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Research on the Operational Strategy of the Hybrid Wind/PV/Small-Hydropower/Facility-Agriculture System Based on a Microgrid

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Abstract: The use of renewable energy sources, such as wind, photovoltaics (PV), and hydropower, to supply facility agriculture may effectively mitigate food and environmental pollution problems and ensure continuity of the energy supply. The operating conditions of a hybrid system are complex, so the operating strategy is very important for system configuration and scheduling purposes. In the current study, first, a hybrid wind/PV/small-hydropower/facility-agricultural system was constructed. Then, the chaotic particle swarm method was applied to optimize hybrid system operation, and a scheduling strategy of the hybrid system was proposed. Finally, combined with an example, according to wind and PV power output and load curves, supply-to-load curves for wind, PV, and small hydropower were obtained. The operational strategy proposed in this study maximizes the utilization of wind and solar resources and rationally allocates hydropower resources. The aforementioned operational strategy provides a basis for hybrid system capacity allocation and scheduling.

Keywords: hybrid system; facility agriculture; chaotic particle swarms method; operation strategy

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1. Introduction

1.1. Literature Review

Food is the major necessity of human beings. As the global population continues to grow, people need increasing quantities of grains and vegetables [1]. Therefore, promoting the efficient and sustainable development of agricultural production methods and improving technology to increase the crop yield per unit area has attracted increasing attention, including in smart agriculture and facility agriculture [2]. These approaches can create a more suitable environment for plant growth, making it possible to grow crops and vegetables out of season and accelerate their growth [3,4]. However, high efficiency has led to increased energy consumption and higher costs [5]. With the increasing pressure on energy conservation and emission reduction, governments have introduced various policies and guidelines to carry out clean energy research and practices. Consideration of the use of renewable and clean energy sources applied to agricultural production can help solve the problem of energy consumption, in addition to effectively mitigating carbon emissions and reducing the pollution of the environment from fossil fuels [6,7].

In recent years, a lot of research has been conducted on clean energy, and renewable clean energy sources such as wind power, PV power and hydropower have received attention. However, wind and PV resources are affected by natural climatic conditions and are characterized by significant randomness and volatility, leading to inefficient energy development and, consequently, to difficulties in accessing the power grid, reducing power quality and reliability [8,9]. Therefore, many people have proposed a mixture of multiple energy sources to compensate for the fluctuations of wind and PV power generation through the advantages of rapid start–stop and the strong peaking ability of hydropower [10]. The study [11] makes full use of the flexibility of hydropower, integrates wind/PV/hydropower, identifies the sites of each power plant, and analyzes the complementary power output benefits of the system. In the combined operation of various energy sources, the power quality of the whole year and the whole day is effectively guaranteed. In the study [12], a hybrid system containing wind, PV, and hydropower plants with pumped storage was established and the impact on the national power system was studied. The results show that the hybrid system can effectively reduce the volatility of the grid. In fact, reducing the instability of wind and PV output by complementing hydro and pumped storage can effectively improve the power quality and system reliability.

New clean energy inputs are obvious and necessary for the development of modern and efficient facility agriculture [13], and wind power/PV power/hydropower is widely used around the world due to its good applicability [14], and there have been many applications of multi-energy complementary participation in agriculture. The study [15] used a combination of wind power and energy storage in agriculture. The study [16] used PV power generation to solve the problem of agricultural irrigation. The study [17] studied hybrid energy systems consisting of PV panels and other necessary accessories to provide electricity to cool greenhouses without the need to obtain energy from the grid. In these studies, the practicality and very promising applications of new energy sources integrated into facility agriculture were predicted.

Scholars of various countries have analyzed the economy and practicability of coordination of various energy sources and output power. Most of the early solution methods were based on linear programming, nonlinear programming, and dynamic programming [18,19]. Due to the depth of research, a class of heuristic algorithms based on biological evolution or natural phenomena, represented by genetic algorithms [20], ant colony algorithms [21], and particle swarm algorithms [22], have been greatly developed, effectively solving the shortcomings of the past algorithms in terms of low adaptability to the objective function and constraints and poor efficiency. In the study [23], an optimal distribution method for multi-energy power supply systems was established with the total cost minimization as the optimization objective. The relationship between the complementary characteristics of multiple energy sources and the planning cost was quantitatively analyzed using two important indicators, energy loss rate and hourly loss rate of distributed generation, and solved by a hybrid genetic algorithm and pattern search algorithm. In the study [24], power loss minimization and voltage profile enhancement in radial distribution networks were considered as the key objectives of the study, and selective particle swarm optimization (SPSO) was used to determine the installation size and location of network capacity enhancement. In the study [25], a multi-objective particle swarm optimization algorithm (MOPSO) was used to optimize a hybrid PV-wind-pumped storage system to obtain the optimal configuration with reduced initial investment cost. By comparison, many new evolutionary algorithms have been proposed or improved and applied to solve the optimal scheduling problem, mainly including the hybrid swarm algorithm [26], the slime mode algorithm [27], and the harmony search [28]. Therefore, proposing or improving algorithms is a key scientific problem for optimizing the coordination of multiple energy sources with each other. Solving this problem can provide technical support for obtaining better convergence and distribution of multi-energy complementary systems.

1.2. Research Gap and Motivation

Indeed, the application of wind/PV energy supports operations that are integrated into facility agriculture [17,29]. In addition, due to the development of large-scale facility agriculture [1,30], it is necessary to develop new approaches to the hybrid use of renewable energy sources and the grid. In the literature, combining electricity generation with agriculture through independent wind and PV has also been studied, but there is little research on the coordinated integration of multiple energy sources with agricultural facilities. Meanwhile, the operating conditions of hybrid energy systems are complicated, especially in regard to systems based on microgrids, for which the operating strategy is very important. The studies [31–33] examined energy management strategies based on distributed microgrids and proposed an economic dispatching strategy of hybrid PV/storage/hydro/diesel microgrids without considering the operation characteristics of wind power. The studies [34,35] proposed an optimal microgrid scheduling method considering a hybrid wind/light/diesel/battery/desalination system but did not consider the operation strategy. The studies [36,37] investigated the impact of the operation strategy and operational characteristics of energy storage devices on the reliability of microgrids but only the energy storage aspect was studied. The study [38] examined the control strategy of a wind/PV/storage microgrid based on hybrid energy, considering the randomness and volatility of the output power and voltage of intermittent power sources, such as wind and PV power generation, and the complexity of microgrid control, but they did not consider the load impact.

