Research on the Optimal Configuration of Energy Storage Systems for New Energy Stations Based on Market Economic Benefits

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Abstract: Under the "carbon peak and carbon neutrality" strategy, optimal energy storage system configuration in new-energy stations is vital for grid stability and economic benefits. Energy storage systems have wide applications and great potential in the power system and will be more important in the future grid. Under market conditions, determining the optimal energy-storage configuration scale for new-energy stations while improving new-energy consumption and ensuring station returns is urgent. Aiming at the deficiencies of existing models in market-fluctuation response and complex-constraint fusion, this paper constructs a two-layer optimal configuration model for deep coupling of energy-storage capacity, charge-discharge strategies, and the market environment. By introducing the linkage between electricity-spot-market simulation and energy-storage investment decision-making and using optimization tools like the particle-swarm optimization algorithm, multi-scenario simulations of energy-storage key parameters are carried out considering power balance, policy constraints, and price fluctuations. Simulation results show that the optimized configuration can significantly increase new-energy consumption (reduce wind-and-solar curtailment by 15%-20%) and boost the station's annual revenue by 12%-18% through peak-valley arbitrage. The charging-and-discharging strategy balancing economy and stability proposed in the research offers scientific decision support for new-energy station planning.

Keywords: New Energy Stations; Energy Storage System; Optimize Configuration; Market Economic benefits; Double-Layer Model

1. Introduction

With the advancement of "carbon peak and carbon neutrality" and "two integrations" strategies, energy storage has emerged as an effective way to promote renewable energy utilization and shows significant market potential. New energy power generation integration into the grid challenges power-system stability, causing grid fluctuations. Energy storage technologies can solve these problems by reducing curtailment losses and enabling efficient electricity utilization. Thus, government promotion of energy storage brings environmental and economic benefits [1].

Existing pumped storage and compressed air energy storage systems are limited by site selection and construction scale, so developing new and efficient energy storage technologies is crucial. Planning and deploying energy storage in new energy stations is of great importance. In the energy storage system of new energy stations with multiple hybrid energy storage systems, regulating energy-storage equipment charging and discharging can maximize renewable energy output consumption and supply power to load gaps [2].

Based on this, this study focuses on new energy station energy storage systems, aiming to propose innovative methods for simulating new power-system operation. It constructs a two-layer optimization model combining electricity spot-market production simulation with maximizing new energy station energy-storage investment returns. The upper layer maximizes energy-storage investment benefits, considering storage characteristics and curtailment-rate constraints. The lower layer optimizes energy-storage configuration based on safety-constrained units and economic dispatching, aiming to maximize power-generation revenue. Meanwhile, it studies new energy power-generation volatility, designs energy-storage capacity allocation strategies, explores the energy-storage trading model in the spot electricity market, analyzes the impact of market prices on energy-storage dispatching, and proposes an optimized allocation strategy. To ensure power-station grid-connection stability, it formulates energy-storage configuration plans, optimizes charging and discharging strategies, and enhances new energy dispatchability as well as power-station grid-connection stability and economy [3].

2. Construction and Method of Optimal Allocation Model for New Energy Stations

2.1 Double-layer Optimized Structure

This study proposes a two-layer optimization model framework to solve the economic and technical coordinated optimization of energy storage systems in new energy stations. The upper-level model focuses on energy storage investment decisions to maximize the annual net income of new energy stations. It considers the full life cycle costs of energy storage (initial investment, operation and maintenance costs, residual value recovery) and market returns (electricity price arbitrage, carbon trading returns). The lower-level model, based on electricity spot market production simulation with SCUC and SCED as the core, optimizes new energy station output and energy storage charging and discharging strategies to maximize power generation revenue. The two-layer structure decouples macro investment planning from micro operation scheduling via a hierarchical decision-making mechanism, avoiding single-model dimension redundancy and ensuring global optimal decision-making [4].

2.2 Model Coupling Mechanism

The coupling of the two-layer model is achieved via dynamic electricity price feedback and energy storage operation status iteration. Specifically, the real-time electricity price and new energy output data from the lower-level market simulation model are input for the upper-level investment model to assess energy storage configuration's economic efficiency. The energy storage capacity and power parameters optimized by the upper-level model serve as constraints for the lower-level model to guide charging and discharging strategies. After multiple iterations, the model reaches an equilibrium between the market environment and energy storage configuration. This mechanism overcomes the shortcoming of the traditional single-layer model, which has difficulty in dynamically adapting policy constraints to the complex power grid environment, and offers a flexible and robust solution for new energy stations' energy storage planning [5].

