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# A Multi-Objective Optimization Framework for Planning and Operation of Wind-Photovoltaic-Energy Storage Systems in Smart Grids

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**Abstract.** Driven by the "dual carbon" goals, the global energy structure is transforming toward clean energy. It aggravates the resource depletion and environmental pollution faced by traditional fossil fuel power systems. Nowadays, the share of wind energy and solar energy is constantly increasing. But due to natural conditions, they still exist characteristics like intermittency. Energy storage systems, become a key solution to address these challenges by balancing supply and demand and enhance grid stability. Nevertheless, existing integrated energy planning models often fail to accurately capture the spatiotemporal correlation between wind and solar resources. To address these issues, this paper raises a multi-objective framework aiming to minimize annual total cost and renewable energy curtailment rate. This framework integrates K-Means clustering used for typical scenario extraction, the Frank-Copula function to model wind-PV correlation, and Kantorovich distance-based scenario reduction to improve efficiency. Taking the Sanjiangyuan Project as an example, after optimization, indicators like wind and solar curtailment rate, and life-all-cycle cost have obviously decreased. At the same time, the probability of insufficient power supply has been reduced, verifying the effectiveness of the model. This work provides a practical and supportive tool for the planning and stable operation of future high-renewable energy systems.

**Keywords:** Wind-Photovoltaic-Energy Storage System; Smart Grid; Multi-Objective Optimization; Uncertainty Modeling.

## 1. Introduction

Under the promotion of "dual carbon" goals,the global energy structure is transforming profoundly towards clean and low-carbon solutions. This transition causes the traditional fossil fuel power systems under the pressures of resource depletion and environmental pollution, making the development of clean and efficient renewable energy a central direction in the global energy field [1].

Among all renewables, wind and solar energy are the most abundant and widely- used. Owing to their strengths, including zero carbon emissions and widespread availability, their proportion of the global power supply is steadily enhancing. However, owing to the reliance on natural conditions, wind energy and solar energy exist inherent intermittence, volatility and randomness, which brings power system enormous challenges [2]. For instance, short-term wind power fluctuations can reach 40%–60% of the rated capacity, while solar energy is affected by day-night changes, seasonal shifts, and weather influence. This makes it geographically limited and unstable in terms of power generation.

When wind energy and solar energy are integrated into the grid on a large scale, the uncertainty can lead to obvious fluctuations in the grid, giving rise to such as frequency changes and voltage instability and even endangering the safe and normal function of the power grid [3]. Now energy storage technology has played a key role in alleviating these fluctuations, acting as an "energy buffer" that balances supply and demand through functions such as peak shaving, valley filling, and frequency regulation [4]. Against this backdrop, integrated Wind-Photovoltaic-Energy Storage (WPES) smart grids have become a research focus. Figure 1 shows the operational mechanism of the smart grid model.

