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Optimizing Capacity Configuration of Photovoltaic and Battery Energy Storage Systems in EV Charging Station based on Time-of-Use Pricing

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Abstract. In order to improve the utilization efficiency of photovoltaic system (PV system) and battery energy storage system (BESS) in photovoltaic and battery energy storage integrated electric vehicle (EV) charging stations, the capacity of PV system and BESS need to be allocated reasonably. In this paper, the maximization of the net annual financial value is used as the objective function of photovoltaic and battery energy storage integrated EV charging station in its whole life cycle. The control strategy of BESS is proposed based on time-of-use pricing. And then the optimization configuration model of PV system and BESS capacity is built. The economic efficiency of EV charging stations is compared and analyzed with actual test system when PV system and BESS configuring. The results indicate that the income and investment payback period of charging stations can be significantly improved through the reasonable configuration of PV system and BESS.

1. Introduction

With the rapid development of electric vehicle (EV), the construction of charging facilities of EVs has been widely concerned by the government and investors. Especially with the developing of special EVs, such as buses and sanitation vehicles, the demands for large EV charging station is increasing at the same time. The photovoltaic and battery energy storage integrated EV charging station project attracts more attention.

As large EV charging stations are usually constructed in the outside, which occupies a large area and are often equipped with rain shelters and other facilities. It provides the basic condition for photovoltaic cell installation. Therefore, it is good for economic and social benefit, that combining the ground resources of EV charging station with photovoltaic power generation system, to build a rooftop photovoltaic system (PV system) operating on a "used by the property, with surplus electricity sale back to the grid" model. However, the fluctuation and randomness of photovoltaic power generation make it difficult to match the charging demands of EVs and increase the burden of power system [1]. And it is not conducive to reduce the electricity cost of charging stations by using low-priced electricity in the off-peak period of time-of-use pricing. As the battery energy storage system (BESS) can save the electricity cost of the EV charging station by taking advantage of the electricity price difference, it is necessary to combine the BESS with PV system and charging facilities to improve the overall load characteristic of charging stations and obtain good economic benefits.



At present, there are many studies focus on the capacity configuration methods of PV system and BESS for photovoltaic and battery energy storage integrated EV charging station. Reference [2] built an economic dispatch model according the economic operation of energy storage devices and PV system. Reference [3] studies the complementary benefits of the integration of PV system and BESS with EV charging stations. It illustrates that this method is economical under the premise of a certain investment cost. Reference [4] and [5] study charging and discharging strategies of charging stations under the condition of satisfying charging demands and power system security and reliability operation. The test example shows that the proposed strategies can reduce the costs and improve voltage problems. Reference [6] establishes a capacity configuration optimization model which verifies the feasibility of this model through numerical simulation and provides foundation for planning and designing photovoltaic power station with BESS. Reference [7] and [8] propose an optimization model of orderly charging of EV charging stations according to time-of-use pricing mechanism. Compared with unordered charging, orderly charging can reduce the cost of purchasing electric power from power grid on the premise of satisfying the charging demands of EVs.

Reference [9] establishes the battery energy storage configuration model with the minimum annual operating cost of the integrated charging station as the objective function. And then it is applied to the BESS configuration in the photovoltaic EV charging station to improve the economy of the optimization scheme. Reference [10] builds the capacity optimization configuration model of EV charging stations with PV system, which can obtain the optimal configuration scheme to suitable for station construction according to different region. It also provides theoretical basis and technical support for the infrastructure construction of demonstration cities and is conducive to improve the economic benefits of EV charging station. In reference [11], a battery storage capacity configuration model was proposed based on improving the utilization efficiency of photovoltaic power generation by equipping with energy storage system. It provides theoretical reference value for investors of photovoltaic power station while not considering the influence of time-of-use pricing. Reference [12] takes the annual net income of the charging stations as the target and then proposes storage capacity configuration model of photovoltaic charging station based on decommissioned battery cascade utilization. Test example illustrates that the using cascade BESS can improve the economic benefits. However, the control strategy does not comprehensively consider the time-of-use pricing and the energy exchange strategy of BESS.

