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Economic Analysis of Energy Storage System Installation by Industrial Users

Sun Wentao¹, Li Haikun^{2*}, Wu Chen¹, Liu Boliang¹, and Han Xingning¹

¹ State Grid Jiangsu Economic Research Institute, Nanjing, Jiangsu, 210024

² Beijing Tsingsoft Technology Co., Ltd, Beijing, China, 100085

*E-mail: lhaikun.cool@163.com

Abstract. Considering the demand of installing energy storage system by industrial users to reduce the basic electricity cost and increase the income of electricity sale, this paper proposes a detailed charging and discharging strategies calculation method to obtain the annual income. Based on the annual load historical data of industrial users, the charging and discharging modes and detailed strategies are determined according to the load characteristic and the electricity price period. Considering the influence of large and dense load on the peak load after peak shifting by storage system, a method of new peak load correction based on dichotomy iteration and backtracking mechanism is proposed. The case verification show that the monthly income is significantly affected by the industrial load characteristics. This method provides accurate income analysis for industrial users to ensure validity and economy of storage system investment.

1. Introduction

With the development of social and economy, the load in power system presents obvious peak-valley difference characteristics [1]. Relying on the investment to increase installed capacity and upgrade transmission and distribution lines, will consume a lot and increase the electricity cost[2]. China National Development and Reform Commission publishes the notice on improving the implementation of two-part tariff [3]. The first part is the basic price corresponding to the peak capacity or load, and the second part is the electricity price. It aims to regulate the electricity consumption in peak period and encourage the electricity consumption in low valley period. Finally, the load characteristics of the system can be improved.

Under this background, energy storage technology has been widely concerned by load users [4,5]. The energy storage system can absorb and stores excess electricity during the low load valley period, then releases electricity during the peak period. This process can effectively eliminates the peak-valley difference [6], and directly obtains income from the peak-valley price.

At present, the research on income of energy storage operation is mainly focused on the following aspects. Reference [7] takes the benefits of electricity sale into the consideration, but ignores the benefits brought by the reduction of user's peak capacity or load. Reference [8] studies the charging and discharging strategies and income of energy storage system from the perspective of increase the electricity sale of photovoltaic power generation. The scenario analysis method is used to realize the economical and effective operation of the grid with large-scale energy storage system in [9]. Its objective is to minimize the total electricity generation cost in the power system. Reference [10] establishes an economic evaluation model, in which the capacity of equipment and the maximum



household electricity demand are optimized. In [11], five indices are established to evaluate the investment and operation cost of energy storage in the PV and storage hybrid system. A mathematical model for optimal energy storage allocation is proposed in [12], taking into account the total life cycle cost of energy storage. Existing researches does not consider the impact of two-part tariff on energy storage income. Especially when the industrial users invest in energy storage system, the income of peak shifting can not be ignored.

With the implementation of two-part tariff, the overall income of the energy storage system are calculated based on the correct charging and discharging strategies, which reflect the peak shifting and electricity sale meanwhile.

This paper builds different energy storage charging and discharging modes considering both peak-valley load and peak-valley price, then calculates detailed charging and discharging strategies for each charging and discharging mode, including time, energy and state of charging(SOC). It can guarantee the industrial user's demand for the basic price reduction and electricity sale increase. Finally, according to the actual historical data of industrial load and peak-valley electricity price, the annual income of industrial users with different capacities and discharging rate is given. The case results provide the guideline for industrial users to invest storage system.

2. Charging and discharging mode

2.1. Load characteristic division

The important purpose of the energy storage system invested by industrial users is to reduce peak load and basic electricity cost. Therefore, the charging and discharging strategies are closely related to the load characteristics. In this paper, in order to obtain the detailed strategies, the charging and discharging modes are first determined. Taking a day as a cycle, the load is divided into peak set and valley set. The distance between the maximum (minimum) load and a load at a specific time point is set as follows:

$$\begin{cases} d_{peak}(t) = (l(t) - \max L_{day})^2 \\ d_{valley}(t) = (l(t) - \min L_{day})^2 \end{cases} \quad (1)$$

Where, $l(t)$ is the load at time t , L_{day} is the set of load in a day, $d_{peak}(t)$ is the distance from $l(t)$ to the maximum load, and $d_{valley}(t)$ is the distance from $l(t)$ to the minimum load.