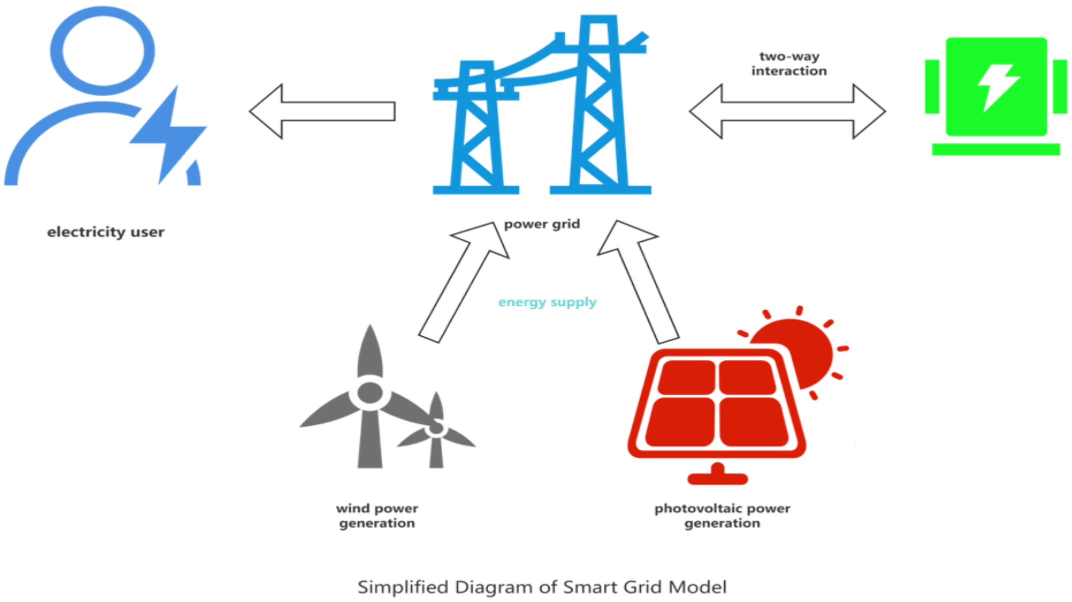

**Figure1:** Simplified Diagram of Smart Grid Model.

However, existing research still existing significant limitations. Many optimization models only focus on a single technical dimension, making it difficult to balance economic costs with environmental benefits [5]. Furthermore, normal methods always model the uncertainty of wind and solar power output independently, ignoring the correlation between the two in practical situations. It causes a huge gap between the simulated scenarios and the actual function of the grid [6]. To fill these research gaps, this paper proposes a multi-objective optimization framework for the planning and operation of WPES smart grids. The core of this framework is a multi-objective model that targets the minimization of both annual investment/operational costs and the renewable energy curtailment rate. To accurately capture the association between wind and solar output, the Frank-Copula function is incorporated for uncertainty modeling, while K-Means clustering and Kantorovich distance-based scenario reduction are applied to enhance computational efficiency. The research uses real data from the Sanjiangyuan Green Power Intelligent Computing Microgrid project to validate the model, with results demonstrating its effectiveness in improving economic, environmental, and reliability performance. The proposed framework provides a reusable and practical tool for configuring and operating WPES systems, offering technical support for the stable and efficient development of high-renewable power systems under the “dual carbon” goals.

## 2. Application of Wind-Photovoltaic-Energy Storage

The core goal of WPES system is to balance wind and solar fluctuations, optimize energy storage dispatching, and ensure reliable energy supply “. Its key functions include peak shaving, valley filling, smoothing power fluctuations, and providing backup power. On the grid side, energy storage systems greatly contribute to stability. Their ability to charge and discharge rapidly helps regulate voltage and supply emergency power. By acting as a flexible buffer, they bridge gaps between supply and demand. Furthermore, these systems also help manage regional power flow, enhancing the overall efficiency of power transmission.

A typical example is the Guodian Investment Ruiguang Photovoltaic Power Station Project in Seda County, Ganzi Tibetan Autonomous Prefecture, Sichuan Province. As China’s first high-altitude demonstration project integrating grid-forming energy storage with renewable energy, the project adopts the NUSP-industry integrated monitoring system. This system is used for the integration of wind, solar, storage, and the grid by an LFP electrochemical energy storage power station. This station operates in coordination with a 100 MW photovoltaic power station. Since its launch, the project has significantly improved the stability and reliability of the northern Ganzi grid while effectively meeting local electricity demands. Smart grids employ advanced control and communication technologies to monitor and predict wind and solar energy in real time, thus realizing the scheduling of energy storage system [7]. This integrated model helps match variable renewable output with grid demand, raises energy utilization efficiency, cuts operational costs, and strengthens grid stability and reliability.

Collaborative optimization is mainly achieved through three aspects. These aspects are wind-solar power generation prediction, energy storage system control, and smart grid dispatching. meteorological information and neural network algorithms are used. They help make relatively accurate meteorological predictions. They also help accurately calculate the output of wind and solar energy generation.

Advanced control strategies are adopted. These strategies allow energy storage systems to store energy when wind and solar power generation is surplus. They also allow the systems to discharge when power generation is insufficient. This process stabilizes voltage fluctuations. Energy storage systems are incorporated into the central coordination of the power grid. Dispatching strategies are optimized based on three factors. The first factor is the prediction results of wind and solar power generation. The second is grid load conditions. The third is the status of energy storage systems. This optimization achieves the collaborative operation of wind-solar-storage systems.

