Research on Optimal Configuration and Economic Evaluation of User-Side Energy Storage

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Abstract. The user-side energy storage plays an increasingly important role in the development of the power grid. This paper focuses on the user-side energy storage configuration strategy and the economic evaluation of energy storage projects. The optimal model of the user-side photovoltaic energy storage system is established in this paper, with the solution of the particle swarm optimization algorithm. The results illustrate that configuration of the user-side energy storage system has good economy when the electricity price has obvious peak-valley difference.

Keywords: user-side · energy storage · economy · particle swarm optimization

1 Introduction

As a buffer between the uncertainty of power generation and the disorder of loads in the energy Internet, energy storage is the key supporting technology. At present, time-of-use price policy has been implemented in many parts of our country. A large number of loads are connected to the power grid, which brings pressure to the operation of the system. It is of great significance to install energy storage devices on the user-side to relieve the pressure of the power grid and ensure the stable and reliable operation of the power grid. Domestic and foreign scholars have conducted in-depth research on the control and economic modeling of energy storage [1–3]. Optimal configuration schemes and economic analysis are provided for energy storage application scenarios based on different perspectives [4, 5].

Literature [6] discussed the user-side energy storage capacity configuration, analyzed its application value and cost control strategy, and proposed the optimal operation model. Literature [7] established a user-side energy storage comprehensive benefit model based on the whole life cycle cost-benefit present value method, and analyzed its economic feasibility with examples. Finally, combined with the break-even point of the economic model, the market size of the user-side energy storage was predicted. Literature [8] comprehensively considers the life-cycle cost and benefit sources of the energy storage system, but does not carry out detailed modeling in the income part, and does not consider the reduction of peak load caused by the energy storage.

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There have been some researches on the application scenarios and optimal configuration of various energy storages. This paper focuses on the user-side energy storage configuration strategy and the economic evaluation of energy storage projects.

2 Cost and Benefit Model of Energy Storage System

In this chapter, the costs and benefits of energy storage systems are economically modeled. The cost includes the initial investment cost, the annual operation and maintenance cost, the annual average cost and so on. Income refers to the annual income of the energy storage system, including the income of time-of-use electricity price of electric storage and the income of power supply reliability improvement [9, 10].

2.1 Cost Model of Energy Storage System

Initial Investment Cost.
The initial investment cost refers to the one-time fixed capital invested in the initial stage of energy storage project construction, which consists of the power cost determined by the rated power of energy storage and the capacity cost determined by the rated capacity. The initial investment cost accounts for the largest proportion of the total cost. The power cost is usually related to the energy storage converter, while the capacity cost reflects the value of the battery energy storage device.

The initial investment cost of the energy storage system is defined as

$$C_{inv} = P_{rate}(C_E \frac{t_{ed}}{\eta_e} + C_P + C_B t_{ed}) \tag{1}$$

where P_{rate} is the rated power of the energy storage; C_E is the price per unit of the energy storage; C_P and C_B are the unit power price of the energy conversion device and unit energy price of auxiliary equipment.

Annual Operation and Maintenance Cost.
The operation and maintenance cost refers to the money invested dynamically to ensure the normal operation of storage during its service life. The annual operation and maintenance cost of the energy storage system is

$$C_{om} = k_e P_{rate} t_e \tag{2}$$

where k_e represents the operation and maintenance cost per unit electric power; t_e is the number of hours a year that electric storage runs.

Annual Cost.
The annual cost of the energy storage system includes the corresponding annual operation and maintenance cost and the annual cost of the initial investment cost.

$$C = C_{om} + C_{inv} \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where i is the discount rate; N is the investment period; $C_{inv} \frac{i(1+i)^N}{(1+i)^N-1}$ is the one-time investment in energy storage allocated to the annual cost within the project cycle.

2.2 Annual Revenue Model of Energy Storage System

The benefits brought by the energy storage system mainly include the benefits of time-of-use electricity price of the energy storage and the benefits of improving the reliability of power supply.

$$u = u_e + u_{rel} \tag{4}$$

where u is the total revenue of the energy storage system; u_e is the benefit of time-of-use electricity price of the energy storage; u_{rel} is the benefit of improving the reliability of power supply.

