

Article

Research on Multi-Objective Energy Management of Renewable Energy Power Plant with Electrolytic Hydrogen Production

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Abstract: This study focuses on a renewable energy power plant equipped with electrolytic hydrogen production system, aiming to optimize energy management to smooth renewable energy generation fluctuations, participate in peak shaving auxiliary services, and increase the absorption space for renewable energy. A multi-objective energy management model and corresponding algorithms were developed, incorporating considerations of cost, pricing, and the operational constraints of a renewable energy generating unit and electrolytic hydrogen production system. By introducing uncertain programming, the uncertainty issues associated with renewable energy output were successfully addressed and an improved particle swarm optimization algorithm was employed for solving. A simulation system established on the Matlab platform verified the effectiveness of the model and algorithms, demonstrating that this approach can effectively meet the demands of the electricity market while enhancing the utilization rate of renewable energies.

Keywords: electrolytic hydrogen; power fluctuation smoothing; peak shaving auxiliary services; fuzzy chance constraints; improved particle swarm algorithm



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1. Introduction

China's "3060 Dual Carbon" target, announced in 2020, has led to a consistent rise in the installed capacity of renewable energy generating units, specifically wind power and photovoltaic systems. As of the end of 2022, China's wind power and photovoltaic capacity reached 7576.1 MW, representing 26.7% of the total installed power capacity. However, the variability of renewable energy output, including intermittency, randomness, and fluctuation, has posed challenges to the stable operation and reliability of the power grid. The lack of dynamic regulation ability of the power system and the issue of growing challenges in renewable energy consumption are becoming more prominent [1,2]. Electrolytic hydrogen production technology, as a flexible resource that can be adjusted, has advantages such as fast response speed and zero carbon emissions [3,4]; moreover, compared with traditional energy storage media, hydrogen energy offers benefits such as high energy density and extended storage duration [5]. The grid-connected operation of the electrolytic hydrogen production system (EHPS) not only helps to improve the fluctuation of wind and solar power output and reduce the rate of wind and solar abandonment (WSA) caused by insufficient power grid consumption capacity but also can participate in peak shaving auxiliary services (PSAS), enhance the dynamic regulation capability of the system, and ensure the secure, stable, and cost-effective operation of the power grid with a high penetration of renewable energy. Therefore, how to effectively use electrolytic hydrogen production technology, enhance the flexibility and regulation capabilities of renewable energy power plants, meet the demand of multiple target scenarios such as smoothing power fluctuation, increasing renewable energy consumption space, and participate in PSAS have emerged as a pressing issue in need of urgent solutions.

There has been a certain research foundation at home and abroad in the coordinated operation of electrolytic hydrogen production systems and renewable energy generating units. The literature [6] investigates a hybrid renewable energy system incorporating hydrogen energy, proposing an efficient hydrogen production system energy management. It considers two different hydrogen production methods and establishes a mathematical model for energy conversion between hydrogen and electricity. The literature [7] explores potential opportunities and risks associated with hydrogen storage systems, assesses the feasibility of using hydrogen storage technology to address the issue of wind and solar energy curtailment in Western China, and proposes two solutions based on fuel cell hydrogen storage systems and hydrogen–natural gas blending. The literature [8] investigates an isolated DC microgrid with a combined electricity–hydrogen storage system. It proposes a cost-minimizing hybrid storage charging and discharging strategy that ensures voltage and power balance within the microgrid. The literature [9] aims to maximize system benefits and reduce environmental costs, constructs a wind–solar complementary hydrogen production system scheduling model, and uses a multi-objective golden eagle algorithm to solve the model. The literature [10] explores refined modeling of hydrogen storage systems and power-to-gas equipment, effectively enhancing the economic performance of integrated energy systems incorporating hydrogen storage. The literature [11] addresses the optimization and scheduling of hybrid systems with hydrogen storage by considering detailed models of flexible loads and hydrogen storage, aiming for an efficient solution. The objective of [12] is to optimize the net income of the microgrid within the service area, with the power balance of the microgrid system as a constraint, construct an optimized dispatching model of the wind and solar power generation service area microgrid including battery and hydrogen energy storage units, and the results show the effectiveness of the optimized dispatching strategy. The literature [13] delves into the capacity configuration of photovoltaic systems combined with hybrid battery–hydrogen storage systems, catering to both electrical and hydrogen loads. It introduces an optimization framework for the energy system servicing the hydrogen load and proposes two energy management strategies to ensure the stable supply of both electricity and hydrogen to the loads. The study in [14] presents an optimized configuration scheme for a wind–solar–hydrogen storage integrated energy system, considering both economic factors and system output fluctuations. The literature [15] studies the control mode of the hydrogen production system, proposes an optimization model of the integrated energy system with hydrogen production, and verifies the role of hydrogen production in system economy and renewable energy consumption in simulation software. The literature [16] based on the wind–hydrogen coupling system develops a capacity optimization model to maximize the revenue of the system and considers the possibility of the system participating in the auxiliary service market to improve system economy. The literature [17] studies integration of the hydrogen production system into the auxiliary peak shaving service of the thermal power unit and proposes a strategy for its participation. The literature [18] investigates integrated electric–gas energy systems incorporating green hydrogen, considering their participation in ancillary services and support for high-proportion renewable energy integration.

The aforementioned research mainly focuses on the operation optimization under a single scenario. However, a single objective is insufficient to meet the demands of the power system; hence, multi-objective optimization scheduling is necessary. The literature [19] proposes a day-ahead optimization scheduling strategy for wind–solar–hydrogen systems, targeting the system's curtailment rate of wind and solar, power deficit rate, and economic efficiency. The feasibility of its day-ahead optimization scheduling strategy was verified through simulation software. The literature [20] crafted an adaptable optimization algorithm focused on reducing expenses and enhancing battery storage capacity. Through the creation and testing of a power flow optimization framework, it facilitated increased adoption of photovoltaic power in standalone microgrids, alleviating the difficulty of managing operational expenses alongside microgrid dependability. The literature [21] proposes an optimized operation focusing on Battery Energy Storage Systems (BESS) and

Power-to-Gas (P2G) technologies, aiming to maximize the benefits of Renewable Energy Sources, P2G, and BESS while minimizing facility costs. Optimization is conducted through Mixed-Integer Linear Programming (MILP), and Stochastic Programming (SP) is employed to manage the uncertainty of renewable energy output.

The aforementioned literature discusses multi-objective energy management in microgrid applications and does not focus on renewable energy power plants as the research objective. The multiple objectives in renewable energy power plants mentioned in this paper and the multiple objectives in a microgrid are not the same, but such objectives are necessary for the electricity market and the power system and demonstrate potential in energy management for renewable energy power plants with electrolyte hydrogen units, such as smoothing renewable energy output fluctuations, participating in PSAS. Meanwhile, the random changes in the output of a renewable energy-generating unit make it a random optimization problem under uncertain conditions, requiring special quantification of the randomness of renewable energy output. This paper quantifies the uncertainty of renewable energy output in the form of fuzzy chance constraints and adopts the method of crisp equivalent classes to convert fuzzy chance constraints into deterministic constraints during the solution process.

This paper considers the use of an electrolytic hydrogen production system to smooth the power fluctuations of renewable energy power generation, participate in PSAS, increase the space for renewable energy consumption, reduce the amount of wind and solar discarded, and other application target scenarios, while considering the uncertainty in renewable energy output. It proposes a multi-objective energy management model based on the coordinated optimization of an electrolytic hydrogen production system and renewable energy power generation, and a particle swarm algorithm based on piecewise mapping and improved Levy flight algorithm has been introduced. Finally, the proposed algorithm and model's effectiveness is validated through case simulations. As a whole, the main contributions of this paper are as follows:

1. Multi-objective energy management: this paper presents a multi-objective energy management strategy that utilizes electrolysis hydrogen production technology to mitigate the adverse effects caused by renewable energy generation. This strategy enhances the stability of the power system, improves energy utilization, and offers a viable solution to address the challenges of renewable energy generation.
2. Economic and operational efficiency: this paper's simulation findings deliver an in-depth assessment of the economic and operational advantages associated with a renewable energy power plant including an electrolytic hydrogen production system. It highlights the potential for considerable progress in energy management for renewable energy generation through the optimization of energy usage, involvement in peak-load adjustment services, and participation in carbon trading activities.
3. Uncertain programming: this paper quantifies the uncertainty of renewable energy output in the form of fuzzy chance constraints and adopts the method of crisp equivalent classes to convert fuzzy chance constraints into deterministic constraints during the solution process. The issue of unpredictability in renewable energy generation's output has been addressed, offering a dependable framework for the enhancement of renewable energy systems.
4. Improved particle swarm algorithm: in this paper, the adoption of the particle swarm algorithm based on piecewise mapping and improved Levy flight algorithm is introduced for achieving comprehensive and effective optimization of the proposed model. This technique contributes to the improvement of the precision and dependability of the energy management approach.