In previous work, we conducted an in-depth study of the hybrid PV/wind/pumped storage system and optimized the system design using particle swarm optimization algorithms. Furthermore, the output smoothing of the hybrid hydro/wind/PV system was studied and analyzed [39,40]. The stability and economy of the multi-energy complementary system were confirmed [41]. In addition, the combination of clean energy and facility agriculture can improve the efficiency of land and energy use [42] and compensate for the energy demand of facility agriculture by directly providing productive energy through clean energy generation [43]. Related practical applications have already appeared in some countries, such as India and Canada [44,45]. Therefore, in this study, a mathematical model of a wind/PV/small-hydropower/facility-agriculture system was established, the operation strategy of the system was proposed, and an example was derived and analyzed using a chaotic particle swarm optimization (CPSO) algorithm. Compared with other algorithms, the CPSO algorithm avoids complex operations and has stronger global convergence and robustness, and it can be used as a new evolutionary algorithm to solve a large number of nonlinear, non-trivial, and multi-peak complex optimization problems [46,47]. The algorithm ensures the optimal capacity allocation of each energy source and establishes the optimal scheduling strategy, which can further enhance the advantages of complementary characteristics among various energy sources.

1.3. Contribution and Paper Organization

The main contributions of this paper are as follows:

(1) A mathematical model of the wind/PV/small-hydropower/facility-agriculture system was established with the load matching degree as the objective function and the power supply reliability as the constraint.
(2) Through the actual data, the control strategy and operation strategy of the wind/PV/small-hydropower/facility-agriculture system were proposed.
(3) The wind/PV/small-hydropower/facility-agriculture system was solved using the CPSO algorithm for the hybrid system, and the operation of the system was analyzed and is discussed.

The rest of this paper is organized as follows. A mathematical model of the wind/PV/small-hydropower/facility-agriculture system is established in Section 2. In addition, the specific steps and calculation process of the CPSO method for the composite system are introduced. In Section 3, the operation strategy flow of the hybrid system is depicted by example analysis, and the calculation results are discussed and analyzed. The conclusions are summarized in the final section.

2. Methods

2.1. System Optimization Design Model

2.1.1. System Optimization Model Building

Mathematically described as Equation (1):

$$\begin{cases} minf(x) \\ g_k(x) < \varepsilon_x \end{cases} \quad (1)$$

where:

$f(x)$—Optimization of the objective function;
$g_k(x)$—Constraint condition function;
ε_x—Tolerance factor of the constraint function, $\varepsilon_x \geq 0$;
x—Optimization variables.

2.1.2. Objective Function

With the load matching degree of the wind/PV/small-hydropower/facility-agriculture system as the optimization objective, using a supply–demand balance calculation model and the error evaluation of the supply–demand difference value root-mean-square, the objective function is expressed by Equation (2):

$$\sigma = \sqrt{\frac{\sum_{t=1}^{T}\left(P_S^t - P_L^t\right)}{T}} \quad (2)$$

where:

P_S^t—The total system power output during calculation period t, kW;
P_L^t—The system load value during calculation period t, kW;
T—Total number of hours, h.

That is, the optimization objective function $f(x) = \sigma$, and the optimization objective is to minimize σ.

2.1.3. Constraints

The power supply reliability of the system is selected as the constraint.

A reliability model of the composite generation system is established to evaluate the reliability of the system's power supply using the loss of power supply probability ($LPSP$), the accumulated power deficit, and the number of continuous days with guaranteed cloudy and windless weather, as follows:

(1) Loss of Load Power Rate

The calculation of the load loss of the power rate for a total time period can be defined as the ratio of the deficit power (LPS) to the total power required by the load during that time period, expressed by Equation (3):

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_L(t)\Delta t} \quad (3)$$

where:

LPS—Insufficient power at time t, kWh;
$P_L(t)$—Total load at time t, kW;
T—Running time, h;
Δt—Calculation step size, h.

The $LPSP$ value is between 0 and 1, and the smaller the value, the higher the reliability. $LPSP = 0$ means that the load needs can be met at all times; $LPSP = 1$ means that the load needs cannot be met at all times. In fact, even the public grid can supply power to large cities with an $LPSP = 10^{-2}$ order of magnitude only, and it is obviously unreasonable to require relatively expensive wind and solar power systems to achieve 100% reliability. Most of the failures that occur during the operation of stand-alone power supply systems are not due to the lack of capacity of the system components, but due to component failures, poor line contact, and operational errors, so the reliability requirements for wind and solar complementary power systems should be reasonable.

(2) Accumulated power deficit

The deficit ΔE can be expressed as:

$$\Delta E = E_W + E_{PV} + E_H - E_L \tag{4}$$

where:

E_W is the power generation of the wind turbine during the calculation period, kWh;
E_{PV}—The power generation of the PV array during the calculation period, kWh;
E_H—The power generation of small hydropower during the calculation period, kWh;
E_L—The power consumption of the load during the calculation period, kWh.

If ΔE is positive, it means that the system power generation during the calculation period is greater than the load power consumption, that is, the surplus amount, and can be used for battery charging; if ΔE is negative, it means that the system power generation during the calculation period is less than the load power consumption, that is, the deficit amount, and can be supplied by small hydropower generation first.