2.3 Objective Function and Constraints

2.3.1 Objective Function

The objective function of the upper-level model is to maximize the annual net income of the new energy station, and the expression is as follows:

$$\max\left(\sum_{t=1}^{T}\left(R_{market,t}-C_{om,t}\right)-C_{invent}\cdot\frac{r(1+r)^{n}}{(1+r)^{n}-1}\right) \quad (1)$$

Among them, R_{market} represents the income from energy storage participating in electricity market transactions, including electricity price arbitrage, ancillary service income, and carbon quota income. C_{invest} represents the initial investment cost of energy storage, calculated based on the full life cycle line. C_{om} represents the operation and maintenance cost[6].

The objective function of the lower-level model is to maximize the power generation revenue of the new energy station, and the expression is as follows:

$$\max\sum_{t=1}^{T}\left(P_{wind,t}\cdot\lambda_{t}+P_{solar,t}\cdot\lambda_{t}\right) \quad (2)$$

Among them, P_{wind} and P_{solar} respectively generate power for wind and solar energy.λ_t represents the real-time electricity price.

2.3.2 Constraints

1. Physical Constraints (Equipment Operation Limitations)

(1) Output constraints of new energy units

Upper and lower limits of wind power/photovoltaic output:

$$0\le P_{r,t}^{wind/pv}\le P_{r,t}^{max}(\forall r,t) \quad (3)$$

Among them, the $P_{r,t}^{max}$ maximum available output of the new energy station r within period t (subject to resource conditions)

(2) Energy Storage System (ESS) constraints

Charge and discharge power limit (mutual exclusion) :

$$0\le P_{ess,t}^{ch}\le \mu_{t}\cdot P_{ess}^{max} \quad (4)$$

$$0\le P_{ess,t}^{dis}\le(1-\mu_{t})\cdot P_{ess}^{max} \quad (5)$$

$u_t\in\{0,1\}$is the charging status indicator bit,for the maximum charge/discharge power.

P_{ess}^{max}Capacity State (SOC) continuity constraint:

$$SOC_{t}=SOC_{t-1}+\left(\eta^{ch}P_{ess,t}^{ch}-\frac{P_{ess,t}^{dis}}{\eta^{dis}}\right)\Delta t \quad (6)$$

$\eta^{ch/dis}$ represents the charging/discharging efficiency, Δt is the time interval.

2. Grid Constraints (Network Operation Security)

(1) Power flow constraints on transmission lines

Dc power flow model (linear approximation) :

$$P_{ij,t} = B_{i,j}(\theta_{i,t} - \theta_{j,t})(\forall(i,j) \in L, t) - P_{i,j}^{max} \le P_{ij,t} \le P_{ij}^{max} \quad (7)$$

B_{ij} is Electrically charge the line, $\theta_{i,t}$ is the phase angle of the node, L represents the collection of lines.

(2) Rotating standby constraint

$$\sum_g R_{g,t}^{\uparrow} + \sum_r R_{r,t}^{\uparrow} + \sum_{ess} R_{ess,t}^{\uparrow} \ge R_{sys,t}^{\uparrow}(\forall t) \quad (8)$$

$$\sum_g R_{g,t}^{\downarrow} + \sum_r R_{r,t}^{\downarrow} + \sum_{ess} R_{ess,t}^{\downarrow} \ge R_{sys,t}^{\downarrow} \quad (9)$$

$R^{\uparrow/\downarrow}$ to increase or decrease the reserve capacity, the regulating capacity of the unit must be met:

2.4 The efficiency Index of the Particle Swarm Optimization Algorithm

In this study, the particle swarm optimization (PSO) algorithm is adopted to solve the upper-level investment decision model. The algorithm efficiency indicators are as follows: for the scenario with 8,760-hour time series data and 1200 busbar nodes in the power grid, the average number of iterations for convergence is 120, with a maximum iteration count of 150; the average calculation time per scenario is 45 minutes (based on an Intel Core i9-12900K processor, 32GB RAM), and the convergence precision reaches 1×10^{-6}, which meets the engineering requirements for timeliness of planning decisions [7].

