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Particle Swarm Optimization Based Optimal Sizing Model of PV-Battery Systems for Utility-scale Photovoltaic Power Plants

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ABSTRACT

The intermittency and instability of solar power generation present significant challenges for its effective integration into the grid. This project introduces an advanced Particle Swarm Optimization (PSO) based model for optimizing the configuration of photovoltaic (PV) and battery systems in power stations. The model tackles the intermittency and unpredictability of solar energy by incorporating an uncertainty set within the PSO algorithm, ensuring robust optimization under varying conditions. It also integrates an attention mechanism to enhance the accuracy of PV power output predictions. The study further develops an economic assessment model to evaluate the financial performance of different configurations, considering equipment, maintenance costs, and market prices. The project's findings demonstrate the model's effectiveness in improving both the operational efficiency and economic viability of PV-battery systems.

Keywords: photovoltaic optimization, particle swarm optimization, energy storage, power curtailment, economic efficiency

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
BESS	Battery energy storage system
SOC	State of charge
R1	Direct Current/Alternating Current ratio (DC/AC ratio)
n	The number of Year
INV	Inverter
NCF	Net Cash Flow
NPV	Net Present Value
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
ROI	Return-on-investment

1. INTRODUCTION

Due to the intermittency and uncertainty of photovoltaic power generation, it poses a challenge to the stability of power grid. Configuration of energy storage in photovoltaic power station can store energy during peak photovoltaic power generation and release it when demand peaks or sunlight is insufficient, thereby reducing power curtailment and improving the economic and environmental benefits of photovoltaic power plants. The frequency modulation and peak regulation services provided by the energy storage system can alleviate the stability problems of the power grid caused by fluctuations in photovoltaic power generation, effectively smooth the output of photovoltaic power generation, and improve the flexibility and stability of the power system[1]. The ability of energy storage systems to enhance overall system flexibility in end-user applications such as transmission and distribution networks and residential building and vehicle-to-grid technologies is critical to increasing the share of renewables in the energy mix and driving the energy transition.

Power curtailment, which refers to the waste of electricity due to the grid's inability to absorb excess generation, not only impacts economic efficiency but also undermines the use of renewable energy. Increased solar penetration leads to higher power curtailment due to grid limitations, but combining solar with energy storage can effectively address this issue[2–4].

This research presents an innovative optimization model which employs a Particle Swarm Optimization (PSO)[5,6] algorithm to address the uncertainties inherent in solar energy generation, ensuring robust system configuration. It also integrates an attention mechanism to refine the accuracy of PV output predictions, adapting to the dynamic conditions of solar energy production. The research further encompasses an economic assessment model to evaluate the financial feasibility of

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various PV and battery configurations, considering operational costs and market dynamics. The findings offer valuable insights into optimizing the design and operation of PV power stations, contributing to the advancement of renewable energy integration and supporting the transition towards a sustainable energy future.

2. MATERIAL AND METHODS

2.1 Research framework

The research begins with system simulation inputs, which include meteorological data such as irradiance, temperature, humidity, and wind speed, along with equipment parameters like storage selection, installation capacity, loss coefficients, and degradation coefficients. The simulation model generates a running curve for the PV-battery system, which is influenced by operational strategies such as fixed boundary strategy and peak shaving strategies. It also considers operational constraints like charging and discharging power and efficiency (Figure 1).

