ingegneria sismica
International Journal of Earthquake Engineering
Anno XLIII - Num. 3 - 2026

Analysis of Grid Access Strategy for New Energy Generation in Power System

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SUMMARY: *Due to the inherent volatility and randomness, the He County power system is facing increasing pressure on peak, and the current regulation capacity of the system is no longer sufficient to meet actual needs. This article constructs a multi-objective optimization scheduling model based on the complementary characteristics of multiple energy sources such as wind energy, solar energy, hydro energy, and thermal storage. This model covers two key levels. One of them is the optimization scheduling layer of the wind solar water storage combined power generation system. The core goal of this layer is to achieve the optimal output effect of the system by minimizing the net load variance and maximizing the clean energy generation. The second is the optimization scheduling layer of thermal power units, which mainly focuses on minimizing the operating costs of the system and optimizing and adjusting the output of thermal power units in various time periods. Then, the artificial fish swarm algorithm is introduced and dynamic growth and reduction strategies are designed for solving. Select the He County power system to construct a simulation system, and conduct a case study on the summer solstice as a typical load day. Case analysis shows that considering the optimal consumption rate of new energy has multiple impacts on the operating costs of wind solar water thermal storage multi energy complementary systems. Overall, it is conducive to reducing the total operating costs of the system, bringing positive cost-effectiveness in thermal power unit peak shaving, clean energy operation, energy storage system operation, and environmental protection, and providing useful reference for the economic and efficient operation of the power system.*

KEYWORDS: *County Power System; New energy generation; Power grid scheduling model; Multi objective optimization; Wind, solar, water, fire, and energy storage complement each other; Cost-effectiveness*

1 Introduction

Under the guidance of the "dual carbon" strategic goal, China's power industry is steadfastly moving towards a green and low-carbon direction. Among them, renewable energy represented by wind and solar energy continues to expand its installed capacity [1, 2]. However, wind and solar power generation have fluctuations and randomness in their output characteristics, which significantly increases the pressure on the power grid in terms of peak shaving and frequency regulation. When the source load fluctuates, it is not uncommon for thermal power units to

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https://doi.org/10.65102/is20261207

frequently start and stop, and the existing regulation capacity of the system can no longer fully meet the requirements of new energy consumption [3]. The National Energy Administration jointly issued the "Guiding Opinions on Promoting the Integration of Grid connected Energy Storage and Multi energy Complementary Development", which clearly stated that priority should be given to promoting the development of new energy and vigorously promoting the upgrading and transformation of existing "wind solar water energy storage integration" projects. Therefore, it is necessary to deeply explore the flexible regulation capability of the power system based on the complementary natural and technological characteristics of various energy sources, and seek better coordination and optimization scheduling schemes for wind, hydro, solar, thermal storage and multi energy complementarity [4].

In the field of clean energy, numerous scholars have conducted in-depth research on the scheduling problem of multiple complementary energy sources. Reference [5] innovatively proposed a long-term optimization scheduling model. This model fully considers the two key factors of maximum power generation and minimum power output fluctuation, and has been successfully applied to the Longyangxia hydropower photovoltaic hybrid power generation system, providing strong support for the optimized operation of the system. Reference [6] proposes an optimization scheduling framework that focuses on two objectives: firstly, to minimize the occurrence of wind and solar power curtailment; The second is to significantly improve the energy storage efficiency of cascade hydropower stations. Empirical research has shown that this model can fully utilize the flexible regulation and energy storage potential of cascade hydropower stations, and mitigate the impact of their fluctuations on the power grid. Although the above research has achieved significant results in controlling power side output fluctuations, there are still shortcomings in the coordination between power output and grid load. Reference [7] proposed a short-term complementary coordination scheduling strategy, mainly aimed at achieving good results for hydro wind hybrid energy. This strategy accurately evaluates output complementarity by defining stationarity index, which can effectively control output fluctuations while achieving good tracking of the load curve. In the research process, Reference [8] focuses on the compatibility of source and load and the efficiency of renewable energy consumption, and constructs a short-term multi-objective optimization scheduling framework for collaborative power generation based on the dynamic matching mechanism of source and load. It introduces multidimensional collaborative optimization strategies and provides a theoretical breakthrough solution for complementary scheduling across energy forms. Reference [9] conducted in-depth research on the joint scheduling of energy storage and new energy, which opened up a new path for the research direction of multi energy complementarity and provided new insights. In addition, considering the current energy situation and future development trends, the supporting position of thermal power as the "basic load" in the current power structure and its role in peak shaving should not be underestimated. Reference [10] focuses on analyzing the technical path of deep peak shaving for thermal power units. By constructing a multi energy complementary and coordinated optimization scheduling system for wind, solar, and water storage, the collaborative control of new energy output fluctuations and system comprehensive energy consumption has been achieved. However, there is less consideration for the actual operational constraints of clean energy such as hydropower. Multi energy complementary optimization scheduling is a complex problem with multiple variables, constraints, and high-dimensional nonlinearity. There is a complementary and mutually exclusive relationship between multiple optimization objectives, and the model solution is difficult and computationally complex. Reference [11] decouples the two optimization objectives of maximizing source load matching and minimizing renewable energy waste into two sub models, and reduces the dimensionality of the multi-objective problem through a double-layer nested pattern, thereby improving computational efficiency. Reference [12] proposes a three-layer nested framework to reduce the complexity of model solving for the power generation scheduling problem of large-scale water solar hybrid systems. According to the flexibility and complementarity of different power sources, reference [13] optimizes the output of wind, solar, hydro, and thermal storage in a layered and individual manner to ensure the overall optimization goal of the system is optimal.