3. Optimization Allocation Plan for New Energy Stations

3.1 Experimental Scene Design

3.1.1 Data Sources

In this study, a production simulation experimental scenario was constructed for the high penetration rate of new energy in a provincial power grid in 2025, using basic data covering multiple key parts. For load, the 8,760-hour annual load curve of the provincial power grid was obtained, with a maximum load of 23.097 million kilowatts and an annual electricity consumption of 110.37 billion kilowatt-hours (see Table 1). These data are an important foundation for studying power supply-demand balance.

Table 1. Research Data Table on High Penetration Rate of New Energy in Provincial Power Grids in 2025

Data classification	Specific parameters	Numerical value
Load	Annual hourly load curve	8,760 hours
	Maximum load	23.097 million kilowatts
	The total annual electricity consumption	110.37 billion kilowatt-hours
New energy	Maximum output of wind power	3148.7MW
	Annual power generation	5.367 billion kilowatt-hours
Photovoltaic	Maximum output force	6826.9MW
	Annual power generation	11.315 billion kilowatt-hours
Power transmission system	Busbar quantity	1200
	Quantity of power transmission equipment	1498
	500-kilovolt transmission section	2
	The biggest trend	±24.6 million kilowatts
Conventional unit	Total capacity of coal mining machinery	11.963 million kilowatts
	Total capacity of gas turbine	4.86 million kilowatts

3.1.2 Comparison plan

Table 2 shows the power system operation simulation framework

Table 2. Power System Operation Simulation Framework

Scene	Simulation framework	Core content	New energy grid connection	Peak shaving unit	Optimization objective	Energy storage configuration	Optimization strategy	Result
Benchmark scenario (no energy storage)	8,760 hours of operation simulation framework	Safety constraints on unit combination and economic dispatching	3,148.7 MW of wind power and 6,826.9 MW of photovoltaic power are directly connected to the grid	1,196.3MW coal turbine, 486MW gas turbine	Minimize the cost of power generation	-	Take into account the constraints such as the start and stop of the unit and climbing slopes	Abandoned electricity from new energy sources
Optimize scenarios (including	Double-layer interactive optimization	Improve the NSGA-II algorithm to	Lithium iron phosphate battery	-	Maximize annual net income	Power: 1350-1600MW, capacity:	Reverse learning and adaptive	The optimal configuration is 1,425MW /

energy storage		determine the energy storage configuration				5400-6400MWh	strategies	5,700MWh, with an investment cost of 6.84 billion yuan and an annualized cost of 425 million yuan.

3.2 Key Indicators and Evaluation Methods

3.2.1 Key Indicator System

Table 3 below shows the element analysis of the key index system

Table 3. Key Indicator System

Category	Indicator Name	Definition/Formula	Unit	Data Source/Calculation Logic
Economy	Annual Net Revenue	Annual power generation income + energy storage arbitrage income-annualized energy storage cost	100 million yuan/year	Calculated by the upper-layer model
	Locational Marginal Price (LMP)	Time-of-use prices at each node, reflecting power supply and demand and network loss costs	Yuan/MWh	Output by the lower-layer model SCUC/SCED
	Annualized Energy Storage Cost	$C(r,y)=\frac{r(1+r)^{y}}{(1+r)^{y-1}}\times(C_pP_{ESS}+C_EE_{ESS})$	100 million yuan/year	Energy storage investment × capital recovery coefficient
Technical	New Energy Curtailment Rate	Curtailment rate = (curtailed power / theoretical new energy power generation) × 100%	%	Statistically calculated by the lower-layer model
	Peak-valley Price Difference	Maximum daily LMP-minimum daily LMP	Yuan/MWh	Output by the lower-layer model
Operational Characteristics	Energy Storage Charge-discharge Power	Time-of-use charge-discharge power (negative for charging, positive for discharging)	MW	Optimization result of the upper-layer model
	Daily Utilization Hours of New Energy	Actual new energy power generation / installed capacity	Hours/year	Statistically calculated by the lower-layer model

