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Two-Stage Stochastic Scheduling of Cascaded Hydropower–Wind–Photovoltaic Hybrid Systems Considering Contract Decomposition and Spot Market

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Abstract: With the advancement of China's electricity markets and the continuous development of renewable energy sources (RESs), it is of great importance to investigate the strategic behavior of RESs in electricity markets. In this paper, a two-stage stochastic optimization model is proposed for a hybrid energy system composed of cascade hydropower plants, wind farms, and photovoltaic stations. Firstly, typical scenarios are generated based on Latin hypercube sampling (LHS) and the K-means clustering algorithm to represent uncertainties of wind–photovoltaic power outputs. Then, with an analysis of China's electricity market structure, a two-stage coordinated scheduling model of hydropower–wind–photovoltaic hybrid systems in electricity markets is established with the objective of maximizing total revenues considering bilateral contract decomposition, the day-ahead energy market, and the real-time balance market. In addition, the proposed model is transformed into a mixed-integer linear programming (MILP) problem for computational convenience. As shown in an analysis of case studies, cascade hydropower plants can compensate for the fluctuation in wind and photovoltaic power outputs to reduce financial risks caused by uncertainties of wind and photovoltaic power generation. Simulation results show that compared with uncoordinated operation, the coordinated operation of hydropower–wind–photovoltaic hybrid systems increases total revenue by 1.08% and reduces the imbalance penalty by 29.85%.

Keywords: hydropower–wind–photovoltaic hybrid systems; electricity markets; two-stage stochastic optimization; bilateral contract decomposition; spot market; mixed-integer linear programming

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1. Introduction

To satisfy China's requirements for achieving low-carbon transformation, clean and renewable energy sources are being developed continuously [1,2]. However, these weather-driven power sources are uncontrollable, intermittent, and uncertain [3,4]. As the penetration of renewable energy sources (RESs) represented by photovoltaic and wind power gradually increases, it brings operational pressure and safety challenges to the power system. Limited by the wind and photovoltaic power absorption capacity of power grids, severe wind and photovoltaic power curtailment has occurred in these areas. In this situation, the complementary operation of RESs with flexible dispatchable power sources like thermal and hydropower systems can help power systems accommodate the fluctuations in non-dispatchable generation and accept larger amounts of wind and solar power [5,6]. Among these flexible dispatchable power sources, hydropower is preferred as a good power source that can compensate for the variability in wind and photovoltaic power, with the advantages of providing a fast response to load variability, robustness in response to weather fluctuations, friendly environmental effects, and energy storage in reservoirs [7,8]. Therefore, it is essential to study the complementary operation of hydropower–wind–photovoltaic hybrid systems to realize large-scale renewable energy integration and the economic and safe operation of power systems [9,10]. There are many combination forms of hydropower–wind–photovoltaic hybrid systems, which have been greatly developed worldwide, especially in China, such as hybrid hydropower–photovoltaic systems [11], hybrid wind–PV–hydropower systems [12], hybrid wind–hydropower systems [13], hybrid wind–hydropower–thermal systems [14], and pumped storage–wind–photovoltaic systems [15].

To utilize RE efficiently, the reform of the electricity market is being continuously improved, and the trial run of electricity market reform is being rapidly promoted in China [16,17]. In addition, most electricity markets combine the medium- to long-term market and spot market jointly to promote the construction of a unified, open, competitive, and orderly electricity market. In the background of the continuous development of RESs, the electricity market is gradually impacting the operation of complementary renewable energy systems. In recent years, some studies have been conducted on the operation of hydropower participating in the electricity market. Lu et al. [18] proposed a method based on time-varying relative risk aversion for the energy allocation of regulable hydropower plants and a two-layer optimal method for obtaining an income-maximizing energy portfolio; these methods can improve the economic income of hydropower plants and the utilization rate of hydropower energy resources. Yuan et al. [19] established an optimized scheduling model for cascade hydropower plants simultaneously participating in the daily contract market, and the impact of the penalty coefficient for the contract electricity imbalance was analyzed; their results can provide an effective reference for market operators formulating electricity trading rules. Pérez-Díaz et al. [20] presented a novel approach to solve the short-term operation scheduling problem of a hydropower plant that sells energy in a deregulated electricity market with the objective of maximizing its revenue. Zhong et al. [21] studied the day-ahead scheduling of cascaded hydroelectric systems in a restructured electricity market with the presence of uncertainties of electricity price and natural water inflow and developed a hybrid robust stochastic optimization model to simultaneously hedge against the uncertainties arising from complicated natural and market environments. Lu et al. [22] proposed a long-term optimal operation method for cascade hydropower stations considering the uncertainty of multiple variables based on the hydro-dominant electricity market structure and settlement rules, and a copula connect function was used to fit the joint distribution of the monthly inflow, the clearing price of the intra provincial market and the delivery volume of the interprovincial market. Yu et al. [23] proposed an economic dispatching model for cascade hydropower plants based on a two-part frequency regulation compensation mechanism for maximizing revenue, which combined the benefits of both energy and frequency regulation.

The above studies mainly focus on the individual operation of hydropower generation in electricity markets. With the coordinated development of hydropower and wind–photovoltaic generation, it is very meaningful to study the coordinated operation of hydropower–wind–photovoltaic hybrid systems. For the coordination of hydropower–wind–photovoltaic hybrid systems, existing research mainly focuses on the short-term scheduling of hybrid systems under uncertainties, including improving the operational economy [24,25] and providing peak-shaving capacity [26,27]. There are few studies on the coordinated operation of hydropower plants with wind and photovoltaic power considering market functionality. Li et al. [28] proposed a medium-term multi-stage distributionally robust optimization scheduling approach for price-taking hydro–wind–solar complementary systems in the electricity market to address the uncertainties of multiple energy resources and market prices that affected the trading strategies. The profits of a complementary wind–solar–hydropower system which can be increased by coordinating the spot market and the forward market may be influenced by complex market mechanisms and uncertainties of multiple energy resources and market prices; Cheng et al. [29] established a stochastic scheduling model to address this issue. Riddervold et al. [30] established the definition of the imbalance cost of hydropower and wind power, which was used to describe the potential benefits of shifting from plant-specific schedules to a common load requirement for wind and hydropower units in the same price area. Li et al. [31] proposed an integrated bidding strategy for a hydropower–wind–photovoltaic hybrid system with a trade-off between current profits and future utilities for hybrid systems that were generally neglected. Behnamfar et al. [32] introduced a stochastic multi-objective structure in a joint energy and reserve market to allow energy generation companies participating in short-term hydro-thermal self-scheduling with wind and photovoltaic uncertainty and small hydropower units to consider uncertainties including energy prices and spinning and non-spinning reserve prices, as well as the uncertainties of renewable energy resources such as the uncertainty of the output power of wind, PV, and small hydropower plants. Xu et al. [33] established an operating model of a hydropower–wind–PV system by considering long-term electricity prices simulated with a short-term model to address the issue of deriving long-term operating rules for a hydropower–wind–PV system in an electricity market because of the difficulty of accurately estimating the benefit and the power curtailment occurring in the short term. However, the impact of the medium- to long-term bilateral contract market has been seldom incorporated, but consideration of this impact is essential for hydropower–wind–photovoltaic hybrid systems to avoid risks of spot price fluctuation. Also, the real-time balance market is seldom considered as well. Therefore, it is necessary to conduct research on integrated bidding to combine the long-term bilateral contract market, day-ahead spot market, and real-time market. In the combined electricity market structure, uncertainties of wind and photovoltaic power outputs will certainly bring financial risks. So, it is important to involve the modeling of wind and photovoltaic power output uncertainty and develop coordinated bidding strategies considering the complementary operation of hydropower, wind, and photovoltaic systems.

