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Optimal Capacity Configuration of Energy Storage in PV Plants Considering Multi-Stakeholders

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Abstract: With the integration of large-scale renewable energy generation, some new problems and challenges are brought for the operation and planning of power systems with the aim of mitigating the adverse effects of integrating photovoltaic plants into the grid and safeguarding the interests of diverse stakeholders. In this paper, a methodology for allotting capacity is introduced, which takes into account the active involvement of multiple stakeholders in the energy storage system. The objective model for maximizing the financial proceeds of the PV plant, the system for the storage of energy, and a power grid company is studied. Then, in order to maximize the benefit of three stakeholders, a modified particle swarm optimization algorithm is devised, employing the prevailing typical allocation strategy. Finally, a case study is provided based on the modified IEEE 14-bus and the actual power grid from South Xinjiang, China. The simulation results and findings of the case study conclusively illustrate that the proposed methodology adeptly ensures the maximization of interests for the triad of stakeholders.

Keywords: multi-stakeholders; photovoltaic (PV) plant; optimal capacity of energy storage; modified particle swarm optimization



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1. Introduction

To address global electricity demand in an environmentally sustainable manner, one pivotal approach involves the establishment of an innovative power system predominantly fueled by the robust advancement of renewable energy sources, encompassing hydropower, solar power, and wind power [1,2]. However, the grid characterized by a substantial share of photovoltaic (PV) faces great risks as PV has strong randomness and volatility owing to the intrinsic characteristic associated with PV generation [3,4]. The integration of energy storage has the capability to mitigate the variability in renewable energy output without necessitating alterations to the current grid infrastructure. Also, it can alleviate the strain caused by the peaking of general units while harnessing the potential of sustainable energy [5–7]. The collaborative undertaking of PV and stored energy can enhance the flexibility and ensure the stability of the sophisticated optical data archival system, which can bring maximum benefits to the grid. Hence, investigating the storage capability of the energy reservoir is crucial given the substantial investment costs associated with energy storage.

Over the past few years, an abundance of research has focused on the configuration to optimize the energy storage capacity of PV plants. Bullichthe-Massagué et al. (2020) and Zhang et al. (2021) summarized and analyzed different characteristics of energy storage. The conclusion was the establishment of an optimal energy storage solution for providing diverse services in large PV plants [8,9]. Shi et al. (2020) introduced an innovative hierarchical optimization approach to enhance the efficiency of both sustainable energy and energy reservoir [10]. Li et al. (2021) and Liu et al. (2021) both proposed optimization models for energy storage systems (ESS) aimed at enhancing PV consumption efficiency

in the distribution network [11,12]. Zhang et al. (2020) proposed an advanced heuristic algorithmic approach of determining capacity for regulatory control in an integrated incremental hydropower PV-pumped storage system [13]. Zhu et al. (2023) developed a profitable energy storage capacity optimization model [14]. Zhang et al. (2019) and Chaima et al. (2021) proposed fast configuration methods for energy storage derived from the forecasting of PV and an energy reservoir topologyed hydro storage–PV plant system [15,16]. Deng et al. (2021) and An et al. (2019) devised an established optimization scheduling model, which ensured the steadiness and dependable functioning of an expansive multi-energy coupling system [17,18]. The above-mentioned results mainly focus on the siting and capacity-setting methods for ESS to promote PV consumption. However, few studies discuss the optimization capacity allocation in terms of the benefits.

Energy reservoirs can also be applied as a flexible adjustable resource to gain some benefits from participation in grid operations. Contreras-Ocana et al. (2017) and Wang et al. (2018) explored mechanisms to enhance the role of energy storage in grid operations [19,20]. Contreras-Ocana et al. developed an optimization model for aggregators to participate in grid peaking and dispatching through competitive bidding, while Wang et al. introduced a capacity contract mechanism for power sellers, facilitating optimal trading strategies. Also, it was argued that power sellers can achieve real-time regulation of distributed energy storage resources through a certain trading mechanism. Mortaz et al. (2019) and Croce et al. (2020) proposed advanced strategies to optimize energy distribution and investment [21,22]. Mortaz et al. utilized a tri-level stochastic optimization program to assess the impact of zonal diversification on investment portfolios. Croce et al. introduced a machine learning-enhanced multi-criteria optimization methodology to optimize energy zone flexibility, aiming to reduce peak power consumption and prevent reverse power flow. By taking into account the cost of the whole life cycle and the benefit of the ESS, Li et al. (2020) established a bilayer optimization model to solve the challenge of voltage fluctuations of distributed power sources in microgrids [23]. Wu et al. (2019) and Mediawathe et al. (2020) both focused on optimizing smart grid operations [24,25]. Wu et al. developed a distributed hierarchical equivalence algorithm to solve economic challenges in smart grids, while Mediawathe et al. explored integrating energy storage with PV for demand management within acceptable voltage levels, employing a Stackelberg game based on a linearized model to enhance energy trading benefits for storage providers. To solve the impossibility of quantifying the indirect benefits of energy storage, Wang et al. (2020) established an economic benefit and evaluation approach taking into account a reduction in unitary deficits and postponed returns from investment [26]. Zhang et al. (2022) proposed a capacity allocation method with maximum energy storage benefit with the life cycle as the optimization objective [27]. The energy management strategy considering peak and valley regulation was proposed for the mixed energy storage system of the electrified railroad. Cui et al. (2017) established a two-stage energy storage arbitrage model to address the chronic energy storage arbitrage problem of maximizing annual returns in a grid characterized by a substantial share of wind energy [28]. Zhao et al. (2021) developed a model to assess the benefits of energy storage system scheduling strategies based on time-of-use tariffs, focusing on maximizing economic gains [29]. Ying et al. (2023) targeted the uncertainties of wind power with a capacity configuration for pneumatic ESS, aiming to enhance economic outcomes [30]. Meanwhile, Sun et al. (2020) proposed an energy flow-based optimization strategy for the integrated energy system, adding a different dimension to optimizing energy resources [31]. All three studies aim at optimizing energy storage for economic benefits. Yang et al. (2021) proposed a framework of analyzing battery operation in an Australian National Electricity Market electricity spot; an operating strategy was proposed based on battery degradation costs [32]. However, most of the aforementioned results mainly focus on analyzing the benefits of energy storage without taking into account other stakeholders. Therefore, an important topic is the optimization of the capacity configuration of ESS from the perspective of multiple interests, which is worth studying.

