Energy Engineering

Tech Science Press

DOI: 10.32604/ee.2023.024426

ARTICLE

Two-Stage Optimal Dispatching of Wind Power-Photovoltaic-Solar Thermal Combined System Considering Economic Optimality and Fairness

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Received: 30 May 2022 Accepted: 26 August 2022

ABSTRACT

Aiming at the problems of large-scale wind and solar grid connection, how to ensure the economy of system operation and how to realize fair scheduling between new energy power stations, a two-stage optimal dispatching model of wind power-photovoltaic-solar thermal combined system considering economic optimality and fairness is proposed. Firstly, the first stage dispatching model takes the overall economy optimization of the system as the goal and the principle of maximizing the consumption of wind and solar output, obtains the optimal output value under the economic conditions of each new energy station, and then obtains the maximum consumption space of the new energy station. Secondly, based on the optimization results of the first stage, the second stage dispatching model uses the dispatching method of fuzzy comprehensive ranking priority to prioritize the new energy stations, and then makes a fair allocation to the dispatching of the wind and solar stations. Finally, the analysis of a specific example shows that the model can take into account the fairness of active power distribution of new energy stations on the basis of ensuring the economy of system operation, make full use of the consumption space, and realize the medium and long-term fairness distribution of dispatching plan.

KEYWORDS

Economic optimality; fairness; combined power generation; the fuzzy comprehensive ranking priority; optimal dispatching

1 Introduction

At present, China has become the country with the largest installed capacity of wind power and photovoltaic power generation in the world, and the problems of wind and solar abandonment have become increasingly prominent [1,2]. The solar thermal power generation technology with the characteristics of clean, good regulation performance and equipped with energy storage system has gradually become a hot spot [3]. With the rapid development of the new energy industry, how to coordinate the fair dispatching of the scenic spots on the basis of ensuring the overall economy of the system is of great significance to the sustainable development of China's new energy industry [4].

Miao et al. [5] proposed the concept of a photovoltaic solar-thermal combined power generation base. After the combined power generation base is connected to the power grid, the optimal dispatching of the power system is realized with the goal of reducing the peak-to-valley difference and reducing costs. Xiao et al. [6] established the hierarchical optimization of photovoltaic-photothermal combined optimization operation system. He et al. [7] studied the grid connected optimal dispatching of integrated energy systems including wind power and photovoltaic power generation. In order to realize the friendly grid connection of a high proportion of new energy in the power system, Zhang et al. [8] integrates wind farms, photovoltaic power plants and solar thermal plants as multi-power systems, and proposes a fuzzy multi-objective optimization model for wind power-photovoltaic-solar thermal combined power generation systems. Xu et al. [9] established the grid connected operation model of wind power-solar thermal power generation system, and took the variance of system joint output as a robust optimization problem, so as to reduce the range of system output. Li et al. [10] established a two-stage comprehensive optimization model based on the robust theory. Eseye et al. [11] proposed a combined operation system of wind power, solar thermal, pumping and storage. In terms of fair dispatch, domestic research on fair dispatch of power systems with new energy focuses on the fairness evaluation of grid dispatch and dispatch mode. Wei et al. [12] proposed a fairness evaluation index considering the differences in dispatching fairness among enterprises in view of the existing "three public" dispatching, which only focuses on the dispatching results and ignores the dispatching execution process, resulting in uneven interests among power generation enterprises. In reference [13], aiming at the fairness of consumption among wind and solar power generation with different field groups and different sections, a multi-level active power control strategy is established by considering the weight of the consumption capacity of different levels of sections. Aiming at the challenges faced by multi-source coordinated control, Wang et al. [14] established a multi-energy coordinated control strategy with real-time control instructions as fairness constraints. Sun et al. [15] established an optimal dispatching model with wind power by introducing the Gini coefficient in economics and taking the power progress as the carrier as the fairness constraint. However, it still considers the fairness of the generation plan of conventional units in the regional system and lacks the research on the dispatching fairness of power stations with new energy. Guo et al. [16] has made a detailed study on the evaluation criteria of fairness of the "three public" dispatching mode applied in Mengxi power grid, but less consideration has been given to the factors affecting fairness, and the analysis is not comprehensive enough. The factors affecting the fairness of power generation plans of new energy enterprises still need to be further improved. The foreign power system is different from that in China, and the priority dispatching research for new energy power generation is earlier. The organic cooperation of scientific dispatching means and flexible power structure has fundamentally solved the priority dispatching problem of new energy [17,18].

To sum up, the research on dispatching fairness mainly focuses on fairness evaluation indicators and traditional fairness dispatching. There is less research on the fairness of multiple new energy entities participating in dispatching in the power market environment, and it is impossible to take into account the economy and fairness of system operation in the power system with new energy. The fuzzy comprehensive evaluation modeling method is different from the traditional objective function modeling or constraint condition modeling to reflect fairness. It mainly considers the intermittency and fluctuation of the wind and solar output of the new energy power system, which makes the model often have no solution. Moreover, at present, the technical level of new energy stations is uneven. On the one hand, it is necessary to ensure the rationality of the scheduling results, on the other hand, it is necessary to ensure that stations with better technical level have higher priority to power generation, which can promote the benign competition between stations and further improve the new energy power generation technology. The application of fuzzy comprehensive evaluation method can give good consideration to this problem.

In view of the above problems, this paper proposes an optimal dispatching method based on fuzzy comprehensive ranking priority evaluation. In the first stage, the calculation of the most output and consumption space of each new energy station is completed based on the regional grid load prediction value and the new energy station day ahead generation prediction value, with the minimum total operation cost of the combined system as the goal, and after comprehensively considering various constraints. In the second stage, based on fuzzy comprehensive ranking priority, carry out an objective comprehensive evaluation of new energy power stations, so as to obtain the comprehensive ranking of new energy power stations, and make a fair distribution of the dispatching plan of each power station in combination with the actual data, so as to ensure the fairness between new energy stations. Finally, the simulation calculation of each scene is carried out, and the optimization results of different scenes are compared and analyzed in the analysis of examples.

2 Two-Stage Optimal Dispatching Strategy

Aiming at the problems of how to ensure the economy of system operation and how to realize fair scheduling between new energy power stations after large-scale wind and solar grid connection, a two-stage optimal dispatching model of wind power-photovoltaic-solar thermal combined system considering the economic optimality and fairness is proposed. The two-stage optimal dispatching is:

In the first stage, the power is predicted according to the short-term predicted output value and regional load value of the wind farm and photovoltaic power station, with the overall economic optimization of the system as the goal, comprehensively considering the operating condition constraints of the wind farm, photovoltaic power station, solar thermal power station and thermal power plant, and taking the principle of maximizing the consumption of wind and solar power output as the principle, the optimal output value under the economic conditions of each power plant is obtained.

The second stage is to calculate the output value under the economic conditions of each station according to the calculation in the first stage, calculate the maximum consumption space of new energy stations, carry out a scientific comprehensive evaluation of new energy stations based on the fairness dispatching method of fuzzy comprehensive ranking priority, prioritize each new energy station according to the correlation degree, and then make a fair allocation to the corresponding wind and solar station dispatching plan, so as to ensure the fairness of consumption between new energy stations, and finally get the best scheme with the best system economy and fairness. The two-stage optimal dispatching strategy in this paper is shown in Fig. 1.

