IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received April 11, 2019, accepted April 30, 2019, date of publication May 10, 2019, date of current version June 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916181

Economic Evaluation of Micro-Grid System in Commercial Parks Based on Echelon Utilization Batteries

XIAOJUAN HAN, FENG WANG, AND MENGJIAO CHEN
School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China
Corresponding author: Xiaojuan Han (wmhxj@163.com)

This work was supported by the National Natural Science Foundation of China under Grant 51577065.

ABSTRACT The rapid growth of the air-conditioning load leads to a further increase in the peak-to-valley difference of the load, which has affected the steady operation of the power grid. An economic evaluation method of the controlled air-conditioning load combined echelon utilization batteries in the micro-grid system of a commercial park participating in the demand side management is discussed in this paper. Through the study of the optimal control mode of air-conditioning load groups, taking the user comfort and the fairness of the air-conditioning control into consideration, an orderly control model of the air conditioning is developed by the improved state-queue (ISQ) control algorithm. Echelon utilization batteries are introduced into the micro-grid system of the commercial park, and a coordinated optimization allocation and economic evaluation model of the micro-grid system in the commercial park is established. The particle swarm optimal algorithm (PSO) and the artificial bee colony algorithm (ABC) are employed to solve the model. The simulation tests of the actual operating data in the commercial park in Shanghai of China show that the controlled air-conditioning load can improve the optimal allocation of resources and promote the energy utilization rate by participating in the demand side management. The optimized regulation of the air-conditioning load not only improves the user's comfort but also reduces the cost of the purchasing electricity from the grid. When the purchasing cost of the unit capacity for the echelon utilization batteries is less than 254.5391 USD/kWh, the economy of the echelon utilization batteries is better than the conventional energy storage batteries. The method presented in this paper provides a theoretical basis for the echelon utilization of retired electric vehicle batteries (REVBs) and has certain engineering application prospects.

INDEX TERMS Echelon utilization, energy storage system, optimal allocation, economic evaluation, commercial park.

I. INTRODUCTION

With the higher living standards of people today, a variety of air-conditioning systems have been widely used, the cooling load in summer and the heating load in winter have accounted for more than 30% of the maximum load in these two seasons. In a commercial park, the air conditioning load of the users accounts for about 40% of the total building load, and it shows a rapid growth trend in the future years [1]. As the air conditioning load participated in the demand side management is still in the exploration period in China, the relevant supporting policies and incentive measures to promote the development of the demand side management are still not perfect [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Khmaies Ouahada.

In traditional operating mechanism of the power grid, the main way to solve the above problems usually adopts the peak unit, power cuts and other load management measures for the users, or increases the installed capacity and the transmission and distribution network capacity to meet the short spikes. But the cost of the peak unit is too high, the power cuts will sacrifice the interests of the users, and the air conditioning load is mainly concentrated in hundreds of hours in the winter and summer peak period, while the increase of the installed capacity will result in the low utilization of the equipment and huge investment. Energy storage system (ESS) is an effective means to decrease the peak load through the dynamic absorption and release of the electricity. However, the current high cost of the ESS restricts the development of the energy storage technology, and the economy is poor when the ESS is simply used to peak load shifting. Therefore, it has great significance to explore the economics of energy storage planning method and low-cost energy storage batteries.

Demand side management technology [3] can effectively reduce the capacity of the ESS and promote the balance of the supply and demand side. Meanwhile it can guide the users to change their electricity habits and optimize the way of the electricity through a certain price signal or incentive policy, thereby reducing or shifting the effect of the electricity load during a period [4]. The load curve of the air-conditioning of the micro-grid system in the commercial park is adjusted to participate in the demand side management on the user side by the optimal control of a large number controlled air conditioning load. The controlled air conditioning can be seen as ''Virtual Energy Storage'' equipment on the user side. The coordinated optimization control between the air conditioning load and energy storage equipment not only helps to ease the power supply shortage contradiction and ensure the security of the power grid, and is conducive to optimizing the power consumption.

In [5], a state queue (SQ) model was used to describe the change of the air conditioning operation state and the performance of the air conditioning load with different electricity price levels. In [6], the SQ algorithm was used to control the switches of the temperature control equipment so that the common heat pump, refrigerator, air conditioning and other temperature control load could participate in the demand side management. In [7], a coordinated optimized dispatch billing method controlled by air conditioning load groups was proposed. The control characteristics and parameters of air-conditioning load group were analyzed, and the load control cost model and air-conditioning load group dynamic economic dispatch model were established. In [8]–[10], a temperature-based priority list model was built, the air conditioning was controlled by the controlled target according to the order of the list. In [11], the load control of air conditioning groups was achieved by directly changing the temperature setting of the air conditioning. However, for the same parameters or high similar degree of air conditioning groups, the lower the temperature is, the greater the load diversity loss is, and the air conditioning groups will appear huge fluctuations of the load. In [12], the closed-loop control method was used to overcome the above problems. Although the control precision of this method was higher, the dispatching center had to set up a two-way information channel to obtain the start-up and indoor temperature of each air conditioner. It requires a higher information processing capability, and the control cost of the air conditioning will increase.