Building upon the preceding discussions, in this paper, a capacity optimization allocation infrastructure is proposed based on maximizing the net benefit by considering multiple interests (such as PV plants, energy storage systems, and grid companies). The auxiliary service benefits of energy storage are fully exploited by an improved particle swarm optimization (PSO). Finally, simulation and analysis are carried out in the adapted IEEE 14-bus network and a real-world electricity grid in a region of South Xinjiang, China, which are expected to demonstrate the efficacy and utility of the proposed approach.

2. Photovoltaic-Storage Architecture

The structure of a typical multi-source interaction system is shown in Figure 1. The integration of large-scale PV into the electricity network, with the inherent randomness of PV generation, will significantly affect the stability of energy supply and power quality in the grid. The energy storage system has the characteristics of rapid bidirectional power regulation. It can significantly enhance the negative impact of PV volatility on the grid. The configuration of the combined ESS for PV is depicted in Figure 1. The energy reservoir device can be selectively connected to either the DC or AC side of the PV inverter as needed. It is convenient to retrofit the existing PV generator set when connected from the AC side. The investment can be reduced when connected from the DC side.

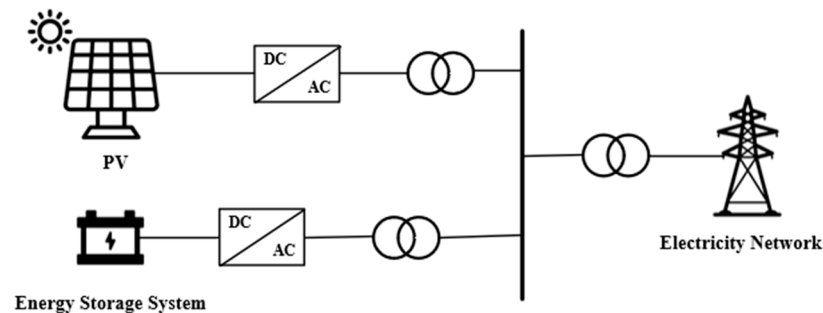


Figure 1. A typical multi-source interaction system.

3. Multi-Stakeholder Model

The reservoir of energy equipment is integrated into the pre-existing power grid to control the storage system to store and release energy according to the change in load and PV plant output. In this paper, three parties' revenue (PV plant revenue, energy storage system revenue, and grid company revenue) is taken as the optimization object and an intricate model for optimizing multiple objectives is developed.

3.1. Revenue Model of PV Plant

Revenues from PV plants can be expressed as

$$F_{1,\text{income}} = W_{1,PSI} + W_{1,NES} + W_{1,RBI} \frac{\tau}{1 - (1 + \tau)^{-T_1}} \quad (1)$$

$$W_{1,RBI} = P_1 D_1 \quad (2)$$

where τ represents the prevailing discount rate, $\tau / [1 - (1 + \tau)^{-T_1}]$ is the equivalent annual coefficient of the device, P_1 is the total installed capacity of the PV plant, D_1 is the scrap price of PV cells per unit of power, $W_{1,PSI}$ is the annual electricity sales revenue, $W_{1,NES}$ is the renewable energy subsidies of government, and $W_{1,RBI}$ is the PV battery scrap income.

$$F_{1,\text{cost}} = C_{1,ICC} \frac{\tau}{1 - (1 + \tau)^{-T_1}} + C_{1,OMC} \quad (3)$$

$$C_{1,ICC} = P_1 U_1 \quad (4)$$

$$C_{1,OMC} = P_1 M_1 \quad (5)$$

where U_1 is the cost of PV cells per unit of power and M_1 is the annual maintenance cost of the PV plant per unit of power. T_1 is the lifespan of the photovoltaic power plant.

Therefore, the net income model of the PV plant can be expressed as

$$F_1 = F_{1,income} - F_{1,cost} \quad (6)$$

3.2. Revenue Model of ESS

The advantages of ESS mainly include peak saving and backup, which can be represented as

$$F_{2,income} = \sum_{t=1}^T c_{PE} E_{2,PE}^t + \sum_{t=1}^T c_{RE} E_{2,RE}^t \quad (7)$$

where c_{PE} represents the unit peak saving income, c_{RE} is the unit standby income, and $E_{2,PE}^t$ and $E_{2,RE}^t$ are the peak saving power and spare capacity delivered by ESS during the specified time period t , respectively.

The expend of storage system can be represented as

$$F_{2,cost} = C_{2,PUR} + C_{2,ICC} \frac{\tau}{1 - (1 + \tau)^{-T_2}} + C_{2,OMC} \quad (8)$$

$$C_{2,PUR} = \sum_{t=1}^T E_{2,PUR}^t \lambda_2 \quad (9)$$

where $E_{2,PUR}^t$ is the energy storage purchased from the grid power in period t , λ_2 is the price of unit power, $C_{2,PUR}$ is the power purchase cost, $C_{2,ICC}$ is the primal capital expenditure, and $C_{2,OMC}$ is the daily expense of operation and maintenance. T_2 is the lifespan of ESS.

Therefore, the net profit model of storage system can be represented as

$$F_2 = F_{2,income} - F_{2,cost} \quad (10)$$

3.3. Grid Company Revenue Model

The income of grid company can be expressed as

$$F_{3,income} = W_{3,SEL} + W_{3,TGC} \quad (11)$$

$$W_{3,TGC} = \lambda_{TGC}(M - N) \quad (12)$$

where λ_{TGC} is the green certificate unit electricity trading price, M is the actual holding of green certificates, N is the renewable energy quota of the grid company, $W_{3,SEL}$ is the electricity sales income, and $W_{3,TGC}$ is the green certificate transaction income.

The cost of the grid company can be expressed as

$$F_{3,cost} = C_{3,PUR} + C_{3,GTR} \frac{\tau}{1 - (1 + \tau)^{-T_3}} \quad (13)$$

where $C_{3,PUR}$ is the purchase cost and $C_{3,GTR}$ is the cost of network expansion. T_3 is the lifespan of the grid structure.

The equation for computing the augmentation expense of the grid is as follows:

$$C_{3,GTR} = \sum_{k=1}^{N_L} C_n L_n \quad (14)$$

where N_L represents the total number of candidate amplification lines, C_n represents average expense of line n , and L_n represents the length of alternative amplification line.