3 The Economic Optimal Dispatching Model for the First Stage

3.1 Objective Function

In the operation of power system with new energy, the basic objective is to minimize the total cost of system operation, maximize the consumption of new energy, minimize the pollutant emission of conventional units, and meet the load requirements of power system [19].

$$\min F = \min (f_1 + f_2 + f_3 + f_4 + f_5) \tag{1}$$

wherein, f_1 is the peak load regulation cost of thermal power unit, f_2 is the penalty cost of carbon emission and pollution, f_3 is the penalty cost of wind abandonment, f_4 is the penalty cost of solar abandonment, and f_5 is the operation cost of solar thermal unit.

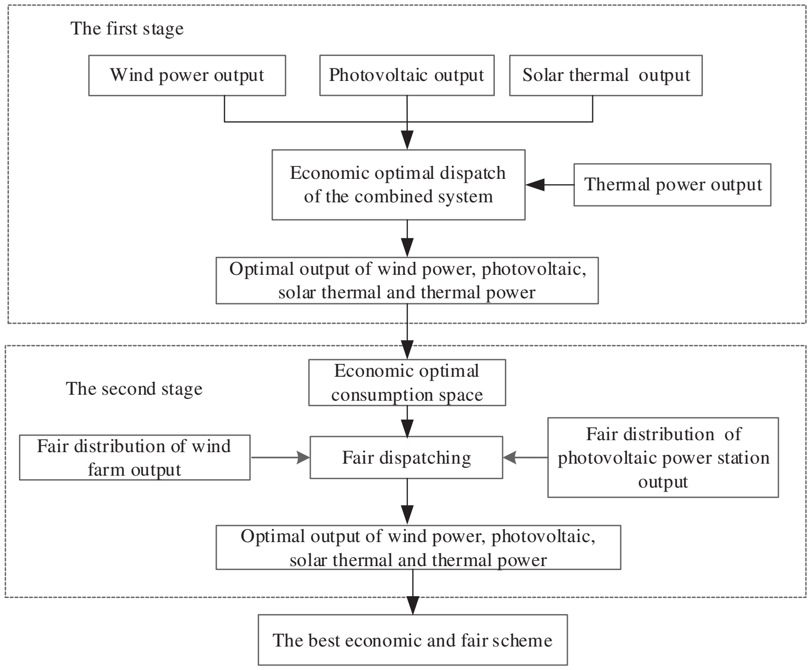


Figure 1: Two-stage optimal dispatching strategy for wind power-photovoltaic-solar thermal combined system

(1) Peak load regulation cost of conventional thermal power units in the dispatching cycle.

$$f_1 = \sum_{i=1}^{N} \sum_{t=1}^{T} \Delta t S_{i,t} B_{i,t} \tag{2}$$

where, i is the serial number of thermal power units, and N is the total number of thermal power units, T is the calculation time length, and Δt is the calculation time step, $S_{i,t}$ refers to the startup and shutdown status of thermal power unit, zero refers to the shutdown status, one refers to the startup status, and $B_{i,t}$ refers to the operating coal consumption cost of thermal power unit (yuan). The specific calculation is as follows:

$$B_{i,t} = \left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i\right) p_{coal} \tag{3}$$

wherein, $P_{i,t}$ is the output value of thermal motor unit i at time t, a_i, b_i and c_i are the coal consumption characteristic function of thermal power unit i respectively, and p_{coal} is the unit price of coal (yuan/ton).

(2) Carbon emissions and pollution penalty costs in the dispatching cycle.

$$f_2 = \sum_{i=1}^{N} \sum_{t=1}^{T} \frac{\Delta t S_{i,t} B_{i,t}}{p_{coal}} \left(H_{\mathrm{CO}} p_{\mathrm{CO}} + H_{\mathrm{SO}} p_{\mathrm{SO}} + H_{\mathrm{NO}} p_{\mathrm{NO}}\right) \tag{4}$$

where, H_{CO}, H_{SO} and H_{NO} are the mass of CO_2, SO_2 and NO_X released by unit mass coal combustion (kg), p_{CO}, p_{SO} and p_{NO} are the environmental penalty cost of CO_2, SO_2 and NO_X per unit mass (yuan/kg).

(3) Penalty cost of wind abandonment in the dispatching cycle.

$$f_3 = p_{\mathrm{w}} \sum_{k=1}^{K} \sum_{t=1}^{T} \Delta t \left(P_{k,t}^{\max} - P_{k,t}\right) \tag{5}$$

where, $P_{k,t}^{\max}$ is the maximum predicted output value of wind farm k in t period, $P_{k,t}$ is the actual output value of wind farm k in period t, and p_{w} is the unit penalty cost of abandoned wind power.

(4) Penalty cost of light rejection in the dispatching cycle.

$$f_4 = p_{\mathrm{s}} \sum_{p=1}^{P} \sum_{t=1}^{T} \Delta t \left(P_{p,t}^{\max} - P_{p,t}\right) \tag{6}$$

where, $P_{p,t}^{\max}$ is the maximum predicted output value of PV power station p in t period, $P_{p,t}$ is the actual output value of PV power station p in t period, and p_{s} is the unit penalty cost of abandoned PV quantity.

(5) Operation cost of solar thermal unit in the dispatching cycle.

$$f_5 = \sum_{t=1}^{T} \left[k_{\mathrm{CSP}} P_t^{\mathrm{CSP}} + S^{\mathrm{CSP}} \left(1 - u_{t-1}^{\mathrm{CSP}}\right) u_t^{\mathrm{CSP}}\right] \tag{7}$$

wherein, k_{CSP} is the power generation cost of the optical thermal power station. P_t^{CSP} is the dispatching output of the optical thermal power station in t period. S^{CSP} is the startup and shutdown cost of the optical thermal power station. u_t^{CSP} is the operation state of the steam turbine generator in the optical thermal power station in t period, and taking 1 means that it is in operation state, otherwise it is in stop state.

3.2 Constrained Condition

(1) System power balance constraint

$$\sum_{i=1}^{N} S_{i,t} P_{i,t} + \sum_{i=1}^{K} P_{k,t} + \sum_{i=1}^{P} P_{p,t} + P_{\mathrm{t}}^{\mathrm{TCES}} = P_{L,t} \tag{8}$$

where, $P_{L,t}$ is the load forecasting power of the joint system in the period.

(2) Output constraints of thermal power unit

$$S_{i,t} P_{i,\min} \le P_{i,t} \le S_{i,t} P_{\max} \tag{9}$$

wherein, $P_{i,\min}$ and $P_{i,\max}$ are the upper and lower limits of thermal power unit output.

(3) Climbing constraint of thermal power unit

$$-\delta_{i,\mathrm{d}} \le P_{i,t} - P_{i,t-1} \le -\delta_{i,\mathrm{u}} \tag{10}$$

where, $-\delta_{i,\mathrm{d}}$ and $-\delta_{i,\mathrm{u}}$ are the decreasing and rising rate of active output of thermal power unit i.