In this paper, the EV charging load characteristic and the output power characteristic curve of PV system is considered. And the economic benefits and operation cost of EV charging station is also taken into consideration, such as power purchase cost of EV charging station, the feed-in tariff of PV system, the price difference between peak and off-peak period, etc. Then the operation strategy of photovoltaic and battery energy storage integrated EV charging station and the capacity optimization configuration model are proposed based on time-of-use pricing. Finally, the optimization model is solved by using loop iteration and the economic benefits of charging stations are also analyzed.

2. The structure of photovoltaic and battery energy storage integrated EV charging station

Photovoltaic and battery energy storage integrated EV charging station is composed of power supply and distribution system, EV charging system, PV system, BESS and monitoring system. The system structure diagram is shown in Fig.1. The power supply and distribution system mainly include 10kV/0.4kV distribution transformer, 10kV inlet cabinet, 10kV metering cabinet, 10kV outlet cabinet, 0.4kV low-voltage inlet cabinet, 0.4kV low-voltage outlet cabinet. The EV charging system, PV system and BESS are directly integrated into the 0.4kV AC bus by AC/DC converter. Lithium iron phosphate batteries are commonly used in the BESS. The monitoring system (including energy management system) is responsible for monitoring the status of each unit in real time. It controls the energy flow of each power unit according to time-of-use pricing and power consumption situation.

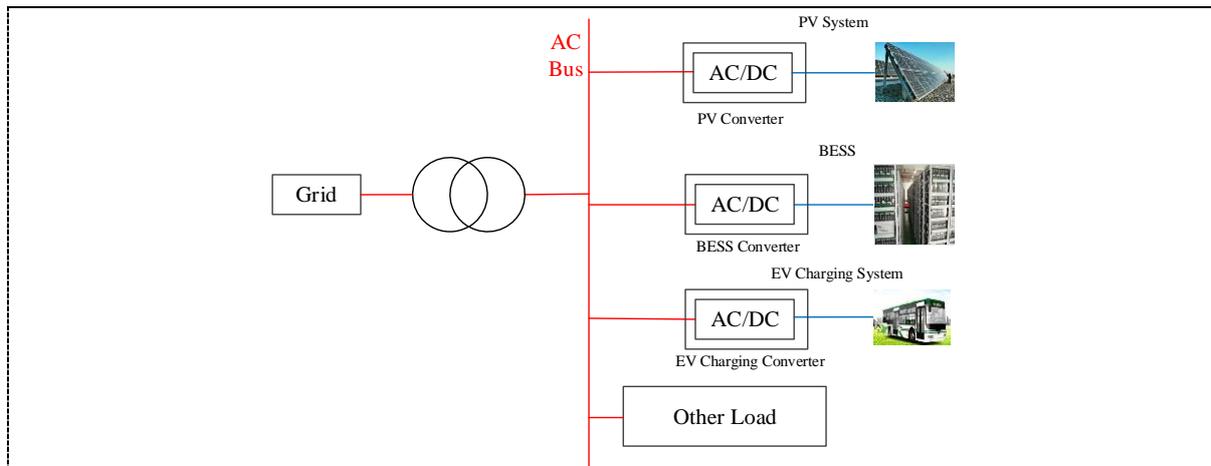


Figure 1. The structure of photovoltaic and battery energy storage integrated EV charging station.

The EV charging system is the main equipment of the charging station, which is used to charge EVs. Its capacity is configured to meet the maximum demands of charging loads of EVs. The main operation mode of the PV System is "used by the property, with surplus electricity sale back to the grid". By this operation mode, it can reduce the amount of electricity absorbed from power grid and electricity purchasing cost. In addition, when the local loads are insufficient, the power generated by PV system can be directly fed into power grid and earn the feed-in tariff.