This article takes the "dual carbon" policy as the research background, and comprehensively considers the coordination of source load, grid constraints, demand for new energy consumption, and power generation economy to establish a multi-objective optimization scheduling model for wind solar water thermal storage. The optimization model (1) is the optimization scheduling layer of the wind solar water storage combined power generation system, with the goal of minimizing net load variance and maximizing clean energy generation to obtain the optimal output of wind solar water storage; Optimization model (2) focuses on the scheduling strategy of thermal power units to minimize the overall operating cost of the system. By constructing a dynamic allocation mechanism for the output of thermal power units in different time periods and introducing an improved artificial fish swarm intelligence optimization algorithm, the convergence speed and global optimization ability of the algorithm in complex solution spaces are significantly improved. Through the dynamic adjustment of this strategy, the algorithm can better adapt to different situations and enhance its optimization ability. Finally, the He County power system was selected as the simulation analysis object to verify the effectiveness of the proposed strategy and model through actual simulation.

2 Related research

Strengthening the interconnection and intercommunication construction in the energy field, promoting the optimization and complementary coordination of various types of energy, is a practical and effective way to address the energy and environmental challenges in the current socio-economic development process [14]. The concept of multi energy complementarity has a long history in the field of energy utilization and has received widespread attention from various countries. Different countries have developed and promoted multi energy complementarity integrated optimization projects that are suitable for their own resources and demand characteristics.

The promotion of the comprehensive optimization project for multi energy complementary systems focuses on two major dimensions. Firstly, focusing on the user side, optimize and adjust the spatiotemporal distribution of diversified load demands such as cooling, heating, electricity, and gas. By building a comprehensive energy supply infrastructure, utilizing natural gas cogeneration technology, distributed renewable energy systems, and energy smart microgrids, we aim to achieve coordinated supply of multiple energy sources and efficient utilization of integrated energy in a cascading manner. Secondly, for the power supply side, achieve the organic integration of large-scale wind, solar, hydro, coal, natural gas and other resources. This integration has effectively promoted the construction and stable operation of multi energy complementary systems. In the field of energy research and exploration, the Swiss Federal Institute of Technology was the first to propose the innovative concept of energy centers in the "Future Energy Network Vision" project [15]. Reference [16] uses an improved genetic algorithm (GA) to statically solve the generation expansion planning of energy hubs. Reference [17] explores an energy center network that includes electricity, heat, and cooling. Based on this, an energy hub structure that integrates energy storage and renewable energy is designed, and a dynamic optimization model based on mixed integer linearity is established. Reference [18] adopts energy loop intelligent exploration technology, actual node layout strategy, and virtual node embedding methods to decompose the complex energy hub model into several simple energy hub models. This method significantly reduces the computational burden while ensuring that the entire multi energy system can achieve global optimal operation decisions, but it also leads to an increase in the memory required for software operation. Reference [19] constructs a scenario based microgrid electricity gas optimization scheduling model using the concept of energy hubs. In this model, all network constraints are considered, and scenario reduction techniques are used to reduce scenarios related to random variables such as renewable energy and electric heating loads. However, this method only considers using coordinated optimization on the energy supply side to solve system uncertainty, ignoring the role of demand side adjustable devices in optimizing scheduling. The University of Manchester, UK, has created an interactive platform between electricity, heat and gas systems and users that integrates energy consumption modes, energy-saving strategies, demand response and other functions in combination with the local regional integrated energy system. Reference [20] utilizes the mutual support of multiple energy sources on the supply side and the participation of direct load control on the demand side to ensure the safe operation of the system. For multi energy systems, an economic optimization model for the electric thermal gas coupling system with direct load side participation in scheduling and control is established. Reference [21] studied the selection and capacity planning of various equipment in a comprehensive energy system that couples electricity, heat, and gas. Based on the established basic framework of comprehensive energy, with the goal of minimizing annual comprehensive costs, a mixed integer linear programming algorithm was used to optimize both equipment types and capacities simultaneously. Since the introduction of distributed energy in Japan in the late 1970s, the academic community has paid high attention to the research on the joint optimization operation of distributed energy power sources [22]. In recent years, major energy companies in Japan have broken the existing supply boundary situation of distributed energy systems, forming a unified regional energy microgrid consisting of multiple adjacent distributed energy sources within the same region, achieving collaborative optimization between different regions and multiple energy sources. Since 2013, an intelligent energy network architecture has been established by utilizing the regional cogeneration system to achieve combined cooling, heating, and power, while implementing demand side response through IT technology. The European Union has released a new roadmap for the joint power grid in the EU region in the 2050 decarbonization project [23]. The roadmap aims to integrate existing multi energy joint networks in various countries and achieve an efficient multi energy interconnection system in the EU region.

At present, China's research and practice on multi energy complementarity mainly includes cold and hot electrical comprehensive parks aimed at efficient consumption of multiple energy sources on the user side, and wind solar water thermal storage complementary power generation systems aimed at efficient power generation through multi energy combination on the power source side. Currently, Guangzhou is closely integrating the future evolution trend of the urban power grid and the coordinated supply and demand situation between different energy sources, striving to build a pearl intelligent industry demonstration park. The park aims to promote the localization and efficient consumption of large-scale renewable energy in the heating and cooling electrical system. At the same time, under the guidance and promotion of State Grid Corporation of China, Zhangjiakou actively promotes the construction of the Zhangbei wind solar thermal energy storage multi energy complementary demonstration project [24]. This project sets an example and opens up a new path for the construction of large-scale multi energy complementary joint power generation systems by comprehensively and comprehensively utilizing various forms of energy generation on the power supply side.

3 Joint scheduling and energy storage model for wind solar hydro power generation

3.1 Energy Storage Model Description

Installing an energy storage pump station structure between cascade hydropower stations, as shown in Figure 1, can pump water from lower level hydropower stations to upper level hydropower stations. Essentially, it can be understood as a cascade hydropower station with pumped storage (hereinafter referred to as "pumped storage").

