} \leq r_{d,i} \quad (26)$$

where $\overline{P}_{r,i,t}$ and $\overline{P}_{s,i,t}$ are declared capacity of frequency regulation and rotating reserve of unit i; $P_{i,\max}$ and $P_{i,\min}$ are the maximum and minimum output of unit i; and $r_{u,i}$ and $r_{d,i}$ are climbing and landslide rate of unit i.

(2) Constraints of wind power units and PV power units

Equations (27) and (28) represent restriction constraints of wind curtailment and PV curtailment.

$$0 \leq W_{i,t}^{W} \leq P_{i,t}^{W} \quad (27)$$

$$0 \leq W_{i,t}^{S} \leq P_{i,t}^{S} \quad (28)$$

5.2.3. Station-Level Constraints

Equation (29) represents the upper and lower limits constraint of upper reservoir capacity for the pumped storage station; Equation (30) represents the changing relationship of upper reservoir capacity for the pumped storage station; Equation (31) represents the upper reservoir capacity balance constraint for the pumped storage station.

$$V_{\min} \leq V_t \leq V_{\max} \tag{29}$$

$$V_t = V_{t-1} + \sum_{i \in P} P_{i,t}^{p} \eta_i^{p} \cdot \Delta t - \sum_{i \in P} P_{i,t}^{g} / \eta_i^{g} \cdot \Delta t \tag{30}$$

$$V_0 = V_T \tag{31}$$

where η_i^g and η_i^p are generating and pumping efficiency of pumped storage unit i.

6. Case Study

6.1. Basic Information

In order to verify the effectiveness of the model, taking regional scheduling as an example, the scheduling cycle was set as 24 h, and the time scale was set as 1 h. The region includes 34 thermal power units; 4 pumped storage units; and multiple wind farms, PV power stations and hydropower stations. The total installed capacity of thermal power, pumped storage, wind power, PV power and hydropower are 17,160 MW, 1200 MW, 5000 MW, 3000 MW and 15,000 MW, respectively. This paper assumed that the maximum generating/pumping power of pumped storage units is 300 MW, the minimum generating/pumping power is 30 MW, and the generating/pumping efficiency is 0.85. The system demand for frequency regulation and the rotating reserve were taken as 3% and 5% of the maximum load, respectively. In terms of quotation, in order to simplify the calculation, for hydropower units and pumped storage units, it was assumed that the generating quotation and pumping quotation are CNY 210/MWh and CNY 138/MWh, respectively, and the frequency regulation quotation and the rotating reserve quotation are CNY 25/MW and CNY 13/MW, respectively. For thermal power units, it was assumed that the frequency regulation quotation and the rotating reserve quotation are CNY 64/MW and CNY 20/MW, respectively. In addition, the simulation model was optimized by calling Gurobi Optimizer in the Python platform.

The predicted curve of the wind power (WP), the PV power (PP), the external electricity (EE), the original load and the net load of a typical day are shown in Figure 4.

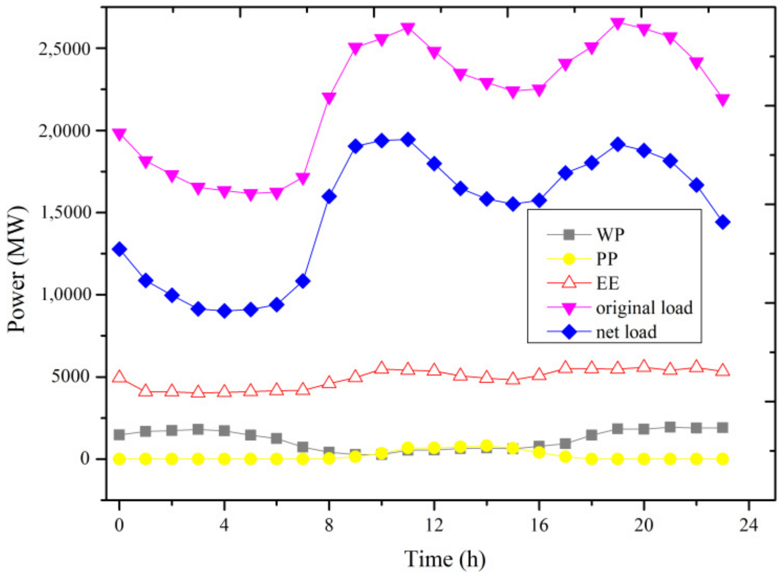


Figure 4. Input Data of Typical Day.