2. Basic Principles of Hydrogen Production from Renewable Energy

The renewable energy power-generating system with an electrolytic hydrogen production system mainly uses the EHPS and the surplus power in the grid-connected consump-

tion process of wind power and photovoltaic power generation to store and utilize in the form of hydrogen energy and chemical energy. Its typical structure is shown in Figure 1.

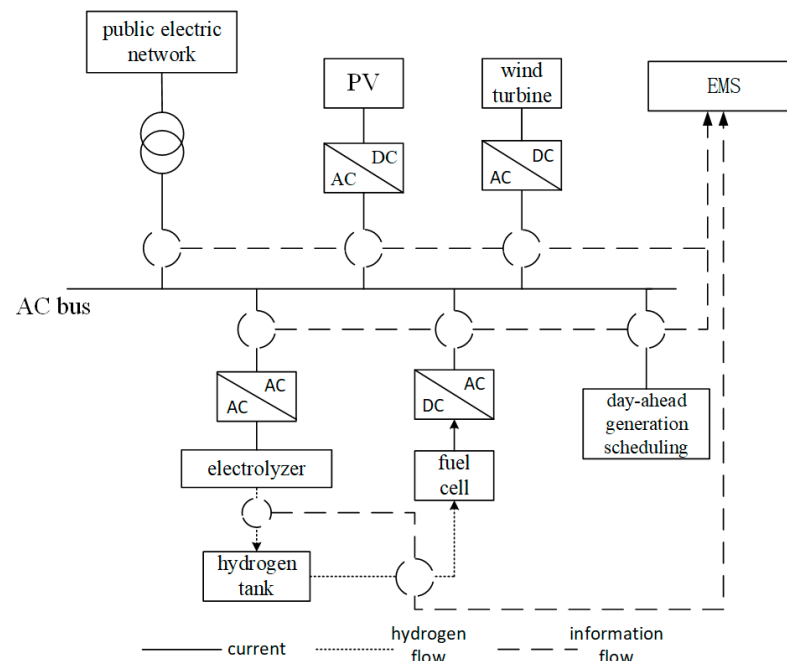


Figure 1. Renewable energy power plant with electrolytic hydrogen production system.

This plant consists of wind power generation, photovoltaic power generation, EHPS, and related power electronic interface equipment. Normally, wind power and photovoltaic power are directly consumed by the grid. However, the intermittent, random, and fluctuating nature of wind power and photovoltaic power generation, influenced by the natural environment, poses challenges, when the flexible regulation ability of the power grid is insufficient, it is necessary to use the EHPS to smooth the output power fluctuations of the renewable energy-generating unit, store the surplus output power of the renewable energy-generating unit, and participate in PSAS under certain price incentives.

The EHPS consists of an electrolyzer, a hydrogen compressor, and a hydrogen storage tank. The EHPS is an important device for electricity conversion and energy storage. It receives direct current from the renewable energy-generating unit and converts electrical energy into chemical energy through the electrolysis process. This conversion process allows the electrolyzer to store electrical energy when the demand of the power system is lower than the supply and to release the stored chemical energy for power supply when the demand is higher than the supply.

3. Technical and Economic Characteristics of Hydrogen Production from Renewable Energy

3.1. Characteristics of Renewable Energy-Generating Unit

3.1.1. Characteristics of Wind Power Generation

The output power P_{wt} of the wind turbine is shown in Equation (1):

$$P_{wt} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 v^3 \quad (1)$$

In the equation, C_p is the wind energy utilization coefficient; λ is the tip speed ratio; β is the pitch angle; ρ is the air density; R is the radius of the wind turbine rotor; and v is the wind speed.

The output power of the fan can be calculated according to Formula (1). This relationship can be described by the operating parameters of the fan. Commonly used parameters include cut-in wind speed, rated wind speed, cut-out wind speed, and rated power.

$$\begin{cases} 0 & 0 \leq v < v_{in} \\ n(A + Bv + Cv^3)P_{wtN} & v_{in} \leq v \leq v_N \\ nP_{wtN} & v_N \leq v \leq v_{out} \\ 0 & v_{out} < v \end{cases} \quad (2)$$

where:

$$A = \frac{1}{v_{in} - v_N} \left[v_{in}(v_{in} + v_N) - 4(v_{in} \times v_N) \left(\frac{v_{in} + v_N}{2v_N} \right)^2 \right] \quad (3)$$

$$B = \frac{1}{(v_{in} - v_N)^2} \left[4(v_{in} + v_N) \left(\frac{v_{in} + v_N}{2v_N} \right)^3 - (3v_{in} + v_N) \right] \quad (4)$$

$$C = \frac{1}{(v_{in} - v_N)^2} \left[2 - 4 \left(\frac{v_{in} + v_N}{2v_N} \right)^3 \right] \quad (5)$$

When approximated by linearization curve, the piecewise function expression of fan output power characteristics can be written as:

$$\begin{cases} 0 & 0 \leq v < v_{in} \\ nP_{wtN}(v^3 - v_{in}^3)/(v_N^3 - v_{in}^3) & v_{in} \leq v \leq v_N \\ nP_{wtN} & v_N \leq v \leq v_{out} \\ 0 & v_{out} < v \end{cases} \quad (6)$$

In the equation, v_{in} and v_{out} are the cut-in and cut-out wind speeds of the fan, respectively; n is the number of wind turbines; and P_{wtN} is the rated power of the wind turbine.

3.1.2. Characteristics of Photovoltaic Power Generation

The power output of photovoltaic can be calculated using an engineering approximation formula, as shown below:

$$P_{pv} = P_{STC} G_{AC} [1 + k(T_c - T_r)] / G_{STC} \quad (7)$$

In the equation, P_{pv} is the output power of photovoltaic power generation; G_{AC} is the irradiance; P_{STC} is the maximum output power under standard test conditions; G_{STC} is the solar intensity under standard test conditions; k is the power temperature coefficient; T_c is the working temperature of the photovoltaic module; and T_r is the reference temperature.

3.2. Characteristics of Electrolytic Hydrogen Production and Hydrogen Usage

3.2.1. Electrolytic

The electrical model of electrolytic water hydrogen production can be represented as follows:

$$\begin{aligned} U_{ele} &= U_r + \frac{r_1 + r_2 T_{el}}{S} I_{el} \\ &+ K_{el} \ln \left(\frac{k_{t1} + \frac{k_{t2}}{T_{el}} + \frac{k_{t3}}{T_{el}^2}}{S} I_{el} + 1 \right) \end{aligned} \quad (8)$$

In the equation, U_{ele} is the working voltage of the electrolyzer; U_r is the reversible voltage of the electrolyzer that varies with temperature; I_{el} is the working current of the electrolyzer; r_1, r_2 is the ohmic resistance parameter of the electrolyte; T_{el} is the working

temperature of the electrolyzer; K_{el} , k_{i1} , k_{i2} , and k_{i3} are the voltage parameters on the electrode of the electrolyzer; and S is the surface area of the electrolyzer motor.

The electrolyzer's hydrogen production rate model is described by the following equation:

$$V_{ele}^{ch}(t) = \eta_{ele} P_{ele}(t) \quad (9)$$

In the equation, $V_{ele}^{ch}(t)$ is the amount of hydrogen output; η_{ele} is the hydrogen production efficiency of the electrolyzer; and P_{ele} is the output power of the electrolyzer.

3.2.2. Hydrogen Storage Tank

According to the different forms of hydrogen, hydrogen storage technology mainly includes solid, gaseous, and liquid hydrogen storage. Industrial hydrogen storage uses gaseous hydrogen storage. The gas pressure $P_{HT}(t)$ in the hydrogen storage tank at time t is related to the amount of hydrogen storage $n_{HT}(t)$, calculated using the ideal gas equation.

$$\begin{cases} P_{HT}(t) = \frac{n_{HT}(t)RT_{H2}}{V_{HT}} \\ n_{HT}(t) = n_{HT}(t-1) + (n_{EL}(t) - n_{FC}(t))\Delta t \end{cases} \quad (10)$$

In the equation, T_{H2} is the temperature of the hydrogen gas; V_{HT} is the volume of the hydrogen storage tank; and $n_{HT}(t-1)$ is the amount of hydrogen gas in the tank at time $t-1$. The hydrogen storage status of the hydrogen storage tank can be calculated as follows:

$$SOHT(t) = \frac{P_{HT}(t)}{P_N} \quad (11)$$

In the equation, P_N is the maximum pressure of the hydrogen storage tank.