(4) Output constraint of photovoltaic power station

$$0 \le P_{p,t} \le P_{p,t}^{\max} \tag{11}$$

(5) Output constraint of wind farm

$$0 \le P_{k,t} \le P_{k,t}^{\max} \tag{12}$$

(6) System rotation reserve constraint

$$\sum_{i=1}^{N} \min\left[S_{i,t}\delta_{i,\mathrm{d}}, S_{i,t}\left(P_{i,\max} - P_{i,t}\right)\right] \geq H_{s,t}, \sum_{i=1}^{N} \min\left[S_{i,t}\delta_{i,\mathrm{d}}, S_{i,t}\left(P_{i,t} - P_{i,\min}\right)\right] \geq G_{s,t} \tag{13}$$

where, $H_{s,t}$ and $G_{s,t}$ are the positive and negative rotating reserve of the combined system in t period.

(7) Output constraint of optical thermal power station

$$P_{\mathrm{t}}^{\mathrm{CSP}} + P_{\mathrm{t}}^{\mathrm{CSP,RsvUP}} \leq P_{\max}^{\mathrm{CSP}}, P_{\mathrm{t}}^{\mathrm{CSP}} - P_{\mathrm{t}}^{\mathrm{CSP,RsvDOWN}} \geq P_{\min}^{\mathrm{CSP}} \tag{14}$$

where, $P_{\mathrm{t}}^{\mathrm{CSP}}$ is the output of optical thermal power station at time t; $P_{\mathrm{t}}^{\mathrm{CSP,RsvUP}}$ and $P_{\mathrm{t}}^{\mathrm{CSP,RsvDOWN}}$ are upper and lower standby of photothermal steam turbine unit respectively; $P_{\max}^{\mathrm{CSP}}$ and $P_{\min}^{\mathrm{CSP}}$ are the maximum and minimum output of the unit, respectively.

Unit climbing constraints:

$$-R_{\mathrm{Down}}^{\mathrm{CSP}} \leq P_{\mathrm{t}}^{\mathrm{CSP}} - P_{\mathrm{t-1}}^{\mathrm{CSP}} \leq R_{\mathrm{UP}}^{\mathrm{CSP}} \tag{15}$$

where, $R_{\mathrm{UP}}^{\mathrm{CSP}}$ and $-R_{\mathrm{Down}}^{\mathrm{CSP}}$ are the maximum upward and downward climbing capacity of the unit, respectively.

(8) Capacity constraints for TCES (thermochemical energy storage) devices:

$$E_{\min}^{\mathrm{TCES}} \leq E_{\mathrm{t}}^{\mathrm{TCES}} \leq E_{\max}^{\mathrm{TCES}}, E_{\max}^{\mathrm{TCES}} = \rho_{\mathrm{flh}} P_{\max}^{\mathrm{CSP}} \tag{16}$$

where, $E_{\min}^{\mathrm{TCES}}$ and $E_{\max}^{\mathrm{TCES}}$ are the minimum capacity and maximum capacity constraints of TCES device respectively. The maximum capacity is measured in ρ_{flh} (full load hours).

The thermal storage and release power constraints of TCES device are:

$$0 \leq P_{\mathrm{t}}^{\mathrm{TCES,ch}} \leq P_{\max}^{\mathrm{TCES,ch}}, 0 \leq P_{\mathrm{t}}^{\mathrm{TCES,dish}} \leq P_{\max}^{\mathrm{TCES,disch}}, P_{\mathrm{t}}^{\mathrm{TCES,ch}} \leq P_{\mathrm{t}}^{\mathrm{TCES,dish}} = 0 \tag{17}$$

where, $P_{t}^{\mathrm{TCES,ch}}$ and $P_{t}^{\mathrm{TCES,disch}}$ are the storage and release power of the TCES device at time t, $P_{\max}^{\mathrm{TCES,ch}}$ and $P_{\max}^{\mathrm{TCES,disch}}$ are the maximum heat storage and release power respectively, and the heat storage and release cannot be carried out at the same time.

When solving the upper economic model, the commercial software package CPLEX is called on the GAMS platform to find the optimal solution to this optimization problem, and the optimal output value of wind power, photovoltaic, solar thermal and thermal power stations under the economic conditions of system operation is obtained, and then the maximum consumption space P_t^{sp} of the system for wind power and photovoltaic power stations under the economic conditions of operation is obtained. As shown in Eq. (18):

$$P_t^{sp} = P_t^{L} - P_t^{a} - P_t^{opT} - P_t^{H,G} + P_t^{oph} \tag{18}$$

where, P_t^{L} is the total load forecast power of the regional system, P_t^{a} is the planned output of the tie line, P_t^{opT} is the optimal output of the thermal power unit under economic conditions, $P_t^{H,G}$ is the rotating reserve, and P_t^{oph} is the optimal output of the solar thermal unit.

4 The Fair Dispatching Model Based on Fuzzy Comprehensive Ranking Priority for the Second Stage

Based on the fair scheduling strategy of fuzzy comprehensive ranking priority, the fair scheduling plan of each period is obtained according to the maximum predicted value of each station and the correlation degree of each station calculated through each index.

Fuzzy mathematics is the basic theory to deal with and study fuzzy phenomena. In the process of measuring the rationality of the dispatching plan issued by the dispatching organization, there will be fuzziness. It is difficult to absolutely say which unit is "fair" or "unfair" in priority, but only how "fair" it is. Based on this characteristic of fair dispatching in power system and considering various influencing factors of fair generation planning, this paper proposes an index calculation system of fuzzy comprehensive ranking priority, which is used as a fair dispatching strategy of power system with new energy to improve the degree of "fairness".

4.1 The Fuzzy Comprehensive Ranking Priority Index Calculation System

The fuzzy comprehensive ranking priority index calculation system contains many factors that affect decision-making, and most of them are difficult to quantify. Using fuzzy language to give different degrees of evaluation values and properly synthesize the evaluation values is to properly combine the analytic hierarchy process with the fuzzy theory, and combine the weight comparison, hierarchical structure and fuzzy mathematics for analysis. This is called the fuzzy comprehensive evaluation method [20,21].

(1) The mathematical models of fuzzy comprehensive ranking priority can be divided into one-level or multi-level models. Generally, it can be summarized into the following steps [22]:

1) According to a certain classification principle, the subject to be decided is divided into n indicators of domain $U = \{u_1, u_2, \cdots, u_n\}$, and each indicator corresponds to an evaluation set $V = \{V_1, V_2, \cdots, V_n\}$.

2) The corresponding relationship between universe U and evaluation set can be obtained from fuzzy mapping, which is expressed by fuzzy matrix $R = U \times V$. Then assign weight coefficients to n evaluation indexes to obtain the weight vector set $A = [a_1, a_2, \cdots, a_n]$.

3) Through fuzzy operation $B = A \circ R$, the fuzzy subset $B = [b_1, b_2, \cdots, b_m]$ can be calculated, and B is expressed as the subordinate degree of the evaluated object to the evaluation principle.