In view of the above problems, this paper proposes a two-stage stochastic short-term scheduling method for hybrid power generation systems including wind farms, photovoltaic stations, and cascade hydropower plants in an electricity market so that these resources can realize complementary operation through joint dispatching. In our opinion, this is the first attempt to propose a two-stage stochastic schedule optimization model for a cascaded hydropower–wind–photovoltaic hybrid system considering contract decomposition and the spot market. The main contributions of this paper can be summarized as follows:

- Based on the current electricity market system in China, a two-stage stochastic schedule optimization model for a cascaded hydropower–wind–photovoltaic hybrid system is proposed to maximize the total revenue in an electricity market. Medium- to long-term bilateral contract decomposition, bidding power in the day-ahead energy market, and the imbalance penalty in the real-time balance market are coordinated in the proposed model.
- Considering the power output uncertainty of wind and photovoltaic units, Latin hypercube sampling and the K-means clustering algorithm are used to generate typical scenarios of wind and photovoltaic power outputs. In the proposed model, nonlinear constraints are transformed using multiple linearization methods, and the proposed model is converted into a mixed-integer linear programming problem that can be solved efficiently.

The remainder sections are organized as follows: Section 2 establishes the market structure. Section 3 presents the coordinated schedule optimization model for cascade hydropower-wind–photovoltaic hybrid systems in an electricity market. Section 4 gives the linearization method of the proposed model. Case studies are presented in Section 5, and conclusions are given in Section 6.

2. Market Structure

Figure 1 shows the scheme of a cascaded hydropower–wind–photovoltaic hybrid system (CHWPS). Hydropower, wind, and photovoltaic power are bundled for participation in an electricity market, using the regulating capacity of cascade hydropower plants to compensate for wind power and photovoltaic power output fluctuation and uncertainty in order to maximize profits.

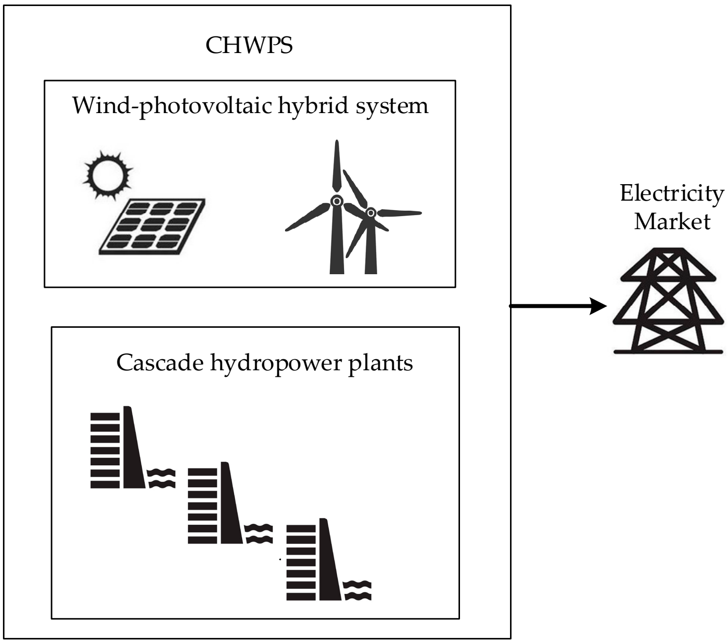

Figure 1. The structure of CHWPS.

China's current electricity market mainly includes the medium- to long-term market and the spot market. For the medium- to long-term market, there are two main types of bilateral contracts (BCs). One is the medium- to long-term financial contract, for which the spot market full-electricity bidding mode is adopted. The financial contract only affects the settlement revenue and does not need physical execution [34,35]. The other one is the medium- to long-term physical contract, for which incremental bidding in the spot market is adopted. It requires physical execution, which will directly affect the bidding space of the spot market. The medium- to long-term contract electricity does not participate in the spot market. This paper assumes that a CHWPS signs physical contracts in medium- to long-term markets. The schematic diagram of medium- to long-term physical contracts with a spot market bidding model is shown in Figure 2. For the spot market, the day-ahead energy market and real-time balance market are considered. The development progress of China's electricity markets varies in different regions. In the western part of Inner Mongolia, a total of 1233.75 TW·h of electricity was traded in the medium- and long-term market in the first half of 2023, accounting for 46.1% of the province's total electricity consumption, with an average transaction price of 335.92 CNY/MW·h. In northern China, taking Shandong Province as an example, the accumulated electricity of medium- and long-term market transactions in the first half of 2023 was 1047.74 TW·h, accounting for 42.8% of the province's total electricity consumption, with an average transaction price of 373.88 CNY/MW·h. In the day-ahead energy market, a CHWPS submits bidding power of the next 24 h to the trading center based on the forecast power outputs and the predicted market clearing prices considering medium- to long-term bilateral contract decomposition. Then, in the real-time market, the imbalance cost caused by the uncertainty of renewable energy will be settled based on imbalance prices. That is, a CHWPS will be punished if its actual power outputs deviate from day-ahead bids, which is a widely used method in China's electricity market [36]. Under the paradigm of the electricity market, decomposing bilateral contracts (BCs) signed in the medium- to long-term market and bidding in the spot market is a promising way for a CHWPS to obtain more revenue by exploiting the synergy of different markets.

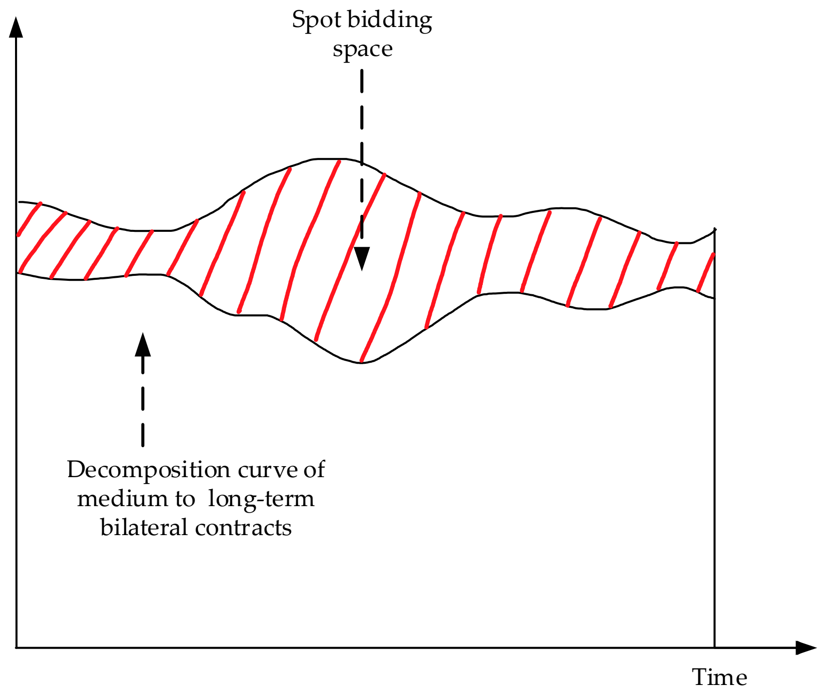

Figure 2. The schematic diagram of medium- to long-term physical contracts with spot market bidding model.

3. Two-Stage Stochastic Optimization for CHWPS

3.1. Assumptions

It is assumed that the hydropower and renewable energy stations in the CHWPS belong to the same stakeholder. The whole CHWPS is integrated into one market bidding unit. The total generation capacity of every utility in the electricity market is relatively small compared to power loads. Therefore, it is assumed that the strategic bidding behavior of the market participant cannot affect the market price. In other words, the CHWPS is regarded as a price-taker in this paper. The bidding power submitted by the CHWPS includes power output values and corresponding prices for each period. For hydropower, wind, and photovoltaic stations, generation costs are relatively low. To avoid renewable energy abandonment and ensure that the declaration curve submitted by the CHWPS wins the bid, the prices for each period are 0. So, only the bidding power should be optimized in this work.

3.2. Modeling of Wind–Photovoltaic Hybrid System Power Output Uncertainty

Since renewable energy generation cannot be predicted, typical scenarios are utilized to characterize the uncertainty of wind and photovoltaic power outputs. Increasing the number of scenarios can accurately simulate the uncertainty, but this causes a huge computational burden as well. To handle this problem, a scenario generation and clustering method based on Latin hypercube sampling and the K-means clustering algorithm is applied in this work. The advantage of this method is that the probability distribution of uncertain parameters in the problem is represented with a moderate number of scenarios, which balances computational accuracy and efficiency.