Therefore, the air conditioning load involved in the demand side management plays a role in the ESS to effectively reduce the required capacity of the ESS. However, the use of the retired electric vehicle batteries (REVBs) is an alternative way to reduce the high cost and meet the required performance of the ESS. When the capacity of the REVBs is reduced to 80%, it will not be able to continue to be used in the EVs. If directly recycled, it will not only pollute the environment, but also bring about a huge waste of the value of the battery. The echelon utilization of the REVBs can give full play to the capacity value of the REVBs, extend its service life, promote the energy conservation and alleviate the pressure of the recycling work of the REVBs. Therefore, the echelon utilization of the REVBs in the micro-grid system of the commercial park instead of the traditional ESS not only reduces the cost of the ESS, but also promotes the healthy development of the electric vehicle (EV) industry, which has important social significance and huge economic benefits [14].

In [15], the initial cost of the echelon utilization of the REVBs was assessed from the perspective of the EV users, and the potential market of the REVBs applied to the ESS was explored in United States National renewable energy laboratory. In [16], taking the whole life cycle value of the REVBs as an object, an economic evaluating method of echelon utilization batteries was put forward from the perspective of the owner of the EVs. In [17], a mixed integer nonlinear programming method for the optimal size and control of fast charging stations and ESS is proposed in order to perform the capacity allocation and the economic evaluation of fast charging stations and ESS. In [18], the annual cost of the typical Canadian housing with or without echelon utilization batteries after the load regulation was determined by the typical residential load curve. The savings cost under different prices and the auxiliary cost level of the EVs were analyzed. In [19], a model of the echelon utilization energy storage system (EUEES) was established to analyze the economy by introducing the value of the EES from the grid. In [20], the REVBs were applied to the peak load management in commercial buildings, the capacity of the EUESS and the number of echelon utilization batteries were obtained by the rule-based control scheme, the charge and discharge control strategy of the EUESS was adopted to improve the life of the echelon utilization batteries.

The above studies mainly focus on the use value of echelon utilization batteries, and a specific cost estimation algorithm of echelon utilization batteries has not been given. Aiming at the optimal configuration and economic evaluation of the EUESS, the involved process and the cost of the REVBs during the whole life cycle applied to the ESS is analyzed in this paper. An optimization planning and economic evaluation model of the micro-grid system in the commercial park considering the cost estimation of echelon utilization batteries is proposed. Through the analysis of the response characteristics of single controlled air conditioning load, the air conditioning orderly regulation model is established to satisfy the comfort of the user and the fairness of the air conditioning control. From the perspective of the whole life cycle of the REVBs, the equivalent cycle life of echelon utilization batteries under different depths of discharge (DODs) is calculated by the rain flow counting method to estimate the life of the echelon utilization batteries. The unit capacity of the EUESS is estimated by the use value of echelon utilization batteries, and the unit capacity of the annual operation cost is calculated according to different initial capacity retention rates and the relationship between the running and maintenance unit price, in order to obtain the cost of the EUESS. The economic evaluation model of the micro-grid system in the commercial park based on the EUESS is established. PSO and ABC algorithms are respectively used to solve the model. The whole economy of the micro-grid system is obtained through the simulation tests of the real operation data in a certain commercial park of Shanghai in China. The simulation results show that the EUESS can be applied for the micro-grid system in the commercial park to coordinate the controlled air-conditioning load and reduce the peak load of the grid by the way of low-storage and high-generation, thereby reducing the cost of the purchasing electricity from the grid.

II. OPTIMIZATION CONTROL OF THE MICRO-GRID SYSTEM IN A COMMERCIAL PARK

A. THE STRUCTURE OF THE MICRO-GRID SYSTEM IN A COMMERCIAL PARK

A schematic diagram of the micro-grid system in the commercial park is shown in Fig.1.