(2) This paper proposes the following fuzzy comprehensive ranking priority fair dispatching method. The basic idea is as follows:

1) Determine the set of multiple factors that need to be considered to affect fair dispatching. It is assumed that there are n influencing factors. According to the influence degree of each factor, the weight factor $a_i \left(a_i \geq 0, \text{ and } \sum_{i=1}^{n} a_i = 1, i = 1, 2 \cdots, n\right)$ is introduced to represent the importance of each influencing factor.

2) Analyze each influencing factor, give its calculation method, give the quantitative index and priority of dispatching plan arrangement under this principle, and give the weight value of each station under this principle to reflect the fairness of arranging the station.

3) After calculating the weight value under each principle, the comprehensive index weight value containing multiple factors is obtained. The dispatching organization can decide which station to dispatch first according to the weight value of the comprehensive index, which is the comprehensive criterion for the fair dispatching.

Considering the production characteristics, technical characteristics, operation characteristics, economic characteristics, reliability and other indicators of new energy stations, as the main factors affecting fair dispatching, a fuzzy comprehensive ranking priority evaluation system for two-tier new energy stations is established. The fuzzy comprehensive ranking priority evaluation system includes five first-class indicators, and each first-class indicator contains corresponding second-class indicators. The evaluation system is shown in Fig. 2.

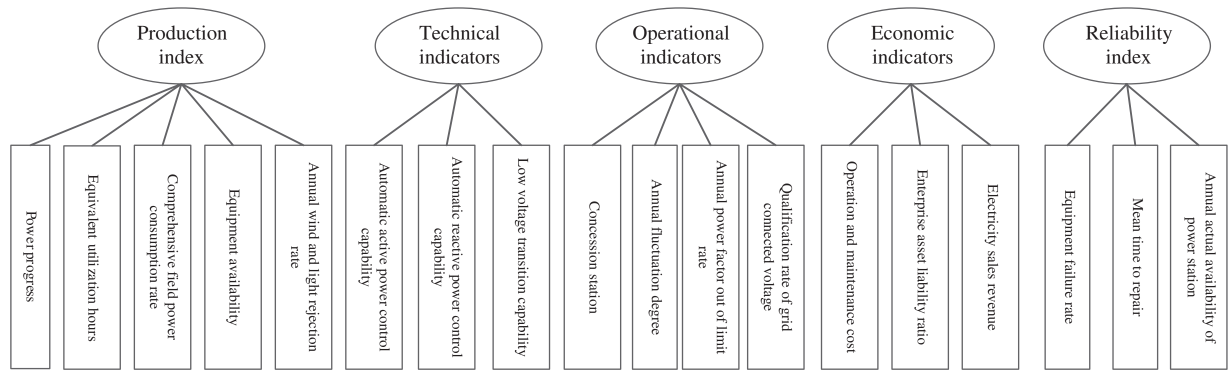


Figure 2: The Fuzzy comprehensive ranking priority evaluation system

4.2 The Fuzzy Comprehensive Ranking Priority Index Calculation System

(1) Production index is the key index to measure the power generation capacity of the power station.

1) The power progress is defined as p_1, and its value is:

$$p_1 = Q_f / Q_{0,f} \tag{19}$$

wherein, Q_f is the actual power generation of new energy stations according to the dispatching plan, and $Q_{0,f}$ is the daily planned power generation of each station.

2) Equivalent utilization hours is defined as p_2, and its value is:

$$p_2 = Q_s / W_r \tag{20}$$

where, Q_s is the actual on grid power of the new energy station, and W_r is the installed capacity of the new energy station.

3) The comprehensive field power consumption rate is defined as p_3, and its value is:

$$p_3 = (Q_{sc} + Q_{sh}) / Q_z \times 100\% \tag{21}$$

wherein, Q_{sc} is the production power consumption of new energy station, Q_{sh} is the domestic power consumption of new energy station, and Q_z is the total power generation.

4) The equipment availability is defined as p_4, and its value is:

$$p_4 = \left\{1 - \left(h_t - h_g\right)\right\} / \left(h_{tj} - h_g\right) \times 100\% \tag{22}$$

where, h_t represents the downtime hours (excluding standby time), h_g represents the downtime hours for non-equipment failure, and h_{tj} represents the total hours in the statistical period.

5) The rate of abandoning wind and light is defined as p_5, and the overall production index is P, which can be defined as:

$$P = (1 - p_1) \times p_2 \times (1 - p_3) \times p_4 \times (1 - p_5) \tag{23}$$

(2) Technical indicators. When measuring the technical level of the power station, the most valuable reference is a series of technical indicators.

1) Active power, reactive power control capability and automatic active power control capability can effectively measure the stability of power stations participating in power system dispatching.

2) Automatic active power, reactive power control capability and low-voltage transition capability, they are respectively defined as k_1, k_2 and k_3. when its values is 1, they have this capability; When its value is 0, it does not have this capability.

The overall technical index is set as K, which is defined as:

$$K = (k_1 + k_2 + k_3)/3 \tag{24}$$

(3) Operational indicators

1) The concession power station is defined as m_1, and when its value is 1, it is the concession power station; When the value is 0, it is a non-concessionary power station.

2) The annual fluctuation variation coefficient m_2 represents the annual fluctuation degree, and the calculation method is:

$$m_2 = S/P_{avg} \tag{25}$$

where, S is the standard deviation of the annual actual output of the new energy station, and P_{avg} is the average value of the annual actual output of the station.

3) The annual power factor out of limit rate is expressed in m_3, and the calculation method is:

$$m_3 = L_y/L_z \tag{26}$$

4) The annual qualification rate of grid connected voltage is defined as m_4, as shown in Eq. (27):

$$m_4 = (1 - t_h/t_z) \times 100\% \tag{27}$$

Wherein, t_h and t_z respectively represent the annual statistical overrun time of power station parallel grid voltage and the annual statistical operation time of power station parallel grid.

The overall operating characteristic index is defined as M, and the calculation formula is:

$$M = (m_1/2) \times m_2 \times (1 - m_3) \times m_4 \tag{28}$$

(4) Economic indicators. The economic indicators have important reference value in the comprehensive priority ranking of the scenic spots, which can not only ensure the fair distribution of the dispatching plan, but also reasonably measure the operation and maintenance costs of the scenic spots.

The annual operation and maintenance cost is defined as e_1, the asset liability is defined as e_2, and the annual power sales revenue is defined as e_3. The data of these three indicators can be obtained from the operation data of new energy stations.

The economic index is defined as E, and the calculation formula is:

$$E = e_3 - e_1 - e_2 \tag{29}$$

(5) Reliability index: common reliability indexes include annual actual utilization rate of equipment, energy storage coefficient, mean time to repair failure and annual failure rate of power generation equipment. The annual failure rate of the power station is defined as r_1. The mean time to repair of a fault is defined as r_2. The energy storage coefficient is defined as r_3, as shown in Eq. (30):

$$r_3 = C_r/C_z \tag{30}$$

where, C_r and C_z respectively represent the energy storage system capacity and the installed capacity of the power station.

The annual actual availability of the power station is defined as r_3, as shown in Eq. (31):

$$r_4 = T_r / T \tag{31}$$

where, T_r represents the cumulative time when the power station is in operation. T represents the statistical time, which is usually equal to 8760 h.