Firstly, Latin hypercube sampling (LHS) is used for the generation of numerous scenarios based on the probability distribution function of uncertain parameters. Compared with simple random sampling, LHS can cover a much larger sampling space of input random variables with the same sample size. Then, the K-means clustering algorithm is utilized to reduce numerous scenarios into typical scenarios, and the corresponding probability of each typical scenario can be obtained. These typical scenarios are used to represent the uncertainty of renewable energy generation, reducing the computational burden at the same time.

3.3. Coordination of Cascaded Hydropower–Wind–Photovoltaic Hybrid Systems in Electricity Markets

The alliance formed by cascaded hydropower, wind, and photovoltaic stations submits the bidding power curve in the day-ahead energy market based on the prediction of future wind and photovoltaic power outputs and electricity prices, combined with the operating characteristics of cascaded hydropower stations. The formation of the bidding power curve involves making optimal schedule decisions for the CHWPS in the day-ahead market, taking into account the actual wind power output scenarios in the future and the regulation capacity of hydropower in corresponding scenarios. That is, the coupling relationship among bilateral contact decomposition, the day-ahead energy market, and the real-time balance market is considered in the day-ahead bidding decision. It is believed that after the launch of the real-time balanced market at various time intervals during the operation day, the CHWPS needs to adjust the operation of the hydropower station based on the updated wind–photovoltaic output and electricity price scenarios to maximize profits. Also, the CHWPS accepts the imbalance power settlement of the deviation between the actual outputs and the day-ahead bidding power.

The joint participation of hydropower plants and wind–photovoltaic stations in the spot market can effectively reduce the output deviation of wind–photovoltaic power during real-time operation, thereby reducing unbalanced settlement costs and improving overall revenue. For example, when wind power exceeds its day-ahead bidding power in real-time operation (i.e., the actual output during that period is greater than the day-ahead bidding power), hydropower plants can store the excess energy, avoiding the unbalanced settlement costs caused by deviations in wind power. Also, hydropower plants can play a supplementary role in the case of the actual wind power being under the day-ahead bidding power.

Based on the above analysis, there are two key issues that need to be addressed in the day-ahead market optimization operation strategy for the joint operation of CHWPSs. The first is how to fully utilize the complementary characteristics between various entities to determine the optimal joint bidding strategy. The second is how to describe the impact of the real-time output uncertainty of wind power on the balance risk faced by a CHWPS. This paper adopts the idea of looking ahead to design a two-stage stochastic optimization model, as shown in Figure 3. In the first stage, considering the forecast wind–photovoltaic power outputs and day-ahead electricity prices for the next day, bilateral contract decomposition and day-ahead joint bidding power are determined. In response to the uncertainty of real-time wind–photovoltaic power outputs, multiple typical scenarios are adopted. The optimal operating strategy for cascaded hydropower plants is determined based on the possibility of real-time wind–photovoltaic power to minimize imbalanced costs, which is a second-stage problem embedded in the day-ahead optimization model. This two-stage model aims to fully consider the uncertainty risks that may arise during real-time operation when formulating the CHWPS's day-ahead optimal bidding strategies.

3.4. Mathematical Model

3.4.1. Objective Function

Under the paradigm of bilateral contract decomposition and the spot market with day-ahead energy and real-time balance markets, the CHWPS schedules power bids in the day-ahead market, taking into account the bilateral contract decomposition and the power output redispatching of hydropower in the real-time stage to compensate for the uncertainty of renewable energy. As the CHEPS is a profit-seeking entity in the electricity market, its objective function is to maximize the total revenue from medium- to long-term bilateral contacts and the spot market as expressed in Equations (1)–(5).

$$\max R = R^{\mathrm{L}} + R^{\mathrm{S}} \tag{1}$$

$$R^{\mathrm{S}} = R^{\mathrm{DA}} + R^{\mathrm{B}} \tag{2}$$

$$R^{\mathrm{L}} = \lambda^{\mathrm{c}} \sum_{t=1}^{T} P_t^{\mathrm{c}} \tag{3}$$

$$R^{\mathrm{DA}} = \sum_{t=1}^{T} \lambda_t P_t^{\mathrm{da}} \tag{4}$$

$$R^{\mathrm{B}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \pi_{s,t} (\lambda_t^{\mathrm{up}} P_{s,t}^{\mathrm{pd}} - \lambda_t^{\mathrm{dn}} P_{s,t}^{\mathrm{nd}}) \tag{5}$$

where R is the total revenue of the CHWPS; R^{L} and R^{S} are the revenue from the medium- to long-term bilateral contract and the spot market, respectively; R^{DA} is the revenue from the day-ahead market; R^{B} is the expected revenue from the real-time balance market caused by the forecast uncertainty of wind and photovoltaic power; λ^{c} is fixed price signed in the medium- to long-term contract; P_t^{c} is decomposed power output of hydropower plants for the medium- to long-term bilateral contract at time interval t; P_t^{da} is bidding power of the CHWPS in the day-ahead energy market at time interval t; S is the number of scenarios; T is the number of time intervals in a bidding horizon; $\pi_{s,t}$ is the probability of scenario s at time interval t; $P_{s,t}^{\mathrm{pd}}$ and $P_{s,t}^{\mathrm{nd}}$ are the positive output deviation and negative output deviation in scenario s at time interval t; λ_t^{up} and λ_t^{dn} are the positive and negative clearing prices of imbalance power in the real-time balance market, respectively; and λ_t is the clearing price of the day-ahead energy market. In order to encourage the market utility to follow the bids in the day-ahead market, the relationship of λ_t^{up}, λ_t^{dn}, and λ_t can be expressed as (6).

$$0 \le \lambda_t^{\mathrm{dn}} \le \lambda_t \le \lambda_t^{\mathrm{up}} \tag{6}$$

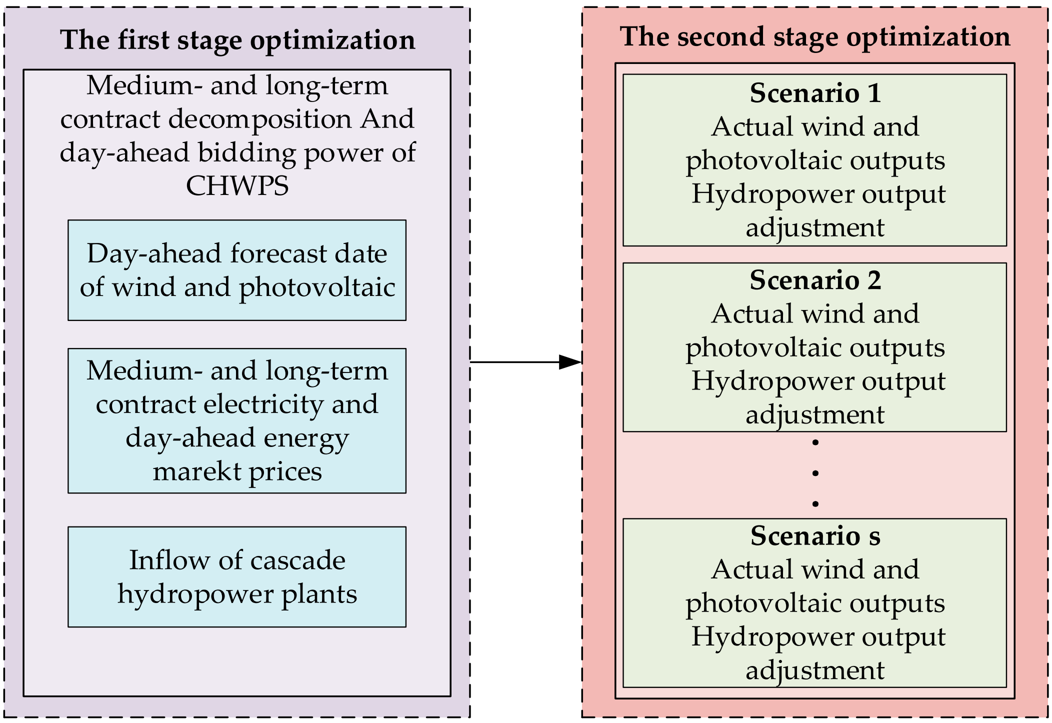

Figure 3. Two-stage stochastic optimization.