Therefore, the net income model of grid company can be expressed as

$$F_3 = F_{3,\text{income}} - F_{3,\text{cost}} \quad (15)$$

3.4. Constraint Conditions

3.4.1. Power Balance Constraint

The balance of power can be expressed as

$$P_{gen}^t + P_{PV}^t + P_h^t = P_{load}^t + P_{bess}^t + P_{loss}^t \quad (16)$$

where P_{gen}^t represents the power of the output for unit i , P_{PV}^t represents the power of output for the PV field in time interval t , P_h^t represents the power of output for the hydroelectric facility during the specified time span t , P_{load}^t represents the load in time interval t , P_{bess}^t represents the power of output for the storage system during the specified time span t , and P_{loss}^t is the active power of network loss.

3.4.2. Constraints on Output of Conventional Unit within the Upper and Lower Bounds

The output of conventional unit can be expressed as

$$P_{gi}^{\min} \leq P_{gi,t} \leq P_{gi}^{\max} \quad (17)$$

where $P_{gi}^{\max}$ and $P_{gi}^{\min}$ represent the upper and lower bounds of the output, respectively.

3.4.3. Conventional Unit Ramp Constraint

The ramp of conventional unit can be expressed as

$$-\Delta P_i^{\text{down}} \leq P_{gi,t} - P_{gi,t-1} \leq \Delta P_i^{\text{up}} \quad (18)$$

where ΔP_i^{down} is the downhill climbing rate limit of conventional unit i and ΔP_i^{up} is the limit of rising ramp rate for conventional unit i .

3.4.4. Reserve Capacity Constraint

To mitigate the unpredictability in grids, a certain amount of reserve capacity should be reserved in the system. However, there will be decreased economy of grid operation due to excessive spare capacity.

$$\begin{cases} \sum_{i=1}^{N_g} \mu_{i,t} (P_{gen,i}^{\max} - P_{gen,i}^t) \geq \lambda_1 P_h^t + \lambda_2 P_{PV}^t + \lambda_3 P_i^t \\ \sum_{i=1}^{N_g} \mu_{i,t} (P_{gen,i}^t - P_{gen,i}^{\min}) \geq \lambda_1 P_h^t + \lambda_2 P_{PV}^t(t) + \lambda_3 P_i^t \end{cases} \quad (19)$$

where N_g represents the number of power plants, $\lambda_1 = \lambda_2 = 10\%$, $\lambda_3 = 2\sim 5\%$, $\mu_{i,t}$ represent the operational cycling status of a conventional power facility i , $\mu_{i,t} = 1$ represents power-on, $\mu_{i,t} = 0$ indicates downtime, and $P_{gen,i}^{\max}$ and $P_{gen,i}^{\min}$ represent the upper and lower boundaries of the conventional unit's output, respectively.

3.4.5. Voltage Constraint

The safety constraint of voltage can be expressed as

$$\begin{cases} V_i^{\min} \leq V_i \leq V_i^{\max} \\ \theta_i^{\min} \leq \theta_i \leq \theta_i^{\max} \end{cases} \quad (20)$$

3.4.6. Line Flow Constraint

The safety constraint of line flow can be expressed as

$$P_t^{\text{flow}} \leq P_t^{\text{flow,max}}, (t = 1, \dots, T) \quad (21)$$

where P_t^{flow} and $P_t^{\text{flow,max}}$ represent the actual power and maximum power on the line, respectively.

3.4.7. Energy Storage State of Charge Constraint

The constraint of energy storage state can be expressed as

$$S_t^{\text{soc}} = \begin{cases} S_{t-1}^{\text{soc}} + \frac{P_t^{\text{bess}} \times \eta_{bc} \times \Delta t}{E_{\text{bess}}(t)}, P_t^{\text{bess}} > 0 \\ S_{t-1}^{\text{soc}} + \frac{P_t^{\text{bess}} \times \eta_{bd} \times \Delta t}{E_{\text{bess}}}, P_t^{\text{bess}} < 0 \end{cases} \quad (22)$$

where P_t^{bess} represents the grid charge and discharge power of ESS during the specified time span t , $P_t^{\text{bess}} > 0$ represents the charging state of the ESS, $P_t^{\text{bess}} < 0$ represents the discharge state of ESS, $E_{\text{bess}}(t)$ represents the remaining capacity of the ESS at the previous moment, S_t^{soc} represents the state of charge of ESS, Δt represents the duration of ESS charging, and η_{bc} and η_{bd} represent the efficiency during charging and discharging in ESS, respectively.

4. Model Solving

4.1. Improved Particle Swarm Optimization

The conventional PSO showcases the benefits of a broad optimization range and straightforward coding. It is often used to obtain the optimal solution, which is given by [33].

$$\begin{cases} V_{i+1}^d = \omega V_i^d + c_1 r_1 \cdot (P_i^d - X_i^d) + c_2 r_2 \cdot (P_i^d - X_i^d) \\ X_{i+1}^d = X_i^d + V_{i+1}^d \end{cases} \quad (23)$$

where V_i^d and X_i^d are the speed and position before the update, V_{i+1}^d and X_{i+1}^d are the updated speed and location, d represents the iteration of population i in X_i^d , ω is weight, and c_1 and c_2 represent learning parameters of population, which are the random values within the range of (0, 1).

However, the standard PSO is susceptible to local optima and premature. In this paper, a modified PSO from two aspects is established.

(1) Improvement in Inertia Weight

In the standard PSO, the weight ω affects the optimization accuracy of the particles. The slower particle flight speed at the smaller weight is beneficial to the local optimum in the later stage. The faster particle flight speed at the larger weight is conducive to a global optimum. Therefore, compared to the weights of traditional PSO, the improved PSO in this paper adopts dynamic weight ω . The improved update formula is as follows:

$$D(x) = \frac{n_{\text{var}}}{x_{\text{max}} - x_{\text{min}}} \sum_{n=1}^{n_{\text{var}}} (x_{\text{gest},n} - x_n) \quad (24)$$

$$\omega = \omega_{\text{min}} + (\omega_{\text{max}} - \omega_{\text{min}}) \times (D(x) - 1) \quad (25)$$

where n_{var} is the number of decision variables, x_{min} is the particle position lower limit, and x_{max} is the particle position and decision variable upper limit.