(3) Number of days with guaranteed continuous rainy and windless weather

The number of days with guaranteed continuous rainy and windless weather can be taken according to the reliability requirements of residential electricity consumption, generally n = 3 to 5 days (specific values are determined according to local meteorological data).

That is, the constraints are:

$g(x_1) = LPSP$, taking the tolerance factor of the constraint function $\varepsilon_1 = LPSP_{req}$ ($LPSP_{req}$ is the required value of load loss rate);

$g(x_2) = \Delta E$, taking the tolerance factor of the constraint function $\varepsilon_2 = \Delta E_{req}$ (ΔE_{req} is the cumulative deficit requirement value);

$g(x_3) = n$, taking the tolerance factor of the constraint function $\varepsilon_3 = n_{req}$ (n_{req} is to ensure the required value of the number of days of guaranteed continuous rainy and windless weather).

2.1.4. Selection of Optimization Variables

The power side mainly contains wind power, PV power, battery and pumped storage, and their operation and complementary methods affect the overall output and power balance of the system; thus, we use the capacity of different power sources (i.e., wind power, PV) and different forms of energy storage (i.e., pumped storage, battery) as optimization variables.

2.2. CPSO Method for Composite Systems

2.2.1. Detailed Steps

The basic idea of the CPSO algorithm is to use chaotic sequences to initialize the positions and velocities of particles; first, a chaotic search is performed for the optimal particle in the current particle population, and then the result of the chaotic search is replaced with a random particle in the particle population. The specific steps of composite system optimization using CPSO are as follows:

(1) Initializing the particles

A population containing n_s particles is randomly generated, the particles are initialized (i.e., the optimization variables: capacity of the wind turbine, PV array, pumped storage, and battery), each particle is given a random velocity (i.e., the step size of the change in the capacity of the wind turbine, PV array, pumped storage, and battery during the optimization), and the number of iterations is set to N.

(2) Update the velocity and position of the particles

Update the velocity and position of the particle according to Equations (5) and (6):

$$\vec{v}_i^{k+1} = \omega \vec{v}_i^{k} + c_1 r_1 \left(\vec{x}_{pbest,i}^{k} - \vec{x}_i^{k} \right) + c_2 r_2 \left(\vec{x}_{gbest,i}^{k} - \vec{x}_i^{k} \right) \tag{5}$$

$$\vec{x}_i^{k+1} = \vec{x}_i^{k} + \vec{x}_i^{k+1} \tag{6}$$

where:

$\vec{v}_i^{k}$—the velocity of the kth iteration of the ith ($i = 1, 2, \ldots, m$) particle;
$\vec{x}_i^{k}$—the position of the kth iteration of the ith ($i = 1, 2, \ldots, m$) particle;
$\vec{x}_{pbest,i}^{k}$—individual optimal position of particle i for the kth iteration;
$\vec{x}_{gbest,i}^{k}$—the population optimal position for the kth iteration;
ω—inertia weights;
c_1—cognitive coefficient;
c_2—social coefficient;
r_1, r_2—random number between [0, 1].

(3) Chaotic optimization of particle swarm optimal positions $\vec{x}_{gbest}$:

① Mapping $\vec{x}_{gbest}$ to the definition domain [0, 1] of the logistic equation $\vec{y}_{n+1}^{k} = \mu \vec{y}_n^{k} \left(1 - \vec{y}_n^{k} \right)$ through Equation (7):

$$\vec{y}_1^{k} = \frac{\vec{x}_{gbest}^{k} - R_{min}^{k}}{R_{max}^{k} - R_{min}^{k}} \tag{7}$$

where μ is the control parameter, R_{max}^{k} and R_{min}^{k} are the upper and lower bounds of the value of $\vec{x}_i^{k}$, respectively.

② The chaotic sequence $\vec{y}_n^{k}$ is obtained by performing M iterations of the logistic equation for $\vec{y}_1^{k} (n = 1, 2, \ldots, m)$.

③ The chaotic sequence is mapped back to the original solution space by the inverse of Equation (8):

$$\vec{x}_{gbest,m}^{*k} = R_{min}^{k} + (R_{max}^{k} - R_{min}^{k}) \vec{y}_m^{k} \tag{8}$$

thus generating a sequence of feasible solutions in chaotic variables $\vec{x}_{gbest,m}^{*k} (m = 1, 2, \ldots, M)$.

④ Calculate the adaptation value of each feasible solution vector in the feasible solution sequence, and keep the feasible solution vector corresponding to the optimal adaptation value, denoted as $\vec{x}_g^{*k}$.

(4) A particle is randomly selected from the current particle population, and the position vector of $\vec{x}_g^{*k}$ is used to replace the position vector of the selected particle.

(5) Skip to step (2) until the algorithm reaches the maximum number of iterations N or the optimal solution is obtained, i.e., the capacity of the wind turbine, PV array, pumped storage, and battery when the load loss rate of the system is minimized and the initial investment cost of the system is lowest.

The flow chart of the algorithm of CPSO is shown in Figure 1.