3.4.2. Constraints of Power Balance

Constraint (6) enforces the power balance of the CHWPS as follows:

$$\sum_{i=1}^{N_{\mathrm{P}}}\sum_{g=1}^{N_{\mathrm{H},i}} P_{i,g,t}^{\mathrm{ch}} + P_t^{\mathrm{w}} + P_t^{\mathrm{pv}} = P_t^{\mathrm{da}} + P_t^{\mathrm{c}} \tag{7}$$

$$P_t^{\mathrm{da}} + P_t^{\mathrm{c}} + P_{s,t}^{\mathrm{pd}} - P_{s,t}^{\mathrm{nd}} = \sum_{i=1}^{N_{\mathrm{P}}}\sum_{g=1}^{N_{\mathrm{H},i}} P_{i,g,s,t}^{\mathrm{cha}} + P_{s,t}^{\mathrm{wa}} + P_{s,t}^{\mathrm{pva}} \tag{8}$$

$$P_{s,t}^{\mathrm{pd}} \cdot P_{s,t}^{\mathrm{nd}} = 0 \tag{9}$$

where P_t^{w} and P_t^{pv} are the wind and photovoltaic power bids in the day-ahead energy market at time interval t, respectively; $P_{i,g,t}^{\mathrm{ch}}$ is the power bid of hydropower unit g in plant i at time interval t in the day-ahead energy market; N_{P} and $N_{\mathrm{H},i}$ are numbers of hydropower plants and units in plant i, respectively; $P_{s,t}^{\mathrm{wa}}$ and $P_{s,t}^{\mathrm{pva}}$ are the real-time wind and photovoltaic power outputs in scenario s at time interval t, respectively; and $P_{i,g,s,t}^{\mathrm{cha}}$ is the real-time cascaded hydropower output of unit g in plant i of scenario s at time interval t. Equation (8) denotes that the positive and negative output deviation caused by wind and photovoltaic units can be mitigated by hydropower using its flexible regulation to increase the expected revenue of the CHWPS from the real-time balance market.

3.4.3. Constraints of the Bilateral Contract

A medium- to long-term bilateral contract usually sets the total electricity quantity in a bidding horizon. Also, the peak, flat, and valley periods and their proportional coefficients in the daily electricity quantity will be set, as expressed in Equations (10)–(13).

$$\sum_{t=1}^{T} P_t^{\mathrm{c}} = E_{\mathrm{C}} \tag{10}$$

$$\sum_{t\in\Omega^{\mathrm{p}}} P_t^{\mathrm{c}} = \alpha^{\mathrm{p}} E_{\mathrm{C}} \tag{11}$$

$$\sum_{t\in\Omega^{\mathrm{f}}} P_t^{\mathrm{c}} = \alpha^{\mathrm{f}} E_{\mathrm{C}} \tag{12}$$

$$\sum_{t\in\Omega^{\mathrm{v}}} P_t^{\mathrm{c}} = \alpha^{\mathrm{v}} E_{\mathrm{C}} \tag{13}$$

where E_{C} is the electricity quantity in a bidding horizon; α^{p}, α^{f}, and α^{v} are the proportional coefficients of peak, flat, and valley periods, respectively; and Ω^{p}, Ω^{f}, and Ω^{v} are sets of time intervals of peak, flat, and valley periods, respectively.

3.4.4. Constraints of Cascaded Hydropower

As the cascaded hydropower system is operated in the real-time stage for coordination with wind and photovoltaic power, the constraints for cascaded hydropower operation should vary with scenarios. Therefore, the subscript s will be in the related variables. To simplify the expression of the constraints, the subscript s of related variables is neglected here.

1. Constraints of reservoir operation

$$V_{i,t} = V_{i,t-1} + \left[I_{i,t} + \sum_{g}^{N_{\mathrm{H},i}} \left(q_{i-1,g,t-\tau_{i-1}} + Q_{i-1,g,t-\tau_{i-1}}^{\mathrm{S}} \right) - \sum_{g}^{N_{\mathrm{H},i}} \left(q_{i,g,t} + Q_{i,g,t}^{\mathrm{S}} \right) \right] \tag{14}$$

$$V_i^{\min} \le V_{i,t} \le V_i^{\max} \tag{15}$$

$$u_{i,g,t} q_{i,g}^{\min} \le q_{i,g,t} \le u_{i,g,t} q_{i,g}^{\max} \tag{16}$$

$$0 \leq Q^{\mathrm{S}}_{i,g,t} \leq Q^{\mathrm{S,max}}_{i,g} \tag{17}$$

where $V_{i,t}$ is the reservoir capacity of hydropower plant i at time interval t; $I_{i,t}$ is the inflow of hydropower plant i at time interval t; $q_{i,g,t}$ and $Q^{\mathrm{S}}_{i,g,t}$ are the generation flow and spillage flow of unit g in plant i of scenario s at time interval t, respectively; τ_{i-1} is the time lag of water flow; $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum reservoir storage capacities of hydropower plant i; $q_{i,g}^{\min}$ and $q_{i,g}^{\max}$ are the minimum and maximum generation flows of unit g in plant i, respectively; and $Q^{\mathrm{S,max}}_{i,g}$ is the maximum allowed water spillage of unit g in plant i.

2. Constraints of hydropower generation

$$P^{\mathrm{ch}}_{i,g,t} = \rho g \eta_{i,g} H_{i,t} q_{i,g,t} \tag{18}$$

$$u_{i,g,t} P_{i,g,\min} \leq P^{\mathrm{ch}}_{i,g,t} \leq u_{i,g,t} P_{i,g,\max} \tag{19}$$

$$-R_{i,g,\max} \leq P^{\mathrm{cha}}_{i,g,t} - P^{\mathrm{cha}}_{i,g,t-1} \leq R_{i,g,\max} \tag{20}$$

$$\delta_{i,g,t} - \sigma_{i,g,t} = u_{i,g,t} - u_{i,g,t-1} \tag{21}$$

$$\delta_{i,g,t} + \sigma_{i,g,t} \leq 1 \tag{22}$$

$$\sigma_{i,g,t} + \sum_{l=t+1}^{\max\{t+\varphi_{i,g}-1,T\}} \delta_{i,g,l} \leq 1 \tag{23}$$

$$\delta_{i,g,t} + \sum_{l=t+1}^{\max\{t+\theta_{i,g}-1,T\}} \sigma_{i,g,l} \leq 1 \tag{24}$$

where ρ is the water density; g is the gravity acceleration, with a value of 9.8; $\eta_{i,g}$ is the efficiency of the hydropower station; $H_{i,t}$ is the net water head of hydropower plant i at time interval t; $u_{i,g,t}$ is a binary variable indicating the on–off state of hydropower units and is equal to 1 if the unit is on; $\delta_{i,g,t}$ and $\sigma_{i,g,t}$ are start-up and shutdown operation variables for unit g in plant i at time interval t, respectively; $\theta_{i,g}$ and $\varphi_{i,g}$ are the minimum online and offline time durations for unit g in plant i; $P_{i,g,\min}$ and $P_{i,g,\max}$ are the minimum and maximum power generation levels for unit g in plant i, respectively; and $R_{i,g,\max}$ is the maximum ramping power of unit g in plant i. Equations (21) and (22) express the constraints between units' on/off state variables and operation variables; Equations (23) and (24) denote the units' minimum online and offline duration constraints.