3.2.3. Fuel Cell

A fuel cell is similar to the reverse process of hydrogen production in an electrolytic cell. The output voltage can be represented as follows:

$$u_{cell} = u_{nernst} - u_{act} - u_{ohm} - u_{con} \quad (12)$$

In the formula, u_{cell} is the output voltage; u_{nernst} is the thermodynamic electromotive force; u_{act} is the activation polarization overpotential; u_{ohm} is the ohmic polarization overpotential; and u_{con} is the concentration difference overpotential.

4. Optimization Model of Multi-Objective Energy Management

4.1. Optimization Objectives of Energy Management

4.1.1. Smoothing of Power Fluctuations

The integration of renewable energy with significant fluctuations into the grid can cause harm to the grid; thus, certain requirements need to be proposed for the grid-connected renewable energy:

$$|P_{net}(t) - P_{net}(t-1)| \leq Det \quad (13)$$

$$P_{net}(t) = P_{wt}(t) + P_{pv}(t) \quad (14)$$

In the formula, P_{net} represents the actual output of renewable energy; Det represents the fluctuation range that the power grid can withstand, calculated as 10% of the total installed capacity of the plant's renewable energy generating units; P_{wt} represents the output power of wind power generation; and P_{pv} represents the output power of photovoltaic power generation.

4.1.2. Participation in Peak Load Regulation Auxiliary Services

Energy storage facilities absorb power during off-peak periods or during periods of wind, solar, and nuclear power curtailment and release power at other times, thereby providing peak load regulation auxiliary services.

According to the “Compensation Management Method” in the “Operating Rules of the Northeast China Power Auxiliary Service Market” released by the Northeast China Power Auxiliary Service Market, a “step-by-step” compensation strategy is proposed. Peak load regulation pricing details are shown in Table 1. The energy storage facilities built within the metering export of the thermal power plant, in conjunction with the unit, participate in peak shaving and are managed, cost-calculated, and compensated according to the “Compensation Management Method”.

Table 1. Peak load regulation pricing details.

Period	Quotation File	Load Rate of Thermal Power Plant	Lower Quotation Limit (CNY/kWh)	Upper Quotation Limit (CNY/kWh)
non-heating season	first gear	40% < load rate ≤ 48%	0	0.4
	second gear	load rate ≤ 40%	0.4	1
heating season	first gear	40% < load rate ≤ 50%	0	0.4
	second gear	load rate ≤ 40%	0.4	1

Due to the current rules and regulations regarding energy storage participation in peak shaving not being fully developed or comprehensive, the energy storage facilities built within the metering export of renewable energy power stations participate in PSAS. The “Compensation Management Method”, in which the energy storage facilities are established within the metering export of thermal power plants, is used as a reference to establish a compensation strategy:

$$E_{\text{sup}} = \lambda_{\text{sup}} \sum Q_{\text{sup}} \quad (15)$$

$$\lambda_{\text{sup}} = \begin{cases} 1000 & 0 < f_i \leq 40\% \\ 400 & 40\% < f_i \leq 50\% \\ 0 & 50\% \leq f_i \end{cases} \quad (16)$$

In the formula, E_{sup} represents the compensation for participating in peak load regulation auxiliary services; λ_{sup} represents the subsidized electricity price; Q_{sup} represents the amount of electricity for output peak shaving; and f_i represents the average load rate of the energy storage facilities. The average load rate is calculated as the power generated by the operating unit divided by the capacity of the operating unit, multiplied by 100%.

4.1.3. Increasing the Absorption Space for Renewable Energy

For renewable energy power plants, there are three factors that cause the system to abandon wind and solar. First, the installed capacity of the electrolytic cell is limited. Second, the capacity of the hydrogen storage tank is limited. Third, the installed capacity of electrochemical energy storage is limited.

The power quantity of the plant’s abandoned wind and solar is:

$$Q_{\text{loss}}(t) = [P_{\text{net,theory}}(t) - P_{\text{net}}(t) - P_{\text{ele}}(t)|_{V_H < V_H^{\text{max}}} - P_{\text{bat}}^{\text{ch}}(t)]\Delta t \quad (17)$$

In the formula, Q_{loss} represents the amount of electricity discarded from wind and solar; $P_{\text{net,theory}}$ represents the theoretical output of renewable energy; $P_{\text{ele}}^{\text{net}}(t)|_{V_H < V_H^{\text{max}}}$ represents the operating power of the electrolyzer when absorbing the surplus output of renewable energy and when the storage volume of the hydrogen storage tank is less than the maximum storage volume; $P_{\text{bat}}^{\text{ch}}$ represents the charging power of electrochemical energy storage; Δt represents the time interval; and Δt equals 15 min.

4.2. Objective Function

Total Benefit Model

$$\text{Max } f = E_{\text{sup}} + E_{\text{co2}} - K_{\text{loss}} - K_{\text{buy}} \quad (18)$$

In the formula, E_{sup} represents the revenue from participating in peak load shifting auxiliary services; E_{co2} represents the revenue from carbon emission reduction; K_{loss} represents the cost of wind and solar power curtailment; and K_{buy} represents the cost of purchasing electricity.

1. Revenue of peak load shifting auxiliary services:

$$E_{\text{sup}} = \lambda_{\text{sup}} \sum P_{\text{sup}}(t) \Delta t \quad (19)$$

2. Revenue of carbon emission reduction:

$$E_{\text{co2}} = A_{\text{co2}}(B_q - B_p) \quad (20)$$

$$B_p = \lambda_p \sum_{t=1}^T P_{\text{buy}}(t) \Delta t \quad (21)$$

$$B_q = \lambda_q \sum_{t=1}^T (P_{\text{wt}} + P_{\text{pv}} - P_{\text{loss}}) \Delta t \quad (22)$$

In the formula, A_{co2} represents the carbon trading price; B_p represents the plant carbon emissions; B_q represents the allocated carbon emission quota; λ_p represents the equivalent carbon emission coefficient of purchasing electricity from the grid [22]; T represents the optimization period (one day is divided into 96 time periods, that is, $T = 96$); P_{buy} represents the power of purchasing electricity; and λ_q represents the carbon emission quota per unit of electricity generation.

3. Cost of purchasing electricity:

$$K_{\text{buy}} = \sum_{t=1}^T A_{\text{buy}} P_{\text{buy}}(t) \Delta t \quad (23)$$

In the formula, A_{buy} represents the time-of-use electricity price and P_{buy} represents the power of purchasing electricity.

4. Cost of wind and solar power curtailment:

$$K_{\text{loss}} = \gamma_{\text{loss}} \sum_{t=1}^T Q_{\text{loss}}(t) \quad (24)$$

$$Q_{\text{loss}}(t) = [P_{\text{net,theory}}(t) - P_{\text{net}}(t) - P_{\text{ele}}(t)|_{V_H < V_H^{\text{max}}} - P_{\text{bat}}^{\text{ch}}(t)] \Delta t \quad (25)$$

In the formula, γ_{loss} represents the penalty for the unit amount of wind and solar power curtailment.

4.3. Constraint Conditions

4.3.1. Overall Operational Constraints of Renewable Energy Power Stations

1. Power and energy balance constraints:

$$P_{\text{wt}}(t) + P_{\text{pv}}(t) = P_{\text{sell}}(t) + P_{\text{ele}}(t) - P_{\text{buy}}(t) - P_{\text{sup}}(t) - P_{\text{fc}}(t) + P_{\text{bat}}^{\text{ch}}(t) - P_{\text{bat}}^{\text{disch}}(t) + P_{\text{loss}}(t) \quad (26)$$

In the formula, P_{sell} represents the power of selling electricity; P_{ele} represents the operating power of the electrolytic cell; P_{sup} represents the power involved in peak shifting; and $P_{\text{bat}}^{\text{ch}}$ and $P_{\text{bat}}^{\text{disch}}$ represent the charging power and discharging power, respectively.