## 3. Optimization Models and Control Strategies for Smart Grids with Wind-Photovoltaic-Energy Storage Systems

### 3.1. Problem Description

During the grid integration planning of a high penetration of wind and solar energy, both the power output from these sources and the system load are highly variable, resulting in a vast number of complex operating scenarios. Therefore, it is necessary to reduce the number of complex operating scenarios and summarize typical scenarios for planning to improve calculation efficiency. The problem of wind and solar curtailment causes great waste of energy and is not conducive to the construction and planning of Photovoltaic and wind power projects. To acquire a relatively economical and environmentally friendly planning scheme, a multi-objective planning model is founded by comprehensively in view of the minimization of the annual investment and operational cost of wind-solar-storage planning and the minimization of the annual curtailment of new energy generation.

### 3.2. Objective Functions

$f_1$ includes the annual investment cost, annual fixed operation cost, and annual variable operation cost. $f_2$ represents the annual curtailment of energy generation.

The specific formula of $f_1$ is presented below

$$f_1 = C_{inv} + C_{ope} + C_{\mathrm{bop}} \tag{1}$$

Where: $C_{\mathrm{inv}}$ is the annual investment cost; $C_{\mathrm{ope}}$ is the annual fixed operation cost; $C_{\mathrm{bop}}$ is the annual variable.

$$C_{inv} = \sum_{i=1}^{m}( R_{\mathrm{w}}\, C_{\mathrm{w}}\, G_i^{\mathrm{w}} + R_{\mathrm{p}}\, C_{\mathrm{p}}\, G_i^{\mathrm{p}} + R_{\mathrm{s}}\, C_{\mathrm{s}}\, G_i^{\mathrm{s}}) \tag{2}$$

$$C_{ope} = \sum_{i=1}^{m}\left(C_{\mathrm{l}w} G_i^{\mathrm{w}} + C_{\mathrm{l}p} G_i^{\mathrm{p}} + C_{\mathrm{l}s} P_i^{\mathrm{s}}\right) \tag{3}$$

$$C_{\mathrm{bop}} = 8760 \sum_{t=1}^{d} p_t \sum_{i=1}^{k} C_{\mathrm{coal}}\, \alpha_i^{\mathrm{th}} P_{i,t} \tag{4}$$

Where: m is the number of installation nodes for wind-solar-storage systems; d is the number of typical scenarios; $P_t$ is the probability of typical scenario t;$k$ is the number of thermal power generating sunits; $\alpha^{th}_i$ is the coal consumption coefficient; $P^{th}_{i,t}$ is the active power output of thermal power unit *i* at time *t*; $C_{coal}$ is the unit price of coal.

$C_W$, $C_P$, $C_S$ respectively stand for the comprehensive unit cost of wind energy, photovoltaic power, and energy storage;$C_{IW}$, $C_{IP}$, $C_{IS}$ respectively represent the installed capacity of wind power, photovoltaic power, and energy storage; $R_W$, $R_P$, $R_S$ respectively represent the capital recovery factor of wind power, photovoltaic power, and energy storage.

The calculation formulas for the capital recovery factor are shown in Equations (5)-(7):

$$\mathrm{R}_{\star} = (1 + \mathrm{r})^{\star}\mathrm{I}[(1 + \mathrm{r})^{\star} - 1] \tag{5}$$

$$\mathrm{R}_{\mathrm{p}} = (1 + \mathrm{r})^{\tau}/[(1 + \mathrm{r})^{\tau} - 1] \tag{6}$$

$$\mathrm{R}_{\epsilon} = (1 + \mathrm{r})^{\epsilon}\lceil(1 + \mathrm{r})^{\epsilon} - 1] \tag{7}$$

Where $n^w$, $n^p$, $n^s$ respectively represent the service life of wind power, photovoltaic power, and energy storage systems; r is the discount rate.

$$f_2 = \sum_{t=1}^{\mathrm{d}} p_{\mathrm{t}} \sum_{i=1}^{\mathrm{m}} \left(P_{i,t}^{wc} + P_{i,t}^{\mathrm{pc}}\right) \tag{8}$$

Where: $\mathrm{P}_{\mathrm{i,t}}^{\mathrm{wc}}$ is the curtailment power of the wind turbine at node i at time t,$\mathrm{P}_{\mathrm{i,t}}^{\mathrm{pe}}$is the curtailment power of the photovoltaic generator at node *i* at time *t* [8].