When new energy generation exceeds the required load, the energy storage pump station pumps water to the higher level to consume excess energy, similar to charging energy storage devices; When the power grid faces a shortage of electricity supply, the water body can be lifted to a high-level reservoir through pumped storage systems, which can effectively convert it into additional power generation output of hydropower stations, achieving spatiotemporal transfer and flexible allocation of electricity [25]. The introduction of energy storage pump stations has reconstructed the hydraulic coupling mode of traditional cascade hydropower stations. By actively regulating the water flow path, the dynamic replenishment mechanism of the upper level power station's water storage capacity has been optimized, while effectively reducing the natural inflow fluctuation amplitude of lower level power stations, significantly enhancing the adaptability of the cascade system to uneven spatial and temporal distribution of runoff. Compared with conventional cascade hydropower stations, installing energy storage pump stations can increase the scheduling flexibility of cascade hydropower stations and achieve the reuse of water energy. Compared to the high construction cost, difficult site selection, and ability to only respond to daily load fluctuations of pumped storage power stations, directly carrying out this renovation between existing cascade hydropower stations can not only reduce project investment, but also provide flexible adjustment resources for smoothing seasonal fluctuations [26, 27].

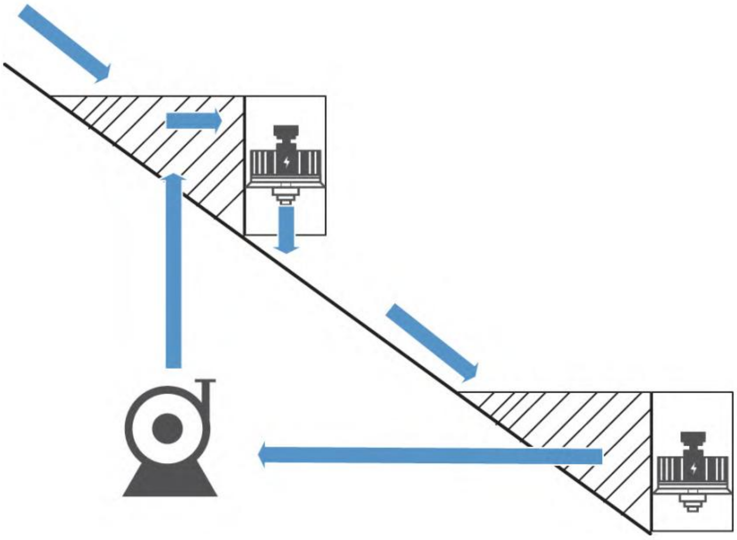

Figure 1: Structure of Cascade Energy Storage Pump Station

3.2 Joint optimization objectives of wind, solar and water storage

(1) The variance of net load is minimized. In order to reduce the frequency of frequent start stop and regulation of thermal power units, while ensuring the priority and full consumption of

wind and solar energy, flexible adjustments are made to the output of hydropower and energy storage to minimize the fluctuation amplitude of the net load curve [28]. The objective function set by the wind solar water storage joint optimization scheduling model aims to minimize the variance of net load, which is specifically expressed as:

$$\begin{cases} \min f_1 = \dfrac{1}{T}\sum_{t=1}^{T}\left(P_t - \bar{P}\right)^2 \\ P_t = P_{\text{load},\,t} - N_t^{\text{Wind}} - N_t^{PV} - N_t^{\text{Hydro}} - N_t^{\text{Storage}} \\ \bar{P} = \dfrac{1}{T}\sum_{t=1}^{T} P_t \end{cases} \tag{1}$$

where, N_t^{Wind} is the wind power output; f_1 is the variance of net load; N_t^{Hydro} is the hydroelectric output; P_t is the net load; $\bar{P}$ is the average value of net load; T is the scheduling cycle; $P_{\text{load},\,t}$ is the initial load; N_t^{PV} is the photovoltaic output; N_t^{Storage} is the energy storage output.

(2) Total power generation of clean energy is the largest. To promote the large-scale consumption of clean energy, taking into account the constraints of power system operation and the fluctuation characteristics of wind and solar power generation output, it is necessary to take maximizing the utilization rate of wind and solar energy as the core goal, construct a multi energy complementary collaborative optimization mechanism, smooth out the random fluctuations of wind and solar power generation and load side, tap into the potential of clean energy generation as much as possible, and achieve dynamic matching between power supply and load demand [29]. The objective function is:

$$\max f_2 = \sum_{t=1}^{T}\left(N_t^{\text{Wind}} + N_t^{PV} + N_t^{\text{Hydro}}\right) \tag{2}$$

where, f_2 is the total power generation of wind, solar, and water.

The constraint conditions are as follows:

(1) Wind solar water storage combined output constraint.

$$P_{\min,t} \le N_t^{\text{Wind}} + N_t^{PV} + N_t^{\text{Hydro}} + N_t^{\text{Storage}} \le P_{\max,t} \tag{3}$$

where, $P_{\min,t}$ is the maximum total output; $P_{\max,t}$ is the maximum total output. The model satisfies the joint output constraint of $N_t^{\text{Hydro}} + N_t^{\text{Storage}} \le P_{\text{load},\,t} - N_t^{\text{Wind}} - N_t^{PV}$ by adjusting the output of hydropower and energy storage. In this article, thermal power plants are required to undertake base load and peak load regulation work, and the net load is greater than 0.