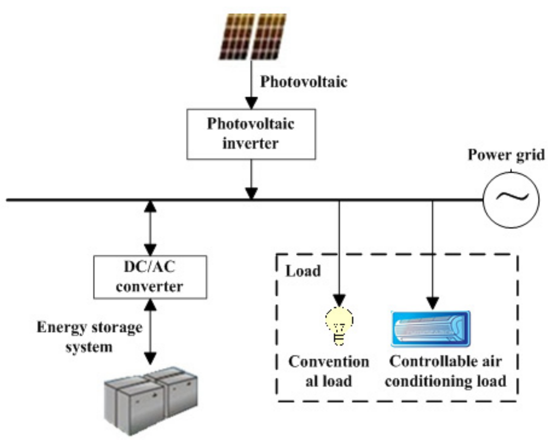

FIGURE 1. Schematic diagram of the micro-grid system in the commercial park.

The micro-grid system in the commercial park (as shown in Fig.1) includes the distributed power system, EES and the load. The electricity load of the commercial park mainly refers to the power supply load required by office buildings, which is divided into the conventional load and the controlled air conditioning load. The conventional load includes the lighting, elevator, office appliances and so on. The cooling load in summer and the heating load in winter cannot exist at the same time, but both are closely related to the users in the commercial park. Due to the fact that the users in the commercial park are hardly affected by the seasons, the conventional load can be considered as consistent throughout the year. The controlled load refers to the cooling and heating load of the air conditioning varying with the change of the season and temperature. When the electric of the distributed generation system in the micro-grid system is insufficient for the load, the electric will be purchased from the power grid; if the electric of the distributed generation system in the micro-grid system is surplus for the load, it will be supplied to the power grid. Thus, the distributed generation system can act as a backup power source for critical loads when the grid is under-powered and can save the cost by reducing the peak demand and the diverting electricity.

According to the power balance of the micro-grid in the commercial park, it can be described as (1).

$$P_{line} + P_{pv} = P_{con} + P_{air} + P_{ess} \quad (1)$$

where P_{line} is the connection line power of the micro-grid system; P_{pv} is the output power of the PV system; P_{con} is the conditional load; P_{air} is the controlled air conditioning load; P_{ess} is the output of the ESS.

In (1), if the micro-grid system purchases the electric from the large power grid, then $P_{line} > 0$; if the micro-grid system transmits the power to the large power grid, then $P_{line} < 0$; if the ESS charges, then $P_{ess} > 0$; if the ESS discharges, then $P_{ess} < 0$.

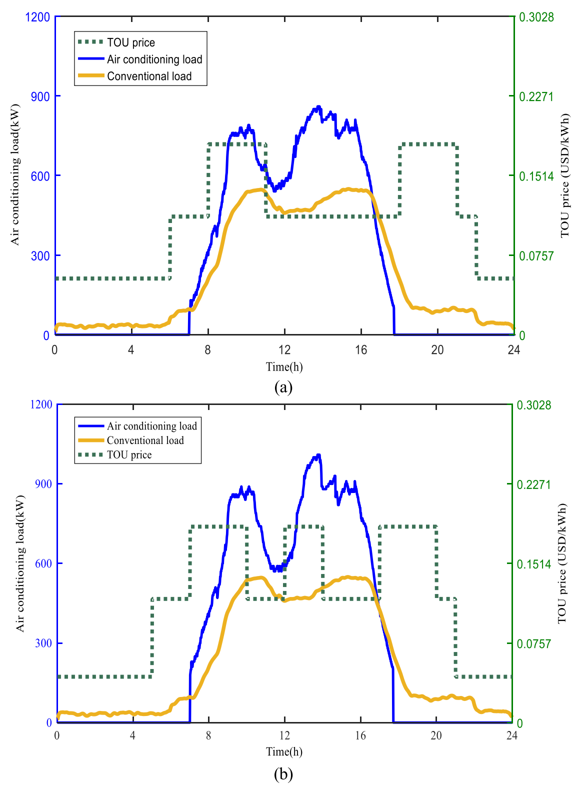

FIGURE 2. The cooling, heating and electrical load curves in commercial park. (a) Heating season. (b) Cooling season.

According to the data coming from the commercial park in Shanghai of China, the typical daily curves of the cooling, heating and electrical load in the cooling season and the heating season are shown in Fig.2.

It can be seen from Fig.2 that as the work of the staff begins, the cooling and heating load of the air conditioner quickly rises to the peak from 8 o'clock, slightly decreases at about 12 o'clock, and drops rapidly around 17:00 at the end of the work. The electrical load varies in the same way, but the electrical load is not zero in the whole day. After the staff in the building leaves, that is, from 22:00 to the next morning, the minimum electrical load is only maintained for the building infrastructure and external lighting.