6.2. Benefit Analysis of Pumped Storage in Ancillary Service Market

By taking the typical day as an example to analyze the benefits of pumped storage in the ancillary service market, assuming that the output error of renewable energy is 10%, the risk–utility functions of concave and convex were fitted. Three scenarios, low, medium and high penetration of renewable energy, were defined to simulate the uncertainty of renewable energy output.

The installed capacity of wind power units and PV power units of the basic information were set as the medium penetration of renewable energy.

The installed capacity of wind power units was set 0.5 times, and the installed capacity of PV power units as the low penetration of renewable energy was set 0.5 times.

The installed capacity of wind power units was set 1.2 times, and the installed capacity of PV power units as the high penetration of renewable energy was set 1.2 times.

According to the clearing calculation mentioned in 4.2, the fitting functions of risk–utility are shown in Figure 5. The green and yellow lines represent the concave and convex utility functions, respectively.

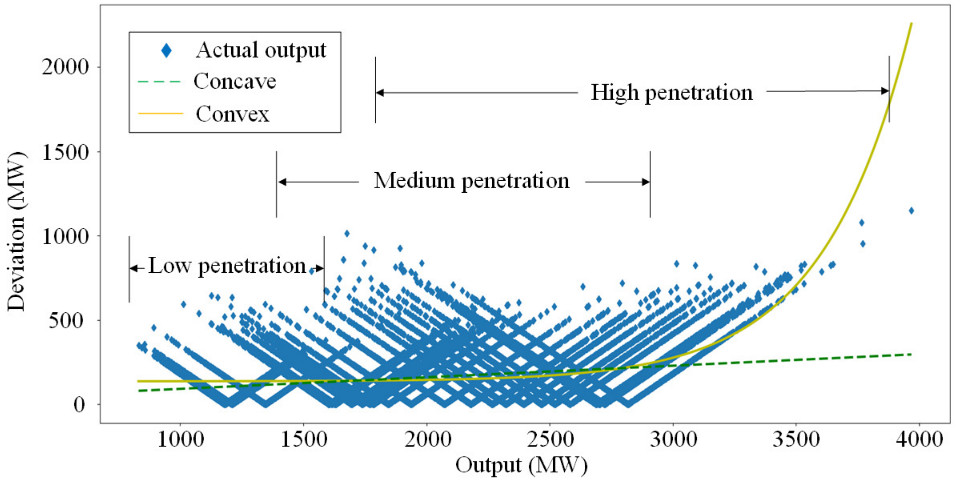


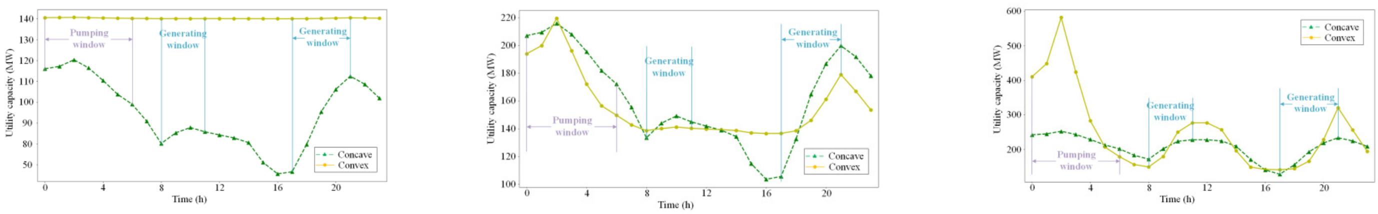
Figure 5. Fitting functions of risk–utility.

Table 2 shows the comparison of unit quotation costs under different penetration scenarios. Under the low, medium and high penetration of renewable energy, the number of start-up thermal power units is 32, 29 and 27, respectively, indicating that the higher the penetration of renewable energy, the lower the electricity cost of thermal power. Furthermore, pumped storage plays a more important role in capacity cost change, which reflects the reserve capacity, rather than electricity cost change, which reflects peak shaving. For example, in the low penetration of renewable energy, the electricity cost of pumped storage increased by 2.19% from CNY 47.89 million to CNY 48.94 million, and the capacity cost of pumped storage increased by 47.8% from CNY 11.61 million to CNY 17.16 million.