The main benefits of BESS include two parts. Firstly, the BESS absorbs electricity from power grid in the off-peak period and releases it for charging EVs in the peak period to earn the price difference between peak and off-peak period of the time-of-use pricing. Secondly, the feed-in tariff of PV system is usually lower than the electricity price of charging station. Consequently, the BESS can absorb part of the electricity power, which is generated by PV system and cannot be used for its own consumption at the same time, and release energy for charging EVs in peak period to make profits.

3. Capacity configuration model of PV system and BESS

3.1. Objective function

Based on system structure, the capacity configuration model of PV system and BESS of EV charging station is established with the goal of maximizing the overall financial net annual value. The objective function is shown as equation (1).

$$F = I_C + I_{PV} + I_A - O_{PV} - O_B - O_E - O_C \quad (1)$$

where F is the financial net annual value of charging station. I_C is annual income from charging EV. I_{PV} is annual income of PV system sale back to the grid. I_A is annual PV System government subsidies. O_{PV} is equivalent annual investment cost of PV system. O_B is equivalent annual investment cost of BESS. O_E is annual electricity purchasing cost from the grid. O_C is equivalent annual investment cost of EV charging system.

The annual electricity sale revenue I_C of EV charging stations is the sum of every day sales revenue within one year, whose expression is shown as equation (2).

$$I_C = 365 \times \int_{t=0}^{24} C_c P_L(t) dt \quad (2)$$

where, C_c is the unit price of per kilowatt-hour of the EV charging station, which includes the cost of purchasing electricity from power grid and the service charge. P_L is the typical daily real-time charging load of EVs, which is the function of time and the positive direction is defined as the active power flowing to EVs.

The income of PV system I_{PV} is shown as follow.

$$I_{PV} = 365 \times \int_{t=0}^{24} C_{PV} P_{PVg}(t) dt \quad (3)$$

where, C_{PV} is the feed-in tariff of PV system. P_{PVg} is the typical daily real-time power feed into power grid which is generated by PV system, and the direction of active power flowing to the grid is defined as the positive direction.

At present, the subsidy of PV system is according to the generated energy of PV system. The annual subsidy income of PV system is calculated by equation (4).

$$I_A = 365 \times \int_{t=0}^{24} C_A P_{PV}(t) dt \quad (4)$$

where, C_A is the government subsidized electricity price of PV power generation. P_{PV} is the real-time power generated by PV system. The direction of active power flowing out to power grid is defined as the positive direction.

The annual equivalent investment cost O_{PV} in the whole life cycle of PV system charging station includes initial investment cost O_{PV1} and the annual operation and maintenance cost O_{PV2} .

$$\begin{aligned} O_{PV} &= O_{PV1} + O_{PV2} \\ O_{PV1} &= C_1 W_{PV} \frac{i(1+i)^{n_1}}{(1+i)^{n_1} - 1} \\ O_{PV2} &= k_1 C_1 W_{PV} \end{aligned} \quad (5)$$

where, C_1 is the initial investment unit price of PV system. W_{PV} is the installed power of PV system. i is discount rate. n_1 is the service life of PV system. k_1 is annual operation and maintenance coefficient of PV system.

The equivalent annual investment cost in the whole life cycle of energy storage system O_B includes the initial investment cost O_{B1} and the operation and maintenance cost O_{B2} .

$$\begin{aligned} O_B &= O_{B1} + O_{B2} \\ O_{B1} &= (C_2 E_B + C_3 W_B) \frac{i(1+i)^{n_2}}{(1+i)^{n_2} - 1} \\ O_{B2} &= k_2 (C_2 E_B + C_3 W_B) \end{aligned} \quad (6)$$

where, C_2 and C_3 is the initial capacity and power investment unit price of BESS. E_B and W_B is the installed capacity and power of BESS. n_2 is the service life of BESS. k_2 is annual operation and maintenance coefficient of BESS.

The power purchasing cost of EV charging station from power grid O_E is shown as follow.

$$O_E = 365 \times \int_{t=0}^{24} C_g(t) P_g(t) dt \quad (7)$$

where, C_g is time-of-use pricing. P_g is the active power absorbed from power grid. The active power from power grid to EV charging station is positive.