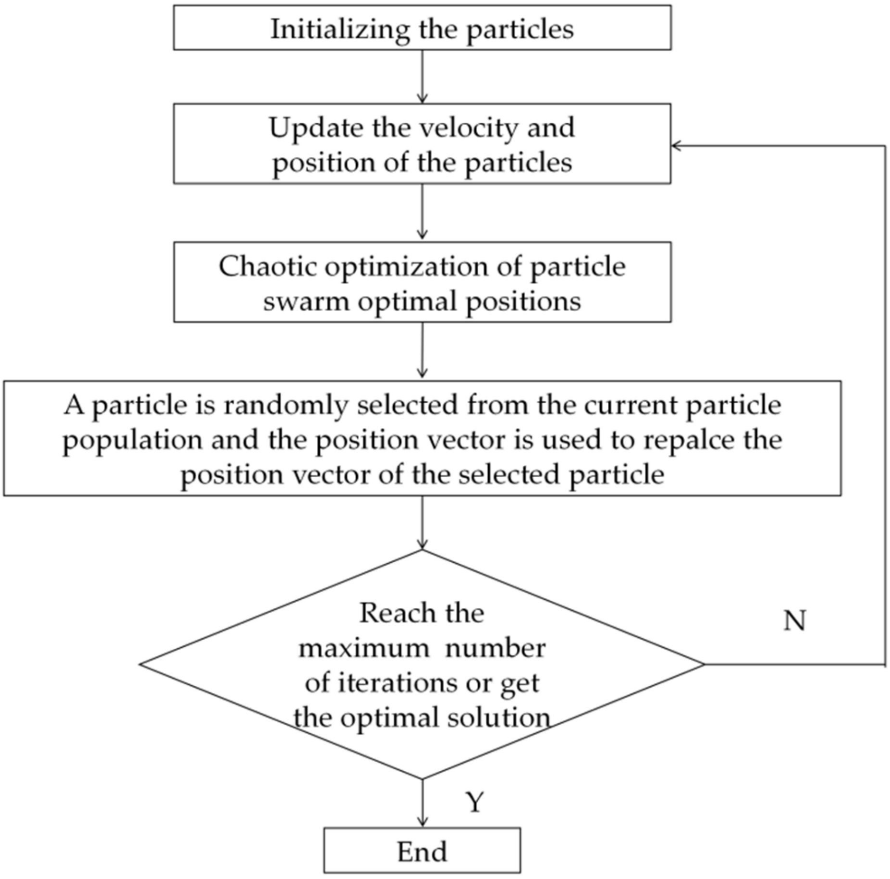


Figure 1. CPSO algorithm flow chart.

2.2.2. Calculation Process

The input raw data are the technical parameters of each component of the system (including the height of the wind turbine rotor, the power curve of the wind turbine, the short-circuit current and open-circuit voltage of the PV arrays, the current and voltage of the maximum power point, and the maximum and minimum head of the small hydropower plant), the wind speed data, the solar radiation data, the load data, and the allowable power loss rate. The initial position of the set particle population includes the capacity of the wind turbine, PV array, pumped storage, and battery.

The power generation of the wind turbine, the power generation of the PV arrays, the power consumption of the load, and the constraints are calculated.

During the optimal configuration of the system, if the reliability condition of $LPSP \leq LPSP_{req}$ cannot be met, the position of each particle, i.e., the capacity of the wind turbines, PV arrays, pumped storage, and battery, is adjusted by the CPSO algorithm until the system load loss rate $LPSP$ meets the requirements. For the given $LPSP_{req}$, the optimization algorithm allows the system to technically meet the requirements. However, the final optimized system to simultaneously achieve the lowest σ can be obtained by building a supply and demand balance calculation model.

3. Example Analysis

3.1. System Construction

The hybrid wind/PV/small-hydropower/facility-agriculture system based on a microgrid is shown in Figure 2, including wind turbines, PV arrays, small hydropower units, batteries, dispatch center, inverters, vegetable multispan greenhouses, orchards, and flower beds. The wind turbines and PV arrays comprise the system power supply. Small hydropower units can be employed as both the system power supply and energy storage devices. Batteries are the main energy storage devices of the system. The system load consists of the loads of vegetable multispan greenhouses, orchards, curtain cooling systems, filling-light systems, ventilation drives, energy-saving lamps, sprinkler system drives, and other daily electricity demands.