The relationship between risk–utility and pumped storage reserve capacity is analyzed. As shown in Figure 6a, in the low penetration of renewable energy, the convex function image is above the concave function image, indicating that as the risk-preference pumped storage units, the utility value of reserve capacity is large, with an average value of 141 MW, accounting for 11.75% of the installed capacity. Compared with the risk-averse, as the risk-preference pumped storage units, the electricity cost of peak shaving increases by CNY 1.05 million, and the capacity cost of reserve capacity increases by CNY 5.55 million, indicating the market performance is more active. However, the total quotation cost increased by CNY 1.16 million. Therefore, in the low penetration of renewable energy, if the purpose is to increase the benefits of the multi-energy system, it is suggested that the pumped storage units should be risk-averse to deal with the uncertainty of renewable energy output. However, if the purpose is to make full use of the ancillary service of pumped storage units, it is suggested that the pumped storage units should be a risk preference to deal with the uncertainty of renewable energy output.

Table 2. Comparison of units quotation cost under different penetration scenarios.

Penetration Scenarios	Risk–Utility Function	Thermal Power		Hydropower		Pumped Storage		
		Electricity Cost /Million Yuan	Capacity Cost /Million Yuan	Electricity Cost /Million Yuan	Capacity Cost /Million Yuan	Electricity Cost /Million Yuan	Capacity Cost /Million Yuan	Total Cost /Million Yuan
Low	Concave	7638.33	56.08	1765.23	43.68	47.89	11.61	9562.84
	Convex	7595.87	52.26	1809.85	39.88	48.94	17.16	9564.00
Medium	Concave	7217.36	47.62	1748.83	43.20	48.87	17.25	9123.16
	Convex	7208.83	47.51	1756.88	42.42	49.04	17.94	9122.63
High	Concave	6966.48	44.74	1739.63	43.44	49.15	18.97	8862.43
	Convex	6962.28	41.78	1742.93	43.00	49.16	21.23	8860.40



(**a**) low penetration (**b**) medium penetration (**c**) high penetration

Figure 6. Utility Capacity of Pumped Storage.

As shown in Figure 6b, in the medium penetration of renewable energy, the pumped storage units are in the pumping state at times 0–6 and in the generating state at times 8–11 and 17–21. It can be seen from Figure 6b that during the above-mentioned period, there is little difference between the concave and convex function images enclosed by the coordinate axis. Compared with the risk-averse, as the risk-preference pumped storage units, the electricity cost of peak shaving increases by CNY 0.17 million, and the capacity cost of reserve capacity increases by CNY 0.69 million, indicating the market performance is slightly more active. Additionally, the total quotation cost decreases by CNY 0.53 million. Therefore, in the medium penetration of renewable energy, it is suggested that the pumped storage units should be a risk preference to deal with the uncertainty of renewable energy output.

As shown in Figure 6c, in the high penetration of renewable energy, similar to the medium penetration of renewable energy, compared with the risk-averse, as the risk-preference pumped storage units, the electricity cost of peak shaving increases by CNY 0.01 million, and the capacity cost of reserve capacity increases by CNY 2.26 million, indicating the market performance is slightly more active. Additionally, the total quotation cost decreased by CNY 2.03 million. Therefore, in the high penetration of renewable energy, it is suggested that the pumped storage units should be a risk preference to deal with the uncertainty of renewable energy output.

6.3. Benefit Analysis of Day-Ahead Scheduling

As shown in Table 3, in terms of simulation time, it is obvious that the simulation time of full-scheduling mode is longer, nearly double that of semi-scheduling mode. Moreover, in the semi-scheduling mode and the full-scheduling mode, the number of start-up thermal power units is the same, but the total cost is lower in the full-scheduling mode. The reasons may be as follows: On the one hand, the closer the thermal power output is to the rated value, the lower the marginal cost. In the full-scheduling mode, the increase in electricity cost of thermal power units indicates that their output is relatively large, which can correspondingly reduce the output of hydropower units and pumped storage units so that hydropower and pumped storage have room to play a regulating role. On the other hand, because the quotation of reserve capacity of hydropower units and pumped storage units are lower than that of thermal power units, the reserve capacity is provided by hydropower units and pumped storage units as far as possible, which results in less capacity cost of thermal power units in the full-scheduling mode.