(2) Improvement in the Learning Factor

PSO has better global optimum ability in the early stage when c_1 is large and c_2 is small. Also, PSO has better local optimum ability in the later stage when c_2 is large and

c_1 is small. Therefore, by adopting a non-linear change method, the improvement in the learning factor can be formulated as

$$c_1 = 2 - \frac{r}{r_{\max}} \quad (26)$$

$$c_2 = 1 + \frac{r}{r_{\max}} \quad (27)$$

where $r \in (0, 1)$ is the random number.

4.2. Solution Process

The solution process of storage system capacity optimization configuration based on modified PSO is depicted in Figure 2. It is important to note that the variable to be optimized in the multi-objective optimal configuration model is the installed capacity of ESS. The spatial positions of the particles are determined through the modified PSO.

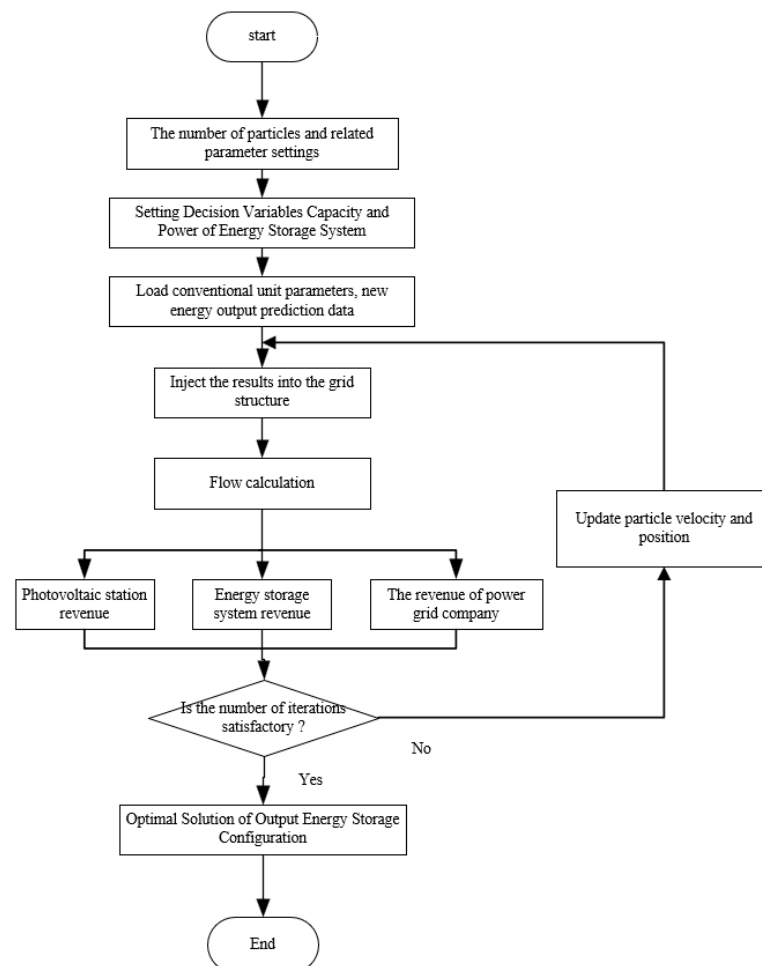


Figure 2. Flowchart of storage capacity optimization configuration.

The depicted flowchart outlines an optimization protocol for an energy system incorporating photovoltaic stations and storage units. Initially, the algorithm's parameters are established, including the number of solutions modeled as particles. Decision variables for the storage system's capacity and power are set, followed by the introduction of parameters for conventional energy units and predictions for renewable outputs. These inputs inform the energy distribution to the grid. Subsequently, energy flow is calculated, and an iterative optimization loop begins, updating the solution candidates' attributes to maximize the system's revenue components. The loop continues until a satisfactory solution is reached.

based on convergence criteria or the iteration count, culminating in the identification of an optimal configuration for the energy storage system output, thereby concluding the optimization process.

5. Case Analysis

5.1. Parameter Setting

The adapted IEEE 14-bus network and the actual power grid in a certain area of Southern Xinjiang are taken as the case models for simulation verification. The load information and PV output curve in the case are shown in Figure 3. The improved network topologies are depicted in Figures 4 and 5, respectively. The operating parameters of thermal units, ESS and hydropower units, the electricity price information, and equipment cost information are shown in Tables 1–4, respectively.

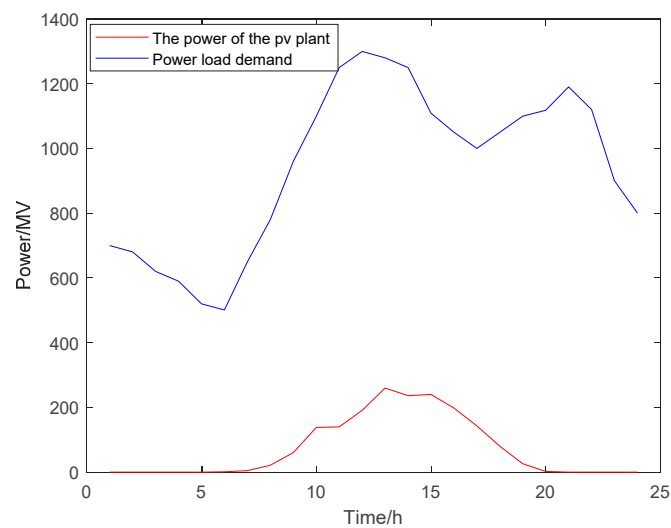


Figure 3. Typical daily operation curve.

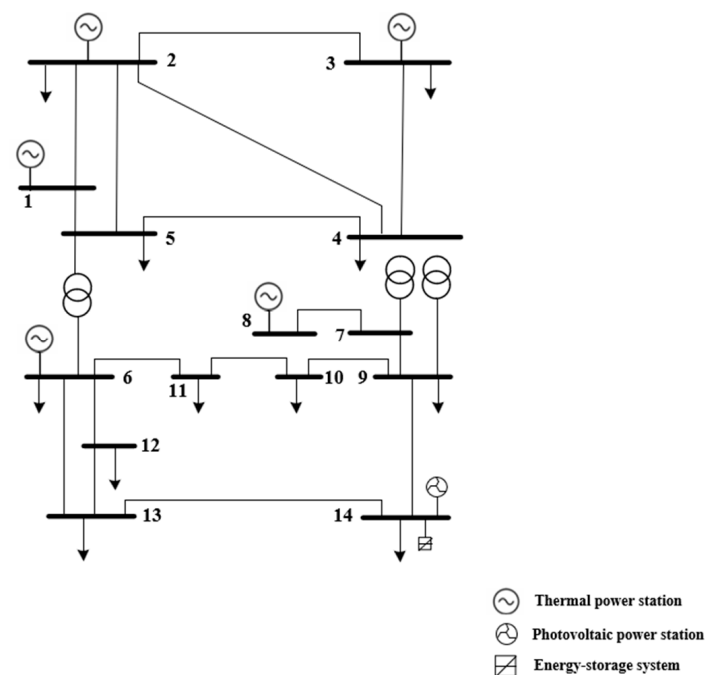


Figure 4. The adapted IEEE 14-bus network.