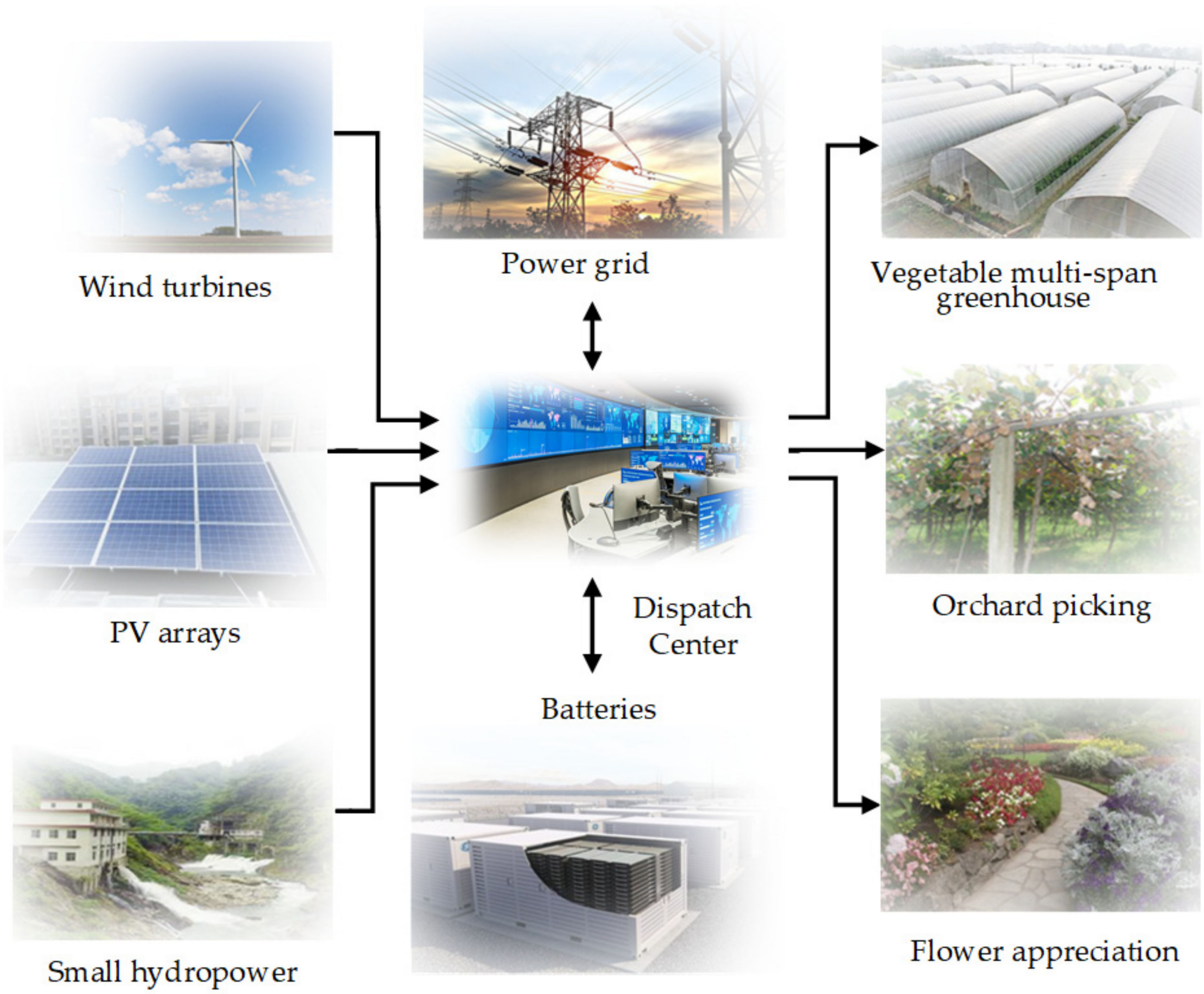


Figure 2. Hybrid wind/PV/small-hydropower/facility-agriculture system based on a microgrid.

Wind turbines are commonly installed in areas with good wind resources. The PV arrays are set up in agricultural greenhouses, higher than the normal elevation of 20 cm, and they span the gaps between adjacent greenhouses, thereby blocking direct sunlight and providing shade to vegetables, while translucent shed walls at a small angle allow sunlight to reach vegetables. In addition, PV arrays are installed along farm corridors and on the roof of the production plant.

3.2. Optimization of the Scheduling Method of the Hybrid System

The chaotic particle swarm method is applied to optimize hybrid system scheduling. The optimization goal load matching degree maximization, namely, the energy consumption and energy supply, should be lower than the allowable value. The optimization condition involves maximizing wind and solar resource utilization.

3.3. Operating Strategy of the Hybrid System

3.3.1. Wind and PV Power Generation Strategies

The wind turbines are operated under the maximum wind energy capture control strategy according to the available wind energy resources, and the PV arrays are operated via the MPPT control method according to the available solar resources.

If the generated wind and PV power meet the load demand, i.e., if $P_W + P_{PV} - P_L > 0$, wind and PV power are first supplied to the batteries to be charged. If the batteries are fully charged and a surplus occurs, power is supplied to the small hydropower system to pump water and then to the power grid.

If the generated wind and PV power do not satisfy the load demand, i.e., if $P_W + P_{PV} - P_L < 0$, the load is supplemented with other power sources.

3.3.2. Operation Strategy of the Small Hydropower Stations

Small hydropower stations are operated according to the water supply. First, the small hydropower stations supply power to satisfy the load, and if there is a surplus, power is supplied to the batteries and then to the power grid.

(1) When wind and PV power cannot meet the load demand, i.e., $P_W + P_{PV} - P_L < 0$, the small hydropower stations supply power to satisfy the load.
   - ① If $P_W + P_{PV} + P_H - P_L > 0$, the small hydropower stations supply power to the batteries to be charged. If a surplus occurs after the batteries have been fully charged, power is supplied to the power grid.
   - ② If $P_W + P_{PV} + P_H - P_L < 0$, other power resources supplement the load.

(2) When wind and PV power do satisfy the load demand, i.e., $P_W + P_{PV} - P_L > 0$.
   - ① If the batteries are fully charged, the small hydropower stations supply power to the grid.
   - ② If the batteries are not fully charged, the small hydropower stations first supply power to the batteries, after which power is supplied to the power grid when the batteries are fully charged.

3.3.3. Operation Strategy of the Batteries

If $P_W + P_{PV} + P_H - P_L < 0$, the batteries supply power to satisfy the load.

3.3.4. Operation Strategy of the System

(1) Generation power strategy
   - ① Wind and PV power first satisfy the load. If there is a surplus, power is supplied to the batteries to be charged. Any remaining power is then supplied to the small hydropower stations for water pumping purposes and finally to the power grid.
   - ② Small hydropower stations first meet the load demand, and surplus power is then supplied to the batteries to be charged and finally to the power grid.

(2) Consumption power strategy

The load is first satisfied via wind and PV power, and if the generated power is insufficient, power is then provided by the small hydropower stations, followed by the batteries and finally by the power grid.

(3) Battery charging strategy

The batteries are first charged via wind and PV power, and if the supplied power is insufficient, the small hydropower stations provide power.

(4) Pumping strategy of the pumps of the small hydropower stations

Only wind and PV power are consumed (only if a wind and PV power surplus occurs is power supplied to the batteries for charging purposes).

A flowchart of the system operating strategy is shown in Figure 3, where t is the charging time of the batteries, and T is the maximum charging time of the batteries to obtain a full charge.