Table 3. Comparison of 0ptimization results under different scheduling mode.

		Semi-Scheduling Mode	**Full-Scheduling Mode**	**Without Pumped Storage**
Simulation time		0.71 s	1.36 s	0.66 s
Number of thermal power units		29	29	32
Thermal power units	Electricity cost/million yuan	7217.36	7299.36	7396.34
	Capacity cost/million yuan	47.62	18.90	57.65
Hydropower units	Electricity cost/million yuan	1748.83	1683.24	1646.67
	Capacity cost/million yuan	43.20	52.94	54.19
Pumped storage units	Electricity cost/million yuan	48.87	21.60	/
	Capacity cost/million yuan	17.25	26.09	/
	Total cost/million yuan	9123.16	9102.16	9154.85

Compared with the semi-scheduling mode, in the scheduling mode without pumped storage, for thermal power units, the electricity cost increased from CNY 7217.36 million to CNY 7396.34 million, increasing by 2.48%, and the capacity cost increased from CNY 47.62 million to CNY 57.65 million, increasing by 21.06%. For hydropower units, the electricity cost decreased from CNY 1748.83 million to CNY 1646.67 million, decreasing by 5.84%, and the capacity cost increased from CNY 43.20 million to CNY 54.19 million, increasing by 25.44%. The increase or decrease in the electricity power cost of thermal power and hydropower is slight. It can be inferred that the three more thermal power units, replacing the pumped storage, are mainly to meet the reserve capacity in the scheduling mode without pumped storage.

As shown in Figure 7a, pumped storage units are in a pumping state at times 0–6 and in generating state at times 8–11 and 17–21. When comparing the scheduling result of wind power at time 0–6 in Figure 7a with that in Figure 7b, it is obvious that in the scheduling mode without pumped storage, the wind power consumption decreases. Generally, the wind power output is large at times 0–6. If there is not enough load consumption, it is bound to result in wind curtailment. However, in the semi-scheduling mode, the pumped storage units could be transformed to load to consume wind power.

Specifically, as shown in Figure 7c, there is no wind power curtailment at time 0–6 in the semi-scheduling mode, but the wind power curtailment is as high as 691.54 MW at time 4 in the scheduling mode without pumped storage. As shown in Figure 7d, the reserve capacity of pumped storage units is 648.89 MW at time 4. In this case, if the pumped storage is bundled with wind power, 93.83% of the wind power curtailment can be consumed in the scheduling mode without pumped storage.

