Research Article

Optimal Model for Complementary Operation of a Photovoltaic-Wind-Pumped Storage System

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An optimization model for the complementary operation of a photovoltaic-wind-pumped storage system is built to make full use of solar and wind energy. Apart from ensuring the maximum economic benefit which is normally used as the only objective, the stable objectives of minimizing the output fluctuation and variation of load and output difference are added to form the multiobjective problems because of lack of study on access capacity of photovoltaic and wind power. The model aims to increase the power benefit and reduce the output fluctuation and variation of load and output difference under the constraints of station, output balance, and transmission limitation. In a case study, four schemes including single-objective independent operation, single-objective complementary operation, and multiobjective complementary operation are compared to discuss the effect of pumped storage station on economic objective and stable objectives. Furthermore, the opposite trend of the two objectives is proved and a compromise optimal solution is given. The results indicate that the pumped storage station can effectively increase power benefit and access capacity of photovoltaic and wind power. The study can provide references to the complementary optimization of the pumped storage station and the intermittent renewable energy.

1. Introduction

Solar and wind energy are attracting increasing attention recently because they are pollution-free, abundant, and renewable. However, the high fluctuation and randomness characteristics of solar and wind energy have a great influence on the stability of power system [1, 2]. Uncontrolled absorption of large photovoltaic and wind power may result in violent power fluctuation of the whole power system in a certain period. Therefore, in consideration of the operation economy of photovoltaic and wind power, it is significant to maximize the consumption of photovoltaic and wind power without affecting the system. An efficient method to overcome the problem is to combine the pumped storage station with intermittent renewable energy [3–5], for the reason that pumped storage plant is a relatively mature way to store energy and the cost of investment is low, which can make full use of the excess energy and ensure smooth operation of the system.

In recent years, there are many studies on modelling and optimizing for complementary operation of pumped storage-wind [6, 7] or photovoltaic-wind-pumped storage [8, 9] systems. Increasing the profit and reducing the fluctuation variance [10] are the primary optimal objectives. Because the solar and wind energy is instable [1, 2], as more power benefit is obtained, the output fluctuation increases. Thus, the change of economic benefit and output fluctuation show an opposite trend. This contradiction can be alleviated by studying the optimal scheduling and complementary mechanism [11]. The Pareto relationship between the two has been found when studying the combined operation of pumped storage and wind power [12–14]. Nevertheless, the benefit objective function was given without considering the operating cost of the pumped storage plant, and as the output fluctuation objective, the fluctuation variance function is not very comprehensive and accurate. Also, the complementary mechanism has not been deeply discussed yet.
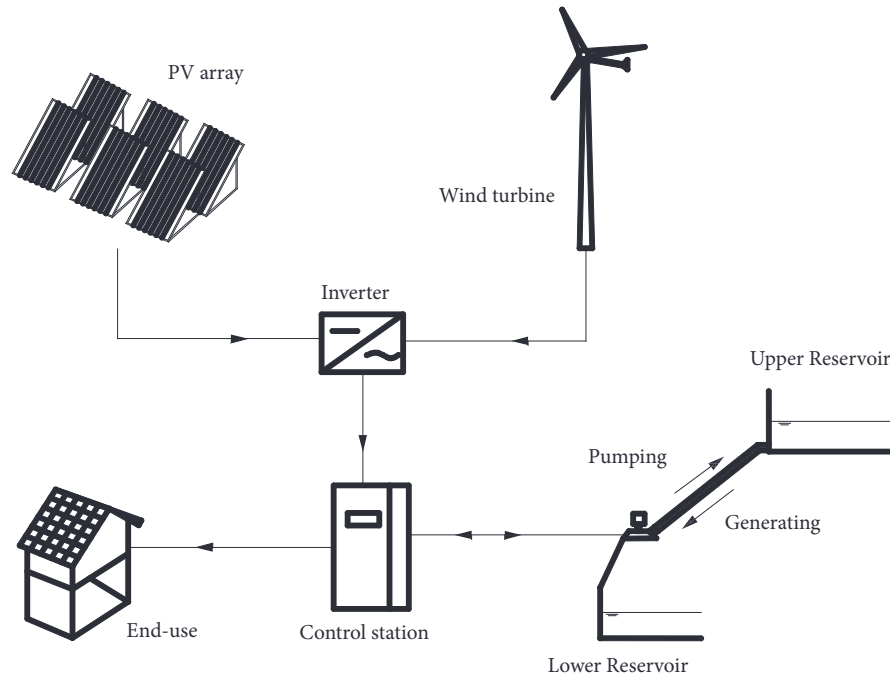
FIGURE 1: A photovoltaic-wind-pumped storage system.