The annual equivalent investment cost of other facilities of charging station O_C includes annual equivalent investment cost in conventional EV charging station O_{C1} and the reduced electrical capacity charge O_{C2} due to the configuration of BESS.

$$\begin{aligned} O_C &= O_{C1} - O_{C2} \\ O_{C2} &= C_4 W_C \end{aligned} \quad (8)$$

where, C_4 is the annual unit capacity price of electric power users. W_C is the reduced distribution capacity due to the configuration of BESS.

3.2. Operation constraints

Power balance constraint:

$$P_g(t) + P_{PV}(t) = P_B(t) + P_L(t) \quad (9)$$

where, P_B is the absorbed active power of BESS. The direction of active power flowing to BESS is positive.

Real-time power feed into power grid constraint of PV system:

$$P_{PVg}(t) = \begin{cases} 0, P_g(t) \geq 0 \\ -P_g(t), P_g(t) < 0 \end{cases} \quad (10)$$

Energy storage state constraint of BESS:

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \quad (11)$$

where, SOC_{\min} and SOC_{\max} is the limitation of energy storage state of BESS. SOC is the real-time energy storage state of BESS.

Since the BESS operates in daily cycle, it should guarantee $SOC(0) = SOC(24) = SOC_{\min}$. The real-time energy storage state of BESS is calculated by equation (12).

$$SOC(t) = SOC(0) + \frac{\int_0^t P_B(t) dt}{E_B}, 0 < t \leq 24 \quad (12)$$

PV system output power constraint:

$$P_{PV}(t) = W_{PV} \cdot P_{PV0}(t) \quad (13)$$

where, P_{PV0} is typical output power curve of PV system with installed per-unit power and is consistent with positive direction of P_{PV} .

Distribution network capacity variation constraint:

$$W_C = \max P_L(t) - \max |P_g(t)| \quad (14)$$

Time-of-use pricing constraint:

$$C_g(t) = \begin{cases} C_L, 0 < t \leq t_1 \text{ or } t_6 < t \leq 24 \\ C_P, t_1 < t \leq t_2 \text{ or } t_3 < t \leq t_4 \text{ or } t_5 < t \leq t_6 \\ C_H, t_2 < t \leq t_3 \text{ or } t_4 < t \leq t_5 \end{cases} \quad (15)$$

The time-of-use pricing is generally composed of peak period price C_H , shoulder period price C_P and off-peak period price C_L . The details of time-of-use pricing in Beijing are shown in Table.1.

Table 1. The time-of-use pricing of EV charging station.

Period	Time	Price
Off-peak	$t_6 \sim t_1$	C_L
Shoulder	$t_1 \sim t_2$	C_P
Peak	$t_2 \sim t_3$	C_H
Shoulder	$t_3 \sim t_4$	C_P
Peak	$t_4 \sim t_5$	C_H
Shoulder	$t_5 \sim t_6$	C_P

Charging and discharging speed constraint of BESS:

$$W_B \leq E_B S_{\max} \quad (16)$$

where, S_{\max} is the maximum charge/discharge ratio of BESS.

Decision variable constraint:

$$\begin{aligned} W_{PV} &\leq W_{PV\max} \\ E_B &\leq E_{B\max} \end{aligned} \quad (17)$$

where, $W_{PV\max}$ and $E_{B\max}$ is the maximum constraint of installed power of PV system and installed capacity of BESS, which depend on the site condition of the EV charging station.

3.3. Operation strategy of BESS based on time-of-use pricing

EV charging stations belong to large industrial power consumption. According to the current electricity price of large industrial power consumption in some cities, the electricity price at any period of time is higher than the feed-in tariff of PV system. Therefore, the power generated by PV system should be directly used for charging EVs in advance and the excess power is stored in BESS, and then it is used during the peak period of time-of-use pricing. If the EV load demands is smaller than the power generated by PV system and the BESS is already full, the surplus electricity power generated by PV system should be fed directly into power grid to earn the benefits with feed-in tariff.