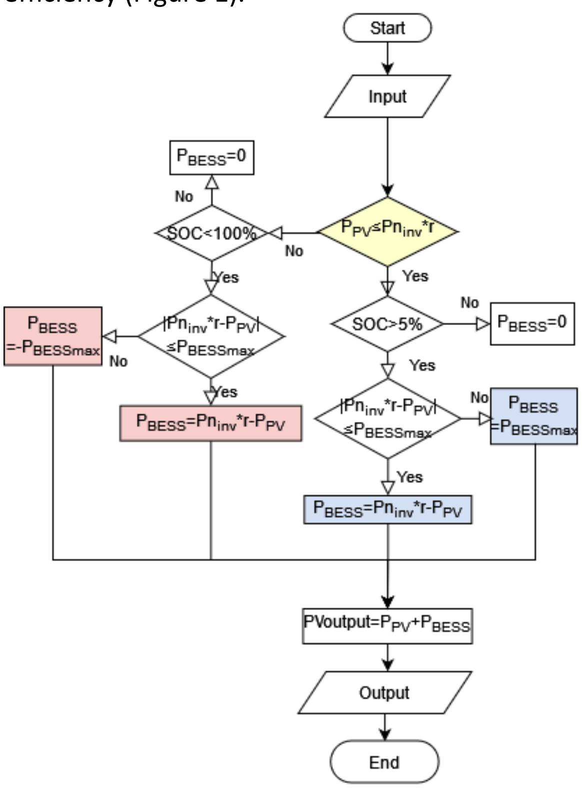

Fig. 1 Power generation mechanism of photovoltaic energy storage integrated system

The framework employs a Particle Swarm Optimization (PSO) model to determine the optimal configuration that maximizes economic efficiency, defined by the net present value (NPV) and utilization hours. The optimization model takes into account constraints such as operational power limits and battery state of charge. The economic assessment, in turn, evaluates the levelized cost of electricity (LCOE), annual energy production, and the internal rate of return (IRR) based on the total utilization hours and other financial metrics. This structured approach provides a scientific basis for designing PV-battery systems that are not only efficient but also economically viable.

2.2 Data processing

The research utilizes four key data sources for developing and validating an optimal sizing model for PV-battery systems. The first is meteorological data from Xining Hongqi I Photovoltaic Power Station spanning 2021 to 2022, including solar irradiance, temperature, humidity, and wind speed. The second consists of the power station's actual power output data for the same period. The third data source includes AGC records of the power station, indicating the grid's energy demand and curtailment. The final source comprises technical specifications for PV system configuration and energy storage parameters.

The meteorological data was cleaned and formatted for PVsyst simulation software, with calculations made for the clearness index and angle of incidence. The PV output data was validated and normalized to reflect performance over time. AGC records were analyzed to understand grid demand and curtailment patterns. Technical specifications were compiled into a database for the optimization model to evaluate system configurations. The integrated data sets inform simulation models, ensuring they are based on reliable information.

2.3 Methods

The study is based on a real-case scenario of a 1 MW PV system located in a region with high solar potential. The system's performance is analyzed over a 25-year period, considering various parameters such as solar irradiance, temperature, system degradation, and battery aging. The following methods are employed:

2.3.1 System Simulation Model

The System Simulation Model for photovoltaic energy storage systems is an essential tool for predicting system behavior under various conditions. It takes into account meteorological inputs along with equipment parameters. The model outputs include the PV system's output curve, detailing electricity generation over time, the operational curve of the energy storage system, indicating how stored energy is used and managed, and the operational curve of power delivered to the grid, showing the flow of electricity from the PV system and energy storage to the grid. The simulation aids in optimizing system performance, ensuring grid stability, and maximizing the use of renewable energy resources.

2.3.2 Economic Assessment Model

The economic assessment model evaluates the levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and return on investment (ROI) for different PV-battery configurations[7]. It ensures accuracy through error analysis and method verification. This provides reliable insights for optimal system design and investment decisions.

$$LCOE = \frac{(C_{PV} + C_{ES}) + \sum_{n=1}^{N} \frac{O_{PV} + O_{ES} + C_F + C_{tax} + C_d}{(1+i)^n} - \frac{V_R}{(1+i)^N}}{\sum_{n=1}^{N} \frac{E_n}{(1+i)^n}}$$

$$NPV(i) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

$$IRR \approx i_1 + \frac{|NPV_1|}{|NPV_1| + |NPV_2|}(i_2 - i_1)$$

$$ROI = \frac{E_t * p - C_{PV} - C_{ES} - O_{PV} - O_{ES}}{C_{PV} + C_{ES} + O_{PV} + O_{ES}} \times 100\%$$

