Valuation of Energy Storage at User Side Considering Total Life Cycle

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Abstract. With the continuous progress of energy storage technology and the substantial reduction of cost, as well as the development of China’s energy Internet, customer-side distributed energy storage has been applied more and more widely. Considering the customer-side distributed energy storage which takes the grid-connected "distributed solar + energy storage" as the main application mode, a distributed energy storage evaluation model based on double-granularity optimal operation strategy is proposed, which is built on life-cycle cost-benefit analysis model for customer-side distributed energy storage considering its operation optimization in advance. Taking large industrial and business consumers in one province in China as an example, the sensitivity analysis of customer-side distributed energy storage value is taken under different load characteristics, price policies, energy costs and energy storage technology characteristics, judging the customer-side distributed energy storage trends and potential of further development.

1. Introduction

Power storage can isolate the production, transmission and consumption of electric energy from time and space. It can be used in the fields of peak load shifting, new energy integration, power supply in remote areas, increasing the reliability of power supply, and balancing regional load [1,2,3].

By the end of 2017, totally 389.8MW electrochemical energy storage had been launched into operation in China where the proportion of installed capacity in the customer-side reached 59%, the highest among all application fields like renewable energy integration, power frequency regulating, electric vehicle charging station, etc.[4]. At present, customer-side energy storage projects are mainly applied in industrial/commercial energy storage, island micro grid, power supply in remote areas, low-carbon/smart city/community construction and other fields. Given the booming concept of energy Internet and the development of distributed PV, micro-grid and e-vehicles, the distributed energy storage and its application in the customer-side turn out to be a new hot topic[5].

The quantitative value assessment of application of distributed energy storage at user side can serve as both the preference of investment value of distributed energy storage and the evidence for study and judgment of future development of energy storage. The present research mainly focuses on the specific application of energy storage with much less effort taken on the application model and value assessment of distributed energy storage [6]. Some literatures[7,8,9,10] analyze the potential application value of energy storage and establish the corresponding models of economic assessment. However, these models are all based upon the theoretical calculation of basic performance parameters...
of energy storage, without considering the impact of actual operation strategy and status of energy storage upon the value assessment.

This paper concentrates on the study of grid-connected "distributed PV + energy storage" as the application model of distributed energy storage at user side, uses the double-granularity optimal operation strategy, and proposes the model of full lifetime energy storage value assessment considering pre-operation optimization. With practical cases data, the paper makes sensitivity analysis from four perspectives: load characteristics, tariff policy, energy storage cost and storage technology performance, to judge the prospect of distributed energy storage at user side.

2. Analysis of application model of distributed energy storage at user side

2.1. Application models
The distributed energy storage installed at user side generally includes the below three application models: off-grid self-sustained system, grid-connected "load + storage" system and grid-connected "PV + storage" system (Figure 1). The users include residents without power access, common residents, schools and governments, common industry and commerce users, and big industry users. The major types of energy storage are lead battery and lithium ion battery, which are flexible and convenient in use.

![Figure 1. System Structure of Distributed Energy Storage at User Side](image)

2.2. Value of application
The installation of distributed energy storage at user side changes more or less the load operation characteristics of power system and the power consumption behaviour of users. Therefore, the major value of application of distributed energy storage at user side can be analysed in two dimensions.

2.2.1 Value of grid
(1) Reduce or postpone the grid expansion
Through the distributed energy storage at user side, the grid capacity demand of users in the peak load time is reduced. Large-scale application of energy storage by primary heavy-load users can to some certain extent cut down the capacity of grid expansion and postpone the grid upgrading and expansion.
(2) Reduce grid loss
When the peak shaving and valley filling of energy storage adequately functions upon the system load, it can significantly reduce the current passing through the trunk lines of distribution network in the time of peak load, which helps reduce the loss of lines and transformers.

2.2.2 Value of user
(1) Reduce the configuration capacity and load loss of user's distribution transformer
If a user considers the installation of power storage at the low-voltage side of distribution transformer to reduce the capacity of grid under peak load, it may reduce the configuration capacity of transformer
or postpone such upgrading. In the meantime, the load loss (copper loss) of transformer is in proportion to the square number of load rate so that the peak shaving function of energy storage can reduce the distribution transformer loss in the time of peak load.

(2) Lower user's capacity tariff
China implements two-part tariff for large industry consumers where the tariff is composed of basic tariff and quantity tariff, in which the basic tariff is charged each month as per the capacity of self-contained dedicated transformer or the 15-minute average maximum load capacity of peak time of that month. Therefore, the energy storage equipment reduces the maximum load demand and thus cuts down the expenditure of capacity tariff.