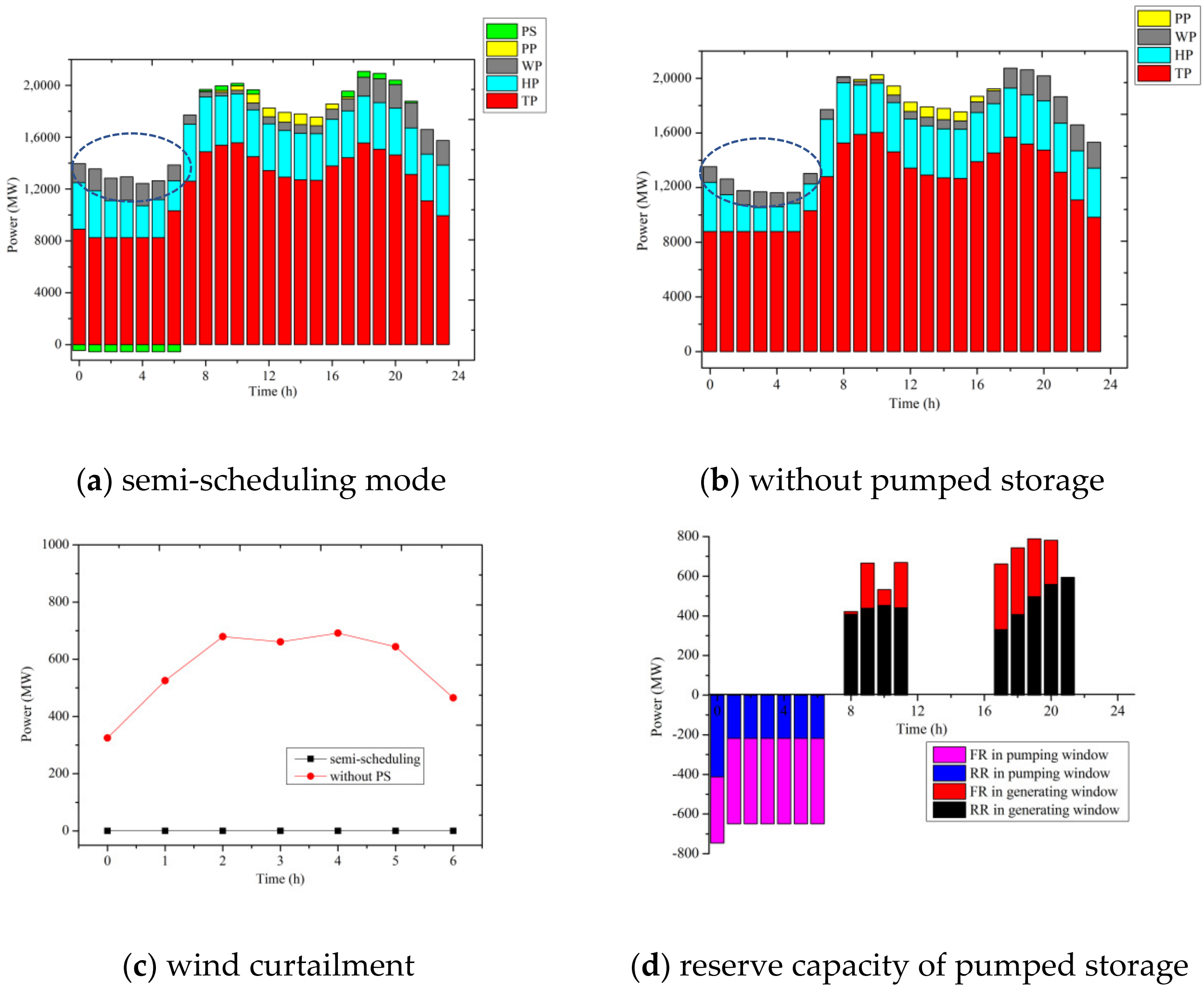


Figure 7. Scheduling results under semi-scheduling mode and scheduling mode without PS (PS means pumped storage, PP means PV power, WP means wind power, TP means thermal power, HP means hydropower, FR means frequency regulation and RR means rotating reserve).

7. Conclusions

As a low-carbon and adjustable power supply, pumped storage has great advantages in coping with the fluctuations and uncertainty of renewable energy. In this paper, a novel semi-scheduling mode and its solution method for the WSHTPC model were established. Additionally, the risk–utility was introduced to provide reserve capacity of pumped storage to promote the consumption of renewable energy. Then, aiming at minimizing the total quotation cost of thermal power, hydropower and pumped storage, the WSHTPC mathematical model was built to optimize scheduling in the day-ahead market.

Through the case study on the typical daily, the risk attitude of pumped storage responding to the uncertainty of renewable energy output in the ancillary service market can be determined: in the low penetration of renewable energy, considering the market performance of pumped storage and the benefit of the multi-energy system comprehensively, the risk attitude of pumped storage participating in the ancillary service market depends on the specific objectives; in the medium and high penetration of renewable energy, it is suggested that the pumped storage units should be a risk preference to deal with the uncertainty of renewable energy output. In addition, by taking a typical day as an example, through jointly scheduling with thermal power units and hydropower units, the regulating ability of pumped storage can be exploited to improve the benefit of the multi-energy system.

It should also be pointed out that under the background of the spot market, the optimal scheduling of the multi-energy system should comprehensively consider the influence of market factors such as bidding strategy, and the establishment of a complete spot market joint optimization model will be the next content in future research.

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