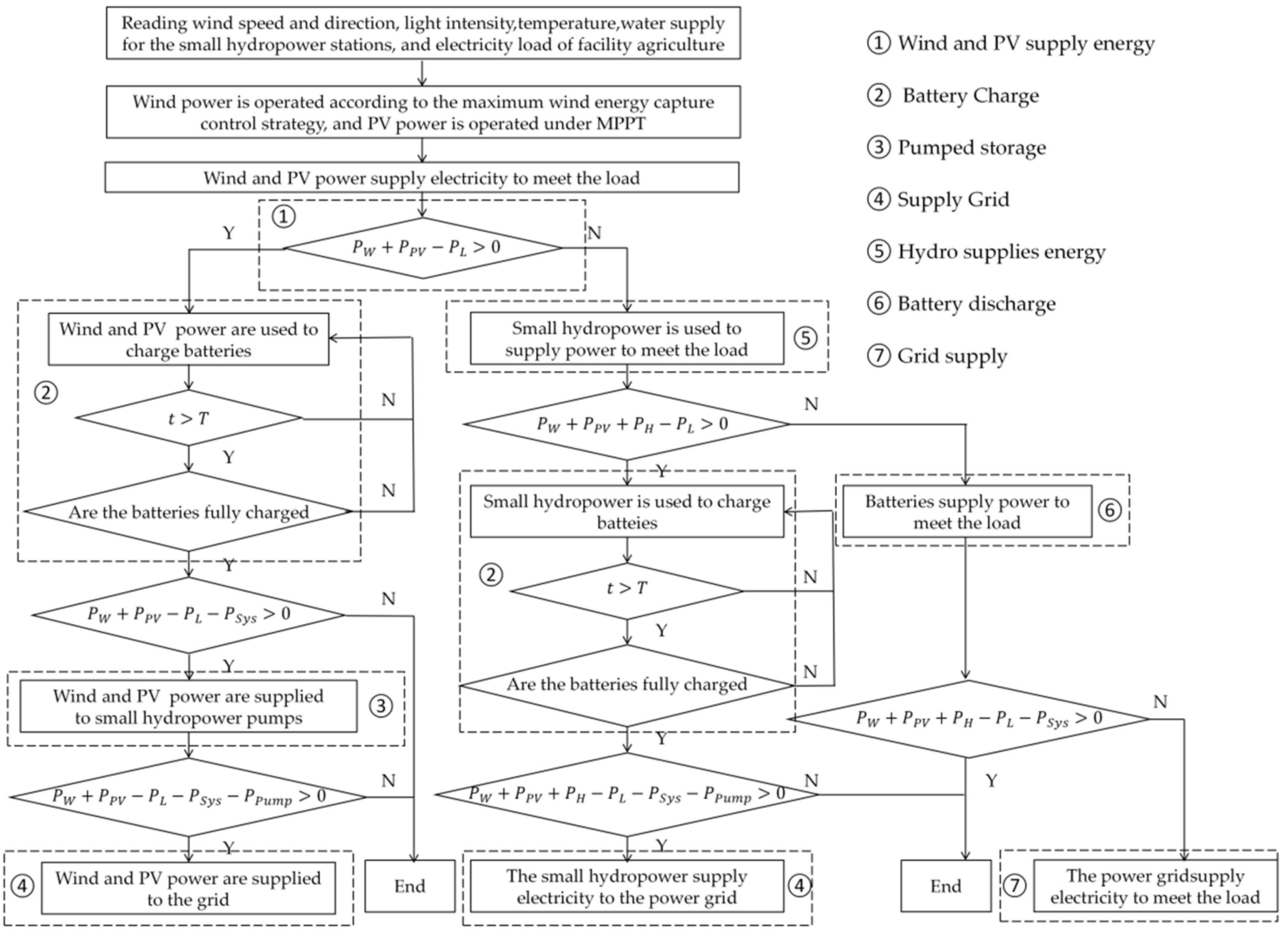


Figure 3. Flow chart of the hybrid system operation strategy.

3.4. Calculation Results and Discussion

In this study, we developed a mathematical model of the hybrid system in Section 2.1, elaborated the chaotic particle swarm optimization algorithm in Section 2.2.1, and explained the optimization problem in Section 2.2.2. The power side mainly contains wind turbines, PV arrays, batteries, and pumped storage units, and their operation and complementary methods affect the overall output and power balance of the system. Therefore, their input or output power are used as the optimization variables. Then, in Section 3, the operating processes of different power sources in the system are described. In a hybrid system, pumped storage and batteries are discharged when wind power and PV are insufficient and charged when wind power and PV are sufficient. The flow chart of the hybrid system operation strategy is shown in Figure 3.

After inputting the optimization variables, P_S is obtained by running the flow in Figure 3, and then the objective function σ is obtained according to Equation (2), after which the optimization is performed by the CPSO algorithm to obtain a better σ. If the maximum number of iterations is reached or the optimal solution is obtained, the calculation is terminated; otherwise the velocity and position of the particle are updated and calculated again. The application of the CPSO algorithm for the optimal operation of the hybrid system is shown in Figure 4.