Table 1 Optical storage project economic parameters

Economic parameter	**Yuan/kW**
Equipment cost	1698.84
module	800.00
support	380.00
inverter	130.00
Box transformer	100.00
Collector line	220.00
Other equipment	68.84
Installation cost Civil construction cost	200.00
Access facility allocation	450.00
Land cost expense	242.14
Other expenses	269.08
Static investment per kilowatt	2860.06
0.5C energy storage battery cost	1.2 Yuan/Wh
Operation and maintenance cost	0.04Yuan/W

2.3.3 Optimization model

A particle swarm optimization (PSO) algorithm is utilized to determine the optimal battery size and the DC-to-AC ratio that maximizes the system's economic efficiency while ensuring grid stability. To address the uncertainty in solar irradiance, battery performance, and electricity prices, a robust optimization model is developed using a probabilistic approach to simulate various scenarios and ensure the reliability of the optimal sizing solution.

Objective Function 1: The Internal Rate of Return (IRR) is a crucial indicator for evaluating the economic viability of a project. It represents the discount rate that makes the Net Present Value (NPV) of a project's cash flows equal to zero, signifying that the present value of inflows equals the present value of outflows. The goal is to maximize the IRR, which is equivalent to minimizing the negative of the IRR. Objective Function 2: The utilization hours' optimization aims to maximize the annual utilization hours of the PV station, reflecting the average number of hours the station generates electricity per kilowatt of installed capacity in a year.

The constraints of the optimization model include running power constraints, charged state constraints and energy balance constraints. Among them, the operating power constraint is mainly that the operating power P_{PV} of the DC side should be within its rated power range, and the charging and discharging power P_{bess} of the energy storage system at any time does not exceed its minimum and maximum rated power. In addition, the state of charge SOC of the energy storage system should be between 5% and 100%, ensuring that the energy storage system will not exceed its design maximum and minimum SOC limits during charging and discharging. This helps to avoid over-charging or over-discharging the battery, thereby extending battery life and preventing potential safety risks. The energy balance constraint means that the sum of the output power of photovoltaic power generation and the discharge power of storage should be less than the power limit of the power grid.

$$\min f_1 = \max \sum_{t=1}^{n} \frac{E_t * P - C_{ini} - C_t}{(1+i)^t}$$

$$\min f_2 = -max \sum_{i=1}^{365} \left(\frac{(P_{PV} + P_{bess})\Delta t}{P_{INV}} \right)$$

$$SOC_{i+1} = \begin{cases} SOC_i - \frac{P_i^{bess} \Delta_t}{\eta_d capacity}, & P_i^{bess} > 0 \\ SOC_i - \frac{\eta_c P_i^{bess} \Delta_t}{capacity}, & P_i^{bess} \le 0 \end{cases}$$

$$\underline{SOC} \le SOC_i \le \overline{SOC}$$

$$-P_{rate} \le P_i^{bat} \le P_{rate}$$

$$0 \le P_i^{PV} + P_i^{bat} \le P_{curt}$$

3. RESULTS

The simulation results indicate that the optimal sizing of the PV-battery system significantly impacts its performance and economic viability. The following key findings are observed:

3.1 Sensitivity analysis

An increase in battery capacity leads to higher energy utilization and a reduction in curtailed energy (Fig.2). However, beyond a certain capacity, the marginal benefit of additional storage capacity diminishes due to the increased investment cost. A higher DC-to-AC ratio(R1) results in better utilization of the PV system's capacity but requires a more significant initial investment in inverters(Fig.3). The optimal ratio is found to balance the trade-off between energy yield and inverter cost.