R stands for reliability index, which is defined as:

$$R = \{(1 - r_1 \times r_2) + r_4\}/2r_3 \tag{32}$$

4.3 Calculation of Comprehensive Weight of Indicators

In this paper, the entropy weight method is used to solve the primary and secondary indicators of new energy power stations, and then the comprehensive weight of secondary indicators is solved. The corresponding steps are summarized as follows:

(1) According to the operation data of new energy power stations and relevant information, calculate the corresponding evaluation index values to obtain the primary and secondary index data of new energy power stations.

(2) Complete the construction of the primary index evaluation matrix X_1 according to the primary index, and complete the construction of the secondary index evaluation matrix X_2 according to the secondary index data. The specific construction method is: given l indicators $x_1, x_2, \ldots, x_l$, then the evaluation matrix of n power stations is $X = x_{ij}\ (i = 1, 2, \cdots, l; j = 1, 2, \cdots, n)$.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1l} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nl} \end{bmatrix} \tag{33}$$

(3) According to the following steps, calculate the weight $w_{k,a}$ of the five primary indicators in matrix X_1 and the weight $w_{i,b-a}$ of the secondary indicators in matrix X_2 corresponding to each primary indicator, respectively.

1) Data standardization.

Standardize matrix X, and the higher the value of the positive indicator, the better:

$$X' = x'_{ij} = \frac{x_{ij} - \min\left(x_j\right)}{\max\left(x_j\right) - \min\left(x_j\right)} \tag{34}$$

For negative indicators, that is, when the indicator value is as small as possible:

$$X' = x'_{ij} = \frac{\max\left(x_j\right) - x_{ij}}{\max\left(x_j\right) - \min\left(x_j\right)} \tag{35}$$

2) Calculate the information entropy of each index

According to the definition of information entropy made by information theory, calculate the entropy e_i of the i-th index:

Among them, $b = 1/\ln n$, $c_{ij} = x'_{ij} / \sum_{j=1}^{n} x'_{ij}$.

3) Determine the weight of each indicator.

The weight of the i-th indicator

$$w_i = d_i \Big/ \sum_{j=1}^{n} d_i \tag{36}$$

Among them, $d_i = 1 - e_i$.

4) Calculate the comprehensive weight of secondary indicators, as shown in formula (37):

$$w_{i,z} = w_{k,a} \times w_{i,b-a} \tag{37}$$

Among them, $w_{i,z}$ is the comprehensive weight of secondary indicators.

4.4 Calculation of Comprehensive Ranking of New Energy Stations

The comprehensive ranking of new energy power stations is calculated by grey correlation analysis method. Calculate the correlation degree between power stations according to the preset reference sequence, and realize the scientific quantification of the comprehensive ranking of power stations according to the actual size of the correlation degree. The basic process is summarized as follows:

(1) Determine the comparison sequence.

X' obtained after data standardization is the comparison sequence of new energy power stations.

(2) Determine the reference sequence F of new energy power stations.

According to the evaluation matrix, list the reference sequence $F = (f_1, f_2, \cdots, f_{\mathrm{n}})$, among them, $f_i = \max(x'_{1j}, x'_{2j} \cdots, x'_{lj})$.

(3) Calculate the comprehensive evaluation index of power station j and its correlation coefficient with F.

$$\varepsilon_{ij}\left(X', F\right) = \frac{\min\limits_i \min\limits_j \left|x'_{ij} - f_i\right| + \rho \max\limits_i \max\limits_j \left|x'_{ij} - f_i\right|}{\left|x'_{ij} - f_i\right| + \rho \max\limits_i \max\limits_j \left|x'_{ij} - f_i\right|} \tag{38}$$

where, ρ is the resolution coefficient.

(4) Calculate the correlation degree R_j between the j-th power station and the reference sequence F as:

$$R_j = \sum_{i=1}^{l} w_{iz}\varepsilon_{ij}\left(X', F\right) \tag{39}$$

4.5 The Fair Dispatching of New Energy Power Stations

As the installed capacity of wind power and photovoltaic power plants in Jiuqvan area is quite different, the wind farm and photovoltaic power station shall be ranked according to the correlation degree under the conditions of the same type of units, so as to obtain a higher degree of fairness dispatching plan. The dispatching plan allocation steps are as follows:

(1) According to the predicted value of maximum output of each wind power and photovoltaic station and the calculated correlation degree, the dispatching plan of each period of each wind power and photovoltaic station is reallocated.

$$G_{p,t} = \left(R_p \times P_{p,\max}\right) \Big/ \sum_{i=1}^{P} \left(R_p \times P_{p,\max}\right) \times \sum_{i=1}^{P} P_{p,t} \tag{40}$$

where, $G_{p,t}$ is the initial dispatching plan of station p based on the correlation degree, and R_p is the correlation degree of station p.

(2) Compare the initial dispatching plan $G_{p,t}$ of station p with the predicted maximum output value $P_{p,\max}$ of the station p in t period. There are two cases:

The first type is $G_{p,t} \geq P_{p,\max}$, then the final dispatching plan $P_{p,t}^{final} = P_{p,\max}$ of station p. At this time, the remaining consumption plan $Q_{p,t}$ of power grid to power station p in the t period is:

$$Q_{p,t} = G_{p,t} - P_{p,\max} \tag{41}$$

The second type is $G_{p,t} \geq P_{p,\max}$, so station p needs to take $G_{p,t}$ as the intermediate dispatching plan, and the remaining power generation space $Y_{p,t}$ of station p in t period is:

$$Y_{p,t} = P_{p,\max} - G_{p,t} \tag{42}$$

(3) In order to ensure the maximum consumption of new energy power generation, the intermediate dispatching plan in the second case shall be adjusted appropriately.

According to the number of power stations in the second case, the residual consumption plan is redistributed according to the correlation degree, so the adjusted output $E_{p,t}$ of the dispatching plan of power station p in the second case is:

$$E_{p,t} = \left(R_p \times Y_{p,t}\right) \Big/ \left(\sum_{i=1}^{P2} R_p \times Y_{p,t}\right) \times \sum_{i=1}^{P1} Q_{p,t} \tag{43}$$

where, P^1 is the number of the first case stations after initial allocation, and P^2 is the number of the second case stations after initial allocation.

Then the final dispatching plan $P_{p,t}^{final}$ of the station in the second case is:

$$P_{p,t}^{final} = G_{p,t} + E_{p,t} \tag{44}$$

5 Example Analysis

5.1 The Basic Data Description of Calculation Example

This paper analyzes the operation of new energy stations in Jiuquan, Gansu province. Four wind farm groups (W_1, W_2, W_3, W_4) with a total installed capacity of 800 MW, four photovoltaic power station groups (S_1, S_2, S_3, S_4) with a total installed capacity of 1600 MW, one solar thermal power station with an installed capacity of 100 MW and four traditional generating units are selected to build a system model to verify the advantages and disadvantages of the adjustment method proposed in this paper. See Table 1 for the data of traditional generating units and Table 2 for the data of new energy stations. A typical daily load forecast curve of the region in 2018 is shown in Fig. 3, and the forecast value of wind and solar output of each station is shown in Fig. 4.