At the same time, in order to make the most of the charging and discharging times of BESS, the non-photovoltaic electricity needed for charging EVs in the first peak period is provided by BESS, whose power is stored in the off-peak period. And during the second peak period, the non-photovoltaic electricity needed for charging EVs is provided by BESS, whose power is stored in the second shoulder period. Therefore, the operation and control strategy of BESS is shown as follow.

When $0 < t \leq t_1$, the BESS makes the most of the off-peak period to be filled up. And then it retains part of the surplus for absorbing the electricity that the PV system cannot be directly consumed by the charging load of EVs in the period $0 \sim t_2$. The strategy is shown as follow.

$$P_B(t) = P_{B1}(t) + P_{B2}(t) \quad (18)$$

$$P_{B1}(t) = \begin{cases} W_B, & P_{PV}(t) - P_L(t) \geq W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & 0 \leq P_{PV}(t) - P_L(t) < W_B \text{ and } SOC(t) < SOC_{\max} \\ 0, & P_{PV}(t) - P_L(t) < 0 \text{ or } SOC(t) \geq SOC_{\max} \end{cases} \quad (19)$$

$$P_{B2}(t) = \begin{cases} W_B - P_{B1}(t), & SOC(t) < \left(SOC_{\max} - \frac{E_1}{E_B} \right) \\ 0, & SOC(t) \geq \left(SOC_{\max} - \frac{E_1}{E_B} \right) \end{cases} \quad (20)$$

where, E_1 is the amount of electricity generated by PV system stored in the BESS in the period $0 \sim t_2$.

$$E_1 = \int_{t=0}^{t_1} P_{B1}(t) dt + \int_{t=t_1}^{t_2} P_{B1}(t) dt \quad (21)$$

When $t_1 < t \leq t_2$, the BESS is used to absorb the electricity generated by PV system that charging load of EVs cannot consumed. The strategy is expressed as follow.

$$P_B(t) = \begin{cases} W_B, & P_{PV}(t) - P_L(t) \geq W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & 0 \leq P_{PV}(t) - P_L(t) < W_B \text{ and } SOC(t) < SOC_{\max} \\ 0, & P_{PV}(t) - P_L(t) < 0 \text{ or } SOC(t) \geq SOC_{\max} \end{cases} \quad (22)$$

When $t_2 < t \leq t_3$, in the peak period, the BESS tries to release electricity to satisfy the difference between EV load and the output power of PV system. The strategy is shown as equation (23).

$$P_B(t) = \begin{cases} W_B, & P_{PV}(t) - P_L(t) \geq W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & 0 \leq P_{PV}(t) - P_L(t) < W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & -W_B < P_{PV}(t) - P_L(t) < 0 \text{ and } SOC(t) > SOC_{\min} \\ -W_B, & P_{PV}(t) - P_L(t) \leq -W_B \text{ and } SOC(t) > SOC_{\min} \\ 0, & \text{Others} \end{cases} \quad (23)$$

When $t_3 < t \leq t_4$, BESS supplements part of energy in the second shoulder period for charging EV in the second peak period. The strategy is shown as equation (24).

$$P_B(t) = P_{B1}(t) + P_{B2}(t) \quad (24)$$

$$P_{B1}(t) = \begin{cases} W_B, & P_{PV}(t) - P_L(t) \geq W_B \text{ and } SOC(t) < \frac{E_1}{E_B} \\ P_{PV}(t) - P_L(t), & 0 \leq P_{PV}(t) - P_L(t) < W_B \text{ and } SOC(t) < \frac{E_1}{E_B} \\ 0, & P_{PV}(t) - P_L(t) < 0 \text{ or } SOC(t) \geq \frac{E_1}{E_B} \end{cases} \quad (25)$$

$$P_{B2}(t) = \begin{cases} W_B - P_{B1}(t), & SOC(t) < \left(\frac{E_1}{E_B} - \frac{E_2}{E_B} \right) \\ 0, & SOC(t) \geq \left(\frac{E_1}{E_B} - \frac{E_2}{E_B} \right) \end{cases} \quad (26)$$

where, E_1 is the released energy by BESS in the period from t_4 to t_5 . It is to ensure that the amount of electricity stored in BESS can be fully utilized and make $SOC(t_5)$ is closely to SOC_{\min} . E_2 is the amount of electricity generated by PV system stored in the BESS in the period $t_3 \sim t_4$, which can be calculated by equation (27).