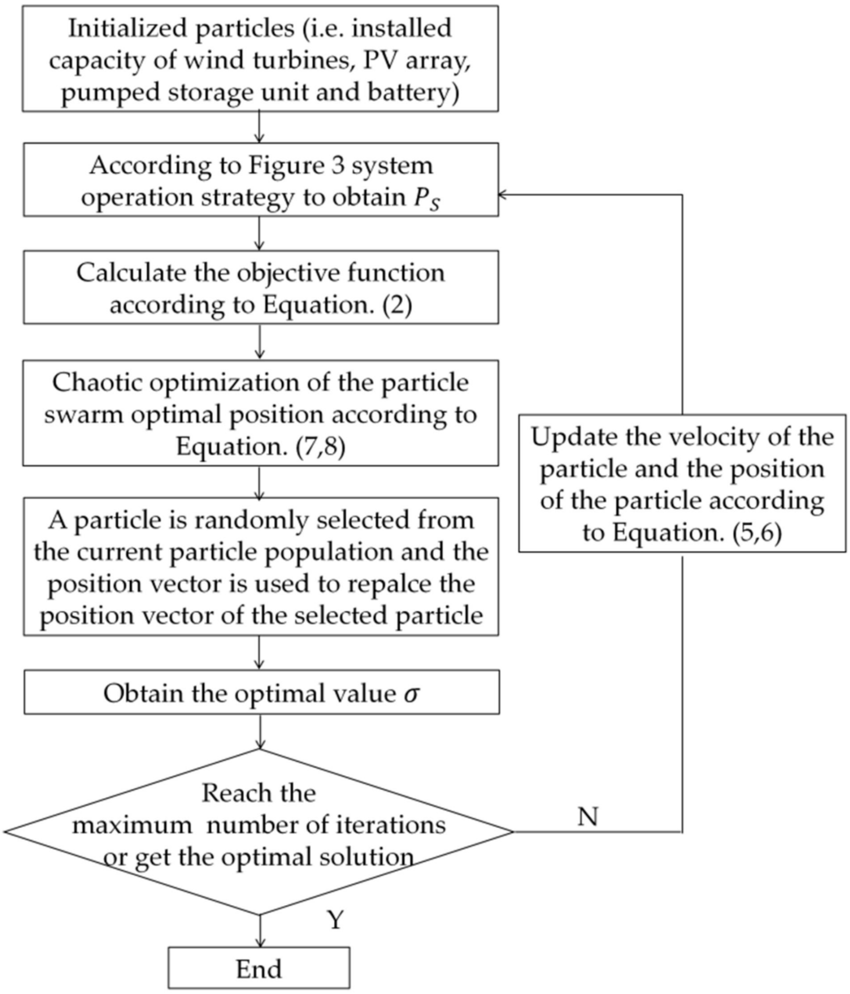


Figure 4. Application of the CPSO algorithm for the optimal operation of the hybrid system.

In the wind/PV/small-hydropower/facility-agriculture system, the installed capacity of wind power is 300 kW, that of the PV arrays is 312 kW, that of the small hydropower stations is 200 kW without regulation, and that of the batteries is 420 kWh. Wind and PV power curves and daily load curves are shown in Figure 5.

A wind and PV power supply-to-load curve is shown in Figure 6. Above the 0 kW line, a surplus occurs after wind and PV power satisfy the load, namely, from 1 to 3 h and 23.5 to 24 h, wind and PV power are supplied to satisfy the load, and any surplus power charges the batteries. Below the 0- W line, wind and PV power are insufficient to meet the load, i.e., from 3 to 23.5 h, other power sources are required to meet the load demand. In this example, no surplus electricity is supplied to the power grid.

From 1 to 3 h and 23.5 to 24 h, wind and PV power and the small hydropower stations supply electricity to satisfy the load. The profit–loss curve of the small hydropower station output after meeting the load demand is shown in Figure 7a. Above the 0 kW line, there is a surplus in the small hydropower station output, i.e., from 1 to 3.9 h and 22 to 24 h, the small hydropower stations first charge the batteries, and any surplus electric energy is then supplied to the grid. Below the 0 kW line, wind, PV power and small hydropower generation cannot meet the load. First, the batteries are used to supply power to satisfy the load, and the power deficit is supplied by the power grid. Figure 7b shows wind and PV power and small hydropower station supply-to-load curves. From 1 to 1.25 h, the small hydropower stations supply power to the grid.

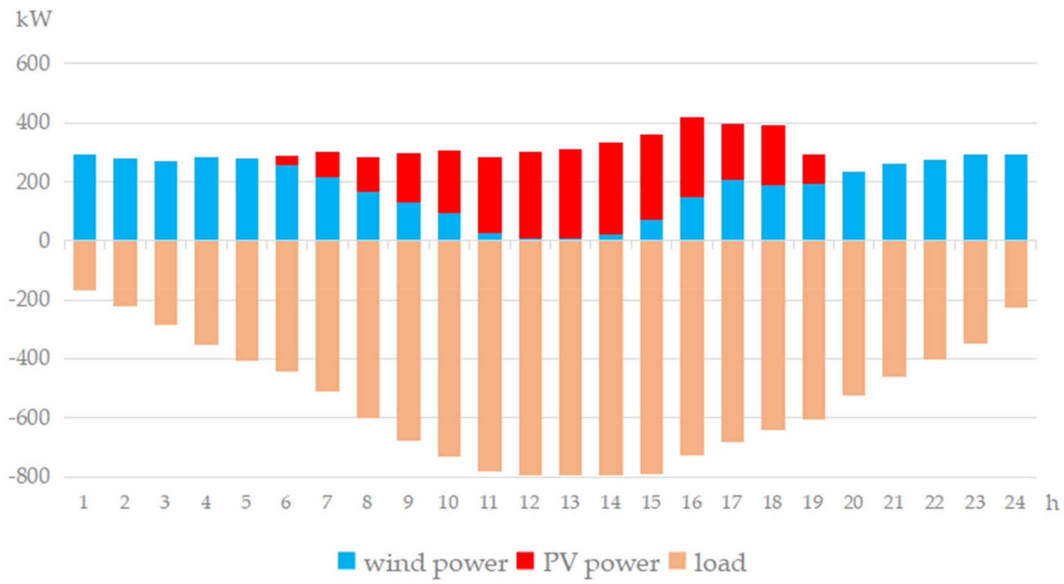


Figure 5. Wind and PV power curves and daily load curve.