2. Hydrogen energy supply and demand balance constraints:

$$V_{hs}(t+1) = V_{hs}(t) + V_{ele}^{ch}(t) - V_{fc}^{disch}(t) \quad (27)$$

$$V_{ele}^{ch}(t) = \eta_{ele} P_{ele}(t) \Delta t \quad (28)$$

$$V_{fc}^{disch}(t) = \eta_{fc} P_{fc}(t) \Delta t \quad (29)$$

In the formula, V_{hs} represents the storage of hydrogen in the hydrogen storage tank; V_{fc}^{disch} represents the amount of hydrogen used by the fuel cell per unit time; η_{fc} represents the hydrogen utilization efficiency of the fuel cell; and P_{fc} represents the operating power of the fuel cell.

3. Power fluctuation constraints:

$$|P_{net}(t) - P_{net}(t-1)| \leq Det \quad (30)$$

4.3.2. Operational Constraints of Each Subsystem

1. Operational constraints of renewable energy-generating unit:

$$P_{wt}^{\min}(t) \leq P_{wt}(t) \leq P_{wt}^{\max}(t) \quad (31)$$

$$P_{pv}^{\min}(t) \leq P_{pv}(t) \leq P_{pv}^{\max}(t) \quad (32)$$

In the formula, $P_{wt}^{\min}$ and $P_{wt}^{\max}$ represent the minimum and maximum output power of wind power, respectively; and $P_{pv}^{\min}$ and $P_{pv}^{\max}$ represent the minimum and maximum output power of photovoltaic power, respectively.

2. Operational Constraints of Hydrogen Energy Systems

• Operational constraints of electrolytic cell:

$$P_{ele}^{\min} \leq P_{ele}(t) \leq P_{ele}^{\max} \quad (33)$$

In the formula, $P_{ele}^{\min}$ represents the lower limit of the power consumed by the electrolytic cell during normal operation, and there is a risk of explosion when the operating power of the electrolytic cell is below 20~25% of the rated power for a long time [23]; $P_{ele}^{\max}$ represents the upper limit of the power consumed by the electrolytic cell during normal operation.

• Operational constraints of fuel cells:

$$0 \leq P_{fc}(t) \leq P_{fc}^{\max} \quad (34)$$

In the formula, $P_{fc}^{\max}$ represents the upper limit of the power consumed by the fuel cell during normal operation.

• Capacity constraints of hydrogen storage tanks:

$$0 \leq V_{hs}(t) \leq V_{hs}^{\max} \quad (35)$$

In the formula, $V_{hs}^{\max}$ represents the maximum hydrogen storage capacity of the hydrogen storage tank.

3. Operational Constraints of Electrochemical Energy Storage Systems

• Charging and discharging power constraints:

$$\begin{cases} 0 \leq P_{bat}^{ch}(t) \leq P_{bat}^{rated} \\ -P_{bat}^{rated} \leq P_{bat}^{disch}(t) \leq 0 \\ P_{bat}^{ch}(t) \cdot P_{bat}^{disch}(t) = 0 \end{cases} \quad (36)$$

In the formula, P_{bat}^{rated} represents the rated power of the electrochemical energy storage.

- Energy storage state constraints:

Considering that overcharging and over-discharging of electrochemical energy storage can significantly reduce the cycle life of the battery, it is significant to impose constraints on the state of charge (SOC) of the energy storage system:

$$SOC(t) = \frac{E(t)}{E_{bat}^{rated}} \quad (37)$$

$$SOC(t) - SOC(t-1) = \left(\frac{P_{bat}^{ch}(t)\eta_{bat}^{ch}}{E_{bat}^{rated}} - \frac{P_{bat}^{disch}(t)}{E_{bat}^{rated}\eta_{bat}^{disch}} \right) \Delta t \quad (38)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (39)$$

In the formula, $E(t)$ and E_{bat}^{rated} represent the current energy state and rated energy state of the electrochemical energy storage, respectively; η_{bat}^{ch} and η_{bat}^{disch} represent the charging efficiency and discharging efficiency, respectively; SOC_{min} and SOC_{max} represent the maximum capacity and minimum capacity of the electrochemical energy storage, respectively.

4.4. Fuzzy Chance Constraints

4.4.1. Fundamental Principle

The modeling idea of fuzzy chance-constrained programming is it allows the decision made to not satisfy the constraint conditions to some extent, but the probability of the fuzzy constraint conditions being established is not less than the preset confidence level.

The single-objective programming with fuzzy chance constraints is as follows:

$$\begin{cases} \min & f(x, \zeta) \\ \text{s.t.} & \Pr\{g(x, \zeta) \leq 0\} \geq \alpha \end{cases} \quad (40)$$

In the formula, x represents the decision variable; ζ represents the fuzzy vector; $\min f(x, \zeta)$ represents the objective function; $g(x, \zeta) \leq 0$ represents the constraint conditions; $\Pr\{\bullet\}$ represents the probability of a certain event occurring; and α represents the confidence level of the system.

4.4.2. Handling of Power and Energy Balance Constraints

Different from traditional optimization methods, due to the randomness of renewable energy output, when a significant amount of renewable energy is integrated into the grid, the error between actual output and predicted output cannot be ignored. In the energy management model, the output of renewable energy has uncertainty. A model is established based on the theory of Chance Constrained Programming, and the fuzzy parameters $\tilde{P}_{wt}$ and $\tilde{P}_{pv}$ of renewable energy are introduced to form fuzzy chance constraints. Therefore, Equation (26) can be relaxed to the power and energy balance constraints under a certain confidence level condition, ensuring that the probability of meeting the balance constraints is not less than α .

$$\Pr \left\{ \begin{array}{l} \tilde{P}_{wt}(t) + \tilde{P}_{pv}(t) = P_{sell}(t) + P_{ele}(t) - P_{buy}(t) - P_{sup}(t) \\ -P_{fc}(t) + P_{bat}^{ch}(t) - P_{bat}^{disch}(t) + P_{loss}(t) \end{array} \right\} \geq \alpha \quad (41)$$

5. Solution Method of Energy Management Model

5.1. Handling Method of Fuzzy Chance Constraints

The methods for handling fuzzy chance-constrained programming are divided into two categories. For simple problems, the fuzzy parameters and decision variables in the constraint conditions can be separated or, when they have a certain linear relationship, they can be transformed into clear equivalent classes for processing and then calculated by traditional methods; for complex problems, random simulation methods can be used for

processing. However, the results of random simulation are not accurate and it is not easy to grasp the size of the sample capacity of the simulation, so the first method is chosen [24].

During the operation of the power system in practice, the requirements for safety are high; therefore, the probability of the power and energy balance constraints being established should be above 0.5, that is, $\alpha \geq 0.5$, so:

Assume the form of function $g(x, \zeta)$ is as follows [25]:

$$g(x, \zeta) = \psi_1(x)\zeta_1 + \psi_2(x)\zeta_2 + \cdots + \psi_t(x)\zeta_t + \psi_0(x) \quad (42)$$

In the formula, represents the trapezoidal fuzzy variable $(\gamma_{k1}, \gamma_{k2}, \gamma_{k3}, \gamma_{k4})$, $\psi = 1, 2, \dots, t$. If $\psi_k^+ \vee 0$ and $\psi_k^- \wedge 0$, $k = 1, 2, \dots, t$. So:

The fuzzy chance constraints in Equation (42) can be clearly equivalent to:

$$\begin{aligned} (2 - 2\alpha) \sum_{k=1}^t (\gamma_{k3}\psi_k^+(x) - \gamma_{k2}\psi_k^-(x)) \\ + (2\alpha - 1) \sum_{k=1}^t (\gamma_{k4}\psi_k^+(x) - \gamma_{k1}\psi_k^-(x)) + \psi_0(x) \leq 0 \end{aligned} \quad (43)$$

This paper describes the fuzzy parameters $\tilde{P}_{wt}$ and $\tilde{P}_{pv}$ of the renewable energy output using trapezoidal fuzzy parameters. Among them, the trapezoidal fuzzy variable is a quadruple $(P_{wt1}, P_{wt2}, P_{wt3}, P_{wt4})$ composed of clear numbers and $P_{wt1} < P_{wt2} \leq P_{wt3} < P_{wt4}$. The quadruple values can be determined based on the predicted renewable energy output:

$$\begin{cases} \tilde{P}_{wt}(\omega_1, \omega_2, \omega_3, \omega_4) = P_{wt}^{fore}(r_1, r_2, r_3, r_4) \\ \tilde{P}_{pv}(\omega_1, \omega_2, \omega_3, \omega_4) = P_{pv}^{fore}(r_1, r_2, r_3, r_4) \end{cases} \quad (44)$$

In the formula, $\omega_1, \omega_2, \omega_3, \omega_4$ represents the membership parameter; r_1, r_2, r_3, r_4 represents the proportionality constant.