Table 1: The data of traditional generator

Unit number	$P_{i,\max}$/MW	$P_{i,\min}$/MW	δ_i/(MW/h)	a_i/(\$/h)	b_i/(\$/MWh)	c_i/(\$/(WM)^{2}h)
G_1	350	100	80	732.1824	38.5427	0.0746
G_2	150	50	40	986.8637	39.2634	0.0236

(Continued)

Table 1 (continued)

Unit number	$P_{i,\max}$/MW	$P_{i,\min}$/MW	δ_i/(MW/h)	a_i/(\$/h)	b_i/(\$/MWh)	c_i/(\$/(WM)^{2}h)
G_3	300	150	80	674.2586	35.6327	0.0845
G_4	250	100	70	1003.8513	39.2638	0.1863

Table 2: The data of new energy stations

Index parameters	S_1	S_2	S_3	S_4	W_1	W_2	W_3	W_4
Automatic active power control performance	1	0	1	1	0	1	1	1
Automatic reactive power control performance	1	0	1	0	1	1	1	1
Low voltage transition performance	1	1	1	1	0	1	1	1
Power generation efficiency/%	73.72	67.68	70.84	69.54	77.56	75.46	78.23	79.23
Generation capacity reliability/%	41.65	37.17	38.03	42.26	35.68	40.36	39.00	46.56
Annual wind/solar rejection rate/%	13.14	11.28	15.36	14.20	15.30	11.36	10.47	14.36
Annual fluctuation variation coefficient	0.35	0.24	0.46	0.36	0.25	0.37	0.26	0.31
Comprehensive power consumption rate of power station/%	4.31	5.68	4.29	3.89	5.31	4.97	5.65	6.79
Annual power factor over limit rate/%	3.36	5.82	4.29	4.03	5.01	4.26	6.03	4.61
Voltage qualification rate/%	75.24	70.56	79.61	80.21	77.20	76.03	80.36	74.25
Initial investment of power station/(yuan/kW)	10000	10000	10000	10000	8500	8000	10000	80000
Proportion of annual maintenance and operation cost to income/%	5.26	5.30	5.21	5.67	7.47	7.45	5.39	7.45
Government subsidies/(yuan/kWh)	0.45	0.45	0.45	0.45	0	0	0	0
Estimated residual value of equipment/(ten thousand yuan)	2033	1982	2011	1666	1886	2040	1990	1952
Failure rate of power generation equipment/(time/a)	0.378	0.346	0.356	0.369	0.412	0.406	0.386	0.423
Repair time of faulty equipment/(a/time)	0.0053	0.0064	0.0058	0.0097	0.0068	0.0056	0.0071	0.0035
Energy storage coefficient	0.0342	0.0682	0.0563	0.0304	0.0402	0.0446	0.0571	0.0631
Annual actual availability of power station/%	89.23	88.42	80.36	90.46	87.36	90.21	85.31	84.12

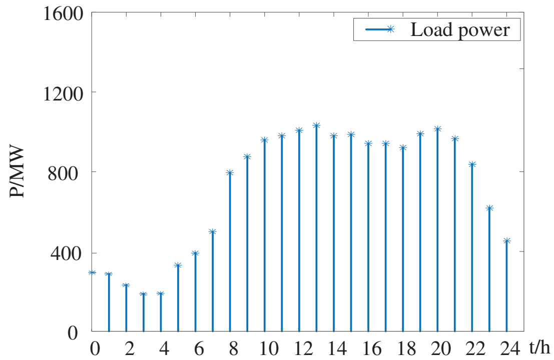
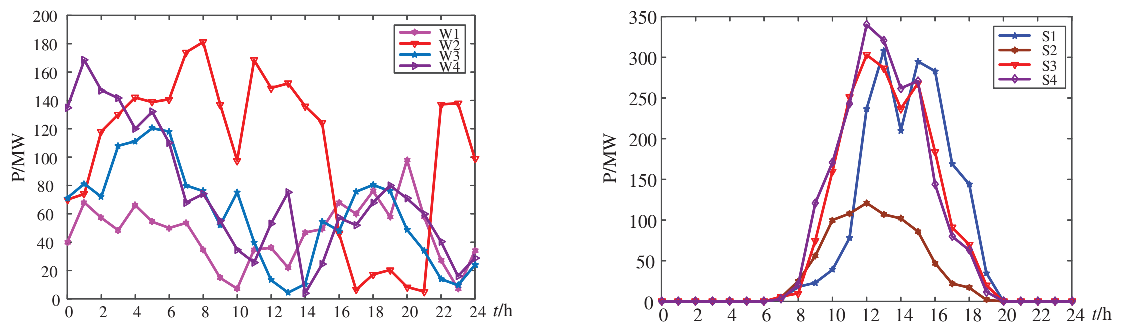


Figure 3: Load forecasting output



(a) Predicted output of wind farm (b) Predicted output of photovoltaic power station

Figure 4: Predicted output of each station

5.2 The Fuzzy Comprehensive Ranking Priority Calculation of New Energy Power Stations

(1) Calculate the weight of primary indicators. According to the data of each new energy station, the primary index coefficient of each station is calculated based on the fuzzy comprehensive ranking priority evaluation system, and the entropy weight method is used to calculate the weight of each primary index relative to the evaluation system, as shown in Table 3.

Table 3: Primary index weight

Index	Production	Technology	Operability	Reliability	Economy
Weight	0.3020	0.2136	0.1568	0.1805	0.1471

(2) Calculate the weight of secondary indicators relative to each primary indicator. See Tables 4–8.

Table 4: Weight of secondary indicators of productivity

Index	p_1	p_2	p_3	p_4	p_5
Weight	0.4533	0.2240	0.0250	0.1355	0.1622

Table 5: Weight of technical secondary indicators

Index	k_1	k_2	k_3
Weight	0.4250	0.4250	0.1500

Table 6: Weight of operational secondary indicators

Index	m_1	m_2	m_3	m_4
Weight	0.3025	0.2460	0.2412	0.2103

Table 7: Weight of secondary economic indicators

Index	e_1	e_2	e_3
Weight	0.2146	0.3436	0.4036

Table 8: Weight of secondary index of reliability

Index	r_1	r_2	r_3
Weight	0.3620	0.3221	0.3159

(3) Determine the comprehensive weight.

See Tables 9–13 for the comprehensive weight values of all secondary indicators.

Table 9: Comprehensive weight of secondary indicators of productivity

Index	p'_1	p'_2	p'_3	p'_4	p'_5
Weight	0.1369	0.0676	0.0250	0.0076	0.0490

Table 10: Comprehensive weight of technical secondary indicators

Index	k'_1	k'_2	k'_3
Weight	0.0908	0.0908	0.0324

Table 11: Comprehensive weight of operational secondary indicators

Index	m'_1	m'_2	m'_3	m'_4
Weight	0.0474	0.0386	0.0378	0.0330

Table 12: Comprehensive weight of secondary economic indicators

Index	e'_1	e'_2	e'_3
Weight	0.0316	0.0505	0.0594

Table 13: Comprehensive weight of secondary index of reliability

Index	r'_1	r'_2	r'_3
Weight	0.0653	0.0581	0.0570

(4) Calculate the correlation degree of each station relative to the reference sequence.