The criterion of load divided into peak set or valley set is as follows:

- (1) if $d_{peak}(t)$ is less than or equal to $d_{valley}(t)$, then $l(t)$ is divided into the peak set.
- (2) if $d_{peak}(t)$ is greater than $d_{valley}(t)$, then $l(t)$ is divided into the valley set.

2.2. Charging and discharging mode Division

Charging and discharging modes of energy storage are determined by load characteristics and peak-valley price. According to these two factors, the charging and discharging modes of energy storage are determined as table 1.

Table 1. Charging and discharging modes classification

	Price valley period	Price flat period	Price peak period
Load peak set	mode 1	mode 2	mode 3
Load valley set	mode 4	mode 5	mode 6

3. Charge and discharge strategy calculation

According to the charging and discharging mode, the charging and discharging strategy are calculated based on the following principles: First ensure its own peak shifting, and then discharge at peak price period. Considering that the basic electricity cost is accounted monthly, the charging and discharging strategies are also calculated monthly. The new peak load after peak shifting(referred to below as new

peak load or L_{peak}) is set in formula (2) initially. However, it is noted that if the load of the industrial user is large and dense, the capacity of peak load shifting of the energy storage system will be reduced, so the new peak load will be lower than the initial value shown in formula (2). The new peak load will be revised iteratively in following part of this section.

$$L_{peak} = \max L_{month} - P_{disch} \quad (2)$$

Where, L_{peak} is the new peak load after peak shifting, $\max L_{month}$ is the monthly maximum load, P_{disch} is the maximum discharge power of energy storage system.

Mode 1: In this mode, if there is a load greater than L_{peak} , it is refined to Mode 1-1, otherwise it is refined to Mode 1-2.

● **Mode 1-1:** In this mode, even if the electricity price is low, the storage system should discharge because the load is greater than L_{peak} . Then it should charge at other times.

As shown in the figure 1, the red line shows the load curve of mode 1-1, where the load in the D-E-F-G-H section is greater than L_{peak} , so the load greater than L_{peak} should be shifted. And it should charge in the A-B-C-D and H-I-J-K sections. Because the charge-discharge transition time points t_s and t_e corresponding to point D and point H are not known, the interpolation calculation is proposed in formula (3) and (4).

$$t_s = t_2 + \frac{L_{peak} - L_2}{L_3 - L_2} (t_3 - t_2) \quad (3)$$

$$t_e = t_6 - \frac{L_{peak} - L_6}{L_5 - L_6} (t_6 - t_5) \quad (4)$$

Where, $t_1 \sim t_7$ are different times, and $L_1 \sim L_7$ are corresponds to the load at different times.

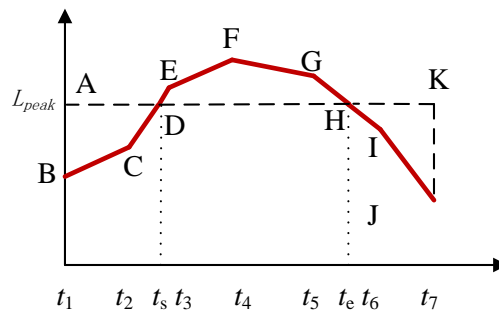


Figure 1 Diagram of charge and discharge energy calculation

The charging energy of each time period is calculated as followed. If the SOC is not taken into account, the ideal charge energy is the area enclosed by the corresponding curve. Taking the area of A-B-C-D as an example, the ideal charge energy can be obtained as follows:

$$S_{ch}^1 = \left(\min \{ L_{peak} - L_1, P_{ch}^{\max} \} + \min \{ L_{peak} - L_2, P_{ch}^{\max} \} \right) \times (t_2 - t_1) / 2 + \min \{ L_{peak} - L_2, P_{ch}^{\max} \} \times (t_s - t_2) / 2 \quad (5)$$

Where, S_{ch}^1 is the charge energy, P_{ch}^{\max} is the maximum charge power of storage system, min indicates that the maximum charge power constraint of storage system and the L_{peak} constraint should be considered both when charging.

The charging energy considering SOC is:

$$S_{ch}^2 = S_n \times (SOC_{\max} - SOC) \quad (6)$$

Where, S_n is the rated energy of the storage system, SOC_{\max} is the maximum SOC.

Considering the load curve and the SOC, the actual charging energy is:

$$S_{ch} = \min \{ S_{ch}^1, S_{ch}^2 \} \quad (7)$$

In this section, the backtracking method is proposed when the initial L_{peak} does not meet the demand for peak shifting. The process details are as follows.