The wind and solar prediction output are parameterized in Equation (44):

$$\begin{cases} \tilde{P}_{wt} \rightarrow \frac{\alpha-1}{4}P_{wt1} + \frac{\alpha}{2}P_{wt2} + \frac{3-\alpha}{4}P_{wt3} + \frac{1-\alpha}{2}P_{wt4} \\ \tilde{P}_{pv} \rightarrow \frac{\alpha-1}{4}P_{pv1} + \frac{\alpha}{2}P_{pv2} + \frac{3-\alpha}{4}P_{pv3} + \frac{1-\alpha}{2}P_{pv4} \end{cases} \quad (45)$$

5.2. Improved Particle Swarm Algorithm

5.2.1. Standard Particle Swarm Optimization (PSO) Algorithm

The update formula for the PSO algorithm is given by the following equation:

$$\begin{aligned} v_i &= \omega \times v_i + c_1 \times rand() \times (P_{best_i} - x_i) \\ &+ c_2 \times rand() \times (g_{best_i} - x_i) \end{aligned} \quad (46)$$

$$x_i = x_i + v_i \quad (47)$$

In the formula, $i = 1, 2, \dots, N$, where N is the total number of particles in this group; ω is the inertia factor; v_i is the speed of the particle; $rand()$ is a random number between $(0, 1)$; x_i is the current position of the particle; and c_1 and c_2 are learning factors.

5.2.2. Particle Swarm Algorithm Based on Piecewise Mapping and Improved Levy Flight (PLPSO)

(1) Piecewise Mapping

Chaos mapping is a method for generating chaotic sequences. Piecewise mapping, as a typical chaos mapping, has a concise mathematical form and good ergodicity and randomness. The definition of piecewise chaotic mapping is as follows:

$$x(t+1) = \begin{cases} \frac{x(t)}{p} & , 0 \leq x(t) < p \\ \frac{x(t)-p}{0.5-p} & , p \leq x(t) < 0.5 \\ \frac{1-p-x(t)}{0.5-p} & , 0.5 \leq x(t) < 1-p \\ \frac{1-x(t)}{p} & , 1-p \leq x(t) < 1 \end{cases} \quad (48)$$

In the formula, $p = 1$; $x(1) = rand$.

(2) Improved Levi Flight

Levy flight is a method of simulating random motion using heavy-tailed distributions. It can describe the dynamic characteristics of some complex systems, such as phenomena in the fields of ecology, geography, physics, etc. The update formula for Levy flight is as follows:

$$X_{t+1} = X_t + a \cdot Levy(\beta) \quad (49)$$

In the formula, X_t is the t -th iteration position of X ; a is the step length scaling factor; and $Levy(\beta)$ is the Levy random path, satisfying: $Levy \sim u = t^{-\beta}$, $1 \leq \beta \leq 3$.

Levy flight is essentially a random step length, and the distribution of the step length satisfies the Levy distribution. The Levy distribution is complex and is usually implemented using the Mantegna algorithm. For the specific implementation process, please refer to reference [26].

Due to the step length scaling factor of Levy flight usually being set to a fixed value, it leads to slow search speed and low search accuracy during the search process [27]. To address these issues, this paper introduces an enhanced Levy flight approach:

$$X_{t+1} = X_t + a \cdot \sin^2\left(\frac{\pi}{2} \cdot \frac{1-t}{iter}\right) \cdot Levy(\beta) \quad (50)$$

In the formula, the fixed step length $a = 0.01$; $\sin^2\left(\frac{\pi}{2} \cdot \frac{1-t}{iter}\right)$ is the adaptive step length factor, where t is the current iteration number and $iter$ is the maximum number of iterations.

(3) Improved Particle Swarm Algorithm

PSO has some disadvantages, such as easy premature convergence, lack of diversity, and susceptibility to initial values. The improved PSO uses chaos mapping to enhance the diversity of particles and combines with improved Levy flight to enhance the vitality and jumping ability of particles [26], realizing the complementary advantages of PSO, chaos mapping, and Levy flight. Due to the complexity of Levy flight, the algorithm's computation time will experience an increase. However, in the later stage of optimization, the particle swarm algorithm will fall into local optimum, and particles need to perform Levy flight to escape from the local optimum. Therefore, an adaptive random number $(1 + \frac{t}{iter}) \cdot rand$ is introduced. Before each update of particles, the generated adaptive random number is compared with 0.5. If it is greater than 0.5, Levy flight is used to update the particles; otherwise, the particles' velocity and position are updated iteratively through Formulas (46) and (47).

The process description of the improved PSO is as follows:

- (a) Population initialization. Randomly initialize the speed of the population and use chaos mapping to initialize the position of the population and find the current optimal particle position and solution.
- (b) Calculate fitness. Evaluate the fitness value of each particle and store it in $pbest$. Compare the fitness values of all particles in the population and store the best individual ($gbest$) in the population.

- (c) Update particle position. Generate an adaptive random number and compare it with 0.5. If it is greater than 0.5, update the particle through Levy flight; otherwise, update the particle through Formulas (46) and (47).
- (d) Update individual best position. Compare the current fitness value of the particle with the fitness value before the update, and use the better particle as the particle after the iteration.
- (e) Update global optimal solution. Compare pbest with gbest. If pbest is better than gbest, assign the value of pbest to gbest.
- (f) Algorithm termination. If the iteration termination condition is met, the algorithm terminates; otherwise, return to step c to continue the search.

The process of the PLPSO algorithm is shown in Figure 2:

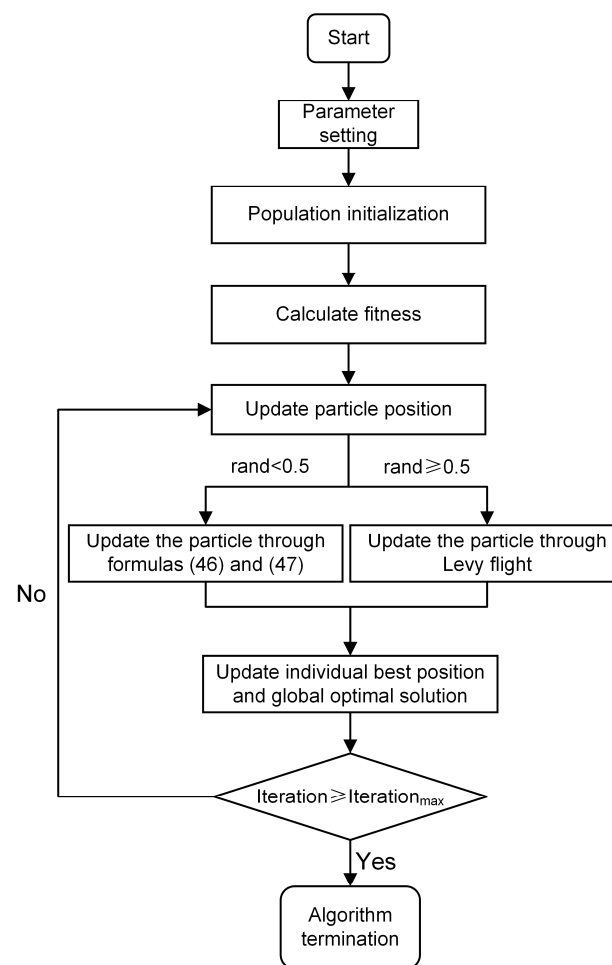


Figure 2. The process of the PLPSO algorithm.

6. Simulation Analysis

6.1. Case Description

Based on the typical daily wind power and photovoltaic output prediction data of a renewable energy power station in a province in Northeast China, with a sampling period of 15 min, the obtained forecast output curve of wind power and photovoltaic on a typical day is shown in Figure 3, and the program output and peak shaving command curve are shown in Figure 4. An EHPS and an electrochemical energy storage system are configured; the installed capacities of wind power and photovoltaics in this region are 25 MW and 200 MW, respectively, the capacity of the electrolytic cell is configured as 25 MW, and the fuel cell capacity is 10 MW; the equipment-related parameters are shown in Table 2 and the economic parameters are shown in Table 3.