After data standardization, determine the reference sequence $C = (1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1)$, take $\rho = 0.5$, and calculate the correlation degree between $W_1, W_2, W_3, W_4, S_1, S_2, S_3, S_4$ and the reference sequence. See Table 14.

Table 14: Correlation degree of each power station

Power station	W_1	W_2	W_3	W_4	S_1	S_2	S_3	S_4
Correlation degree	0.3902	0.7417	0.5030	0.8869	0.5710	0.7925	0.8901	0.8204

5.3 Multi Scenario Operation Result Analysis

In order to verify the effectiveness of the wind solar Pumping Storage joint optimal dispatching model proposed in this chapter, the whole system dispatching situation is analyzed from the macro level. Different scenarios are given as follows:

Scenario 1: Only economic dispatching is conducted for the combined system to meet the load power supply requirements.

Scenario 2: Only fair dispatching is conducted for the combined system to meet the load power supply requirements.

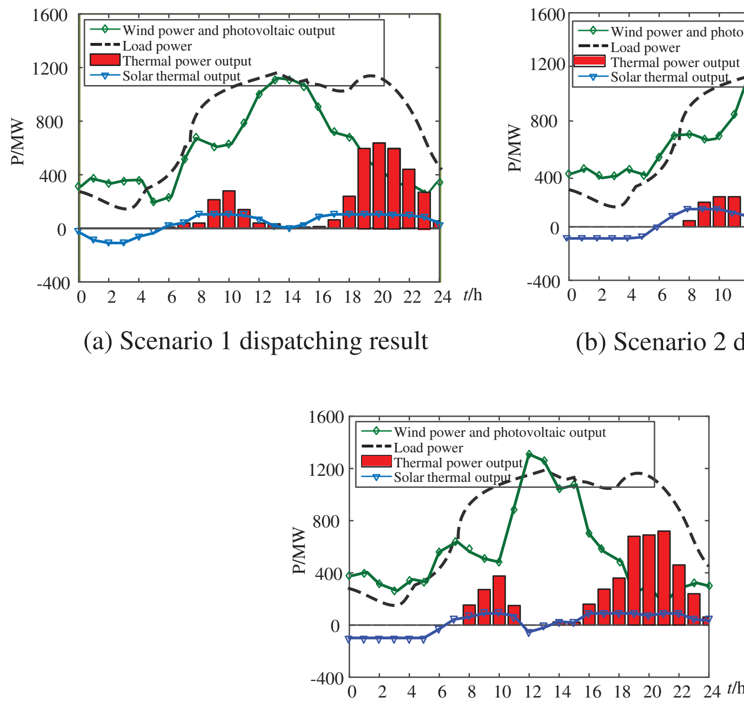
Scenario 3: Carry out economic dispatching for the combined system, and use the fairness dispatching method proposed in this paper to distribute the output of new energy power station fairly, so as to meet the requirements of load power supply.

The dispatching situation of each station under the three scenarios is shown in Fig. 5, and the comparison of total cost and consumption rate is shown in Table 15.

Based on the dispatching of three scenarios, it can be concluded that:

(1) From 0:00 to 6:00, that is, the load of the combined system is low. At this time, the photovoltaic output is 0 and the wind farm output is high. In scenario 1, only the system operation economy is considered. In this scenario, there is a large deviation between the combined output of the wind farm and the predicted output. The combined output of the wind farm is the smallest of the three. The energy storage function of the optical thermal power plant is not maximized, and there is a certain amount of wind and solar abandonment at this stage. In scenario 2, only considering the fair distribution of the dispatching plans of each station, the combined output of the wind farm is

the largest compared with the other two scenarios, but it also restricts the economic operation of the system accordingly. In scenario 3, considering the economy of system operation and the fairness of each wind farm dispatching plan in this period, the combined output of the wind farm is between scenarios 1 and 2. In the three scenarios of this section, the optical thermal power station will store excess electric energy.



(a) Scenario 1 dispatching result

(b) Scenario 2 dispatching result

(c) Scenario 3 dispatching result

Figure 5: Dispatching results of each scenario

Table 15: Correlation value of each power station

Scenario	Scenario 1	Scenario 2	Scenario 3
Total cost/(million yuan)	11.7228	12.6824	12.1124
Scenery consumption rate/(%)	83.23	90.42	88.04

(2) From 8:00 to 12:00 and from 16:00 to 23:00, the output of new energy in this period fluctuates greatly. However, during the peak load of the combined system, the output of new energy under the three scenarios is not enough to meet the requirements of power supply load. Both thermal power units and solar thermal power units start to generate electricity, which reflects their own good peak shaving effect and gives full play to the complementary advantages of wind power, photovoltaic, solar thermal power and thermal power output, it can effectively reduce the fluctuation of new energy output, improve the inherent defects of single power supply, and ensure the safety of power grid operation.

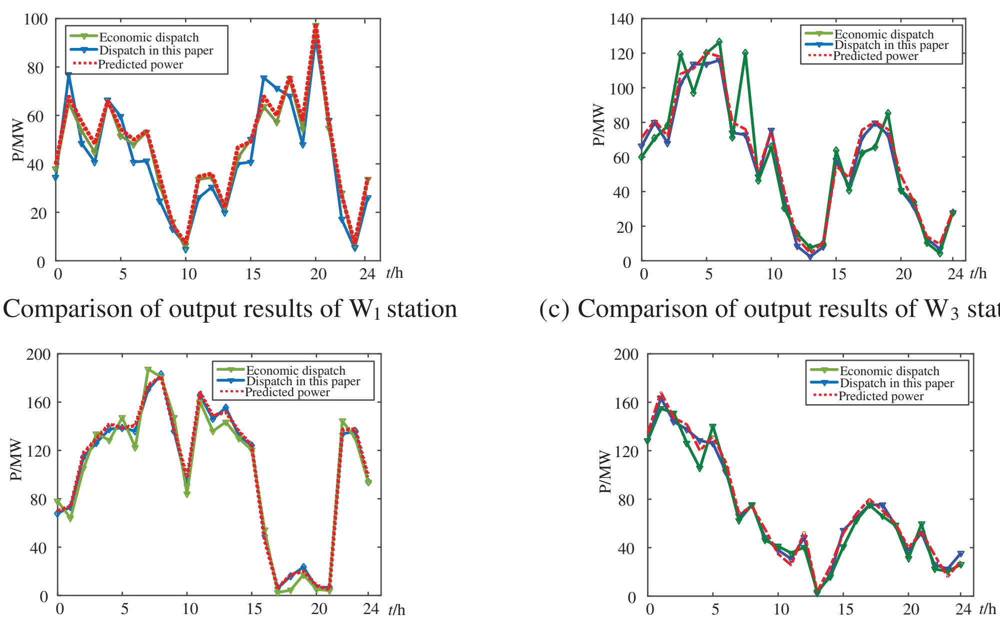
(3) Through the comparison of total system cost and consumption rate under the three scenarios, scenario 1 only conducts economic dispatching for the joint system. At this time, the consumption rate of new energy is the lowest compared with the other two scenarios, but its total operation cost is the lowest; Scenario 2 only carries out fair dispatching, and its new energy consumption rate is the highest, because under the principle of fair dispatching, the joint system gives priority to dispatching new energy stations, and the total operating cost in this scenario is the highest among the three; Scenario 3 uses the strategy proposed in this paper. Its total cost and new energy consumption rate are in the middle of the three scenarios, which can be considered as the optimal scheme.