3. Constraints of net head

$$H_{i,t} = 0.5(Z_{i,t} + Z_{i,t-1}) - D_{i,t} - \Delta H_{i,t} \tag{25}$$

$$Z_{i,t} = f_{i,\mathrm{up}}(V_{i,t}) \tag{26}$$

$$D_{i,t} = f_{i,\mathrm{dn}}(Q_{i,t}) \tag{27}$$

$$Q_{i,t} = \sum_{g}^{N_{\mathrm{H},i}} \left(q_{i,g,t} + Q^{\mathrm{S}}_{i,g,t} \right) \tag{28}$$

$$H_i^{\min} \leq H_{i,t} \leq H_i^{\max} \tag{29}$$

$$Z_i^{\min} \leq Z_{i,t} \leq Z_i^{\max} \tag{30}$$

where $Z_{i,t}$, $D_{i,t}$, and $\Delta H_{i,t}$ are the forebay water level, tail water level, and penstock loss of reservoir i at time interval t, respectively; $H_i^{\min}$ and $H_i^{\max}$ are the minimum and maximum limitations of net water head of plant i, respectively; $Z_i^{\min}$ and $Z_i^{\max}$ are the minimum and maximum forebay water levels of plant i, respectively; and $Q_{i,t}$ is the total release flow of plant i at time interval t. Equation (25) defines the expression of the net head level.

The forebay water level and tail water level are formulated as nonlinear functions of the reservoir volume and water release, respectively, as shown in Equations (26) and (27).

4. Boundary condition

$$V_{i,0} = V_{i,\text{ini}} \tag{31}$$

$$V_{i,T} = V_{i,\text{target}} \tag{32}$$

where $Z_{i,\text{ini}}$ and $Z_{i,\text{target}}$ denote initial and control target water storage of reservoir i, respectively.

4. Solution Method

4.1. Linearization of Hydropower Unit Generation Function

As can be seen from Equation (18), the output of a hydropower unit is a nonlinear expression related to the generation coefficient, generation flow, and net water head. In this paper, assuming that the generation efficiency of each unit is constant [37,38], the output characteristics of the hydropower unit can be linearized by the McCormick convex envelope relaxation method as expressed in Equations (33)–(36).

$$P_{i,g,t}^{\text{ch}} \geq \rho g \eta_{i,g} \left[q_{i,g}^{\min} H_{i,t} + H_i^{\min} q_{i,g,t} - q_{i,g}^{\min} H_i^{\min} \right] \tag{33}$$

$$P_{i,g,t}^{\text{ch}} \geq \rho g \eta_{i,g} \left[q_{i,g}^{\max} H_{i,t} + H_i^{\max} q_{i,g,t} - q_{i,g}^{\max} H_i^{\max} \right] \tag{34}$$

$$P_{i,g,t}^{\text{ch}} \leq \rho g \eta_{i,g} \left[q_{i,g}^{\min} H_{i,t} + H_i^{\max} q_{i,g,t} - q_{i,g}^{\min} H_i^{\max} \right] \tag{35}$$

$$P_{i,g,t}^{\text{ch}} \leq \rho g \eta_{i,g} \left[q_{i,g}^{\max} H_{i,t} + H_i^{\min} q_{i,g,t} - q_{i,g}^{\max} H_i^{\min} \right] \tag{36}$$

4.2. Linearization of Storage-Forebay Water Level Function

$f_{i,\text{up}}(\cdot)$ and $f_{i,\text{dn}}(\cdot)$ in Equations (26) and (27) are nonlinear constraints as well. A segmented linearization method is used to linearize the constraints in Equations (26) and (27) as follows:

The segmented linearization for (26) is accomplished by introducing 0–1 variables. Firstly, the capacity of reservoir i is discretized into L intervals, so the forebay water level will be discretized into L intervals as well, as shown in (37).

$$\begin{cases} V_{i,\min} = V_{i,0} < V_{i,1} < \cdots < V_{i,l} < \cdots V_{i,L} = V_{i,\max} \\ Z_{i,l} = f_{i,\text{up}}(V_{i,l}), l = 1, 2, \ldots, L \end{cases} \tag{37}$$

where $V_{i,l}$ and $Z_{i,l}$ are the endpoints of segment l, respectively.

Then, binary variables $r_{i,t,l}^{\text{up}}$ that indicate if the interpolation point is located in segment l are introduced, which establishes a linear relationship as shown in Equations (38)–(41).

$$r_{i,t,l}^{\text{up}} V_{i,l-1} \leq V_{i,t,l} \leq r_{i,t,l}^{\text{up}} V_{i,l} \tag{38}$$

$$\sum_{l=1}^{L} V_{i,t,l} = V_{i,t} \tag{39}$$

$$\sum_{l=1}^{L} r_{i,t,l}^{\text{up}} = 1 \tag{40}$$

$$Z_{i,t} = \sum_{l=1}^{L} \left[r_{i,t,l}^{\text{up}} Z_{i,l-1} + \frac{Z_{i,l} - Z_{i,l-1}}{V_{i,l} - V_{i.l-1}} \left(V_{i,t,l} - r_{i,t,l}^{\text{up}} V_{i,l-1} \right) \right] \tag{41}$$

where $V_{i,t,l}$ is the auxiliary variable denotes the capacity of reservoir i at segment l at time interval t.

Similarly, the linearization of (27) can be obtained by using the above segmented linearization method as shown in Equations (42)–(46).

$$\begin{cases} Q_{i,\min} = Q_{i,0} < Q_{i,1} < \cdots < Q_{i,l} < \cdots Q_{i,L} = Q_{i,\max} \\ D_{i,l} = f_{i,\mathrm{dn}}(Q_{i,l}), l = 1, 2, \ldots, L \end{cases} \tag{42}$$

$$r_{i,t,l}^{\mathrm{dn}} Q_{i,l-1} \le Q_{i,t,l} \le r_{i,t,l}^{\mathrm{dn}} Q_{i,l} \tag{43}$$

$$\sum_{l=1}^{L} Q_{i,t,l} = Q_{i,t} \tag{44}$$

$$\sum_{l=1}^{L} r_{i,t,l}^{\mathrm{dn}} = 1 \tag{45}$$

$$D_{i,t} = \sum_{l=1}^{L} \left[r_{i,t,l}^{\mathrm{dn}} D_{i,l-1} + \frac{D_{i,l} - D_{i,l-1}}{Q_{i,l} - Q_{i.l-1}} \left(Q_{i,t,l} - r_{i,t,l}^{\mathrm{dn}} Q_{i,l-1} \right) \right] \tag{46}$$

4.3. The Big-M Method for Solving Electricity Market Constraints

In the real-time balance market, positive and negative deviations cannot exist at the same time interval, as shown in (9), which is also a nonlinear constraint. Here, we use the big-M method [39] to transform (9) into the linear constraints shown in Equations (47) and (48).

$$0 \le P_{s,t}^{\mathrm{pd}} \le \mu_{s,t} M \tag{47}$$

$$0 \le P_{s,t}^{\mathrm{nd}} \le (1 - \mu_{s,t}) M \tag{48}$$

where $\mu_{s,t}$ is a 0–1 indicator variable for determining the positive output deviation and negative output deviation. $\mu_{s,t} = 1$ indicates that the system's actual output is greater than the bidding power output; $\mu_{s,t} = 0$ indicates that the system's bidding power output is greater than the actual output. M is the large position number.

5. Case Study

A large-scale cascaded hydropower–wind–photovoltaic hybrid system in southwest China is studied. The system includes a wind farm with a capacity of 1700 MW, a photovoltaic station with a capacity of 1300 MW, and three cascade hydropower plants with a total capacity of 3300 MW. The main characteristic parameters of each hydropower plant are shown in Table 1. The bilateral contract signed in the medium- to long-term market divides the peak, flat, and valley periods, and the specific decomposition period is shown in Table 2.

Table 1. Characteristic parameters for each hydropower plant.

	Hydropower Station #1	**Hydropower Station #2**	**Hydropower Station #3**
Capacity (MW)	4 × 460	4 × 300	3 × 90
Maximum water head (m)	203	121.5	40
Minimum water head (m)	145	80.7	22.3
The maximum power generation flow	4 × 257	4 × 328	3 × 291

Table 2. The medium- to long-term contract electricity division.