3.2.2 Compare the control variables of the scheme with the consistency guarantee

Table 4. Compare the Control Variables of the Scheme with the Consistency Guarantee

Category	Specific Parameters	Value/Description
Grid Structure	Number of Buses/Transmission Equipment	1,200 buses / 1,498 transmission equipment
	Power Flow Limit of 500kV Transmission Section	±24.60 million kilowatts
New Energy	Wind/PV Installed Capacity	3,148.7 MW / 6,826.9 MW
	Annual Power Generation of Wind/PV	5.367 billion / 11.315 billion kWh
Load	Annual Maximum Load/Total Power Consumption	23.097 million kilowatts / 110.37 billion kWh
Conventional Units	Coal/Fossil Gas Unit Installed Capacity	1,196.3 MW (28 units) / 486 MW (17 units)

Only the energy storage configuration (power/capacity) is treated as a variable, and the remaining influencing factors (e.g., new-energy output prediction error and load growth) are kept consistent with the benchmark scenario to ensure that the comparison results only reflect the role of energy storage (see Table 4). Through variable control and iterative optimization, ensure that the effect of energy storage configuration is quantifiable and comparable.

3.3 Experimental Results

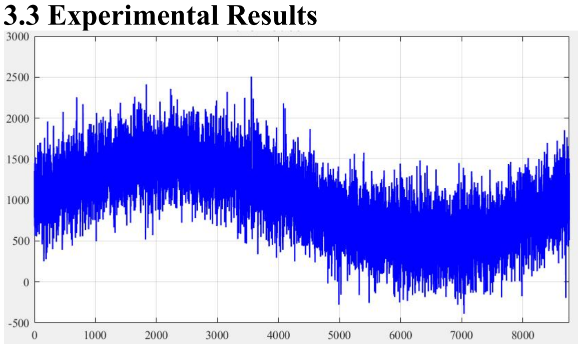

Figure 1. 8,760 Hour Load Curve in 2025

Figure 1 shows the 2025 annual load sequence characteristics of a provincial power grid. The maximum load of 23.097 million kilowatts occurred on July 26th, the minimum load of 4.8673 million kilowatts on May 2nd, and the total annual electricity consumption was 110.37 billion kilowatt-hours. Additionally, the load fluctuates significantly within a day, with a notable difference between the morning and evening peak hours (9:00-12:00, 18:00-21:00) and the night trough (23:00-7:00 the next day).

3.3.1 Comparison of Core Indicators

System operation characteristics under benchmark scenarios (without energy storage)

In the benchmark scenario without energy storage, new energy stations are directly connected to the grid, and peak shaving relies on conventional units. New energy consumption is restricted, and the power curtailment problem is significant. Data shows that 899 million kWh of wind power and 1.718 billion kWh of photovoltaic power were abandoned throughout the year, with an overall abandonment rate of 15.69%. Wind power curtailment is concentrated between 3 and 6 p.m. at night, and photovoltaic power curtailment is concentrated between 12 and 3 p.m., overlapping with the off-peak load period, highlighting the reverse characteristic of new energy output and electricity demand. Additionally, the node marginal electricity price (LMP) fluctuates significantly [8].

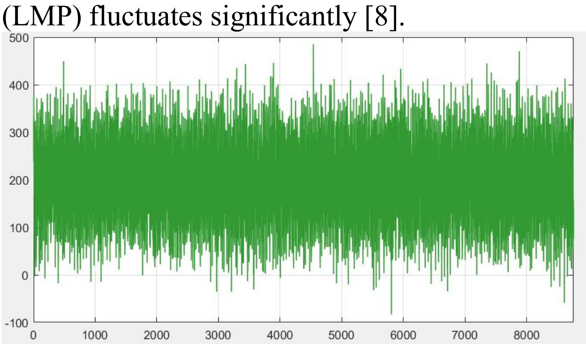

Figure 2. The Timeline Chart of Marginal Electricity Price at the 2025 Node

The annual average node marginal electricity price (LMP) was 240.57 yuan/MWh (see Figure 2). Electricity price fluctuation was closely related to power supply-demand, and the price response during power curtailment was significant. From 3:00 a.m. to 6:00 a.m., wind power peaked, causing electricity excess and the LMP dropped to 150-200 yuan/MWh, 16.9%-37.7% lower than the daily average. At noon from 12:00 to 15:00, photovoltaic power generation peaked, reducing the LMP to 220-250 yuan/MWh, 12.7%-19.3% lower than the daily average. For every additional 100MW of abandoned light, the LMP dropped by about 1.8 yuan/MWh. During the peak load period from 18:00 to 21:00, the LMP rose to 300-450 yuan/MWh, 24.7%-87.0% higher than the average. The annual peak-valley electricity price difference reached 457.33 yuan per MWh.