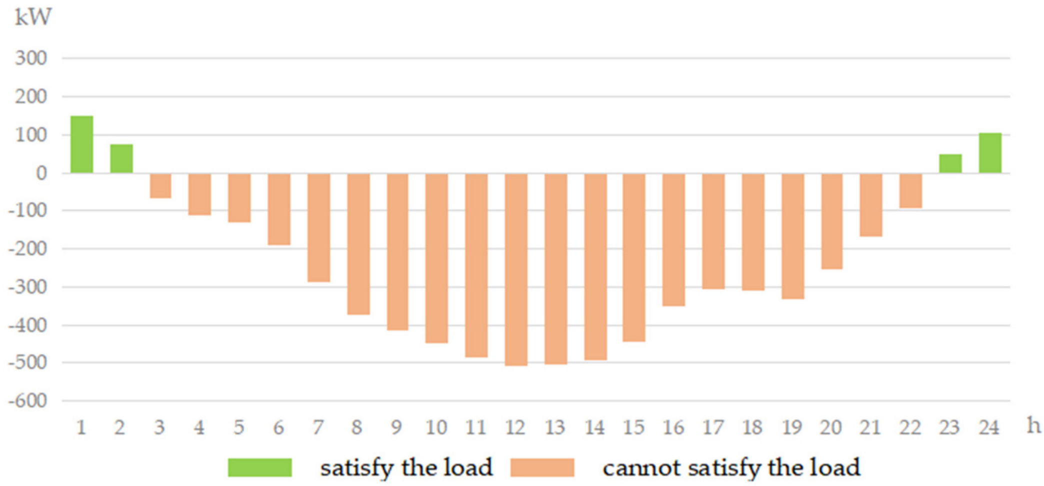
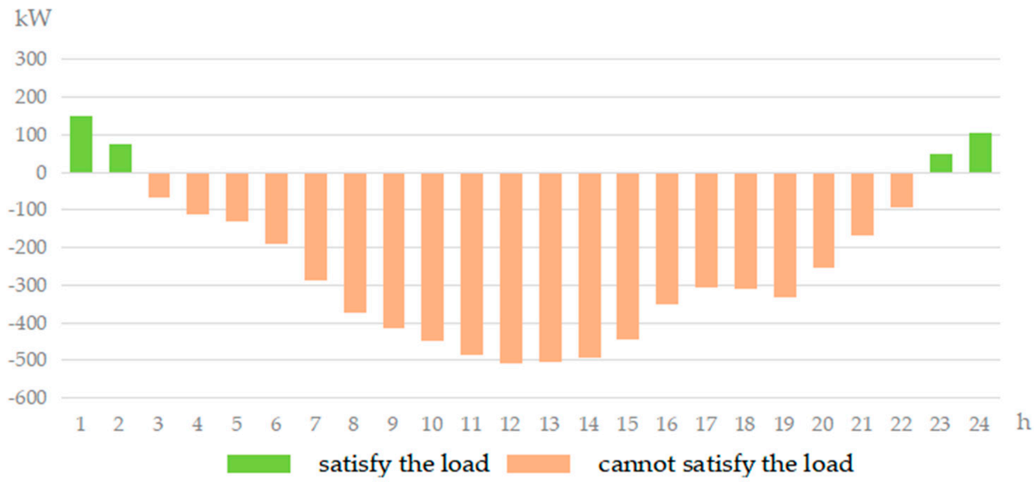
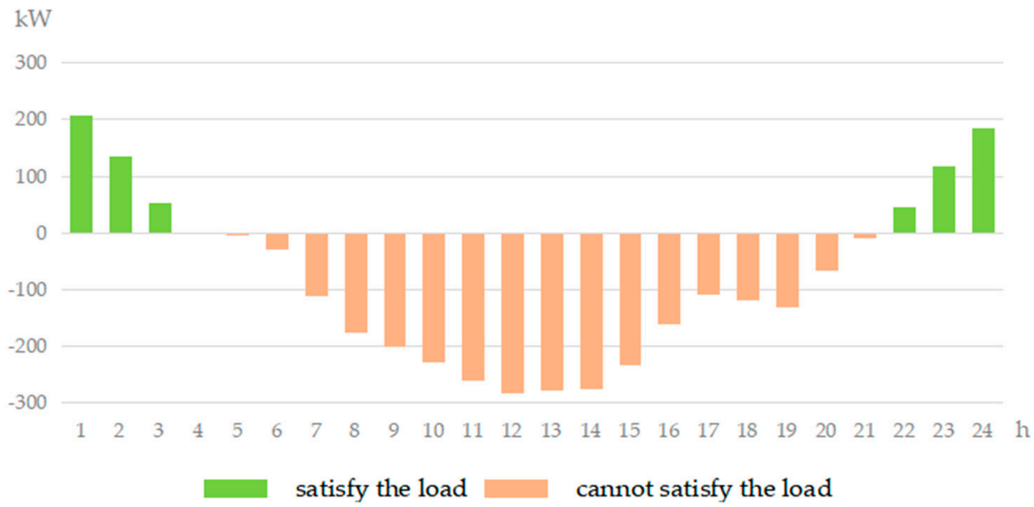


Figure 6. Supply-to-load curve of wind and PV power.



(**a**)

Figure 7. *Cont*.



(**b**)

Figure 7. Supply-to-load curves of wind and PV power and small hydropower stations: (**a**) small hydropower station output after meeting the load demand; (**b**) wind and PV power and small hydropower station supply-to-load curves.

4. Conclusions

The hybrid wind/PV/small-hydropower/facility-agriculture system may effectively mitigate food and environmental pollution problems and ensure continuity of the energy supply.

(1) The maximum wind power capture control strategy is adopted in wind power generation, and the MPPT control approach is applied in PV power generation, which maximizes wind and solar energy resource utilization. The considered small hydropower generating and pumping systems are independent systems, which increase the system's operational flexibility.
(2) The operational strategy of the hybrid system is considered in terms of four aspects: power generation strategy, operation strategy, battery charging strategy, and small hydropower pumping strategy. The load should be prioritized in terms of electricity consumption, batteries should be the second priority, and the power grid should be the final priority. This approach guarantees the electricity required for facility agriculture and fully utilizes the various resources.
(3) As China's largest industry, there are many research results in the field of combining agriculture with clean energy. The research in this paper responds to the carbon peak and carbon neutral requirements proposed by China. Clean energy is certain to be vigorously developed in the agricultural industry, and the development model of "multiple complementary clean energy sources + agriculture" will have far-reaching implications for the sustainable green development of China and the world.

At present, it is still difficult to fully characterize the system operation and control strategies due to the complexity of the model and the limited available data. In order to further improve the effectiveness of the coordinated operation strategy, a more comprehensive simulation of the optimal operation of the system considering water quantity constraints, economics, and other factors is needed in future studies, and the synergy among wind, PV, and water energy sources should be further explored.

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