Periods	**Time Interval**	**Percentage**
Peak	8–11; 18–22	0.5
Plat	6–7; 12–17	0.3
Valley	1–5; 23	0.2

5.1. Wind–Photovoltaic Power Output Scenarios

Based on the historical data of wind power and photovoltaic and the weather forecast of the next day, the wind–photovoltaic hybrid system power output on the next day can be predicted, and 1000 scenarios are generated using LHS. The generated wind–photovoltaic hybrid system power output scenarios are shown in Figure 4. The number of scenarios is reduced to six using the K-means clustering method. The reduced wind–photovoltaic hybrid system power output scenarios are shown in Figure 5. The probability of each scenario is shown in Table 3.

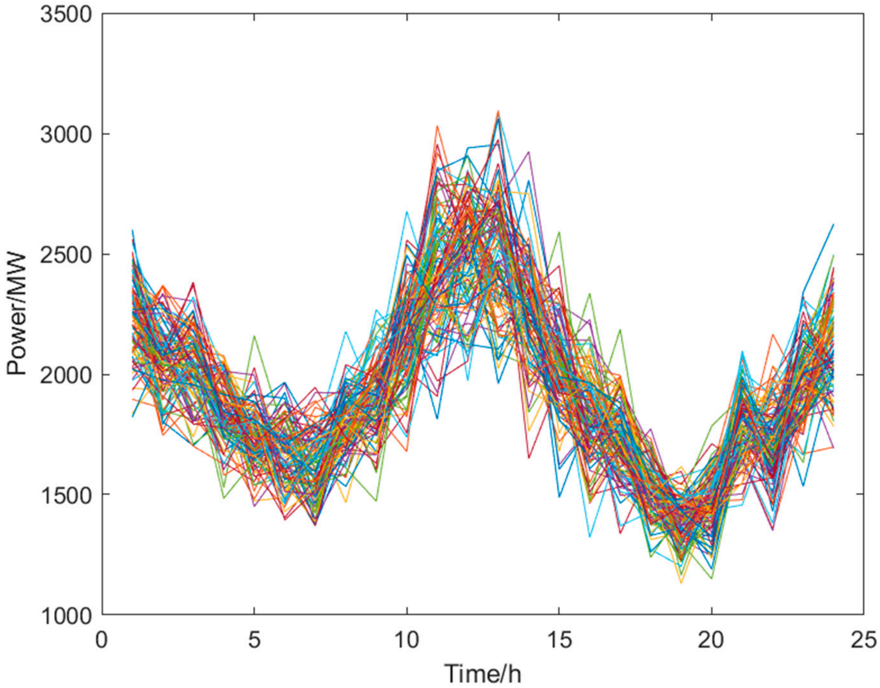

Figure 4. The 1000 scenarios of wind–photovoltaic hybrid system power output.

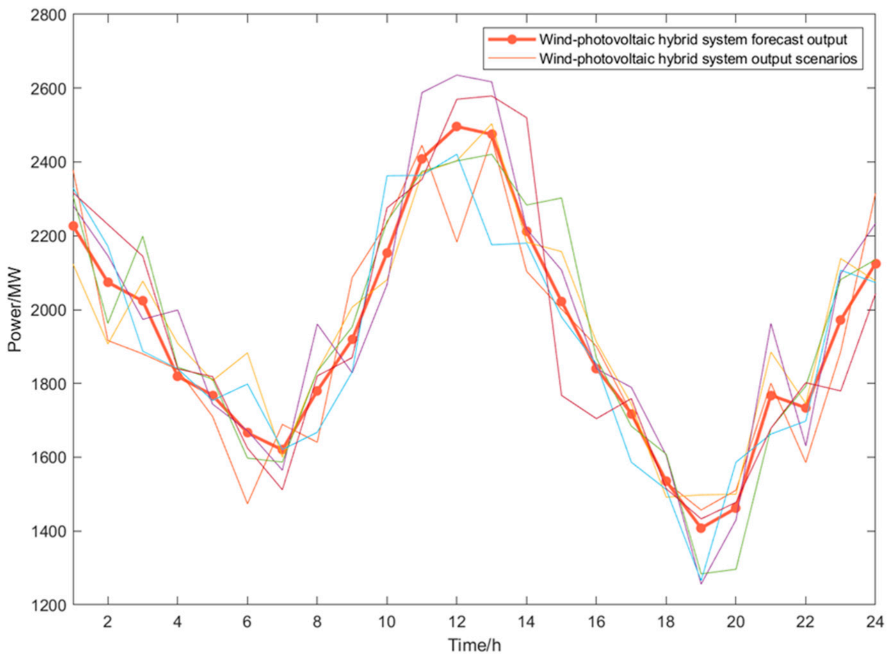

Figure 5. Six scenarios of wind–photovoltaic hybrid system power outputs.

Table 3. Probability of different scenarios.

Scenario	1	2	3	4	5	6
Probability	0.154	0.109	0.096	0.156	0.400	0.085

5.2. Expected Revenue of CHWPS

By combining cascade hydropower plants with wind power and photovoltaic units, the fluctuation in wind power and photovoltaic output can be smoothed, and the imbalance penalty caused by forecast uncertainty can be reduced, improving the revenue of the CHWPS. A comparison of the revenue of the coordinated operation of the hydropower–wind–photovoltaic hybrid system with the uncoordinated operation is shown in Table 4. In this paper, in uncoordinated operation, wind and photovoltaic power participate in the day-ahead energy market based on the forecast power outputs, and the cascaded hydropower prefers to sell energy during high-price hours. In this case, there will be an imbalanced benefit or penalty due to forecast errors between actual outputs and forecast outputs. The coordinated operation is the proposed model in Section 3 with the goal of maximizing revenue through redispatching the hydropower in the real-time stage to reduce imbalance costs. From Table 4, we can see that in the uncoordinated operation, the imbalance revenue is −127.19 (CNY 10^3). For a negative value, there is an imbalance penalty due to the fluctuation in wind power and photovoltaic output. The total expected revenue of uncoordinated operation is 24,235.21 (CNY 10^3). In the coordinated operation, the imbalance penalty of the hydropower–wind–photovoltaic hybrid system is only −89.23 (CNY 10^3), which is a decrease of 29.85%. The revenue of the hydropower–wind–photovoltaic hybrid system is 24,498.02 (CNY 10^3), with an increase of 1.08%.

Table 4. Revenue of uncoordinated operation and coordinated operation.

Categories		Total Expected Revenue (CNY 10^3)	Imbalance Revenue (CNY 10^3)
Uncoordinated operation	Wind–photovoltaic hybrid system	13,191.01	−127.19
	Hydropower	11,044.20	0
	Total	24,235.21	−127.19
Coordinated operation		24,498.02	−89.23

5.3. CHWPS Operation Results

The medium- to long-term contract price and spot market day-ahead price are shown in Figure 6. The scheduled output of the system in the day-ahead market is shown in Figure 7. Scheduled outputs of hydropower and the wind–photovoltaic hybrid system in the day-ahead market are shown in Figure 8. The hydropower plants can be scheduled and coordinated with wind and photovoltaic power outputs to respond to price fluctuations so that the scheduled output changes according to the change in electricity price with the constraints of the medium- to long-term bilateral contract decomposition. The hydropower plants use their regulation capacity to adjust to fluctuations in wind–photovoltaic combined power outputs to maximize the CHWPS's revenue from the day-ahead energy market.