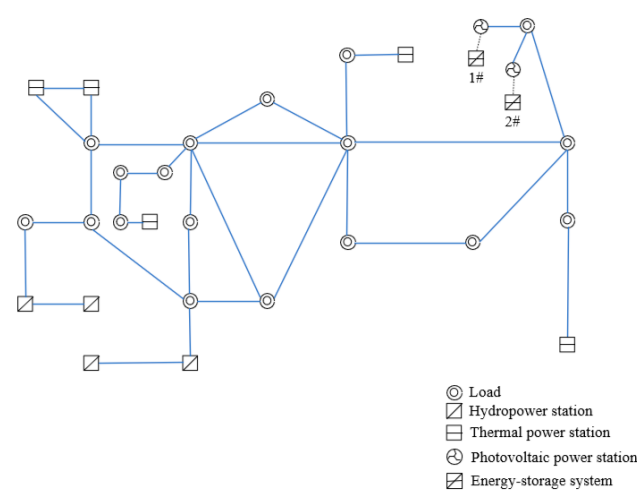


Figure 5. Actual power grid topology of a region in Southern Xinjiang.

Table 1. Parameter settings for the case system.

Parameters	Data	Parameters	Data
PV plant construction cost	11,340 yuan/kW	Number of ESS	2
PV plant maintenance cost	1120 yuan/kW per year	SOC upper limit of energy storage battery	0.9
PV panel scrap income	120 yuan/kW per year	SOC lower limit of energy storage battery	0.1
PV panel life	20 years	Battery life	15 years
Energy storage system construction cost	3800 yuan/kW	Grid expansion cost	1 million yuan/KM
Maintenance cost of energy storage system	300 yuan/kW per year	Government’s expected photovoltaic subsidies	0.3 yuan/kWh
Energy storage unit peaking income	30 yuan/MWh	Photovoltaic grid electricity price	0.7 yuan/kWh
Energy storage unit standby revenue	0.55 yuan/kWh	Power grid selling price	0.5 yuan/kWh

Table 2. Relevant parameters of the thermal power unit.

Unit Number	1	2	3	4	5
Min (MW)	120	120	20	20	20
Max (MW)	455	455	130	130	162
Coal consumption coefficient <i>a</i>	0.00048	0.00031	0.000212	0.00211	0.00398
Coal consumption coefficient <i>b</i>	16.19	17.26	16.61	16.5	19.72
Coal consumption coefficient <i>c</i>	1000	970	700	680	450

Table 3. Relevant parameters of the hydropower unit.

Unit Number	1	2	3	4
V_{min} (10,000 m ³)	80	60	100	70
V_{max} (10,000 m ³)	150	120	240	160
Q_{min} (10,000 m ³ /s)	5	6	10	6
Q_{max} (10,000 m ³ /s)	15	15	30	20
PH_{min} (MW)	10	15	35	20
PH_{max} (MW)	500	350	600	450

Table 4. Parameter settings for the algorithm.

Parameters	Data	Parameters	Data
Iterations	100	Learning factor c_1	0.1
Number of populations	50	Learning factor c_2	0.2
Initial value of inertia weight	0.2	Concluding inertia weight parameter	0.8

The simulation time span is 1 day, the annualized equivalent factor of equipment is 0.08, the upper limit of capacity of PV plant and storage system is set as the maximum load of the system, the trading price of green certificate is set as 0.2 yuan/KWh, and the renewable energy quota obligation of power grid company is set as 15% of the annual load power. The scratch income from photovoltaic panels in Table 1 represents annual data. Therefore, it is necessary to prorate this to daily data when optimizing the established model.

5.2. Case Analysis

In order to validate the viability of the model presented in this paper, three scenarios are formulated for analysis. All scenarios operate under identical system parameters.

Scenario 1: Only the power grid company's revenue;

Scenario 2: Only the energy storage system benefits;

Scenario 3: The income of grid companies, ESS, and PV plants.

Figures 6 and 7 show the state of ESS operation throughout the day under three optimization scenarios, utilizing the adapted IEEE 14-bus network.

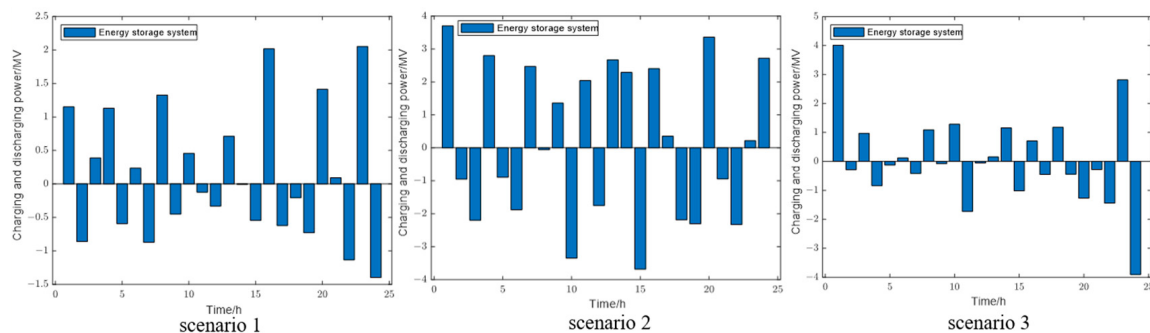
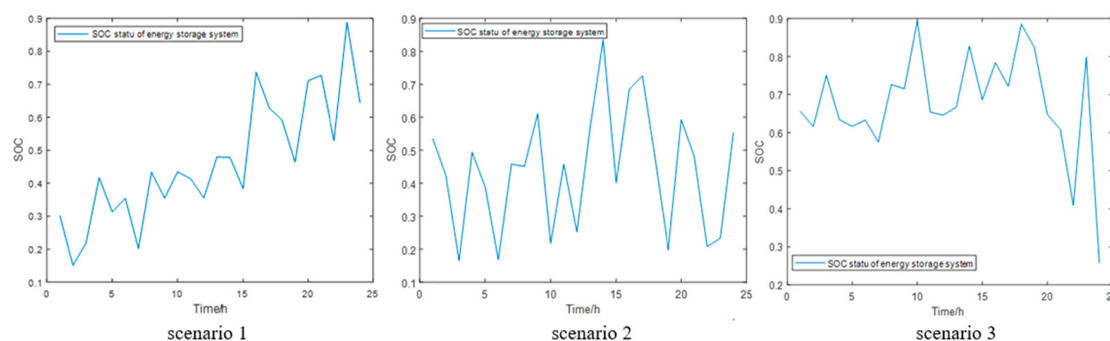
**Figure 6.** Power flow into and out of the ESS for scenario 1 to 3.**Figure 7.** SOC status of ESS for scenarios 1 to 3.