B. DYNAMIC PROCESS MODELING OF SINGLE AIR CONDITIONING EQUIPMENT

According to the equivalent thermodynamic model of single air conditioning, a simplified first-order response model is used to achieve the dynamic process modeling of an air conditioning equipment [21]. When the air conditioning is heating, it can be described as follows:

① *Air Conditioning is on:*

$$T_{in,t+\Delta t} = T_{out,t+\Delta t} + Q \times R - (T_{out,t+\Delta t} + Q \times R - T_{in,t})e^{-\Delta t/R \times C} \quad (2)$$

② *Air conditioning is off:*

$$T_{in,t+\Delta t} = T_{out,t+\Delta t} - (T_{out,t+\Delta t} - T_{in,t})e^{-\Delta t/R \times C} \quad (3)$$

When the air conditioner is cooling, it can be described as follows:

① *Air conditioning is on:*

$$T_{in,t+\Delta t} = T_{out,t+\Delta t} - Q \times R - (T_{out,t+\Delta t} - Q \times R - T_{in,t})e^{-\Delta t/R \times C} \quad (4)$$

② *Air conditioning is off:*

$$T_{in,t+\Delta t} = T_{out,t+\Delta t} - (T_{out,t+\Delta t} - T_{in,t})e^{-\Delta t/R \times C} \quad (5)$$

where $T_{in,t}$ represents the indoor temperature (°C); $T_{out,t}$ represents the outdoor temperature (°C); C represents the equivalent thermal capacity of the air conditioner (J/°C); R represents the equivalent thermal resistance (°C/W); Q represents the equivalent thermal ratio (W).

The dynamic process of the cooling and heating of an air conditioning is shown in Fig.3.

It can be seen from Fig.3 that during the heating season, when the room temperature is lower than the lower bound, the air conditioner starts to heat up (S=1); when it is heated to the upper bound of the temperature, the air conditioner is turned off (S=0); when the temperature falls to the lower bound of the temperature, the air conditioner is turned on to start heating again (S=1). In the cooling season, when the temperature falls to the lower bound of the temperature, the air conditioner is turned on to start cooling (S=1); when the temperature rises to the upper bound of the temperature, the air conditioner is turned off (S=0); when the temperature falls to the lower bound of the temperature, the air conditioner is turned on to start cooling again (S=1). Here, the lower bound of the indoor temperature is 24°C, the upper bound of the indoor temperature is 28°C, and the set point temperature is 26°C.

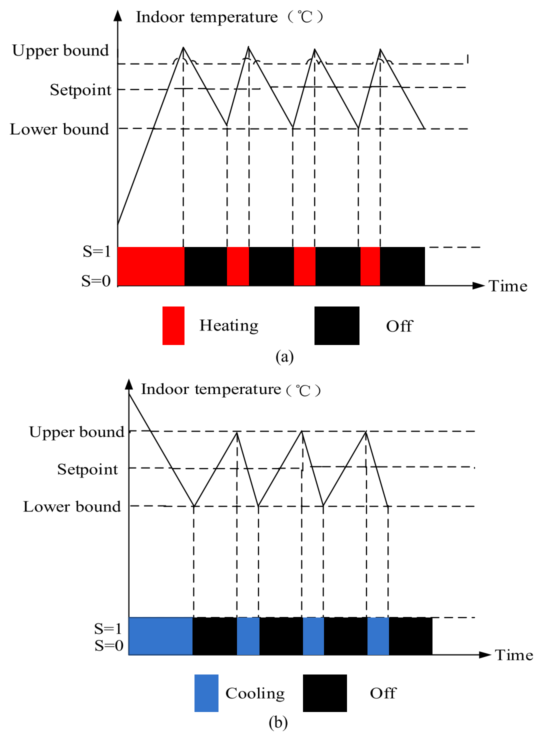

FIGURE 3. The dynamic process of the cooling and heating of the air conditioning. (a) Heating. (b) Cooling.

C. OPTIMAL CONTROL MODELING OF AIR CONDITIONING LOAD GROUPS

The improved state-queue (ISQ) control algorithm, a general model for price response or incentive demand side management tracking the dynamic behavior of the temperature control equipment through the temperature control equipment "switch" state, is used to establish the relationship between the power of air conditioning groups and the switch state of air conditioning aiming at regulating the air conditioning load [22]. The ISQ algorithm may cause the transition control of the air conditioning so that the switching is frequent and the life is decreased or even the air conditioning equipment is damaged, so the restriction on the number of the air conditioning switches is introduced into the ISQ algorithm here. The purpose of the optimal control model of the controlled air conditioning is to meet the user's comfort requirements and the economic efficiency of the user to participate in the demand side management. The user's comfort index *CI* is defined as (6).

$$CI = \sqrt{\frac{\sum_{i=1}^{k} (T'_{room,t}(i) - T_{set}(i))^2}{k}} \quad (6)$$

where $T'_{room,t}(i)$ is the indoor temperature at time i after being controlled; $T_{set}(i)$ is the set point of the indoor temperature at time i; k is the total number of the switch state that the air conditioner is on and off during the operation. From the definition of CI, it reflects the deviation between the indoor temperature controlled by the air conditioner and the temperature set point. Therefore, the smaller the value of CI is, the higher the user's comfort is.