(2) Wind and solar power constraints. This model utilizes a collaborative regulation mechanism between hydropower and energy storage systems, with the priority consumption of wind and solar energy as the core optimization objective, to achieve flexible operation of a multi energy complementary system. The output result is determined based on the predicted value:

$$\begin{cases} N_t^{\text{Wind}} = N_{\text{forecast},t}^{\text{Wind}} \\ N_t^{PV} = N_{\text{forecast},t}^{PV} \end{cases} \tag{4}$$

where, $N_{\text{forecast},t}^{\text{Wind}}$ is the wind power output; $N_{\text{forecast},t}^{PV}$ is the photovoltaic output.

(3) Constraints on hydropower stations.

Output constraint:

$$N_{\min}^{\mathrm{Hydro}} \le N_t^{\mathrm{Hydro}} \le N_{\max}^{\mathrm{Hydro}} \tag{5}$$

Storage capacity constraint:

$$V_{\min,t}^{\mathrm{Hydro}} \le V_t^{\mathrm{Hydro}} \le V_{\max,t}^{\mathrm{Hydro}} \tag{6}$$

Water discharge flow constraint:

$$q_{\min,t}^{\mathrm{Hydro}} \le q_t^{\mathrm{Hydro}} \le q_{\max,t}^{\mathrm{Hydro}} \tag{7}$$

where, for hydropower station, $N_{\min}^{\mathrm{Hydro}}$ is the minimum output, V_t^{Hydro} is the water storage capacity, $V_{\min,t}^{\mathrm{Hydro}}$ is the minimum storage capacity; for hydropower station, $N_{\max}^{\mathrm{Hydro}}$ is the maximum output, $V_{\max,t}^{\mathrm{Hydro}}$ is the maximum storage capacity, q_t^{Hydro} is the discharge flow, $q_{\min,t}^{\mathrm{Hydro}}$ is the minimum discharge flow; $q_{\max,t}^{\mathrm{Hydro}}$ is the maximum discharge flow.

(4) Energy storage constraints.

For the operating energy storage system, the charging status restrictions are as follows:

$$SOC_{\mathrm{Storage},\,t} = SOC_{\mathrm{Storage},\,t-1} + \left(\eta_c N_t^{\mathrm{Storage},\,c} - \frac{1}{\eta_d} N_t^{\mathrm{Storage},\,d}\right)\Delta t \Big/ E_s \tag{8}$$

$$SOC_{\min} \leqslant SOC_{\mathrm{Storage},t} \leqslant SOC_{\max} \tag{9}$$

Energy storage charging and discharging constraints:

$$\begin{cases} N_{\min}^{\mathrm{Storage},\,c} \le N_t^{\mathrm{Storage},\,c} \le N_{\max}^{\mathrm{Storage},\,c} \\ N_{\min}^{\mathrm{Storage},\,d} \le N_t^{\mathrm{Storage},\,d} \le N_{\max}^{\mathrm{Storage},\,d} \\ N_t^{\mathrm{Storage}} = N_t^{\mathrm{Storage},\,d} - N_t^{\mathrm{Storage},\,c} \end{cases} \tag{10}$$

where, $SOC_{\mathrm{Storage},\,t}$ is the state of charge; η_c represents charging efficiency; η_d stands for discharge efficiency; For state of charge, $SOC_{\min}$ is the lower limit, $SOC_{\max}$ is the upper limit, $N_t^{\mathrm{Storage},\,c}$ is the charging power; For charging power, $N_{\min}^{\mathrm{Storage},\,c}$ is the minimum value, $N_{\max}^{\mathrm{Storage},\,c}$ is the maximum value; $N_t^{\mathrm{Storage},\,d}$ is the discharge power; For discharge power, $N_{\max}^{\mathrm{Storage},\,d}$ is the maximum value, $N_{\min}^{\mathrm{Storage},\,d}$ is the minimum value; E_s is the rated capacity; Δt is the duration of each time period, $\Delta t = 1\,\mathrm{h}$ in this article.

3.3 Optimization Objectives for Thermal Power Units

The lowest operating cost of thermal power units:

$$\min f_3 = f_{mh} + f_{qt} = \sum_{t=1}^{T}\sum_{i=1}^{N_G}\left[u_{i,t}\left(1-u_{i,t-1}\right)S_{i,t} + u_{i,t}\left(a_i N_{\mathrm{i},t}^2 + b_i N_{i,t} + c_i\right)\right] \tag{11}$$

where, for thermal power, f_3 is the operating cost, $N_{i,t}$ is the output, f_{qt} is the cost of starting and stopping thermal power plants; $u_{i,t}$ represents the state; a_i , b_i , c_i represent the consumption coefficients; $S_{i,t}$ is the starting cost; f_{mh} is the cost of coal consumption; N_G is the number of thermal power units.

The constraint conditions are as follows:

(1) Power balance constraint:

$$N_t^G + N_t^{\text{Wind}} + N_t^{PV} + N_t^{\text{Hydro}} + N_t^{\text{Storage}} = P_{\text{load},\, t} \tag{12}$$

(2) For the generator set, its output constraints are as follows:

$$P_{i,\min}^G \le N_{i,t} \le P_{i,\max}^G \tag{13}$$

(3) For thermal power generation units, the climbing restrictions they have are as follows:

$$-\delta_i^G \le N_{i,t} - N_{i,t-1} \le \delta_i^G \tag{14}$$

where, δ is the upper and lower limits of the climbing rate.

(4) Line transmission capacity constraint:

$$-P_{ij,\max} \le B_{ij}\left(\theta_{i,t} - \theta_{j,t}\right) \le P_{ij,\max} \tag{15}$$

where, B_{ij} is the admittance between nodes *ij*; $\theta_{i,t}$ is the voltage phase angle; $P_{ij,\max}$ is the maximum transmission capacity; $\theta_{j,t}$ is the voltage phase angle of node *j*.