The constraints are mainly divided into three types: station type [11], output balance type [12], and transmission limitation type [13]. Since pumped storage station has many operating conditions, and its combined operation with photovoltaic and wind power is very complicated, the station type has become a limitation for complementary operation.

Although progress has been made, some problems remain to be solved. Firstly, the objective functions and constraints have not been defined properly. Secondly, the relationship between economic and stable objectives has not been studied sufficiently. Thirdly, the role of pumped storage station in complementary operation of hybrid power system has not been well-considered.

An optimization model with multiple objectives, multiple constraints, and high dimension photovoltaic-wind-pumped storage system has been built. The economic objective and stable objective of the model are to maximize the benefit of power generation and to minimize the output fluctuation, respectively. In the case study, single-objective independent operation, single-objective complementary operation, and multiobjective complementary operation are compared, and the complementary mechanism of the system is discussed. Then the Pareto noninferior solution front of power benefit and output fluctuation in multiobjective cooperative operation is obtained, and the interaction between the two is analyzed. Overall, improving the power benefit and access capacity of photovoltaic and wind power are considered at the same time. The results provide a reliable theoretical reference for the study of complementary operation between hydropower and renewable energy.

2. Multiobjective Model for a Photovoltaic-Wind-Pumped Storage System

The photovoltaic-wind-pumped storage complementary operation system is illustrated in Figure 1. The solar and wind energy have the property of natural temporal and spatial complementarity, and the pumped storage plant has the characteristics of energy storage, peak load regulation, and frequency modulation [15, 16], which make the system operate. If the photovoltaic and wind power are unable to be full output, the excess solar and wind power will be available to pump the lower reservoir for stored gravitational potential energy. If the power generation of wind farms and photovoltaic power stations cannot meet the load requirements, the water from the upper reservoir will be used to drive the turbine to generate power.

The principle of complementary operation is that the photovoltaic and wind power operate in full load according to the pre-day power forecast, and the output fluctuation and intermittence are mainly regulated by pumped storage station [17]. Namely, while a pumped storage plant is included in the system, as the solar and wind energy are fully used and the operation benefit of photovoltaic and wind power is improved, the output fluctuation of complementary operation system will be smoothed.

It is assumed that the initial power output of the photovoltaic and wind power when the pumped storage system is not configured and the capacity of the hydroelectric unit after the pumped storage system is configured, is all determined. The objective functions include the power benefit maximization, the output fluctuation minimization, and variation of load and output difference minimization. Constraints

include station constraints, output balance constraint, and transmission constraint.

2.1. Objective Function

2.1.1. Power Benefit.
A benefit maximization model is set up to study how to optimize the output of wind turbine, photovoltaic cell board, and pump-turbine unit in each period to obtain maximum power benefit under the premise of certain wind energy resources and solar energy resources. Power benefit maximization is an economic objective.

$$\max F_1 = \sum_{i=1}^{T} C_i P_i^{wout} + C_i P_i^{pvout} + C_i P_i^{h} - C_{pi} P_i^{p} - C_h \quad (1)$$

where F_1 is the power benefit of the system; T is the scheduling period; P_i^{wout}, P_i^{pvout}, and P_i^{h} are the output of photovoltaic, wind, and pumped storage power directly transported to the load in the ith period; P_i^{p} is the pumping power of the pumped storage plant in the ith period; C_i is the feed-in tariff in the ith period; C_{pi} is the pumping tariff of the pumped storage station in the ith period; C_h is the start and stop cost of the pumped storage plant.