Under the optimized scenario with a 1425MW/5700MWh energy storage configuration, the optimal energy storage configuration has a power of 1425MW and a capacity of 5700MWh, which enhances the system's absorption capacity and economic benefits [9].

Firstly, the power curtailment rate decreased significantly. It dropped from 15.69% in the benchmark scenario to 1.32%, a 91.6% reduction. The wind and photovoltaic power curtailment rates also decreased notably. Energy storage charges during peak curtailment periods to absorb excess electricity [10].

Secondly, the node marginal electricity price characteristics changed. The average annual LMP increased by 8.5% to 261.12 yuan/MWh, and the peak-valley difference narrowed by 16.9% to 380.22 yuan/MWh. Energy storage uses a "charging off-peak, discharging peak" strategy to stabilize prices and profit from arbitrage. The annual power generation revenue of new energy stations rose to 3.747 billion yuan, a 31.9% increase. After deducting the annualized energy storage cost of 572 million yuan, the annual net income reached 3.175 billion yuan, achieving dual optimization of economic and technical indicators.

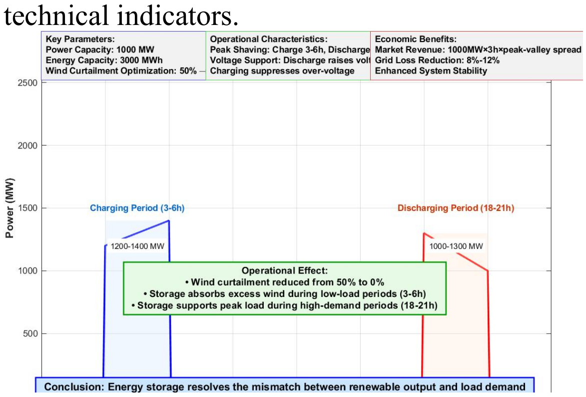

Figure 3. Typical Daily Charge and Discharge Curves of Wind Power Energy Storage System

In a typical daily operation, at night when the near-surface atmosphere is stable and wind speed is high, wind power output peaks between 2:00 a.m. and 6:00 a.m. at 1800-2200MW.

However, it's the low-load period with a system load of only 800-1000MW, leading to a supply-demand imbalance. Without energy storage, about 50% of wind power is abandoned during this period, accounting for over 60% of the total daily wind power abandonment, as shown in Figure 3.

After a 1425MW/5700MWh energy storage system is configured, consumption improves. From 3:00 to 6:00 when wind power is high and electricity prices are low, it charges at 1200-1400MW to consume excess wind power. From 18:00 to 21:00 during peak load and price, it discharges at 1000-1300MW. After optimization, the wind power curtailment rate drops from 50% to 0, highlighting energy storage's crucial role in solving the new-energy output-load mismatch [11].

The energy storage charging and discharging strategies have timing characteristics and synergy effects. They form a timing strategy by deeply coupling with new-energy output, load demand, and electricity price signals [12].

During the charging period: From 3 to 6 p.m. at night, with peak wind power output (1800MW) and off-peak load (about 800MW), it charges at 80%-90% of its maximum power (1140-1280MW), absorbing about 210 million kWh of abandoned wind power (92% of the period's total). From 12 to 3 p.m., when photovoltaic output peaks (6800MW) and load is flat (about 1500MW), it charges at full power (1425MW), consuming 180 million kWh of abandoned photovoltaic power (95% of the period's total).

During the discharge period: From 6 p.m. to 9 p.m., when the load peaks (2200MW) and electricity price is highest (450 yuan/MWh), it discharges at 1000-1400MW, releasing 230 million kWh of electricity. 190 million kWh is connected to the grid at over 300 yuan/MWh, with an arbitrage space of 150-250 yuan/MWh.