2.2.1 Benefit of TOU

The income of TOU of energy storage system mainly comes from its operation mode of discharging at high price and charging at low price. It makes profit by using the difference of peak-valley electricity price. The mathematical model of electricity price income is as follows.

$$u_e = m_e \sum_{t=1}^{24} [P_{dis}(t) - P_{ch}(t)]p(t)\Delta T \tag{5}$$

where $P_{dis}(t)$ and $P_{ch}(t)$ respectively represent the discharging and charging power of the energy storage at time t; $p(t)$ is the electricity price at time t; m_e is the number of days per year that the electric storage operates.

2.2.2 Benefit of Improving the Reliability

In case of a power failure at the user side, the electric energy storage connected to the user can be used as an emergency power supply to ensure the power supply of important loads, reduce power loss, and improve power supply reliability. The power loss evaluation rate method is used to calculate reliability benefit.

$$u_{rel} = \lambda_S R_{IEA} E[1 - f(S_i < E_{ENS})] \tag{6}$$

where λ_S is the power failure rate of the user side; R_{IEA} is the power loss evaluation rate of critical users; E_{ENS} is expected for power shortage of important users; $f(S_i < E_{ENS})$ is the expected value of electric storage failure to supply power to important users during outages.

$$E_{ENS} = T_s(1 - A_s)P_0 \tag{7}$$

$$f(S_i < E_{ENS}) = \frac{T_{ENS}}{24} \tag{8}$$

where T_s is the number of normal hours of electricity used by important users each year; A_s indicates the power supply reliability of the distribution station; P_0 is the load of important users; T_{ENS} indicates hours of the electric storage whose electricity less than E_{ENS}.

3 Operation Constraint Model of Energy Storage System

The energy storage system is generally composed of the energy storage unit and the converter, which are usually connected to the grid together with the controller. As the electrical interface connecting the energy storage unit and the power grid, the converter is the hub of energy exchange between the energy storage system and the power distribution network, which can realize the charge and discharge control of active power[11, 12]. In addition, the converter has a certain reactive power auxiliary function, which can provide voltage support for the power grid through reactive power control while carrying out charging and discharging functions.

Based on the active and reactive power characteristics of the energy storage converter, its rapid charging and discharging process under static cross-section can be described as a four-quadrant operation state. The operation constraints to be met are as follows.

$$\begin{cases} \sqrt{P_k^2(t) + Q_k^2(t)} \le S_{k\max} \\ -P_{k\max} \le P_k(t) \le P_{k\max} \\ -Q_{k\max} \le Q_k(t) \le Q_{k\max} \\ P_k(t) = P_k^{dis}(t), \, if \; P_k(t) \ge 0 \\ P_k(t) = P_k^{ch}(t), \, if \; P_k(t) < 0 \end{cases} \tag{9}$$

where $P_k(t)$ and $Q_k(t)$ are respectively the active power and reactive power output of the $k-th$ converter at time t; $S_{k\max}$, $P_{k\max}$ and $Q_{k\max}$ are respectively the access capacity of the $k-th$ converter and the upper limit of active and reactive power. If $P_k^{dis}(t)$ is greater than 0, the energy storage system is discharged, and if $P_k^{ch}(t)$ is less than 0, the energy storage system is charged.

The State of Charge (SOC) of energy storage unit has absolute continuity in time sequence. SOC is calculated cumulatively according to the charge and discharge power in strict time sequence.

When the energy storage battery is charged, SOC at period t can be expressed as

$$S_{OC}(t) = S_{OC}(t-1)(1-\delta) + \eta_c \frac{P_{ch,t}\Delta t}{E_{bat}} \tag{10}$$

When the energy storage battery is discharged, SOC at period t can be expressed as

$$S_{OC}(t) = S_{OC}(t-1)(1-\delta) - \frac{P_{dis,t}\Delta t}{E_{bat}\eta_d} \tag{11}$$

where $S_{OC}(t)$ represents the state of charged energy storage battery at time t; δ is the parameter of the self-discharge rate of an energy storage battery; η_c and η_d are the charging efficiency and discharge efficiency of the energy storage battery respectively; $P_{ch,t}$ and $P_{dis,t}$ are respectively the charging power and discharging power of the energy storage at the time t; E_{bat} represents the capacity of the energy storage.

In actual operation, the stored energy of the energy storage system should meet the requirements of the upper and lower limits of SOC. The work of energy storage system is usually based on a fixed cycle. The initial and final energy storage in a single cycle should be consistent.

$$S_{OC,\min} \leq S_{OC}(t) \leq S_{OC,\max} \tag{12}$$

$$S_{OC}(0) = S_{OC}(T) \tag{13}$$

where $S_{OC,\min}$ and $S_{OC,\max}$ are the upper and lower limits of SOC respectively.