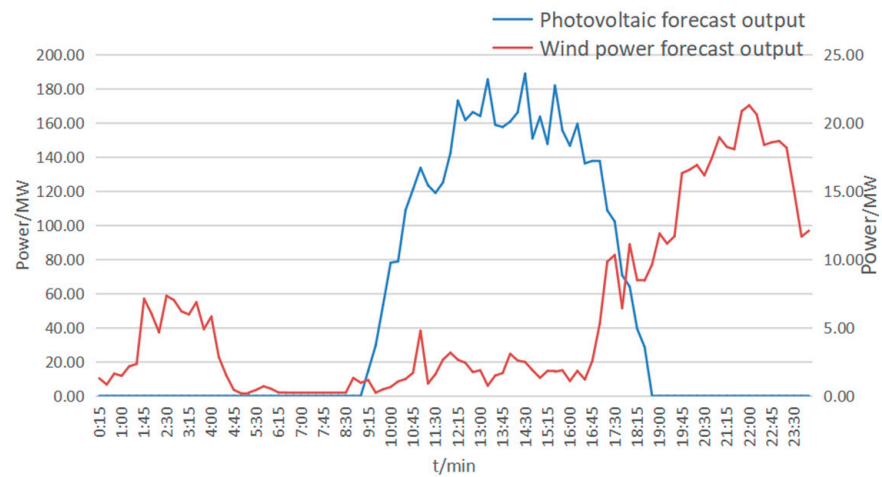


Figure 3. Forecast output curve of wind power and photovoltaic on a typical day.

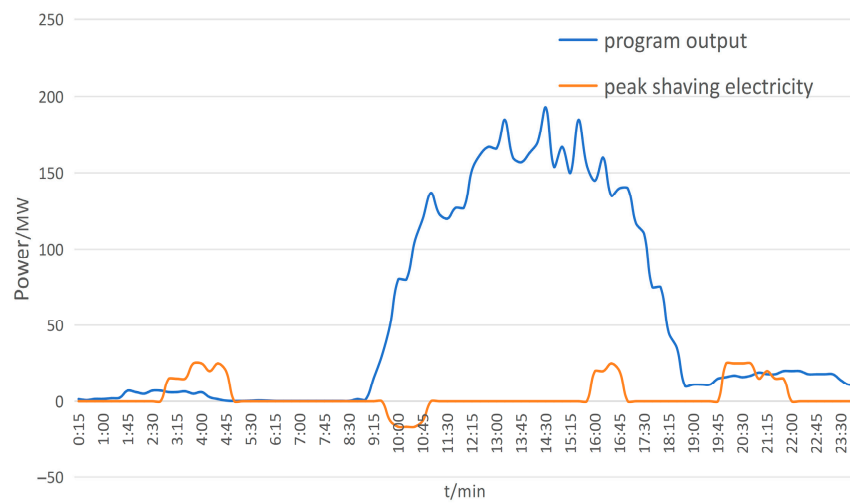


Figure 4. Program output and peak shaving command curve.

Table 2. Operation parameters.

Parameter	Value
p_{wt}^{min} /MW	0
p_{wt}^{max} /MW	25
p_{pv}^{min} /MW	0
p_{pv}^{max} /MW	200
$\eta_{bat}^{ch}, \eta_{bat}^{disch}$	0.9
SOCmin	0.2
SOCmax	0.8
The initial state of SOC	0.5
E_{bat}^{rated} /MW	20
p_{ele}^{min} /MW	6.25
p_{ele}^{max} /MW	25
η_{ele} / (Nm ³ / MWh)	190
η_{fc} / (Nm ³ / MWh)	555.56
V_{hs}^{max} /Nm ³	30,000
$V_{hs}(1)$ /Nm ³	2000

Table 3. Economic parameters.

Parameter	Value
$A_{hyd}/(\text{CNY}/\text{Nm}^3)$	3
$A_{co2}/(\text{CNY}/\text{kg})$	0.075
$\lambda_p/(\text{kg}/\text{MWh})$	500
$\lambda_q/(\text{kg}/\text{MWh})$	798
$\gamma_{fc}/(\text{CNY}/\text{MWh}\cdot\text{Day})$	1136
$\gamma_{hs}/(\text{CNY}/\text{Nm}^3\cdot\text{Day})$	0.5
$\gamma_{ele}/(\text{CNY}/\text{MW}\cdot\text{Day})$	1748
$\gamma_{bat}/(\text{CNY}/\text{MW}\cdot\text{Day})$	850
$\gamma_{loss}/(\text{CNY}/\text{MWh})$	300
$A_{buy}(0:00 \text{ to } 8:00)/(\text{CNY}/\text{MWh})$	135.0
$A_{buy}(9:00 \text{ to } 12:00 \text{ and } 18:00 \text{ to } 23:00)/(\text{CNY}/\text{MWh})$	521.4
$A_{buy}(\text{others})/(\text{CNY}/\text{MWh})$	328.2

6.2. Comparative Analysis of PSO Algorithm before and after Improvement

The mathematical model proposed in this paper is solved by the traditional PSO and PLPSO algorithms, respectively. The two algorithms have the same parameters: $\omega = 0.8$, $c_1 = c_2 = 1.2$, the population size is 100, the maximum number of iterations is 15,000, and both algorithms run 100 times under the scenario with a confidence level of 0.9. Table 4 gives a comparison of the results of the traditional PSO and PLPSO algorithms.

Table 4. Comparison between traditional PSO and PLPSO.

	PSO	PLPSO
Number of runs	100	100
average run time/s	261.3	248.4
mean value	−654,818.07	−768,875.44
optimal value	−807,479.2	−830,172.1
mean absolute deviation (MAD)	62,614.6	17,792.2

As can be seen from Table 4, the PLPSO algorithm is superior to the PSO algorithm in terms of running time, average value, and optimal value. Through the calculation of the average value, it can be known that the fitness value of the PLPSO algorithm is 114,057.37 smaller than that of the traditional PSO algorithm, and the convergence accuracy is improved by 17.4%; the mean absolute deviation (MAD) measures the average distance between data points and their average value. A smaller average absolute deviation value indicates that the data are more stable. The MAD of the data obtained by the PLPSO algorithm is 71.9% smaller than that of the PSO, indicating that the PLPSO algorithm is more stable. The convergence curves of the fitness values of the two algorithms are shown in Figure 5.

As can be seen from Figure 5, due to the use of piecewise mapping by the PLPSO algorithm, the initial fitness value of the PLPSO algorithm exhibits improvement over the initial fitness value of the traditional PSO algorithm; the PLPSO algorithm terminates convergence around the 5000th generation and the traditional PSO algorithm terminates convergence around the 7500th generation. In comparison to the traditional PSO algorithm, the PLPSO algorithm exhibits an approximately 33.3% faster convergence speed. As evident from the zoomed-in figure, at the end of convergence, the convergence accuracy of the PLPSO algorithm is 14.9% higher than that of the traditional PSO algorithm. Therefore, the PLPSO algorithm is superior to the traditional PSO algorithm.

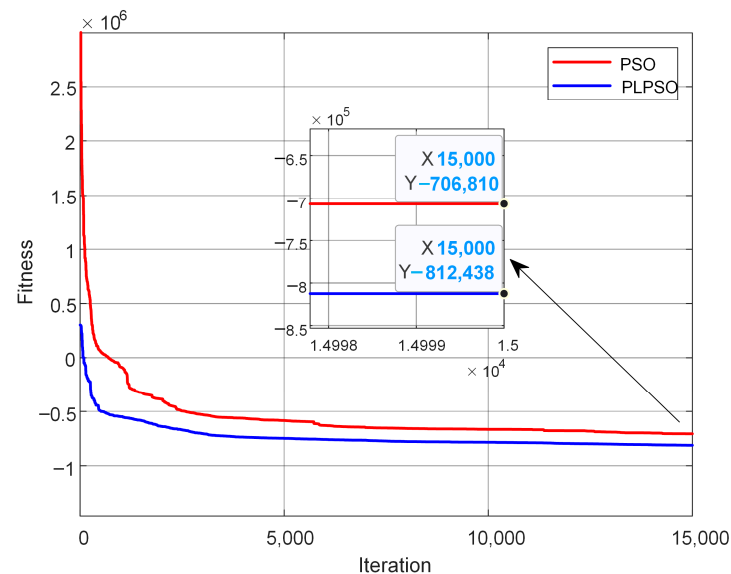


Figure 5. Comparison of convergence curves of two algorithms.

6.3. Analysis of the Impact of Varying Confidence Levels on Decision-Making Outcomes

The confidence level significantly affects the system's economy and safety, and different confidence levels will lead to different scheduling results. As the confidence level increases, the system's rate of WSA and comprehensive benefits are shown in Table 5.