The above data show that in scenario 3, under the requirements of these two main objectives, the new energy dispatching plan and the total system operation cost are the most “reasonable” through the two-stage optimal dispatching of the combined system.

5.4 Comparison and Analysis of Dispatching Plans of Stations

The analysis of the overall output of the wind power-photovoltaic-solar thermal combined system does not reflect whether the internal dispatching of the new energy stations is reasonable. Therefore, this paper focuses on the micro level, that is, the comparative analysis of the day ahead output plans of each wind and solar new energy station, the dispatching plan and real-time predicted power of each unit obtained by the traditional economic dispatching method (i.e., “three public” dispatching mode) and the dispatching method in this paper are compared, respectively.

The situation of each photovoltaic power station is shown in Fig. 6, the output of the wind farm is shown in Fig. 7, and the comparison of dispatching plan allocation of each station is shown in Table 16.



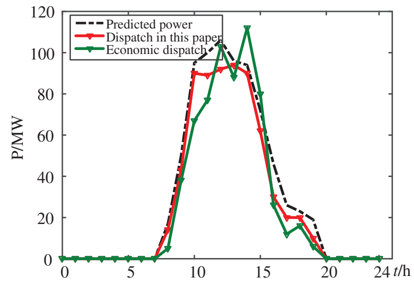
(a) Comparison of output results of W_1 station

(c) Comparison of output results of W_3 station

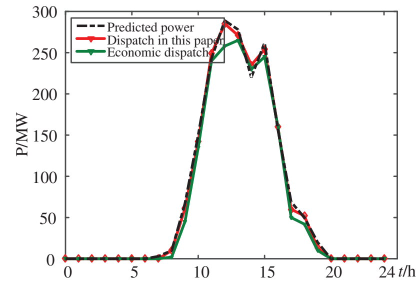
(b) Comparison of output results of W_2 station

(d) Comparison of output results of W_4 station

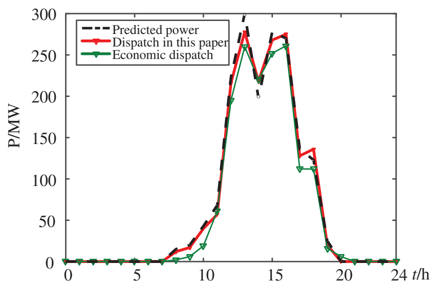
Figure 6: Comparison of output results of each wind farm



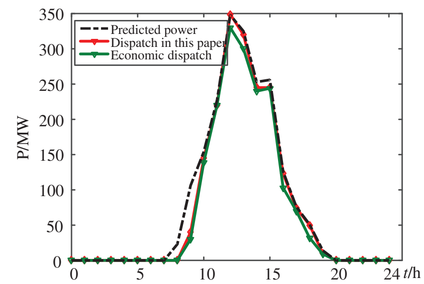
(a) Comparison of output results of S_1 station



(c) Comparison of output results of S_3 station



(b) Comparison of output results of S_2 station



(d) Comparison of output results of S_4 station

Figure 7: Comparison of output results of each photovoltaic power station

Table 16: Comparison of dispatching plan allocation

Station	W_1	W_2	W_3	W_4	S_1	S_2	S_3	S_4
Correlation degree	0.3902	0.7417	0.5030	0.8869	0.5710	0.7925	0.8901	0.8204
Predicted power	1130	2611	1504	1796	1699	744	1818	1959
Traditional dispatching	1113	2526	1474	1694	1655	630	1683	1717
This paper's dispatching	1038	2592	1363	1858	1592	654	1792	1821
New energy output increase plan	−75	66	−111	164	−63	24	109	104
Abandonment power of traditional method	41	214	74	254	44	114	135	242
This paper describes the method of power rejection	116	100	185	90	107	90	26	138

From Figs. 6, 7 and Table 16:

(1) Compared with the economic dispatching, the fair dispatching in this paper has the effect of increasing the issuance of renewable energy in general. The output of four wind farms has increased by 44 MW in total, and the output of four photovoltaic power stations has increased by 174 MW in total, which has increased by 218 MW in total. Therefore, the dispatching method in this paper can make full use of the consumption space.

(2) By analyzing the power limitation period of each unit in the wind farm (i.e., 0:00~6:00), the economic dispatching mode allocates the power generation indicators according to the principle of the lowest total cost while retaining a certain safety margin, and issues the peak shaving command

curve manually. In general, the economic dispatching mode has a limited number of orders and a large adjustment range, which is not conducive to the consumption of renewable energy. In the period of power limitation, the wind abandonment of this strategy is 147.37 MW less than that of economic dispatching strategy; During the period of large output (i.e., 10:00∼15:00), under the fair dispatching plan in this paper, each photovoltaic power station has a high degree of coincidence with the power prediction curve, and can basically achieve the maximum consumption of the predicted power of new energy power stations.

(3) According to the scheduling strategy in this paper, according to the fuzzy comprehensive ranking priority method, stations with large correlation value should get more scheduling plans.

6 Conclusion

A two-stage optimal dispatching model of wind power-photovoltaic-solar thermal combined system considering economic optimality and fairness is proposed. The fair dispatching strategy based on the fuzzy comprehensive ranking priority is used to allocate the fairness of the dispatching plan of new energy stations. Through the calculation of the comprehensive ranking priority of each station, the fair distribution of the day ahead dispatching plan is realized, the new energy is maximized, and the output of each station is optimized. The results of a specific example show that:

(1) Using the strategy proposed in this paper, the total operating cost is 12.1124 million yuan, the scenery consumption rate reaches 88.04%, and the total operating cost and scenery consumption rate are "in the middle", which can be used as the optimal scheme. Moreover, 218 MW dispatching plan has been added to renewable energy under the dispatching method in this paper, which can make full use of the consumption space.

(2) The regional power grid model is established through the combination of multiple types of power sources. Using the flexible coordination and dispatching ability of optical thermal power stations, and the dispatching method based on the fuzzy comprehensive ranking priority, when the system cannot fully absorb new energy, it can make the dispatching plan of new energy power stations distribute fairly, effectively reduce the waste of wind and solar, and protect the interests of new energy power generation enterprises.

(3) While ensuring fairness, it also takes into account the economy of the operation of the multi energy complementary combined power generation system, so that the new energy power generation industry can realize the overall and orderly operation. The medium and long-term dispatching based on this method can also realize the fair distribution of power station dispatching plan.

Funding Statement: This paper is a phased achievement of Gansu Province's Major Science and Technology Project (19ZD2GA003) "Key Technologies and Demonstrative Applications of Market Consumption and Dispatching Control of Photothermal-Photovoltaic-Wind Power New Energy Base (Multi Energy System Optimization)".

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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