$$E_2 = \int_{t=t_3}^{t_4} P_{B1}(t) dt \quad (27)$$

When $t_4 < t \leq t_5$, BESS tries to release electricity to meet the difference between charging load of EV and the output power of PV system in peak period. The strategy is expressed as equation (28).

$$P_B(t) = \begin{cases} W_B, & P_{PV}(t) - P_L(t) \geq W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & 0 \leq P_{PV}(t) - P_L(t) < W_B \text{ and } SOC(t) < SOC_{\max} \\ P_{PV}(t) - P_L(t), & -W_B < P_{PV}(t) - P_L(t) < 0 \text{ and } SOC(t) > SOC_{\min} \\ -W_B, & P_{PV}(t) - P_L(t) \leq -W_B \text{ and } SOC(t) > SOC_{\min} \\ 0, & \text{Others} \end{cases} \quad (28)$$

When $t_5 < t \leq 24$, in order to ensure the optimal economic benefits of EV charging station, it is necessary to make $SOC(t_5)$ is closely to SOC_{\min} . If BESS still has residual power after t_5 , the power can be used for other loads in charging station.

4. Capacity calculation process of PV system and BESS

The solving process of capacity optimization configuration model of PV system and BESS is shown in Fig.2. According to the constraint in practical application, the appropriate step size is determined. The installed power of PV system, configuration capacity of BESS and the rated charging and discharging power can be obtained.