(3) Reduce user's quantity tariff of power charge
For the kWh tariff, many provinces in China implement the policy of peak and valley tariffs that set different tariff criteria of peak time, normal time and valley time. The maximum tariff gap between the peak and valley time may reach 5:1. In addition to the arrangement of delayed load for demand response, the user may install the energy storage apparatus for charging in the valley time and discharging in the peak time, which results in less expenditure of tariff per kWh.

(4) Reduce the loss of outage cost
In addition to the value created by saving power consumption cost in user's normal production and life, the energy storage apparatus may also serve as the UPS power source in the event of power failure that helps reduce the loss of outage cost.

3. Model and operation strategy of distributed energy storage at user side

3.1. Model of energy storage
An ideal model is adopted for energy storage that does not consider the self-wastage rate and the SOC only relates to the charging/discharging quantity. By assuming the constant charging and discharging power of energy storage in the duration of \( \Delta t \), the energy relation of storage system before and after charging/discharging is:

\[
W_{ES}^{1} = W_{ES}^{0} + (P_{ES,C} \eta_{ES,C} - \frac{P_{ES,D}}{\eta_{ES,D}}) \Delta t
\]  

(1)

Where \( W_{ES}^{0} \) and \( W_{ES}^{1} \) are respectively the electricity quantity before and after charging/discharging (kW-h), \( P_{ES,C} \) and \( P_{ES,D} \) are respectively charging and discharging power of energy storage (kW), and \( \eta_{ES,C} \) and \( \eta_{ES,D} \) are respectively the charging and discharging efficiency of energy storage.

The state of charge (SOC) of energy storage system after charging/discharging is:

\[
SOC = \frac{W_{ES}}{W_{ES,R}}
\]  

(2)

Where \( SOC \) is the state of charge while \( W_{ES,R} \) is the rated energy capacity of storage (kW-h).

During the actual operation of energy storage, the terminal voltage is assumed to be constant but needs to be guaranteed within certain \( SOC \) scope and its charging/discharging power is more or less limited, which can be described by the following constraint equation:

\[
W_{ES}^{\text{min}} \leq W_{ES} \leq W_{ES}^{\text{max}}
\]  

\[
0 \leq P_{ES,C} \leq P_{ES,C}^{\text{max}}
\]  

\[
0 \leq P_{ES,D} \leq P_{ES,D}^{\text{max}}
\]  

(3)

(4)

(5)

Where \( W_{ES}^{\text{min}} \) and \( W_{ES}^{\text{max}} \) are respectively the minimum and maximum electric quantity (kW-h) permitted by energy storage while \( P_{ES,C}^{\text{max}} \) and \( P_{ES,D}^{\text{max}} \) are the limits of charging and discharging power of energy storage (kW).
In addition, it is assumed the energy storage longevity is decided by the total quantity of recycling charging and discharging and not related with the depth of discharging.

3.2. Double-granularity optimal operation strategy of energy storage
In selection and development of energy storage operation strategy, the consideration shall be given to both the energy storage benefit and its investment cost and lifetime. Different operation strategies have different impact on energy storage lifetime; frequent charging/discharging can earn higher benefit but shorten the lifetime of energy storage. The cost-benefit analysis of full lifetime helps better determine the result of energy storage strategy. For simplicity, the cost and benefit of unit charging/discharging quantity of electricity is taken into account.

Given the two parts of benefit of energy storage: one is the model of utilization of surplus power that stores the surplus PV power of certain periods to improve the utilization rate of PV power generation; the other is the grid arbitrage model that stores the power of lower tariff and supplies the power of higher tariff to reduce the power purchase cost.

3.2.1 Basic principles. The economic operation strategy of energy storage shall comply with the below basic principles:
1) Under the surplus power utilization model, store the surplus PV power by the maximum charging capacity of energy storage with the priority of supply to the load of peak tariff time;
2) Under the grid arbitrage model, provided the requirement of 1) is satisfied, utilize the grid arbitrage for earning by increase the charging in the valley tariff time;
3) Balance the stored power in the fixed time of a day, e.g. charging in the early hours to guarantee the consistency of SOC before and after charging/discharging, generally 0.8 taken as the intermediate value of SOC.

3.2.2 Criteria of model determination. When determining the application model of energy storage, use the economic criteria to judge its cost efficiency. To facilitate calculation, the paper assumes the constant charging and discharging quantity of battery throughout its lifetime, and thus easily works out the cost of depreciation of discharging 1kWh:

\[ C_{ES,w} = \frac{C_{ES,rep}}{Q_{lifetime}} \]

Criterion 1 (surplus power utilization model):

\[ C_{ES,w} + C_{ES,loss} < C_{grid,pur} - C_{grid,sel} \]

Where \( C_{ES,w} \) stands for the converted cost of charging/discharging 1kWh of energy storage, \( C_{ES,loss} \) for the cost of power loss of energy storage, \( C_{grid,pur} \) for the power purchase price of discharging and \( C_{grid,sel} \) for the feed-in tariff of surplus power. When such feed-in tariff is high, the residual power of energy storage may not be used.