2.1.2. Output Fluctuation.
To minimize the output fluctuation of the complementary operation model, the output fluctuation is calculated by quantifying the fluctuation degree of the process line based on the quantity dimension and the shape dimension [18]. Output fluctuation minimization is a stable objective.

$$\min F_2 = \sum_{i=1}^{T} \left| P_f(i) - \overline{P}_f \right| \sum_{i=1}^{T} \theta_i \quad (2)$$

$$\theta_i$$
$$= \begin{cases} \arctan |k_i| & (i = 1, T), \\ |\arctan k_i - \arctan k_{i-1}| & (k_i k_{i-1} \geq 0, \ 2 \leq i \leq T - 1), \\ \arctan |k_i| + \arctan |k_{i-1}| & (k_i k_{i-1} < 0, \ 2 \leq i \leq T - 1); \end{cases} \quad (3)$$

$$k_i = \begin{cases} \dfrac{P_f(i+1) - P_f(i)}{t(i+1) - t(i)} & (1 \leq i \leq T - 1), \\ \dfrac{P_f(T) - P_f(T-1)}{t(T) - t(T-1))} & (i = T); \end{cases} \quad (4)$$

$$P_f(i) = P_i^{wout} + P_i^{pvout} + P_i^{h} \quad (5)$$

where F_2 is the output fluctuation value of the system; $P_f(i)$ is the output of the whole complementary operation system in the ith period; θ_i is the angle of the two adjacent line segments; k_i is the slope of the ith line segments.

2.1.3. Variation of Load and Output Difference.
Considering the power demand is time-variant in power grid, the sum of squares of load and output difference at each moment in the scheduling period is calculated to minimize the influence to the power grid when the pumped storage plant is added.

Variation of load and output difference minimization is also a stable objective.

$$\min F_3 = \sum_{i=1}^{T} \left(P_f(i) - P_r(i) \right)^2 \quad (6)$$

where F_3 is the variation of load and output difference of the system; $P_r(i)$ is the load forecasting value in the ith period.

2.2. Constraints

2.2.1. Station Constraints

(1) Pumped Storage Plant Constraints

$$E_{\min}^{u} \leq E_i^{u} \leq E_{\max}^{u}$$
$$E_{\min}^{l} \leq E_i^{l} \leq E_{\max}^{l} \quad (7)$$

where E_i^{u} is the reservoir energy of the upper reservoir in the ith period; E_i^{l} is the reservoir energy of the lower reservoir in the ith period; $E_{\min}^{u}$ and $E_{\max}^{u}$ are the minimum and maximum reservoir energy of the upper reservoir, respectively; $E_{\min}^{l}$ and $E_{\max}^{l}$ are the minimum and maximum reservoir energy of the lower reservoir, respectively.

The constraint of reservoir energy variation can be divided into two situations.

When $P_i^{h} > 0$, the reservoir energy variation of the upper and lower reservoirs is, respectively, as follows.

$$E_{i+1}^{u} = E_i^{u} - \frac{\left(\Delta i P_i^{h} \right)}{\eta_1}$$
$$E_{i+1}^{l} = E_i^{l} + \frac{\left(\Delta i P_i^{h} \right)}{\eta_1} \quad (8)$$

When $P_i^{p} > 0$, the reservoir energy variation of the upper and lower reservoirs is, respectively,

$$E_{i+1}^{u} = E_i^{u} + \frac{\left(\Delta i P_i^{p} \right)}{\eta_2}$$
$$E_{i+1}^{l} = E_i^{l} - \frac{\left(\Delta i P_i^{p} \right)}{\eta_2} \quad (9)$$

where η_1 and η_2 are the pumping and generating efficiency of pumped storage station; Δi is the temporal length of a single period.

$$-\mu E_{\max}^{u} \leq E_0^{u} - E_T^{u} \leq \mu E_{\max}^{u}$$
$$-\mu E_{\max}^{l} \leq E_0^{l} - E_T^{l} \leq \mu E_{\max}^{l} \quad (10)$$

where E_0^{u} and E_T^{u} are the initial reservoir energy and final reservoir energy of upper reservoir, respectively; E_0^{l} and E_T^{l} are the he initial reservoir energy and final reservoir energy of lower reservoir, respectively; μ is the maximum allowable

storage energy coefficient of the upper and lower reservoirs during the whole scheduling period.

$$P_{\min}^h \leq P_i^h \leq P_{\max}^h$$
$$P_{\min}^p \leq P_i^p \leq P_{\max}^p \tag{11}$$

where $P_{\min}^h$ and $P_{\max}^h$ are the minimum and maximum output of pumped storage plant; $P_{\min}^p$ and $P_{\max}^p$ are the minimum and maximum pumping output of pumped storage plant.