Table 5 lists the peak saving capacity and reserve capacity that ESS can provide to the grid in a cycle of 24 h.

ESS is equivalent to the provision of energy to the grid when it is in the discharged state again. At the same time, it can also be charged on demand, which is equivalent to a load.

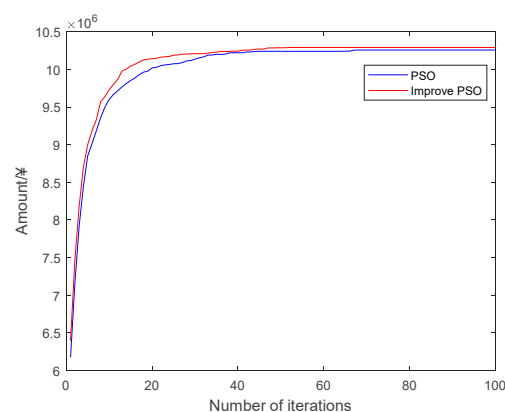
Table 5. Energy storage capacity configuration results.

Scene No.	Configure Capacity/MWh	Peaking Capacity/MWh	Standby Capacity/MWh
1	5.71	7.88	48.9
2	8.51	22.54	68.83
3	7.22	12.35	54.36

Scenario 3's energy management profile, as illustrated by Figure 6, suggests a highly strategic and dynamic system operation, with sharp peaks in charging and pronounced troughs in discharging, indicating aggressive energy turnover within the 24-h cycle. Upon comparative analysis, Scenario 3 emerges as superior for an energy storage system due to its dynamic operation. Unlike Scenario 1, which shows moderate charging and discharging, and Scenario 2, which indicates higher utilization, Scenario 3 demonstrates the most significant range of power fluctuations. With peaks nearly reaching 5 MW and troughs around -4 MW, Scenario 3 suggests an aggressive and responsive energy management strategy. It indicates that the system robustly adapts to varying energy supply and demand conditions, optimizing its storage capacity. The pronounced activity in Scenario 3 likely reflects strategic operational decisions to store energy during periods of low cost or excess supply and discharge during high demand, potentially leading to improved efficiency and cost-effectiveness. Thus, Scenario 3's utilization pattern may be indicative of a more economically savvy and operationally efficient system.

The variability in the SOC graph points to a system that responds actively to the changing energy landscape, possibly accommodating high levels of renewable energy generation and rapid shifts in electricity demand. Scenario 3 may offer advantages in scenarios where energy prices fluctuate widely, allowing operators to buy low during periods of surplus and sell high during shortages, effectively leveraging market dynamics. The pronounced dips in SoC also hint at the potential for deep discharge cycles. When juxtaposed with the charging and discharging profiles, they suggest that ESS is not just a backup but a pivotal component of the energy strategy, engaging in both load leveling and peak saving.

To ascertain the enhanced particle swarm algorithm's efficacy and utility in addressing the issue delineated herein, a comparative analysis of the algorithm's performance pre- and post-enhancement toward solving the designated problem was conducted, with the computational outcomes depicted in Figure 8. An examination of the convergence rates of both algorithms reveals that the post-improvement version exhibits accelerated convergence, thereby underscoring the selected algorithm's superiority.

**Figure 8.** Comparison of optimization results between PSO and improved PSO algorithms.

During the execution of the actual Simulation, three scenarios were systematically configured. Figures 9 and 10 show the state of ESS operation throughout the day un-

der three optimization scenarios, utilizing the actual power grid topology of a region in Southern Xinjiang.

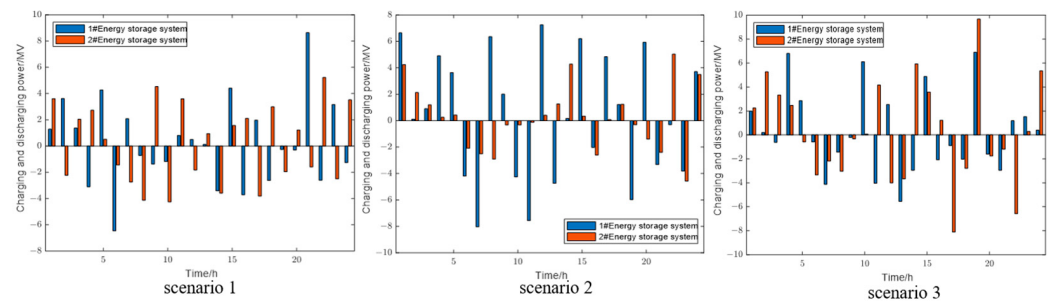


Figure 9. Power flow into and out of the ESS for scenario 1 to 3.

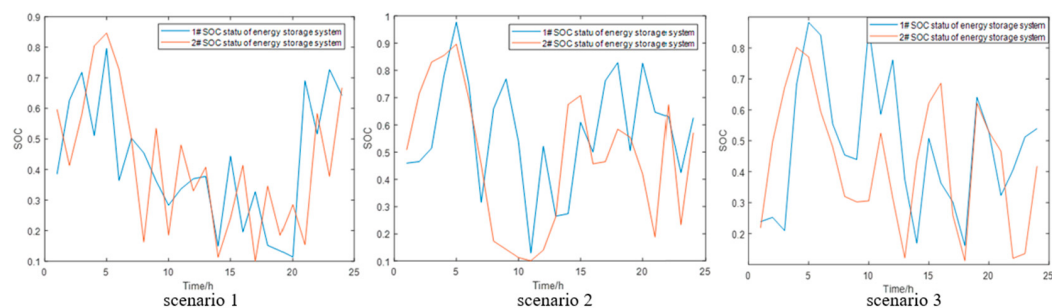


Figure 10. SOC status of ESS for scenarios 1 to 3.