4 Solution Method for Optimal Configuration of Energy Storage System

The optimal configuration of user-side energy storage should consider the planning problems such as the type and capacity of the energy storage and the scheduling problems such as the charging and discharging process of the energy storage. In this paper, the particle swarm optimization(PSO) algorithm is selected as the solution method of the user-side energy storage optimization configuration problem. As a heuristic algorithm, PSO has the characteristics of fast convergence, strong local search ability and easy implementation.

In general, PSO is to constantly update the particle speed and position in the process of particle swarm evolution. PSO can remember the historical optimal position of particles, and search for the optimal solution through iterative calculation of particle fitness. Specifically, suppose that PSO starts with an initial group of random particles. In each iteration, the particles update their position by tracking two extreme points. One is the local optimal solution found by the particle itself, and the other is the extreme point of the entire population or the extreme point of the entire neighborhood. Based on the original inertia, the particle adjusts its flight direction and speed according to these two extreme values to maintain the overall optimum.

Supposing that a population of N particles travel at a certain speed in a D-dimensional space, the position vector x_i^k and velocity vector v_i^k of the particle i in the $k-th$ iteration can be described as

$$x_i^k = (x_{i1}^k, x_{i2}^k, \cdots, x_{id}^k, \cdots, x_{iD}^k) \tag{14}$$

$$v_i^k = (v_{i1}^k, v_{i2}^k, \cdots, v_{id}^k, \cdots, v_{iD}^k) \tag{15}$$

$$x_{id}^k \in [x_{id,\min}, x_{id,\max}] \tag{16}$$

$$v_{id}^k \in [v_{id,\min}, v_{id,\max}] \tag{17}$$

where $x_{id,\min}$ and $x_{id,\max}$ are the lower and upper limit position of the particle i in the D-dimensional space; $v_{id,\min}$ and $v_{id,\max}$ are the lower and upper limit speed of the particle i in the D-dimensional space; x_{id}^k and v_{id}^k represents the D-dimensional component of the position and speed vector of the particle i at the $k-th$ iteration.

The position vectors corresponding to the individual and global optimal positions of the particle i in the $k-th$ iteration are written as:

$$P^k_{s,besti} = (P^k_{s,besti1}, P^k_{s,besti2}, \cdots, P^k_{s,bestid}, \cdots, P^k_{s,bestiD}) \tag{18}$$

$$P^k_{g,besti} = (P^k_{g,besti1}, P^k_{g,besti2}, \cdots, P^k_{g,bestid}, \cdots, P^k_{g,bestiD}) \tag{19}$$

The velocity vector and the position vector of the particle are updated by the following formula.

$$v^{k+1}_{id} = \omega v^k_{id} + c_1 r_1 (P^k_{s,bestid} - x^k_{id}) + c_2 r_2 (P^k_{g,besti} - x^k_{id}) \tag{20}$$

$$x^{k+1}_{id} = x^k_{id} + v^k_{id} \tag{21}$$

where ω is the inertia weight coefficient; c_1 and c_2 are the acceleration coefficients; r_1 and r_2 are two random numbers that vary in the range [0,1]; $P^k_{s,bestid}$ and $P^k_{g,bestid}$ are the d dimension component of the optimal position of the particle i in the individual and global history at the $k-th$ iteration.

Figure 1 shows the flow chart of solving the user-side energy storage optimization configuration model with PSO. The specific steps are as follows.

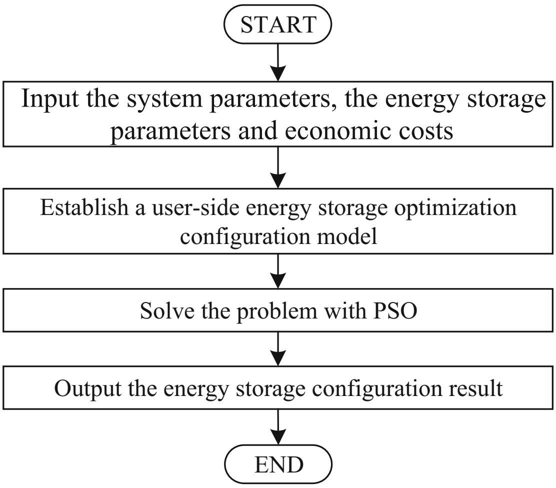

Fig. 1. Flow chart of solving the user-side energy storage optimization configuration model