(2) Wind Power Generation Constraint

$$P_{\min}^w \leq P_i^w \leq P_{\max}^w \tag{12}$$

where $P_{\min}^w$ and $P_{\max}^w$ are the minimum and maximum output of wind power.

(3) Photovoltaic Power Generation Constraint

$$P_{\min}^{pv} \leq P_i^{pv} \leq P_{\max}^{pv} \tag{13}$$

where $P_{\min}^{pv}$ and $P_{\max}^{pv}$ are the minimum and maximum output of wind power.

2.2.2. Output Balance Constraint

$$P_i^w + P_i^{pv} = P_i^{wout} + P_i^{pvout} + P_i^p \tag{14}$$

where P_i^w and P_i^{pv} are the output of photovoltaic and wind power in i^{th} period.

2.2.3. Transmission Limitation Constraint

$$P_{g\min} \leq P_i^{wout} + P_i^{pvout} + P_i^p \leq P_{g\max} \tag{15}$$

where $P_{g\min}$ and $P_{g\max}$ are the transmission power limits.

2.3. Research Scheme. To discuss the multiobjective optimization problem of the complementary operation of the photovoltaic-wind-pumped storage system, the four schemes in application of the above models are compared and analyzed. In scheme 1, the objective is the maximization of the power benefit, and four kinds of power station are independently supplied; that is, if the wind and photovoltaic power is fully connected into the power grid, this result can be used as the benchmark for the optimization for the complementary operation of the photovoltaic-wind-pumped storage system. In scheme 2, the objective is the maximization of the power benefits by utilizing the complementary operation of the photovoltaic-wind-pumped storage system. In scheme 3, the objectives are the maximization of the economic benefits of photovoltaic and wind power stations and suppression of the output fluctuation, with utilization of the complementary operation system. In scheme 4, the objectives are the maximization of the economic benefits of photovoltaic and wind power stations and minimization of the variation of load and output difference by utilizing of the complementary operation system.

TABLE 1: Model parameters of the system.

Parameter	value
E_0^u $(MW \cdot h)$	12
$E_{\min}^u$ $(MW \cdot h)$	4
$E_{\max}^u$ $(MW \cdot h)$	24
$P_{\max}^h$ (MW)	3
E_0^l $(MW \cdot h)$	16
$E_{\min}^l$ $(MW \cdot h)$	4
$E_{\max}^l$ $(MW \cdot h)$	24
$P_{\max}^p$ (MW)	3
$P_{g\max}$ (MW)	12
η_1 (%)	93.75
η_2 (%)	80

3. Model Decomposition

The model needs to obtain the 24 moments of P_i^{wout}, P_i^{pvout}, P_i^p, and P_i^h, $4*24$ dimensions, namely, 96 dimensions, which is a high-dimensional, dynamic, multiconstrained, and multiobjective nonlinear optimization problem.

Elite and fast nonmainstream sorting genetic algorithm (NSGA-II) [19, 20] is widely used to the multiobjective problems because of its fast convergence. In this study, the optimal scheduling of complementary power generation system is determined by NSGA-II, and the Pareto noninferiority relationship between power benefit and output fluctuation is obtained. The solution has following steps:

Step 1. Use NSGA-II toolbox to randomly generate calculation results to form the first population.

Step 2. Judge the fitness of the calculation results.
Compute the expected outputs of hydropower, photovoltaic, wind, and pumping power according to the station constraints.
Correct the output with the output balance and the transmission constraint once the power grid access is limited.
Compute the fitness value according to the target function value of the corrected output.

Step 3. If the terminal condition is met, then export the final optimal complementary operation result; otherwise proceed.

Step 4. Apply crossover, mutation, and selection to update the population using the NSGA-II. Then go to Step 2.

The flow chart of the model is illustrated in Figure 2.