### 3.3. Uncertainty Modeling

First, seasonal typical days are extracted from the annual 8760-hour historical data of wind and photovoltaic power using K-Means clustering. Then, the Frank-Copula function is used to construct the joint probability distribution of wind and photovoltaic output to capture the correlation between them. A large number of scenarios covering the possible states of wind and solar uncertainty are generated based on the joint distribution. The Kantorovich distance between each scenario and other scenarios is calculated, similar scenarios are merged, and the probabilities are updated. This iteration is repeated until the number of scenarios is reduced to the target number, and the final scenarios are output.

K-Means clustering is a core tool for extracting typical days. It divides the dataset into K clusters through iteration, ensuring that the similarity within clusters is the highest and the difference between clusters is the largest. The cluster center is used to represent a typical day. Clustering is performed by season, and the time-series data of annual wind power output, photovoltaic power output, and load are input, with the shape similarity of the load curve as the indicator. Finally, typical days for each season are output.

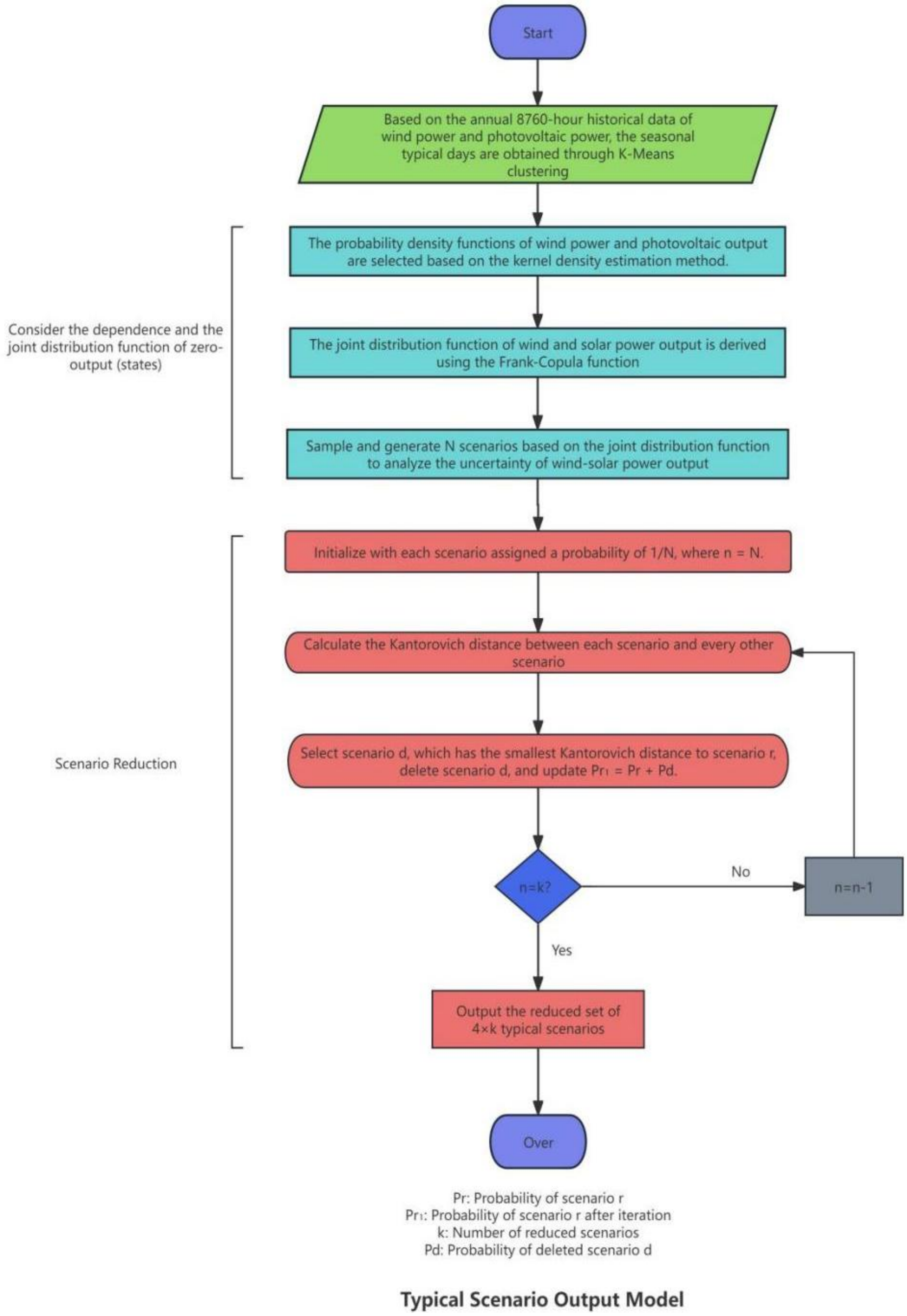

**Figure 2:** Typical Scenario Output Model.

In the “typical scenario generation”, the Frank-Copula function is used to construct the joint probability distribution of wind and photovoltaic output, which establishes a connection between them and overcomes the defect of considering them independently. It accurately depicts the “non-independent relationship” between wind output and solar output. On this basis, it obtains the joint distribution function of wind and solar output. Then, it performs Monte Carlo sampling according to this joint distribution function. Through this sampling process, a considerable number of wind and solar output scenarios are generated. These generated scenarios all include the correlation between wind output and solar output. The Kantorovich distance is an indicator for measuring the difference between two probability distributions. It is used to quantify the similarity between scenarios, identify the most representative scenarios based on this, and reduce the number of scenarios. The operational process of the model is shown in Figure 2.

### 3.4. Constraint Conditions

The optimization model is subject to the following physical and operational constraints:

(1) Power Balance Constraint: The total power generation from all sources must equal the sum of the total load demand and system power losses at any given time.

(2) Equipment Operation Constraint: The power output of wind turbines and photovoltaic panels is constrained by weather conditions and must operate within their respective rated power limits.

(3) Energy Storage System (ESS) Constraint: The State of Charge (SOC) of the ESS must be maintained within safe upper and lower bounds at all times. Furthermore, the ESS cannot be in both charging and discharging states simultaneously.

## 4. Application of the Optimization Framework in the Context of Smart Grids

### 4.1. System Configuration and Technical Overview

A 1.5 MW permanent magnet direct-drive wind turbine is selected, with a cut-in wind speed of 3 m/s, a rated wind speed of 12 m/s, and a cut-out wind speed of 25 m/s. The unit comprehensive cost is 15,000 yuan/kW, The annual routine operation and maintenance cost is 140 yuan/kW, and the design service life $n^W$=20 years. The output follows the Weibull distribution, and the short-term fluctuation range can reach 40%-60% of the rated output. Using the capital recovery factor formula $R_W=(1+r)^{n^W}/[(1+r)^{n^W}] -1]$ (with a discount rate r = 5%), the initial cost and service life could be converted into the annual investment cost, which is embedded into the objective function $C_{inv}$. The annual operation and maintenance cost is directly included in $C_{ope}$.

### 4.2. Operation Strategy and Case Analysis

A typical case is the Trina Solar / China Unicom Sanjiangyuan Green Power Intelligent Computing Integrated Smart Microgrid Demonstration Project. Located in the core area of the Sanjiangyuan National Ecological Protection Zone, this project is the world's highest-altitude "zero-carbon computing power" lighthouse project. It deeply integrates photovoltaic, wind power, energy storage, and computing facilities. Relying on Trina Solar's intelligent dispatching scheme, it implements a "two-charging and two-discharging" strategy to achieve 100% stable green power supply, with an annual power supply of over 10 million kWh [9]. The project adopts N-type double-sided double-glass modules, and the innovative design of the support system balances high efficiency and stability. The energy storage system provides core support for "green power-driven AI computing power", and the design of the photovoltaic support being 0.3 meters above the ground effectively promotes the natural restoration of the grassland [10].