4 Multi objective artificial fish swarm optimization algorithm

4.1 Artificial fish swarm optimization algorithm

Inspired by the collective behavior of certain animals in nature, scholars have proposed swarm intelligence optimization algorithms that simulate the behavior of biological groups to achieve optimization. The Artificial Fish Swarm Algorithm (AFSA) is a random search optimization algorithm built on the behavior patterns of fish schools. The algorithm has a simple structure, a global search range, fast computation speed, and good dynamic tracking performance.

The state of AFSA is defined as $X = \{X_1, X_2, \cdots, X_n\}$, and the algorithm parameters include the visual field range of the artificial fish, the step size Step, the crowding factor δ, and the number of repetitions Try_mount. The current state of the artificial fish is X_i, and its food concentration (objective function value) is $Y_i = f(X_i)$. The artificial fish swarm algorithm mainly achieves global optimization by simulating the four basic behaviors of fish swarm:

(1) Foraging behavior. Randomly select an X_j. If $Y_j > Y_i$ is satisfied, move towards X_j with $X_i^{t+1} = X_i^t + \left[\left(X_j - X_i^t\right)\cdot \text{Step} \cdot \text{Rand}()\right] \big/ \left\| X_j - X_i^t \right\|$. If the forward condition is not satisfied after repeated attempts, perform random behavior $X_j = X_i + \text{Visual} \cdot \text{Rand}()$;

(2) Group behavior. Explore the number of partners n_f and the center position X_c of the partners. If $Y_c / n_f > \delta Y_i$ is met, move towards the center X_c of the partners, $X_i^{t+1} = X_i^t + \left[\left(X_c - X_i^t\right)\cdot \text{Step} \cdot \text{Rand}()\right] \big/ \left\| X_c - X_i^t \right\|$;

(3) Rear end collision behavior. Explore the maximum number of partners n_f and Y_i for partner X_m. If $Y_m / n_f > \delta Y_i$ is satisfied, move towards the optimal partner X_j, $X_i^{t+1} = X_i^t + \left[\left(X_m - X_i^t\right)\cdot \text{Step} \cdot \text{Rand}()\right] \big/ \left\| X_m - X_i^t \right\|$, Otherwise, perform foraging behavior;

(4) Random behavior. Randomly select a state and move in that direction,

$X_i^{t+1} = X_i^t + \text{Step} \cdot \text{Rand}\,()$.

4.2 Population dynamic growth strategy

The non dominated solution set retained in artificial fish populations is a key indicator for evaluating algorithm convergence. To improve the distribution quality and convergence performance of non dominated solution sets, this paper constructs a dynamic strategy system for maintaining population size expansion. The specific implementation steps are as follows:

Step 1: The number of non dominated solutions in the population increases with the number of iterations, and searching for each non dominated solution would consume a significant amount of computational resources. In this regard, this article maps the current non dominated solution file to the non dominated solution target space, and uses a density matrix to achieve the mapping operation, thereby obtaining its density related information. Randomly select a non dominated solution from the grid with the lowest density to expand the search range, and select multiple non dominated solutions to implement perturbation operations.

Step 2: When the number of artificial fish increases excessively, it will significantly increase the computational load and also cause excessive aggregation of artificial fish, slowing down the search process. If the number of artificial fish added is too small, the search scope and intensity will be limited, and it may not be possible to find a better solution. This article constructs a model for determining the increase in the number of artificial fish, in the following specific form:

$$np(t) = \begin{cases} \left(\dfrac{lp}{up - lp} + \left(\dfrac{\sqrt{2}\left(t - t_{\max}\right)}{t_{\max}} \right)^2 \right)(up - lp), t_{\max} \geq t \geq \dfrac{t_{\max}}{2} \\ \left(1 - \dfrac{lp}{up - lp} + \left(\dfrac{\sqrt{2}t}{t_{\max}} \right)^2 \right)(up - lp), \dfrac{t_{\max}}{2} > t \geq 0 \end{cases} \tag{16}$$

where, $1 \leq lp \leq up \leq 3$, *up* is the upper bound, while *lp* represents the lower bound; *T* represents the current iteration count; $np(t)$ is the number of artificial fish; $t_{\max}$ is the maximum number of proxy deliveries.

Step 3: Propose a local boundary perturbation method, but the boundaries used are not fuzzy boundaries, but local boundaries determined based on grid technology. Add artificial fish using the following formula:

$$x_{id}^s = \begin{cases} \left(\dfrac{ld_d}{ud_d - ld_d} + \left(r_4 - 1\right)^2 \right)\left(ud_d - ld_d\right), & r_3 < 0.5 \\ x_{id}, & r_3 \geq 0.5 \end{cases} \tag{17}$$

where, ld_d and ud_d respectively represent the lower and upper bounds; x_{id}^s represents the *s*-th artificial fish added by the disturbance of x_i, while r_3 and r_4 represent random numbers distributed.

4.3 Dynamic Population Reduction Strategy

The steps are as follows.

Step 1: Divide artificial fish into different grades based on non dominated sorting. Each artificial fish layer can dominate any artificial fish layer after that layer. The solution obtained from artificial fish with lower rankings may not be as good as those with higher rankings, and may not bring significant benefits in subsequent searches. Based on the density matrix, determine whether there are artificial fish with a density greater than 10 in the current dynamic population. If there are, calculate their effect value *L*. Based on the *L* value, select candidate artificial fish in a random probability manner. If the number of candidate artificial fish is not greater than *S*, delete them directly. If the number of candidate artificial fish is greater than *S*, randomly delete *S* artificial fish from the current dynamic population. The calculation formula for *S* and *L* is:

$$S(t) = s \times M \tag{18}$$

$$L(x_i(t)) = -\left(\frac{1}{d(x_i(t))} - 1\right) \Big/ r(x_i(t)) \tag{19}$$

where, *M* represents the current dynamic population of artificial fish; $r(x_i(t))$ represents the level value in the *t*-th iteration; $d(x_i(t))$ represents the density value during the *t*-th delivery; The parameter s represents the selection rate. Assuming $s \le 0.2$, a small selection ratio can prevent a large number of uncontrollable artificial fish from being removed.