- (1) The existing storage energy can not meet the demand for peak shifting.
- (2) Calculate if it can meet the demand for peak shifting when SOC is the largest (always 1.0). If it can not meet the demand, the new peak load should be calculated based on dichotomy iteration. The flow chart is shown in figure 2.

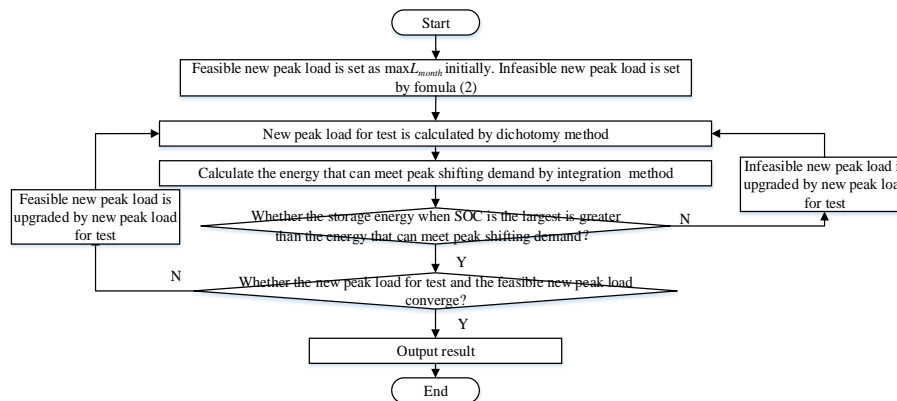


Figure 2 Flow chart of L_{peak} dichotomy iteration

- (3) If it meets the demand of load shifting when SOC is the largest, the process will be traced back and the charging strategies will be revised, as shown in figure 3.

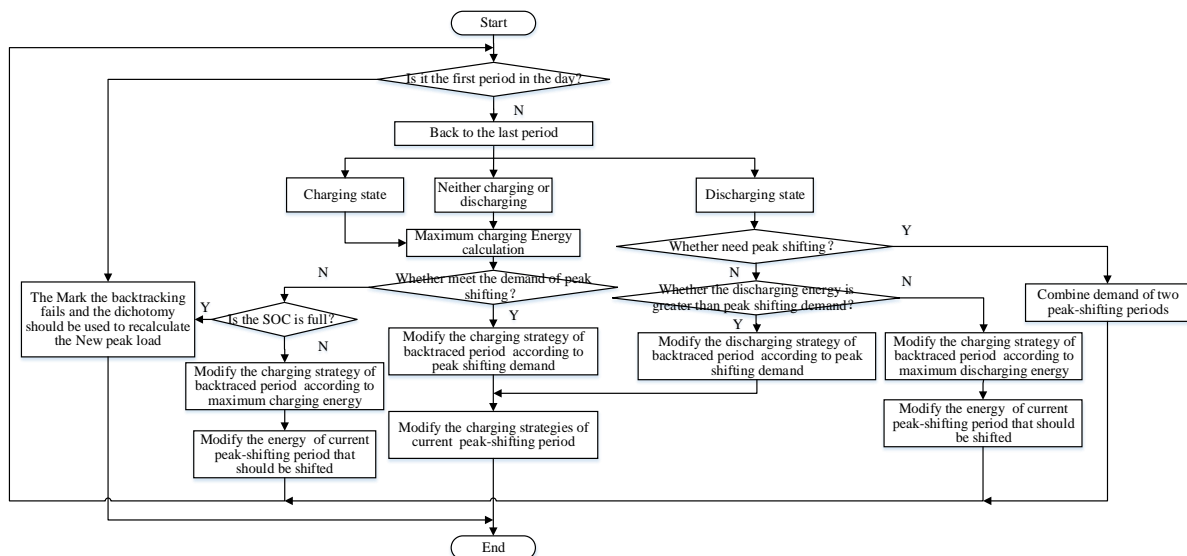


Figure 3 Flow chart of backtracking process

There is a special case that even if the SOC is the largest, the peak shifting demand can not be met due to the large and dense load. In this case, the new peak load needs to be recalculated by the dichotomy iteration. The process is similar to that in Figure 2, which is not described here.

● **Mode 1-2:** In this mode, there are no load greater than L_{peak} , so the storage system charges the whole process. The final charging energy consider the L_{peak} and SOC constraints at the same time, as shown in formula (7).