The purpose of the user's participation in the demand side management is to save the electric power. It can be described as (7).

$$I=\int_0^{24} e_{TOU}(t)\times P_{air}(t)dt-\int_0^{24} e_{TOU}(t)\times P_{obj}(t)dt \quad (7)$$

where $e_{TOU}(t)$ is the TOU price of the peak-valley each moment; $P_{air}(t)$ is the air conditioning load before the user participates in the demand side management, that is, the air conditioning load before being regulated; $P_{obj}(t)$ is the air conditioning load after the user participates in the demand side management, that is, the air conditioning load after being regulated.

The objective function of the optimization control model of the controlled air conditioning load can be expressed as (8).

$$(\min(CI), \min(-I)) \quad (8)$$

III. THE LIFE AND COST ANALYSIS OF THE ECHELON UTILIZATION BATTERIES

A. EQUIVALENT CYCLE LIFE ESTIMATION OF ECHELON UTILIZATION BATTERIES

The cycle life is related to the DODs of the battery, the different DODs will lead to different cycle life. Therefore, unifying the cycle life at different DODs to 100% is defined as the equivalent cycle life [23]. In this paper, the rain flow counting method is used to calculate the DODs of the ESS [24].

According to the corresponding relationship between the DODs of the lead-acid battery and the cycle life [25], the function curve of the DODs corresponding to the cycle life is obtained by (9).

$$\begin{aligned} N_{ctf} &= -3278\cdot D_{oD}^4-5\cdot D_{oD}^3 \\ &\quad +12823\cdot D_{oD}^2-14122\cdot D_{oD}+5112 \end{aligned} \quad (9)$$

It is known that the operating cycle of the battery can be decomposed into N cycles, with the depth of discharge $D_{oD1}, D_{oD2}, \cdots, D_{oDN}$. The DODs of the battery in the ith cycle is D_{oDi}, and the corresponding equivalent cycle life is described as (10).

$$L\left(D_{oDi}\right)=\frac{N_{cff}\left(D_{oD1}\right)}{N_{cff}\left(D_{oDi}\right)} \quad (10)$$

where $N_{ctf}\left(D_{oD1}\right)$ is the corresponding cycle life when the DOD is equal to 100%; $N_{ctf}\left(D_{oDi}\right)$ is the cycle life when the DOD is equal to D_{oDi}.

The equivalent full charge and discharge times of the battery in the running cycle (ie, one day) is calculated by (11).

$$N_{day}=\sum_{i=1}^{i=N} L\left(D_{oDi}\right)=\sum_{i=1}^{i=N}\frac{N_{ctf}\left(D_{oD1}\right)}{N_{ctf}\left(D_{oDi}\right)} \quad (11)$$

B. CALENDAR LIFE ESTIMATE OF ECHELON UTILIZATION BATTERIES

The life of the battery includes the cycle life and calendar life. The calendar life means to the time from the beginning to the end of the battery (usually taking year as the unit) [26]. The calendar life of echelon utilization batteries can be estimated by the capacity retention rate, the cycle life and capacity retention at the beginning and the end of the echelon utilization.

By performing a secondary cycle test on the REVBs, it is estimated that the cycle life of the REVBs for the echelon utilization can be predicted by (12).

$$\beta=-2.6043\times 10^{-5}n+0.8347 \quad (12)$$

where β is the capacity retention rate of the REVBs, named as the ratio of the actual capacity and rated capacity of the battery; n is the cycle times of the battery. The relationship between the capacity retention rate of the REVBs and the cycle times of the battery is shown in Fig.4.

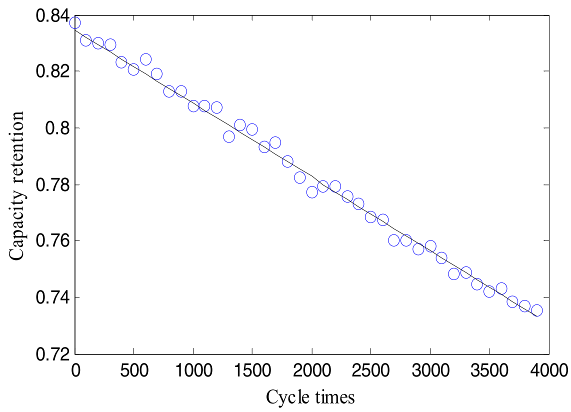

FIGURE 4. The relationship between the capacity retention and cycle life of the REVBs.