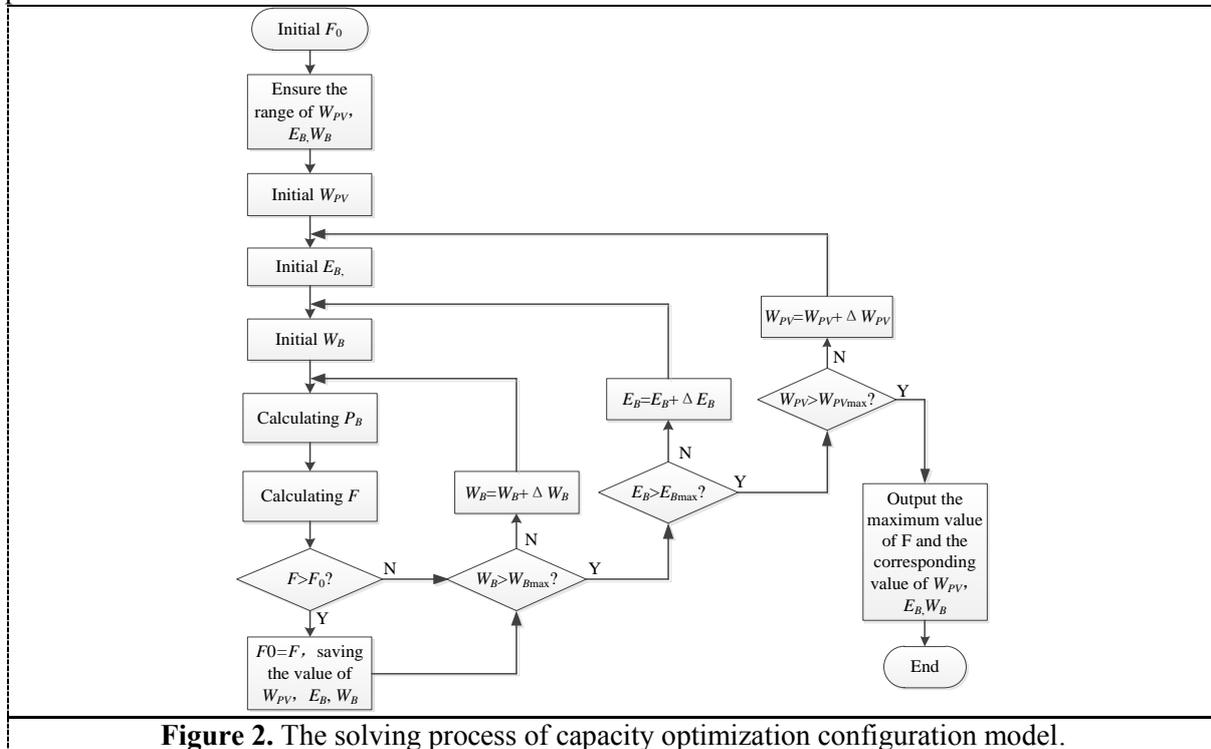


Figure 2. The solving process of capacity optimization configuration model.

5. Case study

This section takes a conventional quick charging station in Beijing as an example for case analysis. The station has 10 quick charging piles whose power is 60kW and the total charging power is 600kW. The investment is 1.5 million RMB. The annual management, finance, operation and maintenance and other costs is the 10% of total investment. The operating life of charging station is 20 years and the discount rate is 6%. The charging and service fee is 1.1 RMB/kWh. The operating life of PV system is 20 years and the life of lithium iron phosphate BESS is 10 years. The number of battery replacement is 1. The time-of-use pricing is shown in Table.2.

Table 2. Time-of-use pricing.

Period	Time	Hours	Price (RMB/kWh)
Off-peak	23:00~7:00	8	0.3766
Shoulder	7:00~10:00	3	0.677
Peak	10:00~15:00	5	0.9864
Shoulder	15:00~18:00	3	0.677
Peak	18:00~21:00	3	0.9864
Shoulder	21:00~24:00	2	0.677

The load curve of this charging station on typical day is shown in Fig.3. Since this kind of charging stations do not implement time-of-use pricing for EV users, the charging load characteristics of EVs are determined by users' own.

Taking the maximum annual net financial value of the EV charging station as the objective function, the capacity configuration optimization model of PV system and BESS of EV charging station is established and solved in this paper. The relevant parameters required for calculation are shown in Table.3.

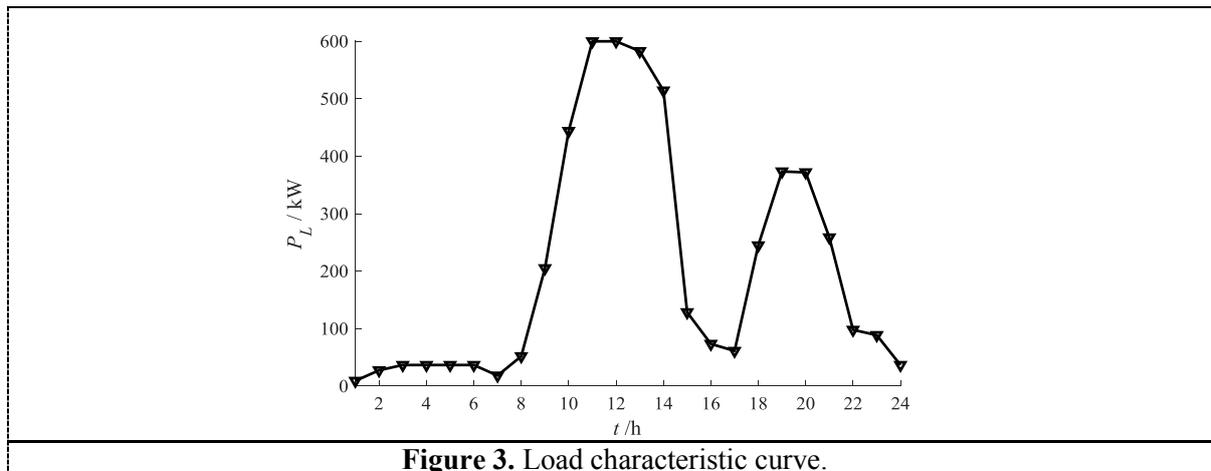


Figure 3. Load characteristic curve.