Criterion 2 (grid arbitrage model):

\[ C_{ES,w} + C_{ES,loss} < C_{peak,pur} - C_{valley,pur} \]

Where \( C_{peak,pur} \) stands for the tariff of peak time while \( C_{valley,pur} \) for the tariff of valley time.

3.2.3 Optimized strategy of energy storage. The details of double-granularity optimal strategy are as follows:
1) In the first stage, determine the energy storage state of different times, i.e. whether charging/discharging is required under the surplus power utilization model and arbitrage model. Firstly select the typical day and determine the charging/discharging state of different time as per the tariff, load and sunlight of the typical day. The flow chart of this stage is as Figure 2 below:
2) In the second stage, based upon the charging/discharging state of energy storage of different time, conduct simulative analysis of all-year data to get the yearly operation cost under the strategy including the power purchase cost, total charging/discharging quantity of energy storage, etc. Since the energy storage operation strategy under the conditions of typical day is broken down to the specific time period, in developing the dispatching plan the charging/discharging quantity is decided by the actual conditions only. The flow chart of this stage is as Figure 3 below:

3) Calculate the operation cost of each operation day, and given the investment, operation and maintenance costs of system throughout the project cycle, calculate the net present value of system and unit power consumption cost.

4. Value assessment modeling of distributed energy storage at user side

4.1. Energy storage value model
4.1.1 Net present value. The net present value is generally used in project investment to assess the benefit of investment. The smaller total cost NPV in the lifetime of project means the better investment plan. Therefore, users in decision making can make use of the comparison of total cost NPVs of different plans to decide whether to install energy storage and the specific configuration of energy storage. The formula of total cost NPV is as below:

$$C_{NPV} = \frac{C_{ann,t}}{K_{CRF}(r,T_{Pro})}$$

Where $C_{NPV}$ is the total cost net present value of project, $C_{ann,t}$ is the total annual average cash flow, $K_{CRF}(r,T_{Pro})$ is the capital recovery factor of the project cycle, the present value of annual average cash flow is calculated by the following formula:

$$K_{CRF}(r,T_{Pro}) = \frac{r(1+r)^{T_{Pro}}}{(1+r)^{T_{Pro}}-1}$$

Where $r$ is the interest while $T_{Pro}$ is the project cycle.

4.1.2 Cost benefit model. For the user equipped with energy storage, the main purpose is to reduce the power purchase cost to avoid the total cost higher than the total benefit. The total present net value input is selected in analysis and the formula is as below:

$$C_{ann,t} = C_{ann,cap} + C_{ann,rep} + C_{ann,om} + C_{ann,ele} + C_{ann,bas} - B_{sel} - B_{sub}$$

Where $C_{ann,cap}$ stands for the annual capital cost, $C_{ann,rep}$ for the annual replacement cost, $C_{ann,om}$ for the annual operation and maintenance cost, $C_{ann,ele}$ for the annual electricity cost, $C_{ann,bas}$ for the annual basic electricity cost, $B_{sel}$ for the annual benefit of selling power and $B_{sub}$ for the benefit of subsidy.

The annual electricity selling benefit $B_{sel}$ refers to the benefit selling the surplus electricity to grid gained by the "PV + storage" user system, and its calculation formula is:

$$B_{sel} = \sum_{i=1}^{8760} W_{sel,i} \cdot c_{sel}$$

Where $W_{sel,i}$ is the quantity of electricity sold to the grid in the $i$th hour and $c_{sel}$ is the selling price to grid. The current feed-in tariff of PV surplus power in China is the same as the local benchmark tariff of coal-fired power.

4.2. Process of assessment
Figure 4 shows the value assessment process of energy storage proposed by this paper.
The annual capital cost, annual replacement cost, annual operation and maintenance cost and subsidy benefit are mostly irrelevant with the system operation strategy except the consideration of lifetime of energy storage, which may be directly calculated after input of basic parameters and configuration of apparatus scheme; but the annual electricity cost, annual basic electricity cost and annual electricity selling benefit have different results under the variant energy storage charging/discharging strategies and grid power sale and purchase behaviors. Therefore, the charging/discharging model and operation mode of energy storage shall be decided as per the logic judgment of dual-grain energy storage optimized strategy of this paper, thus yielding the total cost NPV throughout the project lifetime.