Suppose that the capacity retention rate of the purchased REVBs is β_1 and the capacity retention rate at the end of the EUEES is β_2, the total cycle times of the REVBs$n_{\sec}$ can be calculated according to (12) at the stage of the echelon utilization, then the calendar life of echelon utilization batteries $m_{\sec}$ is obtained by (13).

$$m_{\sec}=\frac{n_{\sec}}{365\times N_{day}} \quad (13)$$

where $n_{\sec}$ is the total cycle times of the REVBs applied to the energy storage stage; N_{day} is the equivalent full charge and discharge times of the EUESS calculated by (11) during operating period (it generally takes one day).

C. THE COST ESTIMATION OF THE EUESS

Based on the cycle life and calendar life from Section III.A and Section III.B, the cost estimation method of the EUESS are calculated by (14).

$$C_{1\_sec} = (C_{E\_sec}E_{\text{sec}} + C_{P\_sec}P_{\text{sec}}) \times \frac{r(1+r)^{m_{\text{sec}}}}{(1+r)^{m_{\text{sec}-1}}} \quad (14)$$

where C_{E_sec}, C_{P_sec} are respectively the unit capacity cost and unit power cost (USD/kWh, USD/kW), the unit power cost is consistent with the power convert system (PCS) unit price of the conventional battery ESS; E_{sec} and P_{sec} are respectively the rated capacity (kWh) and rated power (kW); m_{sec} is the calendar life (Year), r is the currency discounted value.

The operation and maintenance cost of the EUESS can be calculated by (15).

$$C_{2\_sec} = K_{E\_\text{sec}}E_{\text{sec}} + K_{P\_\text{sec}}P_{\text{sec}} \quad (15)$$

where K_{E_sec} is the operation and maintenance unit capacity (USD/kWh/Year), its value is affected by the initial capacity retention rate of the EUESS; K_{P_sec} is the operation and maintenance unit price of the PCS (USD/kW/Year), its value is consistent with that of conventional energy storage batteries.

It can be seen from (14) and (15) that when the EUESS and conventional battery ESS are used to calculate the costs, in addition to the different calendar life, the purchase cost of the unit capacity C_{E_sec} and operation and maintenance cost K_{E_sec} are also different.

The purchase cost of the unit capacity C_{E_sec} is estimated by the use value of the EUESS in this paper. A simple estimation of C_{E_sec} is calculated by (16).

$$C_{E\_\text{sec}} = C_{E\_con} \times \frac{m_{\text{sec}}}{m_{con}} \quad (16)$$

where C_{E_con} is the unit capacity of the conventional storage battery price (USD/kWh); m_{con} is the life of the conventional ESS (Year).

The operation and maintenance cost of the unit capacity EUESS K_{E_sec} is different when the initial capacity retention rate of echelon utilization batteries is different. Take the lithium ion battery as an example, the running capacity with different initial capacity retention rates is shown in Table 1.

TABLE 1. The operation and maintenance unit price of the lithium battery with different capacity retention rate.

Capacity retention rate of the lithium battery	1	0.8	0.7	0.6	0.5	0.4	0.3
Unit capacity maintenance costs (USD/kWh)	0.05	0.20	0.44	1.11	3.31	12.61	70.87

The relationship between the operation and maintenance cost of the unit capacity echelon storage battery K_{E_sec} and the initial capacity retention rate is obtained by exponential function fitting. It can be described as