Step 2: If there are no artificial fish with a density value greater than 10 in the current dynamic population or the number of deleted artificial fish has not reached *S*, calculate the deviation level value *R* of the artificial fish with a density value not greater than 10 in the dynamic population, and randomly select the artificial fish with a larger *R* value as the candidate artificial fish, and randomly select *S* artificial fish for deletion. The calculation formula for *R* is:

$$R(x_i(t)) = \text{rand} \times \left(1 - \frac{1}{r(x_i(t))}\right) \tag{20}$$

5 Case analysis

This article takes the He County power system as the research object, A multi energy complementary simulation system of He County wind solar water storage is built, and case analysis is carried out based on it. In the research process, the summer solstice was selected as a typical load day. The He County Wind, Solar, Water, Fire, and Storage Multi energy Complementary System, with Unit 1 and Unit 2 only participating in conventional peak shaving and a minimum load rate of 50%, and Unit 3 participating in deep peak shaving, with a unit cost of 3457 yuan/kW and an oil price of 6126 yuan/t. Currently, the proportion of new energy generation installed capacity in the total power installed structure has reached 27.43%. According to policy requirements, wind power development projects must construct energy storage facilities according to a standard of not less than 15% of their installed capacity, while centralized photovoltaic power generation projects must be equipped with energy storage devices at a ratio of not less than 5%. As of the end of 2024, the energy storage configuration standards for new energy projects issued by 20 provincial-level administrative regions in China show that the proportion of energy storage configuration ranges from 5% to 30%, with a typical single station energy storage capacity of 200MW selected for engineering projects.

By introducing the optimal consumption ratio of new energy on the power supply side of the He County power system, a multi-objective optimization scheduling model focusing on the optimal consumption of new energy in the He County wind solar thermal multi energy coordinated complementarity is constructed. When solving the model, a multi-objective artificial fish swarm intelligence optimization algorithm equipped with dynamic population adjustment strategy was selected. Analyzing the optimal consumption level of wind solar energy, Table 1 provides a detailed list of the key parameters of net load for the wind solar thermal multi energy complementary system in the range before and after the optimal consumption rate, while Figure 2 intuitively presents the optimal consumption rate characteristic curve of the wind solar joint system.

Table 1: Net load parameters considering optimal consumption rate

Net load	Peak value	Valley value	Peak valley difference
Fully absorb the scenery	1432 MW	331.69 MW	1086.31 MW
Optimal Consumption of Scenery	1432 MW	624.28 MW	793.57 MW

According to Table 1, the peak valley difference of the He County power system during full wind and solar power consumption is 1086.31 MW, and the peak valley difference during optimal wind and solar power consumption is 793.57 MW. The difference between the two is 292.74 MW, a decrease of 26.95%. If the optimal utilization and consumption of wind and solar energy are fully considered in the operation planning of the county power system, it will significantly reduce the peak valley difference of net load, and effectively alleviate the many difficulties faced by thermal power units in peak shaving process.

When the night load of the He County power grid is relatively low, the power generation output of wind power is at a relatively high level, while the power generation output of photovoltaics is zero. If wind power is fully consumed during this period, the peak valley difference in net load of the county power system will further increase. Therefore, considering the optimal consumption of wind power output during the period of 00:00 to 4:00 instead of full consumption can help improve the "valley value". If the optimal consumption ratio of wind and solar energy is fully considered, it can increase the valley value of net load to a certain extent. In the He County power system, wind power output exhibits significant characteristics of resistance to peak shaving, while photovoltaic output and load fluctuations generally converge. During the peak load phase during the day, the county power system can fully absorb the output of wind and solar energy, thereby effectively reducing the peak net load.

According to Figure 2, the optimal consumption rate of wind power in the He County power system reached over 90% during the period of 0:00-1:00, about 40%~70% during the period of 2:00-3:00, the minimum optimal consumption rate of wind power at 4:00 was only about 10%, and the wind power was fully consumed during the period of 05:00-23:00. This is consistent with the anti peak characteristic of wind power.

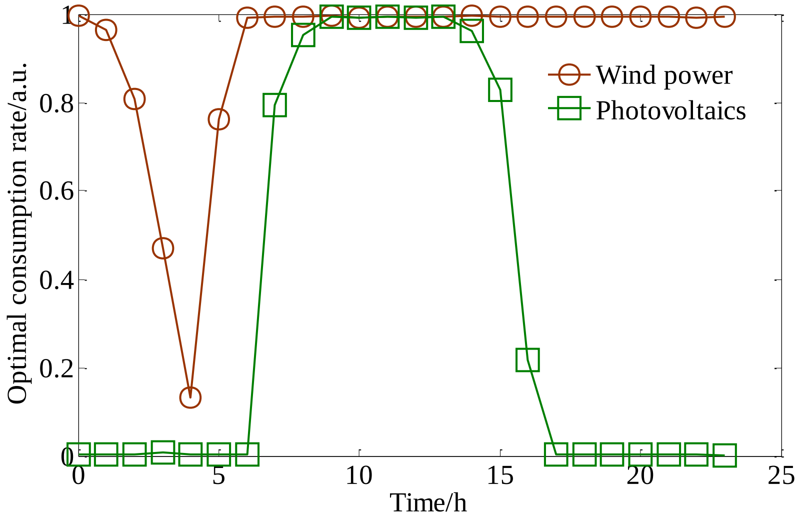

Figure 2: Optimal Consumption Rate Curve of Wind and Solar Energy

It can be seen that there are two peak periods for wind power output in the He County power system: 0:00-5:00 and 16:00-21:00. Among them, 0:00-6:00 is at night, and the demand for nighttime load is relatively low and continues to decline, resulting in a state of oversupply. The optimal consumption rate of wind power is also continuously decreasing and reaches its minimum value at 4:00; Starting from 05:00, people follow the rule of working at sunrise, and the electricity load of the He County power system also increases significantly from this moment until 23:00, when most people fall asleep. During this period, the overall electricity load of the He County power system is at a high level and can fully absorb wind power output.