4. Case Study

4.1. Data. The system of 12MW wind power, 3MW pumped storage power, and 5MW photovoltaic power is simulated and analyzed to prove the applicability of the model. The scheduling period is set to 24 hours. The basic model parameters are shown in Table 1.
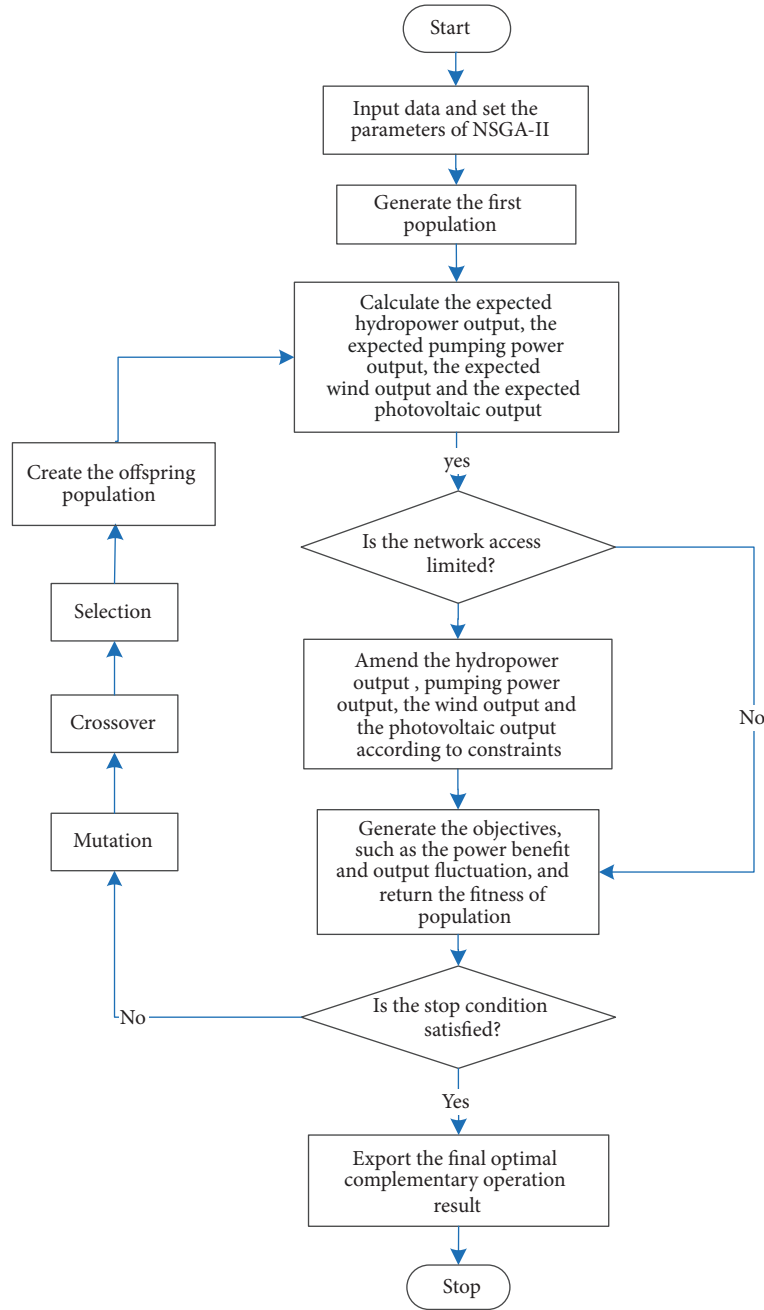
FIGURE 2: Flow chart of the model.

Consulting [12, 21] to the peak-valley feed-in tariffs policy at home and abroad and combining with the actual situation, the feed-in tariffs of the complementary system are set as shown in Table 2.

4.2. Results and Discussion

4.2.1. Optimal Results of Scheme 1. In scheme 1, only the power benefit is taken into account, with the three stations operating independently. When the total amount of photovoltaic power and wind is connected into the power grid,

TABLE 2: Feed-in tariffs in different periods.

Period (h)	C_i (¥/kWh)	C_{pi} (¥/kWh)
$0 \leq i < 8$	0.54	$0.25C_i$
$8 \leq i < 22$	1.0384	$0.25C_i$
$22 \leq i < 24$	0.54	$0.25C_i$

the power benefit and output fluctuation are ¥87,800 and 158.6MW, respectively.

FIGURE 3: Single-objective optimization results of scheme 2.