$$K_{E\_\text{sec}} = 0.05165 \times \beta^{-6} \quad (17)$$

IV. ECONOMICAL EVALUATION MODELS OF THE MICRO-GRID SYSTEM IN A COMMERCIAL PARK BASED ON ECHELON UTILIZATION BATTERIES

A. THE OBJECTIVE-FUNCTION OF THE MICRO-GRID SYSTEM IN A COMMERCIAL PARK

The net load of the micro-grid system in the commercial park is defined as

$$P_{net} = P_{con} + P_{air} - P_{pv} \quad (18)$$

If P_{net} is more than 0, it indicates that the PV output power can't meet the load demand, and the lack electricity needs to be purchased from the grid. If P_{net} is less than 0, it indicates that the PV output is so sufficient that it is still surplus after meeting the load demand. It can be seen from (1) and (18) that the power of the micro-grid tie line is equal to the net load before the ESS is arranged, that is, $P_{line} = P_{net}$. However, the uncertainty and volatility of the net load will make the tie line power not meet the requirements of the micro-grid system connected to the grid, the average power of the net load every 30min is regarded as the target power of the micro-grid tie line P_{line_obj}, and the difference between P_{line} and P_{line_obj} is made up by the ESS. If the ESS is only used to smooth the fluctuation of tie line power and does not fully play the role of the ESS, the optimal configuration model of the micro-grid system in the commercial park combined with the time-of-use price is established, in which the purchasing electricity cost from the grid will be saved by making the ESS low storage and high generation.

A multi-objective optimization model to estimate the economics of the micro-grid system in the commercial park is established.

1) OBJECTIVE FUNCTION 1

Minimize the cost of the configured ESS. The cost includes the initial investment cost and operation cost, namely:

1) The initial investment cost composed of the power cost and capacity cost (converted to day) are calculated by (19).

$$C_1 = (C_E E_b + C_P P_b) \times \frac{r(1+r)^m}{(1+r)^m - 1} \times \frac{1}{n} \quad (19)$$

2) The operation cost (converted to day) are calculated by (20).

$$C_2 = (K_E E_b + K_P P_b) \times \frac{1}{n} \quad (20)$$

2) OBJECTIVE FUNCTION 2

Minimize the cost of the purchased electricity from the grid (Here Day is equal to 1440 min).

$$C_3 = (\int_1^{\text{Day}} TOU(t) \times P_{line}(t)dt) \times \frac{1}{60}(P_{line}(t) > 0) \quad (21)$$

The objective function of the optimal allocation and economic evaluation model can be expressed as (22).

$$(\min(C_1), \min(C_2), \min(C_3)) \quad (22)$$

B. CONSTRAINTS OF THE OPTIMAL ALLOCATION AND ECONOMIC EVALUATION MODEL

1) The limit constraint of the micro-grid tie line power. Limit the system to reverse power to the grid and the power limit to be sold from the grid to the system.

$$P_{set_sell} \leq P_{line} \leq P_{set_buy} \tag{23}$$

2) The balance constraint of the charge and discharge for the ESS:

$$\sum_{t=1}^{\text{Day}} P_{ess}(t) = 0 \tag{24}$$

3) The SOC constraints of the ESS:

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{25}$$

$$SOC(t) = \begin{cases} SOC(t-1) + \dfrac{P_{ess}(t)\Delta t \eta_{charge}}{E_{ess}}, & P_{ess}(t) > 0 \\ SOC(t-1) + \dfrac{P_{ess}(t)\Delta t}{E_{ess}\eta_{discharge}}, & P_{ess}(t) < 0 \end{cases} \tag{26}$$

where the E_{ess} is the rated capacity of the ESS, η_{charge} and $\eta_{discharge}$ are respectively the charge and discharge efficiency of the ESS.

V. CASE STUDIES

A. THE SETTING OF MODEL PARAMETERS

Taking the winter period of the micro-grid system in a commercial park in Shanghai of China as an example, the goal of regulation is to reduce at least the maximum load power to 90% of the original. Echelon utilization batteries are used to allocate the capacity in this scenario. The PV output power, conventional load, air conditioning load before the optimal regulation and time-of-use (TOU) electricity pricing of the micro-grid system in the commercial park are shown in Fig.5.

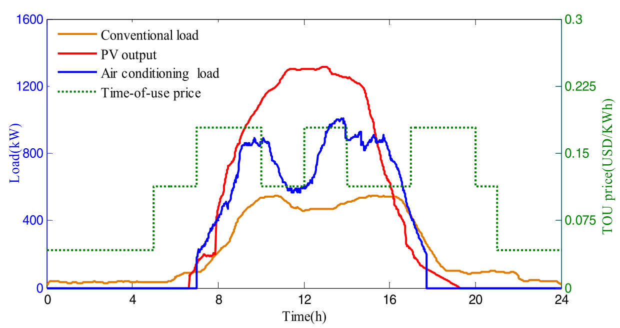

FIGURE 5. The curve of the source, load and TOU price of the micro-grid system in the commercial park.

The required parameters of the micro-grid system in the commercial park are given in Table 2 and the TOU electricity price of Shanghai in China is given in Table3.

TABLE 2. The parameters required for the model.