5 Analysis of Optimal Configuration of the Residential Photovoltaic Energy Storage System

5.1 Optimal Model

The objective of the optimal configuration model is to minimize the average annual cost of the user system after the energy storage is configured. Combined with Eq. (3) and (4), the objective function can be written as

$$\min f = C_{om} + C_{inv}\frac{i(1+i)^N}{(1+i)^N - 1} + u_e + u_{rel} \tag{22}$$

After installing the energy storage system, the photovoltaic energy storage system should ensure that all photovoltaic consumption, as shown in Eq. (15).

$$P_{PV}(t) + P_{grid}(t) + P_{dis}(t) = P_{ch}(t) + P_{load}(t) \tag{23}$$

where $P_{grid}(t)$ and $P_{load}(t)$ are respectively the input power and load power of the photovoltaic energy storage system at time t; $P_{PV}(t)$ is the photovoltaic output power at time t.

5.2 Case Study

5.2.1 Residential Energy Storage

A residential building containing photovoltaic is selected as the research object. Take one hour as a running period and 24 h as a simulation cycle. The peak annual load is 100kW, while the photovoltaic capacity is 20kW. The typical daily curve is shown in Fig. 2. TOU electricity price is shown in Table 1.

Considering the economy and technological maturity of various energy storages, the battery energy storage is the main method for the user-side energy storage systems at present. Table 2 lists the economic specifications of common battery energy storage systems.

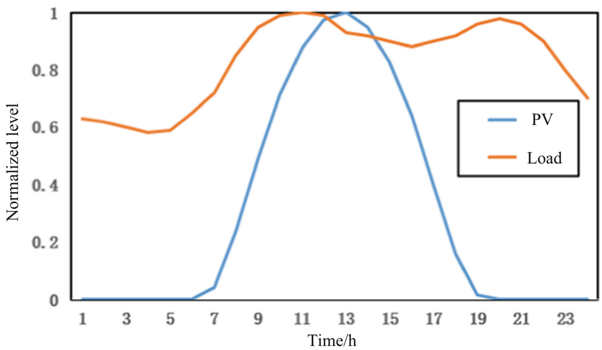

Fig. 2. The load and PV curve on the typical day of the residential building

Table 1. Residential TOU electricity price

	Peak period (8:00–21:00)	Valley period (0:00–8:00)
Price (yuan/kWh)	0.5583	0.3583

Table 2. Economic indicators of different energy storage systems

	Lead-carbon	Vanadium-flow	Sodium-sulfur	Li-ion
Cost of converter (yuan/kW)	1000	1000	1000	1000
Unit capacity cost (yuan/kWh)	800	6000	2500	1800
Operation cost (yuan/kW)	100	200	300	100
Replacement cost (yuan/kWh)	800	6000	2500	1800
cycle index	3000	13000	3000	4000
efficiency %	88	70	80	90
life span /a	10	20	10	12

The vanadium-flow battery occupies a large area, while the sodium-sulfur battery lacks safety and requires complex operating temperature. Lead-carbon battery and Li-ion battery are used to establish the optimal configuration model. The energy storage capacity required by the optimal operation of the two types of energy storages under typical days is obtained by PSO. Then the annual operation cost and annual investment cost are calculated. The cost of lead-carbon battery and lithium-ion battery is compared to give the type and capacity of energy storage equipments recommended to the user, as shown in Table 3.

After energy storages is configured, the annual power purchase cost of users is reduced. When only the arbitrage income of peak-valley electricity price is considered, the investment cost and maintenance cost of energy storages lead to the increase of the total cost of users, which means that the income of peak-valley electricity price is less than the energy storage cost. In view of this situation, in order to promote user-side energy storage installing, measures such as setting peak-valley electricity price with a large peak-valley price difference or setting energy storage subsidies should be taken. The peak-valley price shown in Table 4 is adopted. Compared with TABLE I, there is a significant difference between the peak-valley setting of the price, so as to improve the peak-valley arbitrage income of energy storage and contribute to the application of energy storage. Table 5 illustrates the results corresponding to Table 4.