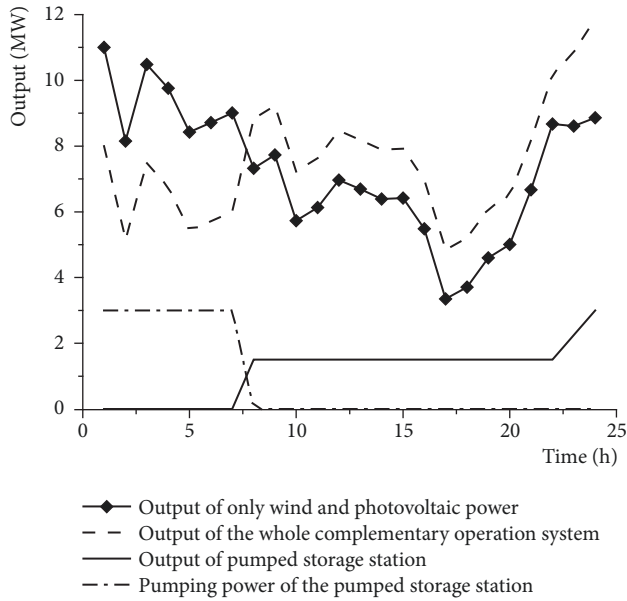FIGURE 4: Noninferior solution of multiobjective optimization model of scheme 3.

FIGURE 5: Multiobjective optimization results of scheme 3.

4.2.2. Optimization Results of Scheme 2. Similar to scheme 1, only power benefit is considered, but optimizing with the complementary operation in scheme 2. The genetic algorithm is used to solve the single-objective optimization problem. The energy dispatch within one day of three power supply complements' operation is shown in Figure 3.

It can be seen from Figure 3 that if only the maximum power benefit is optimized as a single objective, obviously the power benefit is the greatest. Under the circumstances, the output of complementary operation system is concentrated in the peak and middle peak feed-in tariff period, while less in the low valley feed-in tariff period, with the output fluctuation of complementary operation system of the whole dispatching period being more intense.

4.2.3. Optimization Results of Scheme 3. In contrast, scheme 3 is a multiobjective optimization problem, aimed at obtaining the maximum power benefit and the minimum output fluctuation, and the NSGA-II algorithm is applied to simulate and analyze the optimal scheduling model of the complementary operation system.

According to the above algorithm steps and parameter settings, the Pareto noninferior solution sets are obtained for the optimization problems of scheme 3, as shown in Figure 4.

The output fluctuation of complementary operation system increases with the power benefit, as shown in Figure 4. For the reason that the objective F_1 is to obtain the maximum power benefit and the objective F_2 is to obtain the minimum output fluctuation, which means the objective functions F_1 and F_2 cannot be maximal simultaneously. Thus, choose a compromise point in the solution set, namely, the inflection point in Figure 4.

The power benefit of the complementary operation system is ¥121, 440 per day, and the output fluctuation is
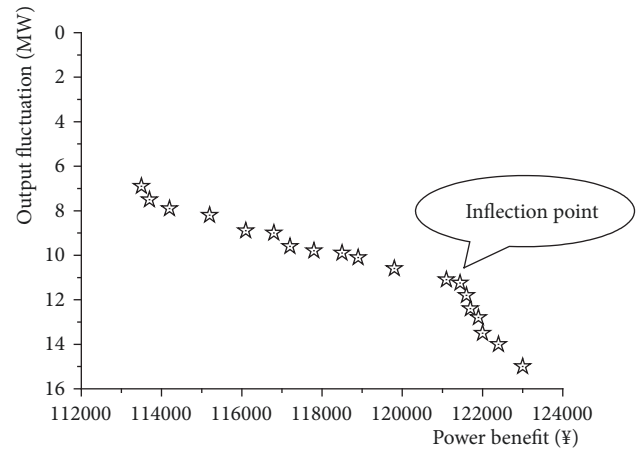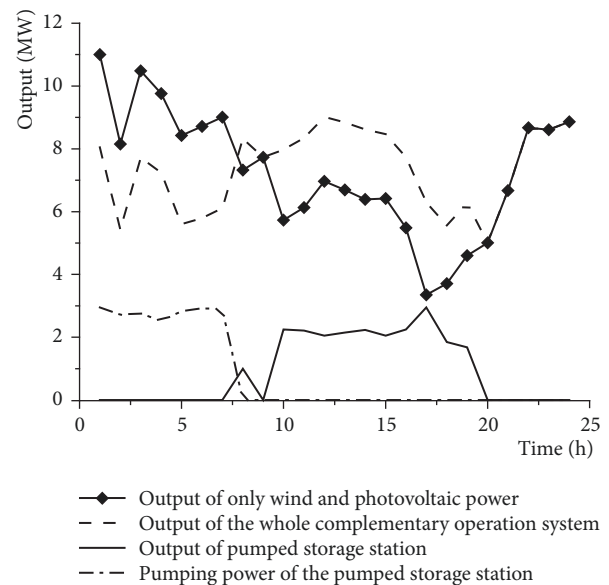
11.25MW. The hourly energy dispatch value corresponding to 1 day is shown in Figure 5.