Drawing on the actual operation data of the Sanjiangyuan Project in July 2024 (provided by Trina Solar's microgrid monitoring platform), two comparison scenarios are set up: "before optimization (no energy storage + fixed intelligent computing load)" and "after optimization (implementation of the operation strategy generated by the model)". The analysis is carried out from two balance dimensions, namely "economy-environmental protection" and "reliability-economy", to verify the practical validity of the optimization model.

A seasonal typical day with sunny weather and good stability of wind and solar output is selected, and the comparison of core indicators is exhibited in Table 1. It can be seen that the "economy-environmental protection" balance effect of the system after optimization is significant: the wind and solar curtailment rate decreases from 18.2% to 4.8%, which is lower than the policy upper limit of 5%. Among them, the photovoltaic curtailment rate decreases from 22.5% to 5.0%, and the wind power curtailment rate decreases from 14.8% to 4.6%. This benefit comes from the "two-charging and two-discharging + intelligent computing load adjustment" strategy, which fully absorbs the surplus new energy and avoids the waste of wind and solar resources in high-altitude areas. The daily converted value of the full-life-cycle cost decreases from 116,400 yuan to 89,200 yuan, with a reduction rate of 23.4%. This is mainly due to two aspects: first, the collaboration between energy storage and intelligent computing reduces the number of starts of the backup diesel generator (from 3 times to 0 times; the backup power source of the Sanjiangyuan Project is a diesel generator), and the diesel consumption decreases from 12 tons to 0 tons; second, the intelligent computing load operates at full load during the peak output period of energy, which increases the computing power output by 30% and indirectly increases economic benefits.

The “reliability-economy” balance effect is also prominent: the power supply insufficiency probability decreases from 2.1% to 0.3%. A short-term power gap only occurs at the evening peak (19:00) due to a sudden drop in wind power (from 20 MW to 8 MW). The rapid response of the supercapacitor (increasing the output to 5 MW within 0.1 seconds) and the instantaneous derating of the intelligent computing load (from 25 MW to 20 MW) work together to reduce the gap from 12 MW to 3 MW, without affecting the power supply of the basic load. The zero start of the diesel generator not only reduces the cost but also reduces carbon emissions (from 1,250 tons to 780 tons, with a reduction rate of 37.6%), achieving a linked improvement in reliability and environmental protection. This result verifies the adaptability of the model to the off-grid microgrid scenario in high-altitude areas, which is consistent with the conclusion of paper [11] in the optimization of plateau wind-solar-storage systems.

**Table 1.** Comparison of Typical Daily Operation Indicators of the Sanjiangyuan Project

| Indicator | Before | After | Improvement Rate |
|---|---|---|---|
| Wind and Solar Curtailment Rate (%) | 18.2 | 4.8 | 73.6% |
| Full-Life-Cycle Cost (10,000 yuan/day) | 11.64 | 8.92 | 23.4% |
| Carbon Emissions (tons/day) | 1250 | 780 | 37.6% |
| Power Supply Insufficiency Probability (%) | 2.1 | 0.3 | 85.7% |
| Diesel Consumption (tons/day) | 12 | 0 | 100.0% |
| Intelligent Computing Power Output (PFlops/day) | 864 | 1123 | 30.0% |

## 5. Development Trends, Challenges, and Model Adaptability

Smart grids with wind-solar-storage systems show a good development trend under the support of government policies and technological innovation, but they still face some problems and challenges that need to be solved urgently.

### 5.1. Development Trends and Challenges

(1) Large-Scale and Integrated Development

Wind-solar-storage integrated projects are showing a trend of large-scale development, such as the construction of the 1 million kW wind-solar-storage integrated base in Hainan Prefecture, Qinghai Province. At the same time, the construction of large-scale integrated projects is still being promoted continuously. However, there are too many uncertain factors. In addition to weather conditions, factors such as user behavior and economic development also increase the difficulty of modeling.