Mode 2: In this mode, if there is a load greater than L_{peak} , it is refined to Mode 2-1, otherwise it is refined to Mode 2-2.

● **Mode 2-1:** In this mode, if there is a load greater than L_{peak} , only the discharge should be applied to shift the peak load. The steps are the same as those in mode 1-1.

● **Mode 2-2:** In this mode, the storage system does nothing because there is no load greater than L_{peak} .

Mode 3: In this mode, if there is a load greater than L_{peak} , it is refined to Mode 3-1, otherwise it is refined to Mode 3-2.

● **Mode 3-1:** In this mode, the peak shifting should be guaranteed first. If the existing storage energy does not meet the peak shifting requirement, the backtracking method like in mode 1-1 is performed; if the existing energy meets the peak shifting requirement, the storage discharge is performed.

According to the discharge power constraint, the discharge energy is:

$$S_{dis}^1 = P_{dis}^{max} \times (t_7 - t_1) \quad (8)$$

Where, P_{dis}^{max} is the maximum discharge power of energy storage.

According to SOC, the discharge energy is:

$$S_{dis}^2 = S_n \times (SOC - SOC_{min}) \quad (9)$$

Where, SOC_{min} is the minimum SOC.

$$S_{dis} = \min \{ S_{dis}^1, S_{dis}^2 \} \quad (10)$$

● **Mode 3-2:** In this mode, the discharge with maximum discharge power is performed.

Mode 4: The storage charges the whole process, and the final charging energy considered both the L_{peak} and the SOC constraints, as shown in formula (7).

Mode 5: In this mode, the storage system does nothing.

Mode 6: In this mode, the discharge with maximum discharge power is performed.

4. Case Study

The typical industrial load curve is shown in figure 4. Based on the load data, the charging strategies and income are calculated under different storage capacity and charging characteristics. The industrial load base value is 1000kW. In this case, the storage system conversion efficiency is 90%, and the normal range of SOC is 0.0-1.0. Peak-valley price periods are divided into peak period(19:00-21:00), flat period(8:00-11:00, 13:00-19:00, 21:00-22:00) and valley period(11:00-13:00, 22:00-8:00 next day). The electricity price of peak, flat and valley periods are 1.2696, 0.9716 and 0.4596 yuan/kWh respectively. The maximum load demand price is 40 yuan/kW/month.

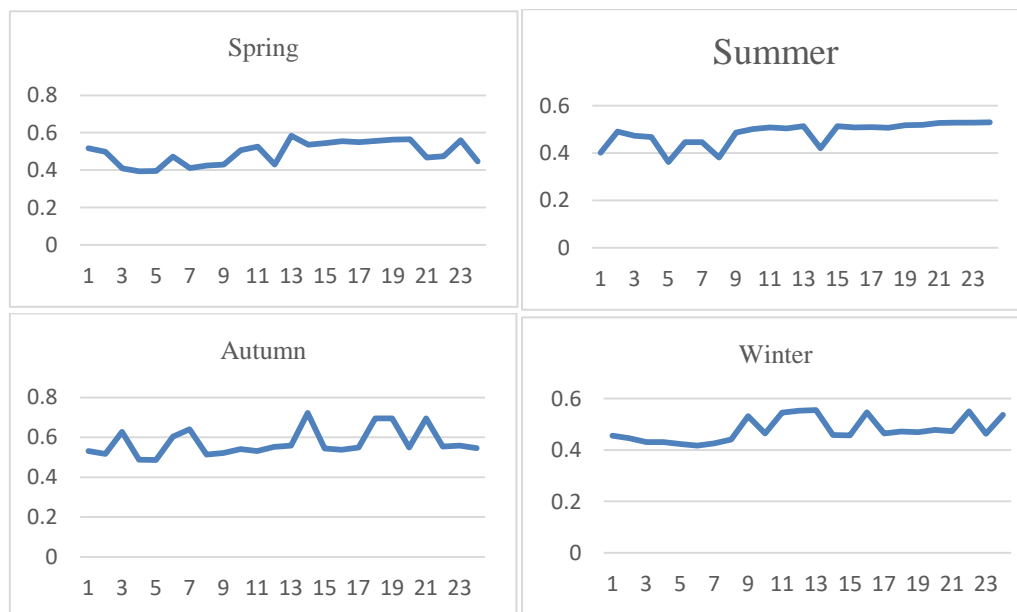


Figure 4. Typical industrial load curve

Considering the influence of different energy storage parameters, two capacities, 100 kWh and 150 kWh, are set respectively in the case. And two discharge rates, 0.5C (finish discharging in 2 hours) and 1C (finish discharging in 1 hour), are considered for each capacity. After calculation based on the method proposed in this paper, the monthly economic income based on the historical load data are obtained, which is shown in table 2.