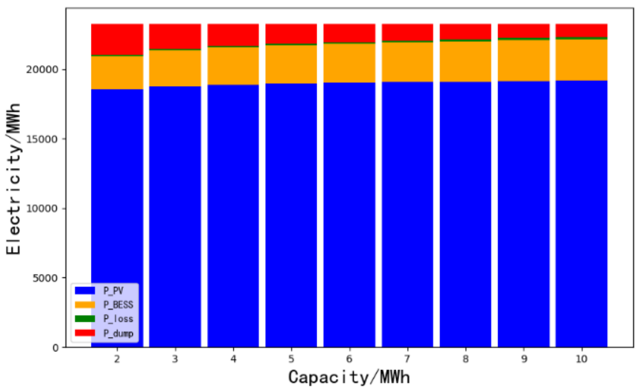

Fig. 2 Curtailment results of different battery capacity

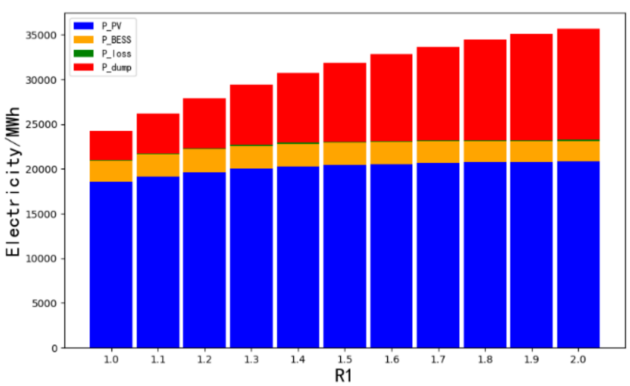

Fig. 3 Curtailment results of different DC-to-AC ratio

The graph illustrates the impact of storage capacity on both the Internal Rate of Return (IRR) and the number of operational hours (Fig.4). As the storage capacity increases from 0 to approximately 2000 units, the IRR initially rises sharply, indicating a higher return on investment at lower capacities. However, beyond this point, the IRR begins to decline, suggesting diminishing returns as capacity continues to increase. Conversely, the operational hours (represented by the red line) show a different trend.

Fig.5 depicts the influence of the Ratio R1 (DC/AC ratio) on the Internal Rate of Return (IRR) and operational hours, given a fixed storage capacity of 2265 kWh. As R1 increases from 1.0 to 2.0, both IRR and operational hours demonstrate a steady upward trend. Specifically, the IRR starts at approximately 0.08 and rises to about 0.15, indicating that a higher R1 correlates with a better return on investment. Similarly, operational hours increase from around 1600 to nearly 3000 hours, suggesting that a higher R1 also enhances the efficiency and utilization of the system.

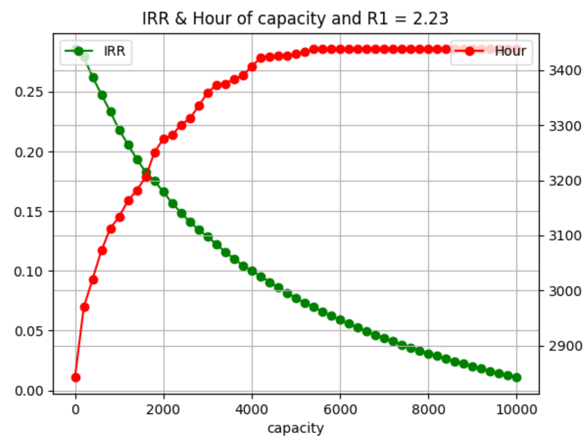

Fig. 4 Results of different battery capacity

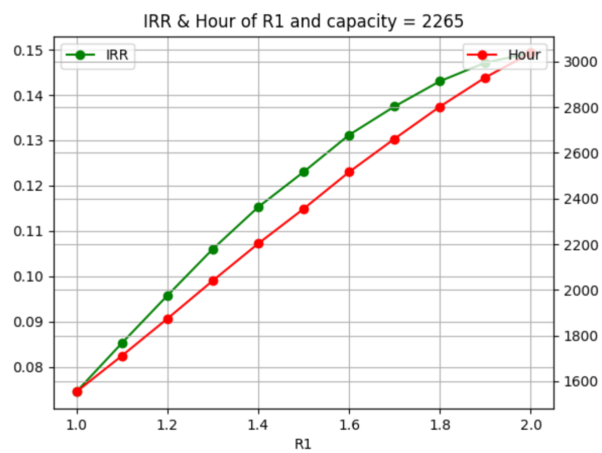

Fig. 5 Results of different DC-to-AC ratio

3.2 Economic Analysis

The economic assessment reveals that configurations with higher battery capacities and optimal DC-to-AC ratios exhibit higher NPV and IRR, indicating better investment potential (Table 2).