According to Figure 5, in the low feed-in tariff period, output of some of the available solar and wind power is used to meet the load, and the rest is for pumping and storing energy. Instead, in the high feed-in tariff period, the output of wind and the photovoltaic is relatively small, which means that the solar and wind power cannot meet the load requirements, the pumped storage station will run in the condition of power generation to supplement the remaining part, so that the larger power benefit is obtained, and the output fluctuation is reduced.

4.2.4. Optimization Results of Scheme 4. Similar to scheme 3, scheme 4 is also a multiobjective optimization problem, for obtaining the maximum power benefit and the minimum variation of load and output difference by using NSGA-II

TABLE 3: Results of comparison of the four schemes.

Scheme	Power benefit (¥)	Output fluctuation (MW)	Variation of load and output difference (MW^2)	The maximum peak-valley difference (MW)
1	87,800	158.6	77.33	8.0
2	125,600	236.2	93.48	7.5
3	121,440	11.25	—	4.0
4	123,200	—	16.65	4.6

FIGURE 6: Noninferior solution of multiobjective optimization model of scheme 4.

— ■ — Output of only wind and photovoltaic power
— — Output of the whole complementary operation system
—— Output of pumped storage station
— · — Pumping power of the pumped storage station
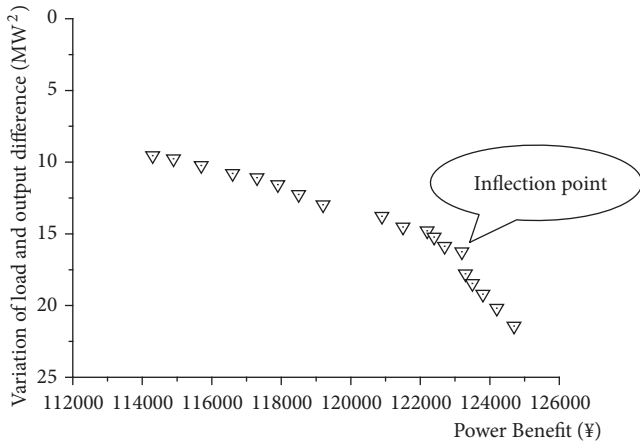
FIGURE 7: Multiobjective optimization results of scheme 4.

algorithm. The Pareto noninferior solution sets are obtained for scheme 4, as shown in Figure 6.

It can be seen from Figure 6 that the results are also similar to scheme 3; the objective functions F_1 and F_3 cannot be maximal simultaneously. Therefore, choose the inflection point in Figure 6. The power benefit of the system is ¥123, 200 per day, and the variation of load and output difference is 16.65MW^2. The hourly energy dispatch value corresponding to 1 day is shown in Figure 7.

In Figure 7, in the low feed-in tariff period and the high feed-in tariff period, the hourly energy dispatch value has the same distribution laws in Figure 5.

4.2.5. Comparison of the Schemes. The comparison results of the four schemes are illustrated in Table 3.

Combined with data analysis in Figures 3, 4, 5, 6, and 7 and Table 1, the following is shown.

(1) Scheme 1 and Schemes 3, 4. The output fluctuation and the variation of load and output difference of the power grid are very intense, and the maximum peak-valley difference even reaches 8 MW, as the wind farm and the photovoltaic power station operate independently. Also, in the peak feed-in tariff period of 07:00-11:00 and middle peak feed-in tariff period of 11:00-15:00, the wind farm and the photovoltaic power station are less productive, and obviously the operation benefit is not high.