Based on the predicted output of photovoltaics, it can be concluded that the optimal absorption rate of photovoltaic power generation in the He County power system reached 100% from 7:00 to 14:00, around 90% at 15:00, and zero from 16:00 to 18:00; Therefore, the photovoltaic output of the He County power system only has a low consumption rate during periods of low load, and the trend of photovoltaic output and electricity load is consistent during other periods. During the nighttime hours of 00:00 to 6:00 and 19:00 to 23:00 in the He County power system, photovoltaics do not generate electricity, and there is no optimal consumption situation for photovoltaics. Therefore, considering the optimal consumption rate of photovoltaic power generation is beneficial for reducing the peak valley difference of the He County power system's net load.

Taking the optimal consumption rate of wind and photovoltaic power generation as an important consideration factor, the energy storage system is included in the research system. This study can accurately analyze the charging and discharging power characteristics of energy storage systems at different time periods, and quantify the impact mechanism of energy storage configuration on the optimal consumption level of wind solar combined power generation in county-level power grids during different operating cycles, as shown in Figure 3.

According to Figure 3, the reduction of peak valley difference in net load of the He County power system is mainly reflected in four periods: 0:00-5:00, 9:00-13:00, 15:00-18:00, and 19:00-22:00; Among them, 0:00-5:00 and 15:00-18:00 are the low periods of electricity load. After the introduction of energy storage systems, the net load curve has a significant upward trend, which can play a role in "filling the valley"; 9: The two peak periods of electricity load are from 00 to 13:00 and from 19:00 to 22:00. After introducing the energy storage system into the power operation system, the system not only effectively reduces the peak level of power load, but also makes the transition of load from peak state smoother. In the county power system, energy storage systems can play an important compensatory role. Through this compensation, the output of the entire power system can be made more stable, thereby effectively reducing the difficulty of peak shaving operations for thermal power units. Firstly, it can increase the "valley value" of power load, allowing the system to maintain a relatively stable operating state during low load periods; Secondly, it can reduce the "peak" of power load and avoid excessive tension in the system during high load periods. Through the synergistic effect of these two aspects, the good effect of "shifting peaks and filling valleys" was ultimately achieved.

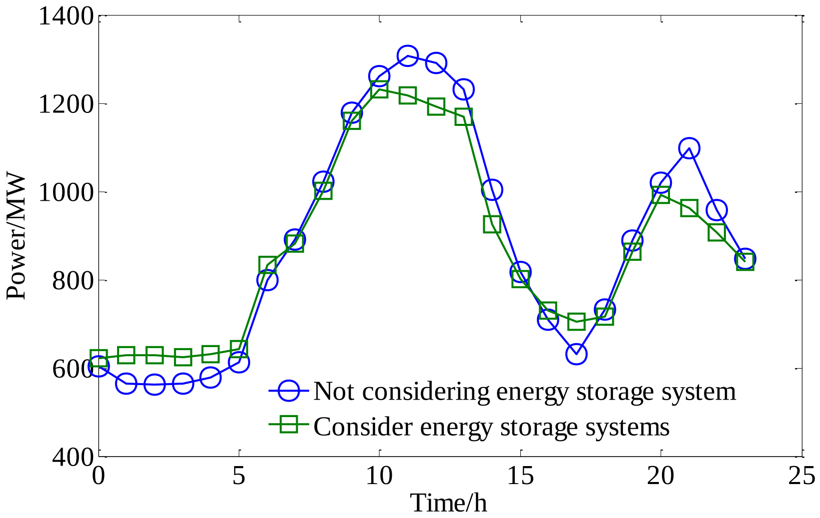

Figure 3: Net load curve considering energy storage system

In the operation of the He County power system, not only the operating cost of the power source needs to be considered, but also various additional costs during the operation process, such as the pollution caused by coal-fired power combustion to the environment, namely environmental protection taxes, the benefits brought by clean energy generation to the environment, and the additional cost of rotating backup to ensure safe and stable operation during system operation. In the scheduling of multi energy complementary systems, the key factors of optimal consumption rate of new energy have been fully considered, and their impact on various operating costs of the county power system has been deeply analyzed, as shown in Table 2.

According to the comparative data of various operating costs of the county power system shown in Table 2, it can be concluded that:

From the perspective of the total operating cost of the He County power system, without considering the optimal consumption rate of new energy, it was 3.7713 million yuan, but after considering it, it decreased to 3.7074 million yuan, a decrease of 63900 yuan. The above research results indicate that incorporating the optimal consumption rate of new energy into the system operation optimization framework can significantly reduce the full cycle operating costs, achieve efficient allocation of resource elements, effectively compress redundant cost inputs, and thereby improve the overall economic operation efficiency of the power system. In terms of peak shaving cost for thermal power units in the He County power system, it was 3.7139 million yuan before consideration, but decreased to 3.6348 million yuan after consideration, a decrease of 79100 yuan. The core purpose of thermal power units participating in peak shaving is to cope with the dynamic changes in power system load. When considering the optimal consumption rate of new energy, the fast response and flexible adjustment capabilities of new energy generation can partially replace the peak shaving role of traditional thermal power units in specific scenarios, achieving flexible and economic operation of the power system. In the He County power system, the operating costs of clean energy have been effectively reduced, specifically from the original 225300 yuan to 205900 yuan, a decrease of 19400 yuan. This reflects that considering the optimal consumption rate of new energy can help to more efficiently utilize clean energy, optimize the power generation plan and operation mode of clean energy, reduce energy loss and equipment wear during the power generation process, and thereby lower operating costs.