Table 2 Economic results of different configuration strategies

DC/AC ratio	Battery capacity (kWh)	Hours	IRR (%)	NPV (yuan)	LCOE (yuan/kWh)	ROI (%)
1.69	302.93	30.02	25.12	9409884.14	0.1569	6.74
1.61	245.09	31.26	24.18	9137861.52	0.1532	6.89
1.63	142.63	32.68	24.17	9216517.62	0.1492	7.07
1.71	182.63	31.70	25.13	9527203.02	0.1518	6.96
1.82	410.92	28.23	26.69	9861246.54	0.1626	6.51
1.88	565.83	26.38	27.57	10023264.21	0.1693	6.26
1.81	233.86	30.41	26.23	9858075.94	0.1556	6.80
1.84	333.86	28.99	26.71	9930423.31	0.1600	6.61
1.85	319.41	29.12	26.79	9969024.35	0.1596	6.63

3.3 Pareto optimal frontier

The Pareto frontier as a set of solutions that represent optimal trade-offs among multiple conflicting objectives. It may explain how different solutions on the Pareto frontier cannot be improved in one objective without sacrificing performance in at least one other objective[8,9].

In the calculation results of the multi-objective particle swarm optimization algorithm (MOPSO), the relative relationship between the economically optimal result and the optimal result of utilization hours is shown in figure 6. The "All solution set" represents all possible combinations of the capacity ratio and energy storage capacity. The "Pareto solution set" indicates the subset of solutions that are Pareto optimal, meaning they offer the best trade-offs between the relevant objectives. The horizontal axis represents the Internal Rate of Return (IRR). The vertical axis represents the utilization hours in a typical year. The points on the graph represent specific solutions based on their positions on the axes.

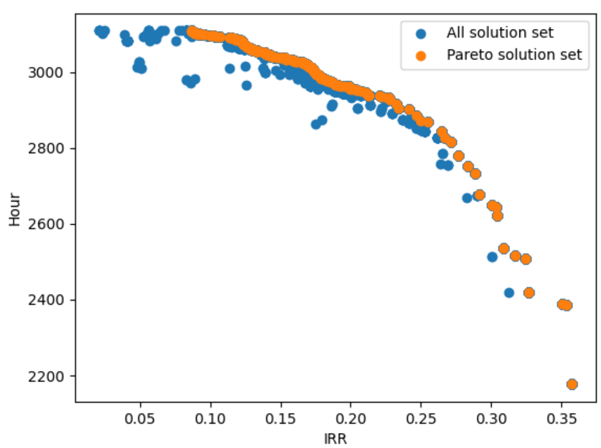

Fig. 6 Pareto optimal solution set

4. DISCUSSION

The "Optimal Sizing Model of Photovoltaic-Battery Systems" project report offers valuable insights into enhancing system efficiency and economic returns. Key findings include identifying the optimal DC-to-AC ratio and energy storage capacity, recognizing the influence of PV and storage system sizes on economic metrics like NPV, IRR and ROI. The study also demonstrates the potential of optimal configurations in reducing energy curtailment. The implications of this research are significant for shaping policies and market designs to foster the adoption of PV-battery systems. For future research, the study suggests investigating the long-term performance and degradation of PV-battery systems, exploring their integration with other renewables, applying machine learning for predictive maintenance, and assessing the overall environmental impact of these systems.

5. CONCLUSIONS

The optimal sizing model of PV-battery systems presented in this paper provides a valuable framework for enhancing the economic efficiency and grid stability of solar power systems. The study highlights the importance of considering battery size, DC-to-AC ratio, and uncertainty in system performance when designing PV-battery systems. The findings contribute to the development of more sustainable and reliable solar energy solutions, supporting the transition towards a low-carbon energy future.

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