Table 5. Scheduling results under different confidence levels.

Confidence Level	Proportion of the Wind and Solar Energy Abandon	Comprehensive Benefit/CNY
0.55	9.97%	720,723
0.60	7.17%	714,133
0.65	5.36%	731,836.8
0.70	2.06%	736,225.2
0.75	2.32%	730,571.3
0.80	1.98%	738,359.2
0.85	1.25%	748,917.6
0.90	1.42%	762,298.3
0.95	1.16%	774,511.2
1.00	0.67%	784,582.3

As shown in Table 5, as the confidence level continues to increase, the system's wind and light abandonment rate generally shows a downward trend; under the premise that the installed capacity of the EHPS and the electrochemical energy storage system is certain, when the confidence level is low, due to the insufficient installed capacity of the EHPS and the electrochemical energy storage system, the rate of WSA is larger. To mitigate the rate of WSA, a portion of its capacity is allocated to participate in the PSAS, absorbing excess electricity, thereby reducing the economic benefits brought by engaging in the PSAS. Since the plant still has a high rate of WSA, it causes a large WSA penalty. Therefore, when the confidence level is low, the comprehensive benefits are low; when the confidence level is high, due to the sufficient installed capacity of the EHPS and the electrochemical energy storage system, the plant can easily decrease the rate of WSA and has more capacity to engage in PSAS to obtain the highest peak-shaving subsidy. Therefore, as the confidence level increases, the comprehensive benefits show an increasing trend.

The operation of the EHPS and the electrochemical energy storage system is intricately linked to the confidence level. During the scheduling decision-making process, the sched-

uler must carefully weigh the plant demand, safety, and economy factors to determine the optimal confidence level.

6.4. Analysis of Energy Management Decision-Making Scheme

Taking the confidence level as an example, using the PLPSO algorithm for solving, we can obtain the scheduling situation of the renewable energy output, the EHPS, and the electrochemical energy storage system 24 h before the day. Among them, the peak-shaving subsidy and the peak-shaving command curve are depicted in Figure 6.

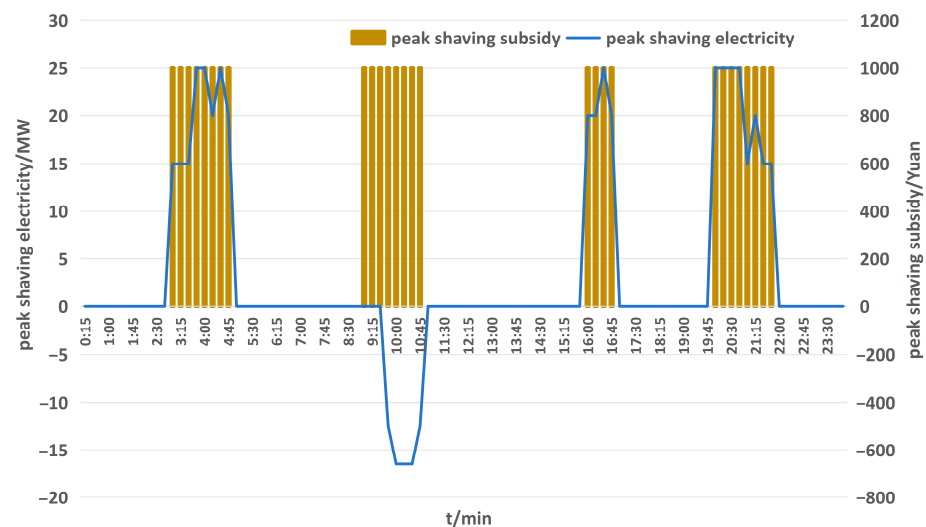


Figure 6. Peak-shaving subsidy and peak-shaving electricity curve.

The renewable energy power plant containing electrolytic hydrogen is derived from the planned output reported to the upper-level power grid, taking into account the time-of-use electricity price, power fluctuation suppression, peak-shaving ladder subsidy, carbon-trading benefits, WSA penalties, and various system operation constraints. It ensures that the actual output fluctuates between 90% and 110% of the planned output. While completing the PSAS, the excess electricity is utilized for hydrogen production (charge) through the EHPS and the electrochemical energy storage system. In the case of insufficient renewable energy output, it discharges. The output curves of the EHPS and the electrochemical energy storage system are displayed in Figures 7 and 8, respectively.

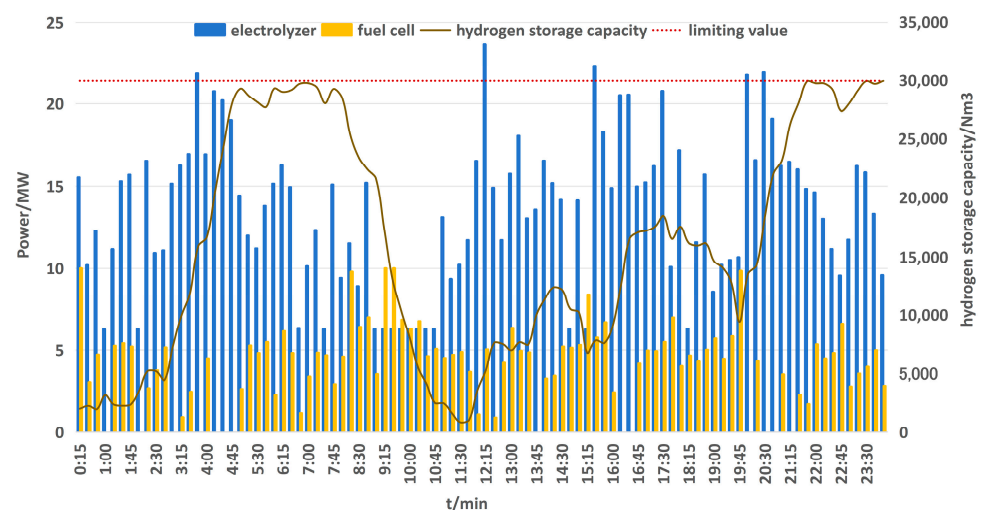


Figure 7. Operation of electrolytic cell, fuel cell, and hydrogen storage tank.

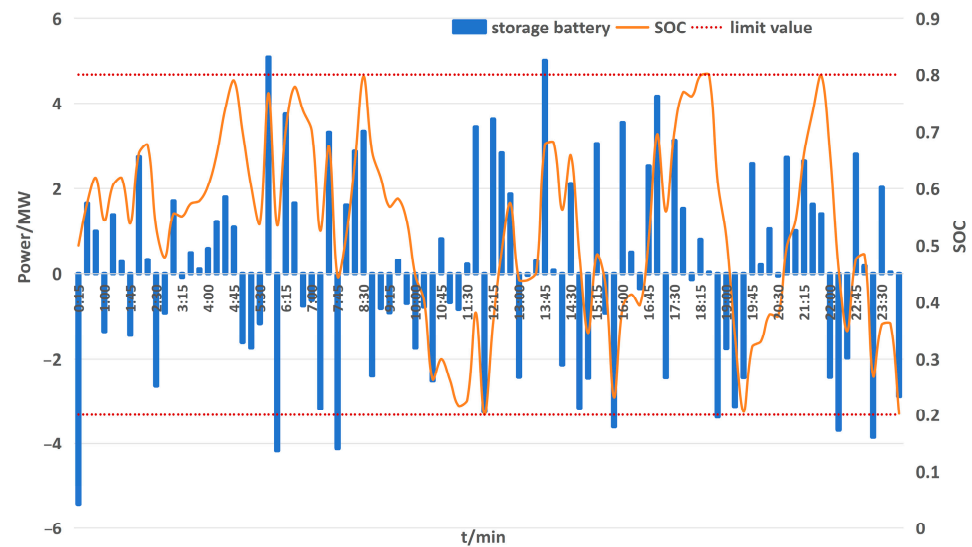


Figure 8. Operation of electrochemical energy storage.