Table 2: Comparison of Operating Costs for Various Items

Category	Not considering the optimal consumption rate of new energy	Consider the optimal consumption rate of new energy
Total operating cost of power system/10000 yuan	377.13	370.74
Peak shaving cost of thermal power units/10000 yuan	371.39	363.48
Operating cost of clean energy/10000 yuan	22.53	20.59
Operating cost of energy storage system/10000 yuan	6.48	5.81
System rotation backup cost/10000 yuan	33.36	33.06
Environmental protection tax/10000 yuan	9.35	9.04
Wind and solar water storage environmental benefits/10000 yuan	67.48	62.51

The operating cost of the energy storage system in He County's power system also showed a downward trend, dropping from 64800 yuan to 58100 yuan, a decrease of 6700 yuan. When considering the optimal consumption rate of new energy, it is possible to plan the charging and discharging strategies of energy storage systems with higher accuracy. In this way, it can effectively avoid problems such as excessive charging and discharging of energy storage systems and unreasonable energy storage arrangements, thereby reducing the losses suffered by energy storage equipment and lowering its operating costs. The cost of rotating backup in the He County power system has relatively small changes, ranging from 333600 yuan when not considered to 330600 yuan when considered, a decrease of only 3000 yuan. The rotational reserve cost is the cost incurred by reserving reserve capacity to cope with possible sudden failures or load fluctuations in the system. Although the impact of considering the optimal consumption rate of new energy on the cost of rotating standby is not significant, it also reflects to some extent the optimization of the system's standby arrangement, making the standby resources more reasonably utilized. The environmental protection tax for the He County power system decreased from 93500 yuan to 90400 yuan, a decrease of 0.31 yuan. This is because after considering the optimal consumption rate of new energy, the proportion of new energy generation increases, and the power generation of traditional energy such as coal-fired power is relatively reduced, thereby reducing pollutant emissions and reducing the payment of environmental protection taxes.

However, in the He County power system, the environmental benefits generated by wind energy, solar energy, and pumped storage energy have decreased from 674800 yuan to 625100 yuan, a decrease of 49700 yuan. The reason for this may be that after considering the optimal consumption rate of new energy, the scheduling strategy and operation arrangement of new energy power generation tend to become more complex, which in turn has a certain degree of weakening effect on the environmental benefits of new energy power generation. Overall, taking into account the optimal consumption rate of new energy still demonstrates outstanding advantages in reducing the overall operating costs and other related costs of the system. Further analysis shows that when the optimal consumption rate of new energy is taken as the key variable, it will trigger multidimensional linkage effects on the multi energy complementary system composed of wind energy, solar energy, hydro energy, and thermal storage devices in the county-level power system at the operational cost level. This measure has produced positive and outstanding cost-effectiveness results in multiple dimensions such as deep peak shaving operation process of thermal power units, efficient operation and control of clean energy, dynamic operation monitoring of energy storage systems, and ecological environment protection. Although the environmental benefits of wind energy, solar energy, and pumped storage energy have shown a certain degree of decline in the county's power system, after systematic comprehensive evaluation, they still have significant value that cannot be ignored, providing practical guidance for achieving the goal of coordinated development of economy and efficiency in the county's power system.

6 Conclusion

This article aims to address the pressure brought by the volatility and randomness of wind and solar power output in the He County power system on grid peak shaving and frequency regulation. Firstly, taking into account factors such as source load coordination, grid constraints, demand for new energy consumption, and power generation economy, a multi-objective optimization scheduling model based on the complementary characteristics of wind, solar, water, and thermal storage multiple energy sources was constructed. This model includes an optimization scheduling layer for wind solar water storage combined power generation systems and an optimization scheduling layer for thermal power units. The former aims to obtain the optimal output by minimizing the variance of net load and maximizing clean energy generation, while the latter aims to optimize the output of thermal power units at various time periods by minimizing system operating costs. Secondly, the introduction of artificial fish swarm algorithm and the design of dynamic growth and reduction strategies have improved its optimization performance, enabling it to solve complex multi-objective optimization problems more efficiently. Finally, by selecting the county power system to construct a simulation system, the summer solstice day was chosen as the typical load day for case study. Case analysis shows that considering the optimal consumption rate of new energy will have multidimensional and complex impacts on the operating costs of wind solar water energy storage multi energy complementary systems. In the peak shaving process of thermal power units, the operation of clean energy, the operation status of energy storage systems, and the field of environmental protection, positive cost-effectiveness has been generated.

In the next research direction, on the one hand, the proposed multi-objective optimization scheduling model can be further optimized. Considering more complex factors in actual operation, such as more accurate predictions of new energy output and more detailed constraints on the grid structure, to make the model more closely aligned with actual operating conditions and improve the accuracy and practicality of scheduling strategies. On the other hand, the improvement of artificial fish swarm algorithm can continue to deepen. Explore more effective dynamic adjustment strategies to improve the convergence speed and solution quality of algorithms when dealing with large-scale, high-dimensional optimization problems. In addition, collaborative optimization research on multi regional power systems can be carried out to promote the optimization strategies of the county power system to a larger scale power network, achieve larger scale energy optimization configuration and efficient utilization, and promote the development of the entire power industry towards a greener, low-carbon, and more economical direction.

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