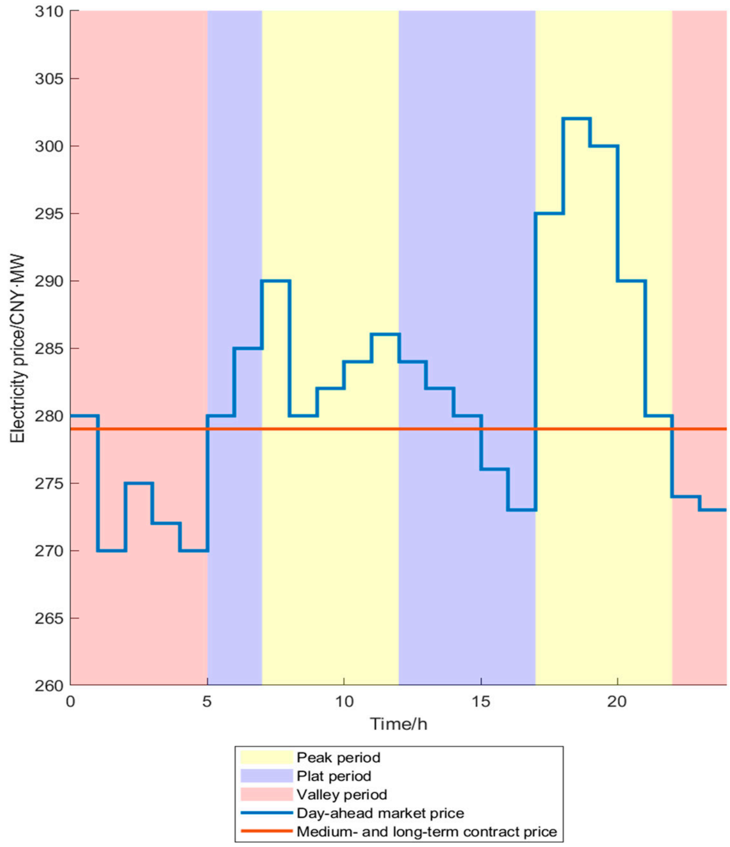

Figure 6. Prices of the medium- to long-term bilateral contract and day-ahead spot market.

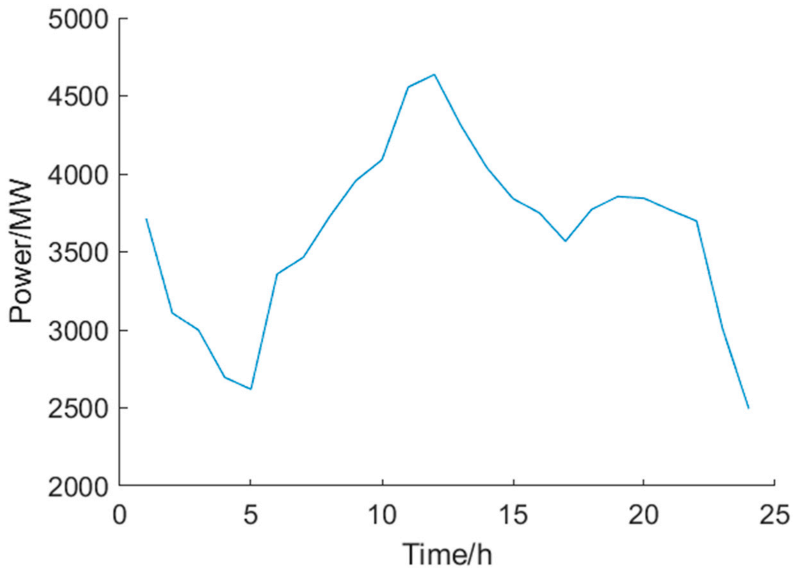

Figure 7. The scheduled output of CHWPS.

Figure 9 shows the power outputs of each cascade hydropower plant. Figure 10 shows the operational statuses of hydropower units. The reservoir capacity and inflow of hydropower plant #1 are both large. It has a relatively more adjustable capacity. The power generation and reservoir capacity of hydropower plant #2 are not as good as those of hydropower plant #1. The output is relatively stable. During the peak period of electricity prices at night, more units will be turned on, which increases the power output of the hydropower plants. Hydropower plant #3 has the worst regulation capacity and weak power generation capacity. Therefore, the power outputs of hydropower plant #3 vary with those of plant #2.

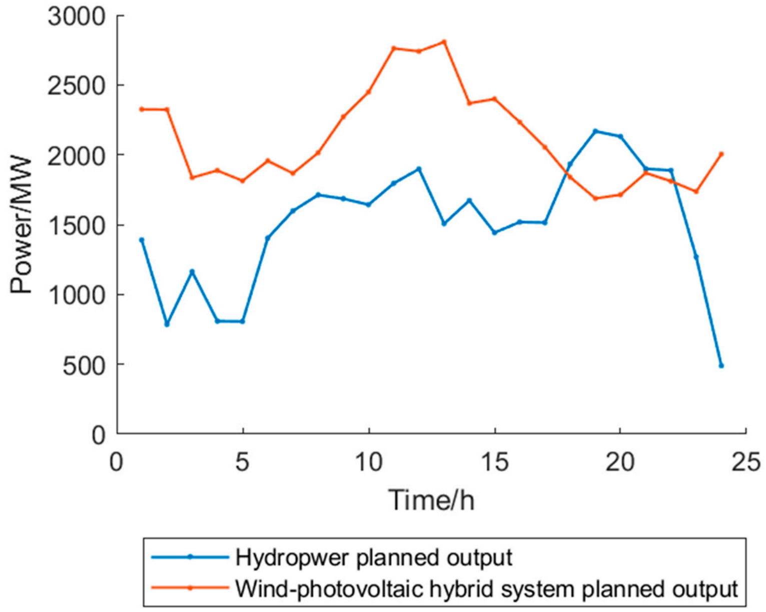

Figure 8. Bidding power outputs of hydropower and the wind–photovoltaic hybrid system.

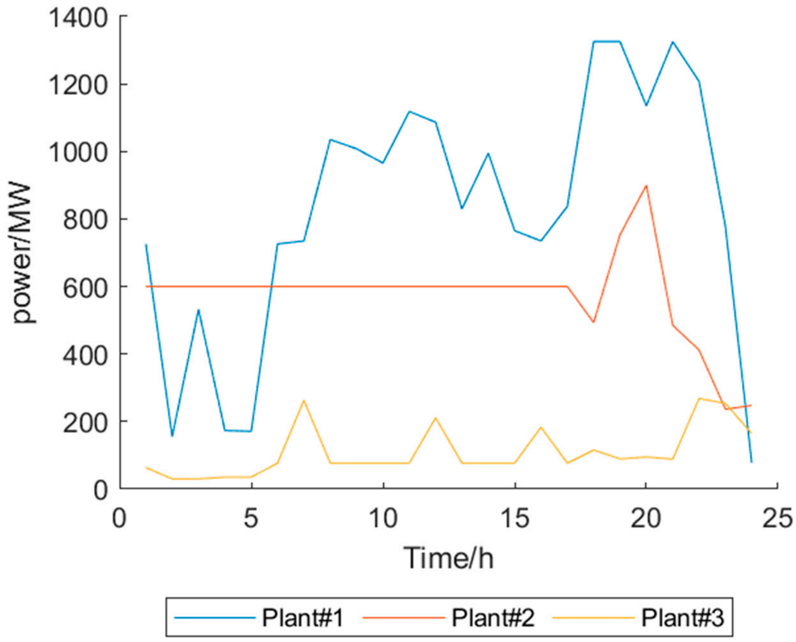

Figure 9. The output of each cascade hydropower plant.

For the real-time balance market, the power outputs of hydropower with wind–photovoltaic power variation of six scenarios are shown in Figure 11. In six different scenarios, the power outputs of the wind–photovoltaic hybrid system deviate from scheduled bids in the day-ahead market. In this case, the hydropower plants will adjust their power outputs to reduce the deviation between the actual outputs and scheduled bids of the CHWPS, which can reduce the imbalance penalty.

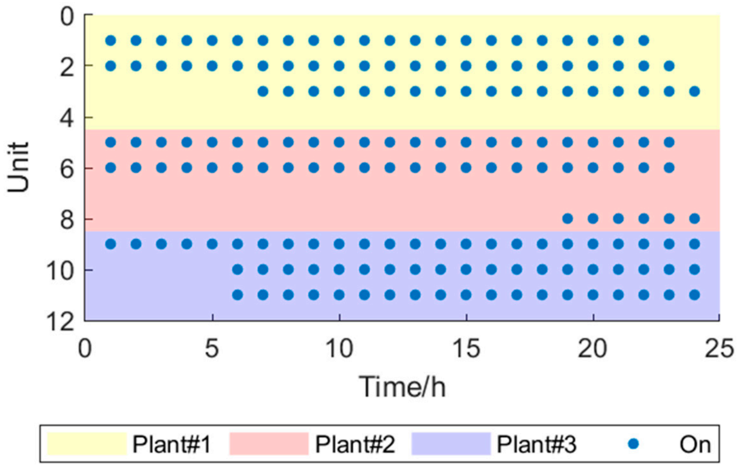

Figure 10. The operational statuses of hydropower units.