This paper configures ESS in the place where the PV farms gather more densely according to the actual grid structure of South Xinjiang, China. The final determination of energy storage capacity allocation is 14.4 MWh and 19.1 MWh, respectively, taking into account the interests of the three parties.

The peaking capacity and standby capacity that the two energy storage systems can provide to the grid in one cycle of 24 h are presented in Table 6. In analyzing the ESS across three scenarios, it becomes evident that Scenario 3 offers a more balanced and efficient configuration. This scenario showcases System 1 and System 2 with configured capacities of 14.4 MWh and 19.1 MWh, peaking capacities of 29.1 MWh and 36.9 MWh, and substantial standby capacities of 138.7 MWh and 168.6 MWh, respectively. The distribution of capacities in Scenario 3 suggests an optimized balance between the immediate availability of energy for peak demand (peaking capacity) and the strategic reserve for unforeseen circumstances (standby capacity), without excessively prioritizing one over the other. This balanced approach not only ensures a reliable energy supply during peak times but also maintains a higher level of preparedness for emergency situations. Furthermore, the relatively high configured and standby capacities of both systems in Scenario 3 indicate a robust framework designed to accommodate fluctuations in demand and supply, enhancing the overall efficiency and stability of the energy grid. Consequently, Scenario 3 emerges as the superior configuration, demonstrating an effective integration of energy storage capabilities to meet diverse operational demands while ensuring grid reliability and efficiency. Meanwhile, the above results indicate that considering multiple interests simultaneously will result in a more balanced outcome.

It can be concluded that the total revenue of the established model is the highest in the PV plant energy storage system from Table 7. Scenario 2 has a higher charging and discharging capacity than Scenarios 1 and 3, as it considers the maximum benefit of ESS. However, scenario 3 has a relatively flat charging and discharging capacity because it integrates the revenue objectives of multiple parties. The revenues of the three parties of interest in the simulation case and actual case are enumerated in Table 7. The findings indicate that the revenue of PV plants mainly comes from their power sales revenue and

government subsidy policies. Auxiliary services are the main source of revenue for ESS. Grid companies' revenues are closely related to the installed renewable energy capacity in the region. A higher price of green certificate trading can increase the incentive for energy storage and grid companies to invest. ESS can increase the utilization of sustainable energy resources.

Table 6. Energy storage capacity configuration results.

Scene No.	Energy Storage System No.	Configured Capacity/MWh	Peaking Capacity/MWh	Standby Capacity/MWh
1	1	15.1	27.1	128.7
	2	12.2	30.1	101.1
2	1	18.4	44.2	217.7
	2	10.3	19.52	102.5
3	1	14.4	29.1	138.7
	2	19.1	36.9	168.6

Table 7. Third party income of three scenarios.

Scene No.	Subject of Interest	Total Revenue in 14-Bus Network/¥	Total Revenue in Actual Power Grid/¥
1	PV plant	499,722	240,898
	ESS	70,878	16,628
	Grid company	9,701,638	1,333,863
2	PV plant	504,338	247,063
	ESS	113,620	17,869
	Grid company	9,602,817	1,314,823
3	PV plant	504,603	246,790
	ESS	101,236	17,392
	Grid company	9,683,937	1,328,108

6. Conclusions

The energy storage system can efficaciously mitigate a range of issues arising from large-scale PV into grids. By the combination of multi-stakeholders and an improved PSO, a multi-faceted optimization model was introduced for the PV of ESS. The simulation results demonstrated that the reasonable allocation of ESS in the grid could enhance the harnessing of alternative energy sources. The rational arrangement of the ESS can achieve the maximum benefit for multiple parties. Simultaneously, the adapted PSO devised in this study could efficiently compute multi-objective optimization models and achieve good performance.