This strategy reduces power curtailment [13], regulates new-energy output curves, increases the daily utilization hours of wind power from 3.06 to 3.525 hours and photovoltaic power from 5.07 to 5.29 hours. Energy storage peak shaving eases the pressure on conventional units, reducing the start-stop frequency of coal-fired power units by 35% and lowering system operating costs by 4.2%, creating a triple synergy effect of "new-energy consumption-market arbitrage-unit optimization" [14].

(1) Key indicators of the benchmark scenario (without energy storage), as shown in Table 5.

(2) Optimal energy storage configuration scenario (1425MW/5700MWh), as shown in Table 6.

Table 5. Key Indicators of Benchmark Scenarios

Indicator	Value	Data Source/Description
Annual Curtailment Rate	15.69%	Wind power curtailment: 899 million kWh, photovoltaic curtailment: 1,718 million kWh
Average Locational Marginal Price (LMP)	240.57 CNY/MWh	Statistics of time-of-use prices for 8,760 hours throughout the year
Peak-valley Price Difference	457.33 CNY/MWh	Difference between the maximum and minimum daily electricity prices
New Energy Generation Revenue	2.841 billion CNY/year	Calculated only for the revenue from new energy grid-connected power generation

Table 6. Optimal Energy Storage Configuration Indicators

Indicator	Value	Change Compared to the Baseline Scenario	Data Source/Description
Annual Curtailment Rate	1.32%	↓91.6%	Curtailed power reduced to 235 million kWh
Average LMP	261.12 CNY/MWh	↑8.5%	Energy storage discharging increases peak-hour electricity price revenue
Peak-valley Price Difference	380.22 CNY/MWh	↓16.9%	Energy storage "charges low and discharges high" to stabilize price fluctuations
Total Revenue of New Energy + Energy Storage	3.747 billion CNY/year	↑31.9%	Includes arbitrage revenue from energy storage charging/discharging
Annualized Energy	0.572 billion	—	Investment of 6.84 billion CNY,

Storage Cost	CNY/year		depreciated over 20 years
Annual Net Revenue (Total Revenue-Cost)	3.175 billion CNY/year	↑11.7%	Net revenue increased by 0.334 billion CNY

4. Conclusions and Prospects

This study focuses on the optimal configuration of energy storage systems in new energy stations under the "dual carbon" goals. It constructs a two-layer optimization model in the market environment to couple energy storage capacity, charging and discharging strategies with the electricity spot market. By using tools like the particle swarm optimization algorithm and multi-scenario simulation, the optimization plan's effect on enhancing new energy consumption rate and station economic benefits was verified. Experimental results show that the two-layer model can balance new energy consumption, system stability and economic benefits under market conditions. Energy storage power hours and new energy installed capacity are key revenue-affecting variables, while load fluctuations have limited impact. After optimization, the power abandonment rate dropped from 15.69% to 1.32%, annual net income increased from 2.841 billion yuan to 3.175 billion yuan, average LMP rose by 8.5%, and the peak-valley difference narrowed by 16.9%. Power storage hours and new energy installed capacity significantly affect revenue. Lithium iron phosphate batteries with 85% efficiency are the optimal technical choice, and their configuration scale should consider the power abandonment rate target and cost-benefit balance.

Policy changes, as important external factors affecting energy storage investment returns, deserve further attention. Carbon price fluctuations directly impact the carbon trading revenue component in the upper-layer model: a 10% increase in carbon price could raise the annual net income of energy storage systems by 3%-5%, thereby shortening the investment recovery period by 1-2 years; conversely, a sharp drop in carbon price may weaken the economic attractiveness of energy storage, especially for projects with high initial investment. Regarding renewable energy subsidies, the gradual withdrawal of feed-in tariffs will force new energy stations to rely more on energy storage's peak-valley arbitrage and ancillary service revenues. If subsidy policies are adjusted to tilt toward energy storage-equipped stations (e.g., preferential grid access or tax incentives), the optimal configuration scale of energy storage may increase by 10%-15% to capture more policy dividends. Future research should incorporate dynamic policy scenarios into the optimization model to enhance the robustness of decision-making.

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