Table 3. Simulation result

	Without storage	Lead-carbon battery	Li-ion battery
Annual electricity purchase cost(yuan)	332272	331929	332073.2
Annual cost of investment(yuan)	0	800.62	821.23
Annual operation cost(yuan)	0	150.53	114.08
Annual total cost(yuan)	332272	332880.1	333008.6
Optimal capacity (kWh)	0	8.13	4.71
Optimal power (kW)	0	1.51	1.14

Table 4. Residential TOU electricity price

	Peak period (10:00–15:00; 18:00–21:00)	Normal period (7:00–10:00; 15:00–18:00; 21:00–23:00)	Valley period (23:00–7:00)
Price (yuan/kWh)	1.055	0.633	0.291

Table 5. Simulation result

	Without storage	Lead-carbon battery	Li-ion battery
Annual electricity purchase cost(yuan)	510345.65	316899.83	325087.62
Annual cost of investment(yuan)	0	61879	92608
Annual operation cost(yuan)	0	11171	10337
Annual total cost(yuan)	510345.65	389949.83	428032.62
Optimal capacity (kWh)	0	633.79	548.42
Optimal power (kW)	0	111.71	103.37

It can be seen that the annual cost of the energy storage system with the lead-carbon battery and li-ion battery will decrease by about 100,000 yuan after the difference between peak and valley price is increased. The economy of the lead-carbon battery is the best, followed by the li-ion battery. It is recommended that the capacity of the lead-carbon battery be 633.79kWh and the power be 111.71kW. The recommended capacity and power of the li-ion battery are 548.42kWh and 103.37kW.

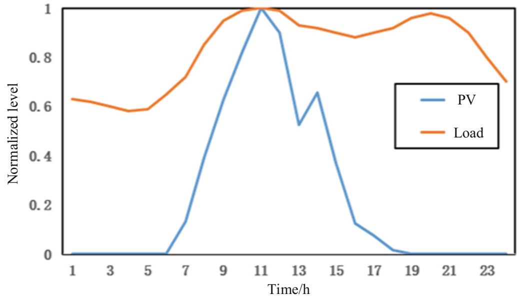

Fig. 3. The load and PV curve on the typical day of the factory

5.2.2 Industrial Energy Storage

A factory with distributed PV is selected as the research object. The installed photovoltaic capacity is 1500kW, the maximum load is 2000kW, and the maximum back-feed power is 1500kW. The typical daily curve is shown in Fig. 3. The system adopts the peak-valley TOU price of industrial electricity. It is assumed that the price of reverse power supply from the energy storage station is consistent with the price of power purchase, as shown in Table 6.

According to the results in Table 7, energy consumption costs of this factory can be effectively reduced by setting the energy storage station. The lead-carbon battery has the

Table 6. Industrial TOU electricity price

	Peak period (10:00–15:00; 18:00–21:00)	Normal period (7:00–10:00; 15:00–18:00; 21:00–23:00)	Valley period (23:00–7:00)
Price (yuan/kWh)	1.1002	0.6601	0.3200

Table 7. Simulation result

	Without storage	Lead-carbon battery	Li-ion battery
Annual electricity purchase cost(yuan)	8268710	2320232	3357708
Annual cost of investment(yuan)	0	2163100	2288300
Annual operation cost(yuan)	0	335110	326620
Annual total cost(yuan)	8268710	4818442	5972628
Optimal capacity (kWh)	0	22848	13077
Optimal power (kW)	0	3351	3266

best economy, while the annual cost of the system is reduced by nearly 50%. Therefore, the lead-carbon battery has great application potential. Lithium-ion batteries come in second, reducing annual costs by about 20 percent. For the lead-carbon battery, the capacity is 23MWh and the power is 3351kW. For the lithium-ion battery, the recommended capacity and power are recommended as 13MWh and 3,266kW respectively.

6 Conclusion

This paper establishes the cost and benefit model of the energy storage systems. The optimal configuration method of the user-side photovoltaic energy storage system is also studied. Furthermore, the economy of the lead-carbon, vanadium-flow, sodium-sulfur and li-ion batteries is compared in this paper. The particle swarm optimization algorithm is used to solve the optimization model proposed in this paper. The results of example analysis show that the larger the peak-valley price difference is, the more obvious the advantage of the energy storage system is. In order to promote the further development of energy storage system, peak-valley electricity price can be appropriately increased to improve the economic benefits of energy storage system.

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