5. Case analysis

5.1. Case system structure
The grid-connected "distributed PV + energy storage" system is adopted where the distributed PV and energy storage are connected to the grid by respective inverters and supply power to load with directly feed-in surplus power.

5.2. Data input
The hourly tariff data of Zhejiang Province are selected. The feed-in tariff of solar power is CNY0.4/kWh and the capacity electricity cost is CNY40/kW/month. The commercial load is the data of actual consumers with an all-year maximum load of 16kW. The sunlight data source is the NASA data source that the history data of Hangzhou, capital of Zhejiang Province are selected. The present cost of distributed PV investment is around CNY7,500-8,500/kW and the benchmark data is CNY8,000/kW; the costs of lithium battery range between CNY2,000 and CNY3,000/kWh and thus the benchmark data is CNY2,500/kWh.

5.3. Case results

5.3.1 HOMER strategy. The fixed operation strategy of HOMER reduces the PV investment cost and increases the optimal installed capacity of PV. When the investment cost is reduced by 20%, the PV installed capacity reaches 43.8kW. On this occasion, the optimal installed capacity of energy storage is 1kWh and the proportion of new energy power generation reached 90%.
When the PV cost is lower than certain value (e.g. 50%), the PV capacity reaches the upper limit. It means the PV power only can yield earnings, and therefore PV will be installed as far as possible to gain the grid-connected earnings. On this occasion, the proportion of new energy depends on the upper limit of PV capacity.

From now on, despite of lowering cost of energy storage, the HOMER optimized plan has no change at all. See Table 1. The reason is the HOMER fixed strategy separately studies the operation of each time period but does not make use of the value of energy storage in utilization of surplus PV power and integrated grid arbitrage.

| Cost of PV (CNY/kW) | PV capacity (kW) | Energy storage capacity (kWh) | Total economic cost (TEN THOUSAND CNY) | New energy ratio (%) |
|---------------------|------------------|-------------------------------|---------------------------------------|----------------------|
| 8000                | 14.6             | 0                             | 24.1                                  | 67                   |
| 7200                | 20.3             | 0                             | 22.7                                  | 77                   |
| 6400                | 43.8             | 1                             | 20.4                                  | 90                   |
| 4000                | upper limit      | 1                             | -                                     | -                    |

5.3.2 Double-granularity optimal strategy. The double-granularity optimal strategy proposed by this paper is adopted. Firstly, judge the value of surplus power model and arbitrage model under different conditions and determine their cost efficiency; then decide the optimal configuration capacity of energy storage and calculate the economic cost, energy storage lifetime and proportion of new energy power generation. See Table 2.

| Cost of PV (CNY/kW) | PV capacity (kW) | Energy storage capacity (kWh) | Total economic cost (TEN THOUSAND CNY) | New energy ratio (%) |
|---------------------|------------------|-------------------------------|---------------------------------------|----------------------|
| 8000                | 14.6             | 0                             | 24.1                                  | 67                   |
| 7200                | 23.5             | 1                             | 21.6                                  | 80                   |
| 6400                | upper limit      | 3                             | 20.4                                  | 95                   |
| 4000                | upper limit      | 3                             | 18.7                                  | 95                   |

The case study shows that the cost efficiency of project investment relates to both equipment cost and operation strategy. The reasonable energy storage charging and discharging strategy can effectively reduce the operational cost of system, improve cost efficiency and help popularize the application of energy storage.

6. Conclusion
The decrease of cost plays a decisive role in the configuration of energy storage. However the configuration capacity is under multiple effects like PV cost, load, PV power generation, etc.

As the PV cost declines, the PV installed capacity will climb up but the value of grid-connected surplus PV power will also increase together with higher demand of total quantity of remaining stored PV power. However, the critical point of energy storage application does not change. The decrease of energy storage cost will have critical influence on the application of energy storage, but the capacity of energy storage is decided by the load of system, PV power generation, etc. Further reduction of energy storage cost does not uplift the capacity requirement of energy storage in the system.

The charging/discharging strategy plays an important role in the realization of energy storage value. The double-granularity optimal strategy in this paper can significantly add benefit to users and thus more effectively improve the benefit of PV energy storage system. On one hand the strategy gives full play to the arbitrage value of energy storage and makes it more cost efficient under the hourly tariff model, which consolidates the cost efficiency of distributed PV energy storage system; on the other hand, by efficient utilization of peak and valley tariffs, the strategy offers a better profit-making model of configuration of energy storage and improves its capacity and benefit, thus beneficial to the application of distributed energy storage.
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