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References

- Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [\[CrossRef\]](#)
- Kim, Y.; Wilson, C. Analyzing future change in the EU's energy innovation system. *Energy Strategy Rev.* **2019**, *24*, 279–299. [\[CrossRef\]](#)
- Qiu, Y.; Lin, J.; Liu, F.; Song, Y.; Chen, G.; Ding, L. Stochastic online generation control of cascaded run-of-the-river hydropower for mitigating solar power volatility. *IEEE Trans. Power Syst.* **2020**, *35*, 4709–4722. [\[CrossRef\]](#)
- Ding, Y.; Xie, D.; Hui, H.; Xu, Y.; Siano, P. Game-theoretic demand side management of thermostatically controlled loads for smoothing tie-line power of microgrids. *IEEE Trans. Power Syst.* **2021**, *36*, 4089–4101. [\[CrossRef\]](#)
- Li, X.; Wang, L.; Yan, N.; Ma, R. Cooperative dispatch of distributed energy storage in distribution network with PV generation systems. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 1–4. [\[CrossRef\]](#)
- Li, F.; Li, C.; Sun, K.; Zhang, J.; Li, H. Capacity configuration of hybrid CSP/PV plant for economical application of solar energy. *Chin. J. Electr. Eng.* **2020**, *6*, 19–29. [\[CrossRef\]](#)
- Wang, Q.; Zhang, X.; Yi, C.; Li, Z.; Xu, D. A novel shared energy storage planning method considering the correlation of renewable uncertainties on the supply side. *IEEE Trans. Sustain. Energy* **2022**, *13*, 2051–2063. [\[CrossRef\]](#)
- Bullich-Massagué, E.; Cifuentes-García, F.-J.; Glenney-Crende, I.; Cheah-Mañé, M.; Aragües-Peñalba, M.; Díaz-González, F.; Gomis-Bellmunt, O. A review of energy storage technologies for large scale photovoltaic power plants. *Appl. Energy* **2020**, *274*, 115213. [\[CrossRef\]](#)
- Zhang, D.; Mubaarak, S.; Jiang, S.; Wang, L.; Liu, J.; Chen, Y.; Li, M. Optimal allocation method of energy storage in PV station based on probabilistic power flow. *Energy Storage Sci. Technol.* **2021**, *10*, 2244–2251.
- Shi, Z.; Wang, W.; Huang, Y.; Li, P.; Dong, L. Simultaneous optimization of renewable energy and energy storage capacity with hierarchical control. *CSEE J. Power Energy Syst.* **2020**, *8*, 95–104.
- Yan, D.; Chen, Y. Distributed coordination of charging stations with shared energy storage in a distribution network. *IEEE Trans. Smart Grid.* **2023**, *14*, 4666–4682. [\[CrossRef\]](#)
- Zhu, H.; Hou, R.; Jiang, T.; Lv, Q. Research on energy storage capacity configuration for PV power plants using uncertainty analysis and its applications. *Glob. Energy Interconnect.* **2021**, *4*, 608–618. [\[CrossRef\]](#)
- Zhang, S.; Xiang, Y.; Liu, J.; Liu, J.; Yang, J.; Zhao, X.; Jawad, S.; Wang, J. A regulating capacity determination method for pumped storage hydropower to restrain PV generation fluctuation. *CSEE J. Power Energy Syst.* **2020**, *8*, 304–316.
- Zhu, B.; Wang, Y.; Guo, H.; Yang, N.; Lu, L. Improved model of base station power system for the optimal capacity planning of photovoltaic and energy storage system. *Electronics* **2023**, *12*, 4826. [\[CrossRef\]](#)
- Zhang, J.; Gao, H.; Wang, J.; Hong, J.H.; Liu, J.Y.; Zhuang, H.M. Economic allocation of energy storage in photovoltaic power station considering prediction accuracy and topological structure. *Electr. Power Autom. Equip.* **2019**, *39*, 115–121.
- Chaima, E.; Lian, J.; Ma, C.; Zhang, Y.; Kavwenje, S. Complementary optimization of hydropower with pumped hydro storage-photovoltaic plant for all-day peak electricity demand in Malawi. *Energies* **2021**, *14*, 4948. [\[CrossRef\]](#)
- Deng, X.; Huang, Y.; Chen, Y.; Chen, C.; Yang, L.; Gao, Q.; Chen, X.; Hou, W.; Lin, Z. Multi-scenario physical energy storage planning of integrated energy systems considering dynamic characteristics of heating network and demand response. *Front. Energy Res.* **2021**, *9*, 783588. [\[CrossRef\]](#)
- An, Y.; Zhao, Z.; Wang, S.; Huang, Q.; Xie, X. Coordinative optimization of hydro-photovoltaic-wind-battery complementary power stations. *CSEE J. Power Energy Syst.* **2019**, *6*, 410–418.
- Contreras-Ocana, J.; Ortega-Vazquez, M.; Zhang, B. Participation of an energy storage aggregator in electricity markets. *IEEE Trans. Smart Grid* **2017**, *10*, 1171–1183. [\[CrossRef\]](#)
- Wang, K.; Chen, Q.; Guo, H.; Xia, Q. Mechanism design and trading strategy for capacity contract of energy storage towards transactive energy. *Autom. Electr. Power Syst.* **2018**, *42*, 54–60.
- Mortaz, E. Portfolio diversification for an intermediary energy storage merchant. *IEEE Trans. Sustain. Energy* **2019**, *11*, 1539–1547. [\[CrossRef\]](#)
- Croce, V.; Raveduto, G.; Verber, M.; Ziu, D. Combining machine learning analysis and incentive-based genetic algorithms to optimise energy district renewable self-consumption in demand-response programs. *Electronics* **2020**, *9*, 945. [\[CrossRef\]](#)
- Li, T.; Xu, Y.; Chen, J.; Wang, K. Optimal configuration of energy storage for microgrid considering life cycle cost-benefit. *Proc. CSU-EPSC* **2020**, *32*, 46–51.
- Wu, X.; Sun, Y.; Wei, Z.; Sun, G. Distributed hierarchical consensus algorithm for economic dispatch in smart grid. *IET Gener. Transm. Distrib.* **2019**, *13*, 5541–5549. [\[CrossRef\]](#)
- Mediwaththe, C.P.; Blackhall, L. Network-aware demand-side management framework with a community energy storage system considering voltage constraints. *IEEE Trans. Power Syst.* **2020**, *36*, 1229–1238. [\[CrossRef\]](#)
- Wang, J.; Liu, W.; Li, S.; Liu, Z.; Yang, M.; Guo, H.M. A method to evaluate economic benefits of power side battery energy storage frequency/peak regulation considering the benefits of reducing thermal power unit losses. *Power Syst. Technol.* **2020**, *44*, 4236–4245.
- Wang, C.; Jiao, S.; Li, Y.; Zhang, Q. Capacity optimization of a hybrid energy storage system considering Wind-Solar reliability evaluation based on a novel Multi-strategy snake optimization algorithm. *Expert Syst. Appl.* **2023**, *231*, 120602. [\[CrossRef\]](#)

28. Cui, H.; Li, F.; Fang, X.; Chen, H.; Wang, H. Bilevel arbitrage potential evaluation for grid-scale energy storage considering wind power and LMP smoothing effect. *IEEE Trans. Sustain. Energy* **2017**, *9*, 707–718. [[CrossRef](#)]
29. Zhao, D.; Wang, H.; Huang, J.; Lin, X. Time-of-use pricing for energy storage investment. *IEEE Trans. Smart Grid* **2021**, *13*, 1165–1177. [[CrossRef](#)]
30. Ying, Y.; Tian, Z.; Wu, M.; Liu, Q.; Tricoli, P. Capacity configuration method of flexible smart traction power supply system based on double-layer optimization. *IEEE Trans. Transp. Electr.* **2023**, *9*, 4571–4582. [[CrossRef](#)]
31. Sun, Y.; Zhang, B.; Ge, L.; Sidorov, D.; Wang, J.; Xu, Z. Day-ahead optimization schedule for gas-electric integrated energy system based on second-order cone programming. *CSEE J. Power Energy Syst.* **2020**, *6*, 142–151.
32. Yang, J.; Wang, W.; Ma, K.; Yang, B.; Dou, C.-X. Optimization and self-adaptive dispatching strategy for multiple shared battery stations of electric vehicles. *IEEE Trans. Ind. Inform.* **2021**, *17*, 1363–1374. [[CrossRef](#)]
33. Clerc, M.; Kennedy, J. The particle swarm—Explosion, stability, and convergence in a multidimensional complex space. *IEEE Trans. Evol. Comput.* **2002**, *6*, 58–73. [[CrossRef](#)]

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