Table 2 Monthly economic income of storage system

Month	100kWh & 0.5C		100kWh & 1C		150kWh & 0.5C		150kWh & 1C	
	Income (yuan)	Peak shifting power (kW)	Income (yuan)	Peak shifting power (kW)	Income (yuan)	Peak shifting power (kW)	Income (yuan)	Peak shifting power (kW)
1	4181.0	50	5372.5	81	6265.9	75	7143.2	98.4
2	3980.1	50	5940.3	100	5974.2	75	7852.8	129.1
3	4219.8	50	6142.8	100	6310.9	75	8038.2	120.3
4	4160.1	50	5360.6	81	6218.6	75	7351.8	105.3
5	3760.5	45.1	3765.3	45.1	5230.5	58.1	5520.8	67.9
6	4121.5	50	5150.1	76	6178.6	75	6999.0	95.8
7	4219.6	50	6138.9	100	6311.0	75	8393.2	130
8	4216.0	50	5026.9	81.2	6973.2	75	7362.7	95
9	3332.8	37.6	3304.3	37.6	4673.4	49.5	4651.4	49.5
10	4208.6	50	5569.9	95	6186.8	75	7147.0	114
11	3989.8	50	4793.3	73.8	5863.1	75	6311.5	89.3
12	4203.9	50	5626.6	91	6114.7	75	8092.0	112

It can be seen that even with the same maximum discharge rate of storage system, due to the differences the monthly load characteristics, the final L_{peak} is different. With the same storage capacity, the larger the discharge rate is, the higher the income will be, which benefits from the lower basic electricity cost considering two-part tariff. But it isn't reasonable that the larger the capacity or the discharge rate is, the higher the income will be. From the result of 150kWh capacity and 1C discharge rate, it can be seen that the all of L_{peak} can not reach the maximum discharge power, so the investment of the corresponding inverter with higher power is not appropriate.

Because there is only one price period in this case, most of the time, the energy storage system has only one deep charge and discharge every day. A slight change occurs only when the load is large and dense. The charging strategies in a day are given in table 3. It can be seen that the backtracking mechanism can solve the problem that some periods do not meet the peak shifting demand. It verifies the effectiveness of the backtracking mechanism.

Table 3 Charging strategies in a day

Start time	End time	Without backtracing			With backtracing	
		Charging energy (kWh)	SOC	Insufficient discharging energy (kWh)	Charging Energy (kWh)	SOC
0	7	25.7	1	/	25.7	1
10.9	11	-0.9	0.99	/	-0.9	0.99
11	13	-39.6	0.57	/	-39.6	0.57
13	15.1	-46.7	0.08	/	-46.7	0.08
15.1	19	0	0.08	/	50.5	0.56
19	19.8	19.3	0.26	/	19.3	0.82
19.8	21	-25.2	0	7.6	-32.8	0.48
21	22	0	0	25.7	-25.7	0.21
22	23.1	0	0	20.0	-20.0	0
23.1	24	22.8	0.22	/	22.8	0.22

5. Conclusion

In this paper, the income of storage systems for industrial users is analysed. Based on the load historical data of industrial users, the charging and discharging modes are divided according to the load and electricity prices. Then the detailed charging and discharging strategies are calculated according to the charging and discharging modes, including time, energy and state of charging(SOC). Especially for the peak shifting of energy storage considering two-part tariff, a L_{peak} calculation method based on dichotomy iteration and backtracking mechanism is proposed, to solve the problem that L_{peak} can not reach the maximum discharge power due to the large and dense load. The case results show that the impact of industrial load characteristics on the monthly income is very significant. Even for the same energy storage capacity and discharge rate, the differences of income are obvious in different months. So the planning and design of energy storage system can not be separated from the load characteristics. It may cause storage capacity wastage. The detailed calculation of annual charging and discharging strategies based on historical data can provide auxiliary data for industrial users to ensure the economy of storage system investment.

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