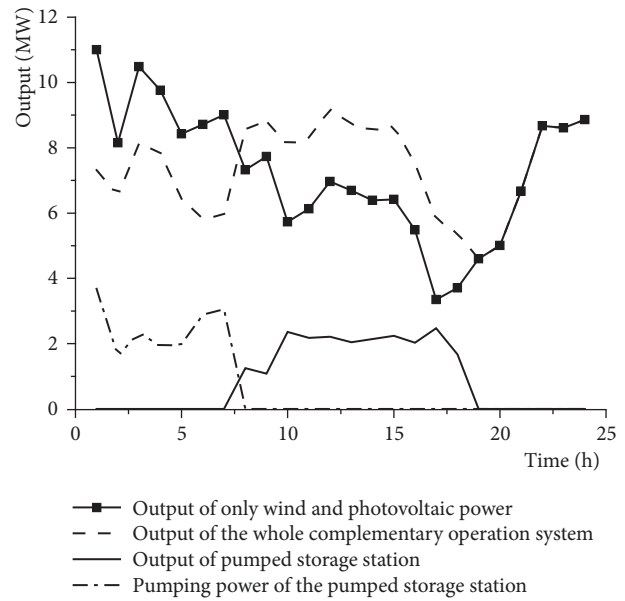But after the pumped storage plant is added, the output fluctuation and variation of load and output difference of the complementary operation of the photovoltaic-wind-pumped storage system are remarkably reduced. The output fluctuation of the complementary operation system is only 7.1% of the single operation of the photovoltaic and wind power, the variation of load and output difference is only 21.5% of the single operation of the photovoltaic and wind power, and the maximum peak-valley difference is only 50% of the single wind and the photovoltaic power. In the peak feed-in tariff period of 07:00-11:00, 17: 00-21:00, and so on, the photovoltaic and wind power are less productive, and the operation benefit is considerably improved.

(2) Scheme 2 and Schemes 3, 4. With the maximum power benefit of the complementary operation system regarded as a single objective, clearly, the benefit is biggest. In the situation, the output of the complementary operation system is concentrated in the peak and middle peak feed-in tariff period, and the low valley feed-in tariff period is less, which makes the output fluctuation and the variation of load and output difference of the complementary operation system more intense in the whole scheduling period.

In contrast, as can be seen from the results of Scheme 3 and Scheme 4 in Table 3, each objective has made certain concessions and achieved the optimal result of the whole benefit,

which means complementary operation of the photovoltaic-wind-pumped storage system can achieve optimal output power in different periods by multiobjective optimization.

(2) Scheme 3 and Scheme 4. In both scheme 3 and scheme 4, there are economic objectives and stable objectives. The economic objectives of the two schemes are all power benefit, but the stable objectives are different.

The results of scheme 3 reveal that the power benefit maximization and output fluctuation minimization cannot be achieved at the same time. In contrast, scheme 4 is aimed at increasing the power benefit and decreasing the variation of load and output difference, and the results not only verify the relationship between economic objective and stable objective in scheme 3, but also reflect the power demand time-variant in the real power system.

5. Conclusions

To improve the power benefit and the access capacity of photovoltaic and wind power, the storage function of the pumped storage station is used to balance the maximum benefit and the minimum output fluctuation of the photovoltaic-wind-pumped storage system.

The optimization model is established after properly defining the economic and stable objectives and constraints. By comparing and analyzing the four schemes, the role of the pumped storage energy in the complementary operation and the relationship of the three objectives are studied. The main results are as follows.

  (i) After the pumped storage plant is added, the output fluctuation, the variation of load and output difference, and the maximum peak-valley difference of the complementary operation system is only 7.1%, 21.55%, and 50% of the single operation of the photovoltaic and wind power, respectively, which means that the pumped storage station can suppress the output fluctuation and reduce the variation of load and output difference of the photovoltaic-wind-pumped storage system.

 (ii) In the peak feed-in tariff period of 07:00-11:00, 17:00-21:00, and so on, the power benefit is notably improved as the pumped storage station is added, indicating that the pumped storage plant can improve the benefit of photovoltaic and wind power.

(iii) The output fluctuation and variation of load and output difference increase with the power benefit, which proves the interaction and competition relationship between the economic and stable objectives. Then a compromise point in the Pareto optimal solution set is chosen to obtain the optimal result of the whole benefit of the system.

 (iv) Comparing the four schemes, it is clear that the pumped storage plant has the advantage of improving the benefit and the access capacity of photovoltaic and wind power.

At last, the accuracy and the availability of the multiobjective optimization model are proved. To conclude, a hybrid energy system has been modelled and the complementary mechanism of the system has been deeply discussed in this paper.

Data Availability

The parameter data of wind farm, photovoltaic power station, and pumped storage station used to support the findings of this study have not been made available because it is from an important project which involves issues of confidentiality.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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