Table 3. Relevant parameters for PV system and BESS capacity configuration calculation.

Parameter	Value
Annual unit capacity electricity price (RMB/kW)	360
Feed-in tariff for PV system (RMB/kWh)	0.3515
Government subsidized electricity prices for PV power generation (RMB/kWh)	0.32
Initial capacity investment for PV system (RMB/kW)	1800
Operation and maintenance coefficient of PV system	0.01
Initial capacity investment for BESS (RMB/kWh)	1600
Initial power investment for BESS (RMB/kW)	800
Operation and maintenance coefficient of BESS	0.01

According to model calculation and solution, when the installed power of PV system is 300kW and the rated power and capacity configuration of BESS are 170kW and 610kWh respectively, the financial net annual value of charging station project is the maximum. The output power curves of system are shown in Fig.4.

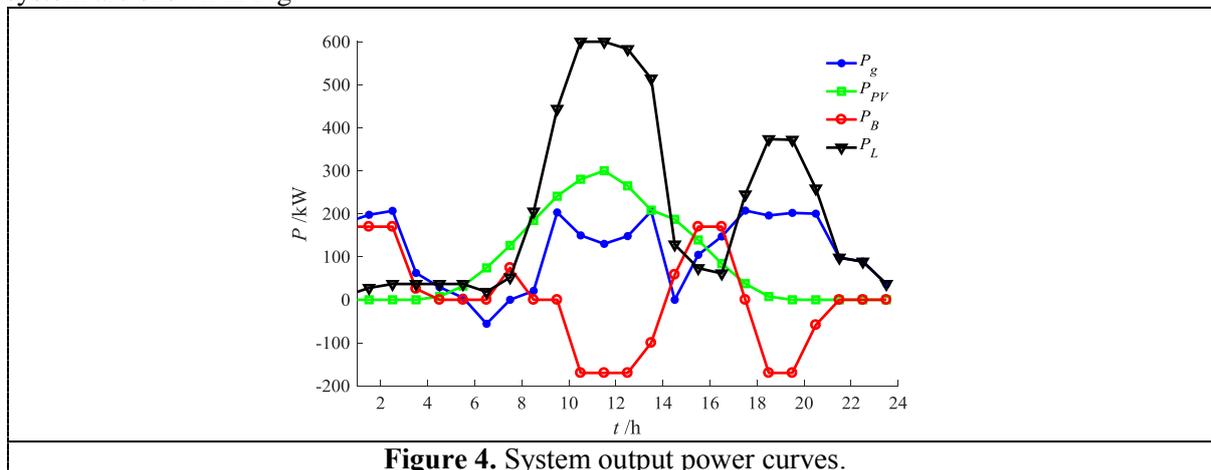


Figure 4. System output power curves.

By properly configuring PV system and BESS, the income capacity and investment payback of charging station can be significantly improved, which is shown as Table.4.

Table 4. Economic comparison of charging station with optimization.

Project	Without PV and BESS	With PV and BESS
Initial investment (million RMB)	1.50	3.15
Financial net present value (million RMB)	1.38	13.27
Financial net annual value (million RMB)	0.12	1.16
Internal rate of return	16%	47%
Payback period of investment (year)	5.98	2.12

6. Conclusion

This paper proposes the optimal economic control strategy of BESS based on time-of-use pricing. And then the capacity optimization configuration model of PV system and BESS is built with the maximum financial net annual value in whole life cycle of EV charging station. The model considers the charging load characteristics of EVs, the output characteristics of PV system, charging and discharging speed of BESS, time-of-use pricing and other relevant constraints. By simulation example, the proposed model can provide guidance for PV system and BESS capacity configuration of EV charging station. And the results illustrate that it can effectively improve the income capacity of charging station, shorten the payback period of investment and has good economic benefits.

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