As evident from Figure 7, between 0:00~2:45, 11:00~15:45, and 17:00~19:45, the electrolyzer and fuel cell operate at a certain power to maintain a lower level of hydrogen storage, leaving enough hydrogen storage space for the subsequent periods (3:00~4:45, 16:00~16:45, and 20:00~21:45) to prepare for peak shaving. During the peak-shaving period, the maximum operating power of the electrolyzer is 21.94 MW, the minimum operating power is 14.84 MW, and a total of 68,590 Nm³ hydrogen is produced; between 5:00 and 8:45, the fuel cell maintains a low-power operation to maintain a higher storage amount of hydrogen in the hydrogen storage tank, preparing for the next period (9:00~10:45) for peak shaving. During the peak-shaving period, the electrolyzer maintains operation at 25% of the rated power (i.e., 6.25 MW) to ensure the electrolyzer operates safely, and the fuel cell is in a high-power working state, with a maximum discharge power of 10 MW, a minimum discharge power of 3.52 MW, a total discharge of 52.02 MW, and a hydrogen consumption of 16,866.8 Nm³; between 22:00 and 24:00, the electrolyzer operates at high power and the fuel cell operates at low power to ensure that there is a higher amount of hydrogen storage in the hydrogen storage tank at 24:00 to obtain higher hydrogen sales benefits. In one operating cycle, the electrolyzer produces a total of 244,691.03 Nm³ hydrogen, the fuel cell consumes a total of 218,985.38 Nm³ hydrogen, and the final hydrogen storage amount is 29,993.85 Nm³, which is close to the maximum hydrogen storage amount and can obtain higher hydrogen sales benefits.

As shown in Figure 8, during the peak-shaving periods of 3:00~4:45, 16:00~16:45, and 20:00~21:45, the electrochemical energy storage is charged, with a total charge of 23.77 MW in the three peak-shaving periods; during the peak-shaving period of 9:00~10:45, the electrochemical energy storage discharges, with a total discharge of 6.34 MW during the period; the SOC of the electrochemical energy storage is maintained between 0.2 and 0.8, ensuring that the electrochemical energy storage works in a “shallow charge and shallow discharge” state, which helps prolong the service life of the electrochemical energy storage system; the SOC of the electrochemical energy storage is maintained between 0.45 and 0.8 for a total of 66 periods (i.e., 68.75% of a cycle), leaving sufficient power and capacity for scheduling.

Through the operation control of the electrolytic hydrogen production system and the electrochemical energy storage system, the renewable energy power generation system has achieved higher economic benefits under the premise of completing multiple target application scenarios. Among them, the income from PSAS is CNY 524,500, the income from carbon emission reduction is CNY 297,325.2, the income from hydrogen sales is CNY 89,981.55, the cost of electricity purchase is CNY 87,909.82, the penalty for abandoning wind and solar energy is CNY 13,851, and the comprehensive benefit is CNY 810,045.93.

As shown in Figure 9, after calculation, it is found that there is a positive under-compensation of 48.78 MW and a negative under-compensation of 31.18 MW before suppression. The power fluctuates greatly between 9:00 and 7:00, with a total of 14 time periods exceeding the fluctuation limit of renewable energy grid-connected power, and the over-limit probability is 14.58%, which brings a significant negative impact to the power system; after suppression by the EHPS and the electrochemical energy storage system, all the renewable energy outputs participating in the grid connection meet the grid-connected power fluctuation limit.

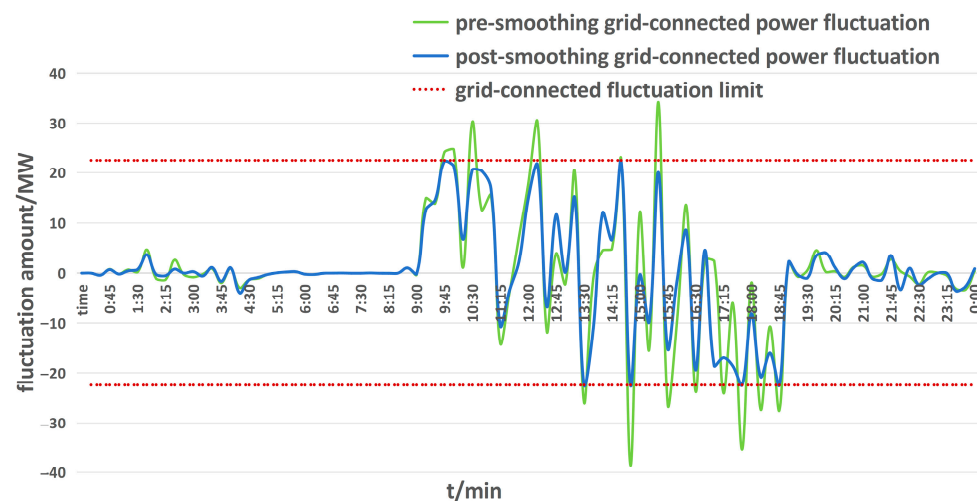


Figure 9. The grid-connected power fluctuation before and after stabilization.

6.5. Effect of Electrolytic Hydrogen Production on Economic Benefits

The effectiveness analysis of the three scenarios—no electrolytic hydrogen with electrochemical energy storage, electrolytic hydrogen without electrochemical energy storage, and electrolytic hydrogen with electrochemical energy storage—are shown in Table 6. The installed capacity of equipment under the three scenarios is as follows:

Table 6. Effectiveness analysis in three scenarios.

	Scenario 1	Scenario 2	Scenario 3
electricity purchasing cost/CNY	28,280.5	71,492.4	87,909.8
abandoned wind power and solar/MW	500.0	308.5	46.2
Hydrogen sales revenue/CNY	0	109,449.0	89,981.6
Peaking revenue/CNY	524,500	512,500	524,500
carbon trading income/CNY	297,789.9	302,926.6	297,325.2
comprehensive benefit/CNY	644,002.6	760,831.5	810,045.9

Scenario 1 (no electrolytic hydrogen with electrochemical energy storage): no electrolyzer, fuel cell, or hydrogen storage tank is set up, and the electrochemical energy storage is 25 MW;

Scenario 2 (electrolytic hydrogen without electrochemical energy storage): in this scenario, the operation and maintenance expenses of the 25 MW electrochemical energy storage in Scenario 3 is proportionally allocated to the EHPS and the fuel cell, among which the electrolyzer is 30 MW, the fuel cell is 10 MW, the hydrogen storage tank is 36,483 Nm³, and no electrochemical energy storage is set up;

Scenario 3 (electrolytic hydrogen with electrochemical energy storage): the electrolyzer is 25 MW, the fuel cell is 10 MW, the hydrogen storage tank is 30,000 Nm³, and the electrochemical energy storage is 20 MW. This scenario is the scenario of the proposed mathematical model.

As evident from Table 6, the comprehensive benefit of Scenario 3 proposed in this paper is optimal. Compared with Scenario 1, due to the constraint that electrochemical energy storage cannot perform simultaneous charging and discharging operations, it is impossible to flexibly absorb or release electricity in Scenario 1, and the hydrogen sale benefits brought by electrolytic hydrogen is lacking. Therefore, compared with Scenario 1, Scenario 3 reduces the amount of wind and solar energy discarded by 393.8 MW, reduces the penalty for discarding wind and solar energy by CNY 118,140, increases carbon trading benefits by CNY 10,218.5, and increases comprehensive benefits by CNY 123,247.6. Compared with Scenario 2, due to the lack of electrochemical energy storage and the lower conversion rate of electrolytic hydrogen, Scenario 3 reduces the amount of wind and solar energy discarded by 262.3 MW compared to Scenario 2, reduces the penalty for discarding wind and solar energy by CNY 78,690, and increases comprehensive benefits by CNY 49,214.4. Scenario 3 combines the flexibility of the electrolytic hydrogen production system and the higher conversion rate of the electrochemical energy storage system. Under the premise of completing the multi-objective application scenarios of smoothing power fluctuations, participating in PSAS, and reducing the amount of wind and solar energy discarded, it can still obtain higher comprehensive benefits.

7. Conclusions

This paper focuses on a renewable energy power plant that includes hydrogen production through electrolysis. It considers the use of electrolytic hydrogen to smooth out fluctuations in renewable energy power generation, participate in peak-shaving auxiliary services, and increase the absorption space of renewable energy. It proposes a multi-objective energy management model and algorithm based on the co-ordinated optimization of electrolytic hydrogen and renewable energy power generation. Through simulation, based on the analysis of the operating conditions and safety factors of various facilities in the power station, the advantages of this model for power system safety were carefully studied. With participation in the power market, the system's economics have been greatly improved.

At the same time, the PLPSO algorithm improves the convergence accuracy, convergence speed, and stability of the proposed model compared with the basic algorithm.

The research presented in this paper offers a valuable theoretical reference for energy management in renewable energy-generating plants that include an electrolytic hydrogen production system.

The next step will be to further study the capacity configuration of renewable energy power stations that include an electrolytic hydrogen production system, providing technical support for the installation and construction of renewable energy power stations.

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