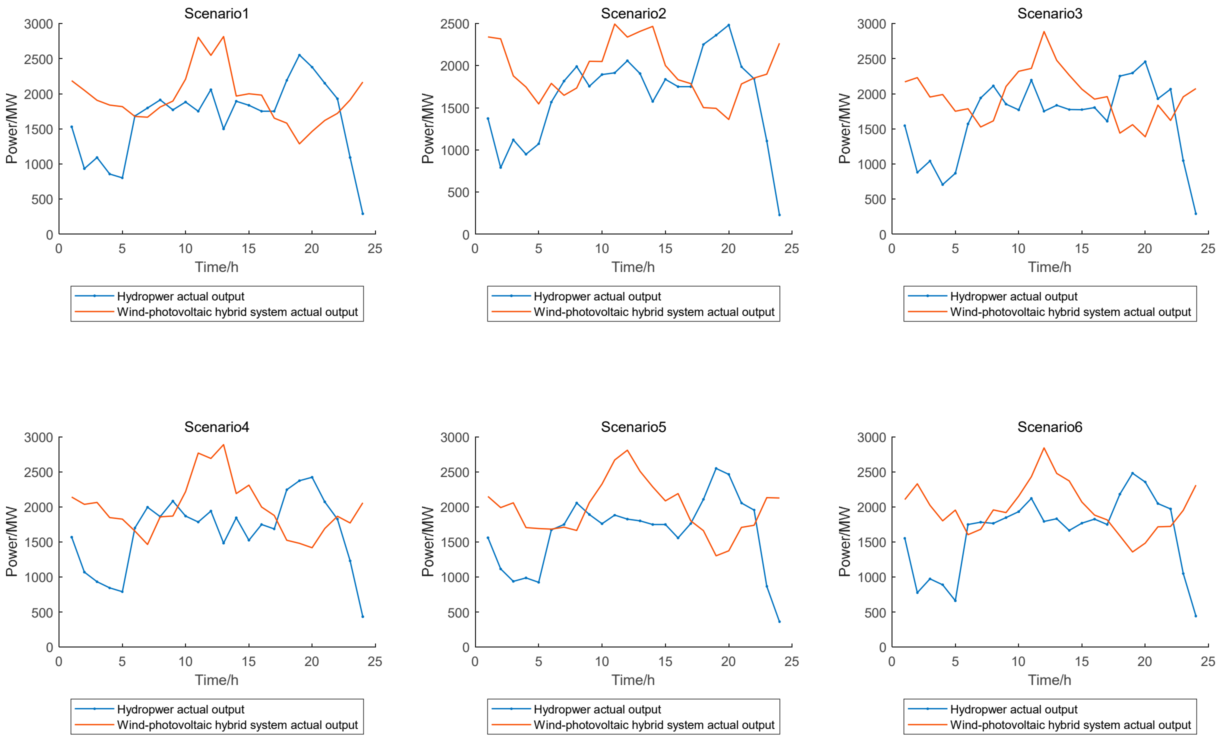

Figure 11. Power outputs of hydropower and wind–photovoltaic hybrid system in the real-time stage.

5.4. Medium- to Long-Term Contract Decomposition and Day-Ahead Spot Market Bids

By solving the proposed model, the scheduled day-ahead bids of the CHWPS can be obtained. In addition, the medium- to long-term bilateral contract decomposition can be gained. The medium- to long-term contract decomposition and spot market day-ahead scheduled output distribution are shown in Figure 12. As mentioned before, the medium- to long-term contract decomposition output needs to be decomposed according to the peak, flat, and valley periods. From Figure 12, we can see that during the period when the bilateral contract price is higher than the spot market day-ahead price, the CHWPS will prioritize the distribution of power outputs to meet the daily contract decomposition requirements of the medium- to long-term bilateral contracts. During the period when the medium- to long-term market price is lower than the spot market day-ahead price, the hydropower–wind–photovoltaic hybrid system will prioritize power output distribution to the spot market output to increase revenue.

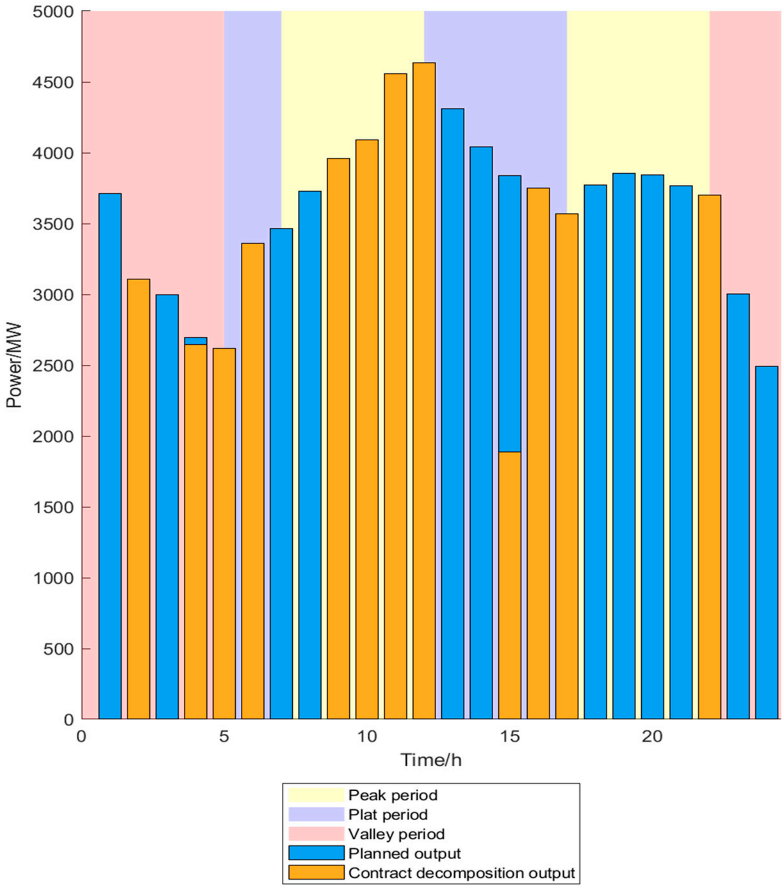

Figure 12. The medium- to long-term contract decomposition and spot market day-ahead scheduled output distribution.

6. Conclusions

A two-stage stochastic scheduling method for cascaded hydropower-wind–photovoltaic hybrid systems considering contract decomposition and the spot market is proposed in this paper. Scenarios generated based on LHS and the K-means clustering method are used to analyze the uncertainty of wind–photovoltaic power outputs. With the objective of maximizing the revenue of bilateral contracts and the spot market, two-stage stochastic optimization is adopted to establish a mixed-integer linear programming problem for the short-term scheduling of CHWPSs. The effectiveness and feasibility of the proposed method are verified in case studies.

Hydropower plants can compensate for wind and photovoltaic power outputs, which improves the CHWPS's revenue. In six different scenarios, wind and photovoltaic power outputs deviate from the bidding power in the day-ahead market. In this case, hydropower plants adjust their power outputs to reduce the deviation between the actual output and the scheduled bidding power of the CHWPS. Considering the synergy between the medium- to long-term bilateral contract and the spot market, the outputs of the CHWPS are distributed in the two electricity markets. A reasonable power output distribution method can improve the revenue of CHWPSs and promote the promotion and development of China's electricity market mechanism with a high penetration of renewable energy. The coordinated operation of hydropower with wind–photovoltaic generation can reduce risks caused by uncertainty of wind–photovoltaic power outputs.

At present, renewable energy is developing rapidly in China, and many wind farms and photovoltaic power stations have been built in areas where hydropower plants have been developed, constituting hydropower–wind–photovoltaic hybrid systems. With the continuous advancement of China's electricity market, it is of great significance to study the optimal scheduling of hydropower–wind–photovoltaic hybrid systems in electricity markets. In our future work, the coordination of hydropower, wind, and photovoltaic power with different stakeholders will be further investigated.

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