(2) Precision of Uncertainty Modeling

With the development of big data technology and artificial intelligence, uncertainty estimation models will become more accurate. Integrating multi-source data algorithms can improve the prediction accuracy of wind and solar output and load; at the same time, combining real-time data to dynamically adjust optimization strategies can enhance the adaptability of the model to deal with uncertainties. However, how to balance the model’s calculation efficiency while ensuring accuracy and obtain the optimal solution within a reasonable time is a current breakthrough point.

(3) Policy Support and Market Mechanism Improvement

The state has issued a series of policies to support the development of smart grids with wind-solar-storage systems. For example, the “Action Plan for Accelerating the Construction of a New-Type Power System (2024-2027)” proposes the construction of a number of smart microgrid projects. At the same time, the market mechanism is also constantly improving. Green certificate trading and carbon financial derivatives will drive the proportion of market-oriented income to exceed 45%. However, the inconsistent standards in grid-connected regions bring difficulties to the grid connection of wind-solar-storage equipment and the unified dispatching of the power grid. The high expense of energy storage still affects the economy of energy storage systems and restricts their large-scale development. In addition, there is a lag in the construction of power transmission channels in the northwest region, which increases the risk of clean energy curtailment; eastern provinces are facing constraints on land resources, and the available roof resources for distributed photovoltaics will be close to saturation, which limits the further development of wind-solar-storage projects. Most of the current output models focus on technical optimization, but they cannot adapt to changes in the market environment. How to integrate market signals into the optimization model in real time is an important challenge.

### 5.2. Model Adaptability

Through the collaboration of multi-objective functions (minimization of $f_1$ and $f_2$), the model reduces costs while improving energy utilization efficiency, indirectly alleviating the pressure of high costs. Taking the Sanjiangyuan Project as an example, through the “two-charging and two-discharging “energy storage dispatching strategy, the model reduces the number of starts of the backup diesel generator (from 3 times to 0 times) on the one hand, resulting in zero diesel consumption costs; on the other hand, it improves the operating efficiency of the intelligent computing peak output period load of wind and solar energy, increasing the computing power output by 30% and indirectly increasing economic benefits. Finally, the daily converted value of the full-life-cycle cost decreases from 116,400 yuan to 89,200 yuan (a reduction rate of 23.4%), which verifies the adaptability of the model to alleviate the challenge of high energy storage costs through the dual paths of “cost control + benefit improvement”.

## 6. Conclusion

This paper proposed a multi-objective optimization model for Wind-Photovoltaic-Energy Storage (WPES) systems in smart grids. The model, centered on minimizing the total annualized cost($f_1$)and the annual renewable energy curtailment ($f_2$), and integrated with scenario processing techniques—K-Means clustering, the Frank-Copula function, and Kantorovich distance—effectively addresses planning challenges arising from the uncertainty and correlation of wind and solar power output. It can be seen that this model provides a relatively refined and effective quantitative tool for the planning of wind-solar-storage smart grids. It converts abstract economic and environmental objectives into calculable and visual mathematical indicators, improves calculation efficiency through scenario reduction, and ensures the practicality of the planning scheme. It successfully balances the system’s economy and environmental benefits and provides technical support for the stable operation of the power grid with a high share of renewable energy connected.

The core contribution of this paper lies in filling the gap that traditional planning methods are difficult to balance multi-objectives and uncertainties. The multi-objective optimization framework proposed by the model provides reusable scenario modeling and solution ideas for researchers in the energy field, and also provides a quantitative basis for the configuration of wind-solar-storage systems and the formulation of operation strategies in engineering practice, which is conducive to promoting the efficient implementation of the new-type power system under the “dual carbon” goals.

The current model still has limitations. Future research needs to make breakthroughs in the following aspects: first, integrating models of new energy storage technologies such as hydrogen energy storage to enrich the selection dimensions of energy storage systems; second, incorporating market mechanisms such as green certificate trading and carbon finance into the objective function to enhance the adaptability of the model to the market environment; third, optimizing the uncertainty modeling method, exploring dynamic adjustment algorithms combined with real-time meteorological data, and further improving the calculation efficiency while ensuring prediction accuracy to cope with more complex grid operation scenarios.

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