Name	Value
Air conditioning equivalent thermal capacitance	3579.3 J/□
Air conditioning equivalent thermal resistance	0.1008 □/W
Air conditioning equivalent thermal ratio	398 W
Number of air conditioning participating in the regulation	230
Air conditioning temperature setting	26□
Air conditioning temperature upper and lower limits	[24,28] □
Single air conditioning rated power	10kW
Unit capacity price of conventional EES	362.6080USD/kWh
The unit price of PCS	145.0432USD/kW
Service life of conventional EES	10 years
The margin of the ESS	0.02
Annual operation and maintenance cost of the unit capacity conventional ESS	0.0073USD/kWh
Annual operation and maintenance cost of the unit power conventional ESS	2.9010USD/kW
The discount rate	0.06
Power limit for power supply to the system	500kW
System to the power grid reverse power limit	300kW

TABLE 3. The TOU electricity price of Shanghai in China.

Summer			
Time period		TOU price (USD/kWh) Buy	TOU price (USD/kWh) Sell
Flat	06:00~08:00 11:00~13:00 15:00~18:00 21:00~22:00	0.113	0.142
Peak	08:00~11:00 13:00~15:00 18:00~21:00	0.179	0.142
Valley	22:00~next day 06:00	0.043	0.142
Winter			
Time period		TOU price (USD/kWh) Buy	TOU price (USD/kWh) Sell
Flat	06:00~08:00 11:00~18:00 21:00~22:00	0.101	0.142
Peak	08:00~11:00 18:00~21:00	0.168	0.142
Valley	22:00~next day06:00	0.049	0.142

B. OPTIMAL CAPACITY CONFIGURATION OF THE MICRO-GRID SYSTEM IN THE COMMERCIAL PARK OBTAINED BY THE PSO ALGORITHM AND ABC ALGORITHM

The purpose of the air conditioning optimization and control is to the maximum extent to meet the user comfort requirements and take the maximum economy of air conditioning users to participate in the demand side management as the target according to (18). The optimal allocation and economic evaluation model of the micro-grid system is to minimize the cost of the configured ESS and the purchase cost of the micro-grid system in the commercial park from the grid according to (22). The PSO algorithm is a global optimization algorithm. The basic idea of the PSO algorithm is inspired by the behavior of many birds [27]. Compared with other population-based evolutionary algorithms, they are initialized into a set of random solutions, and the optimal solution is searched by multiple iterations. Due to its simple operation and fast convergence, it has been widely used in the optimal scheduling of power system and capacity configuration of the ESS [28], [29]. The ABC algorithm is a novel global optimization algorithm based on swarm intelligence [30], which has widely been used in many optimization problems without any modification with the advantage of high search precision and strong robustness [31], [32].

For comparative analysis, the PSO algorithm and ABC algorithm are respectively used to solve the model in this paper. The PSO algorithm was used to solve the model, the population size is set to 40, the number of iterations is set to 60, the inertia factors $w_{\max}$=1.2 and $w_{\min}$=0.1. The optimized result is that the rated capacity of the ESS in the micro-grid system is 422.8301 kWh and the rated power is 239.5854 kW obtained by the PSO algorithm. The change curve of the air conditioning temperature before and after the optimal control is shown in Fig.6.

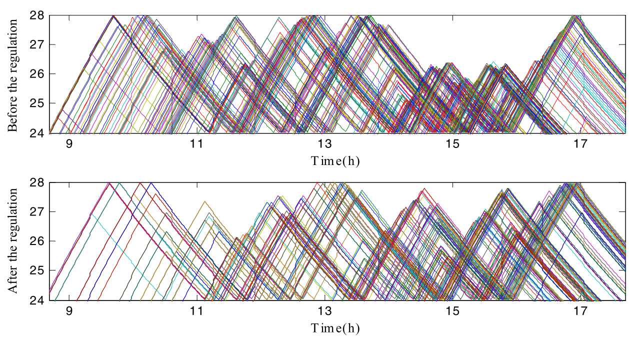

FIGURE 6. The curve of the air conditioning temperature before and after the optimized regulation obtained by the PSO algorithm.

The user comfort index is 1.1110 before the regulation control and the user comfort index is 1.0793 after the regulation control. The purchase electricity cost of the air conditioning users before the regulation control is 814.0982 USD/day, the purchase electricity cost of the air conditioning users after the regulation control is 780.3610 USD/day, and the daily electricity savings is 33.7372USD. Without affecting the comfort of users, the economy of air conditioning users can be improved by the optimal regulation of the controlled air conditioning load. The curves of the controlled air conditioning load and the tie line power of the micro-grid system before and after the optimal regulation are shown in Fig.7.

In Fig.7(a), the peak load of the controlled air conditioning after the regulation has been shifted; In Fig.7 (b), the tie

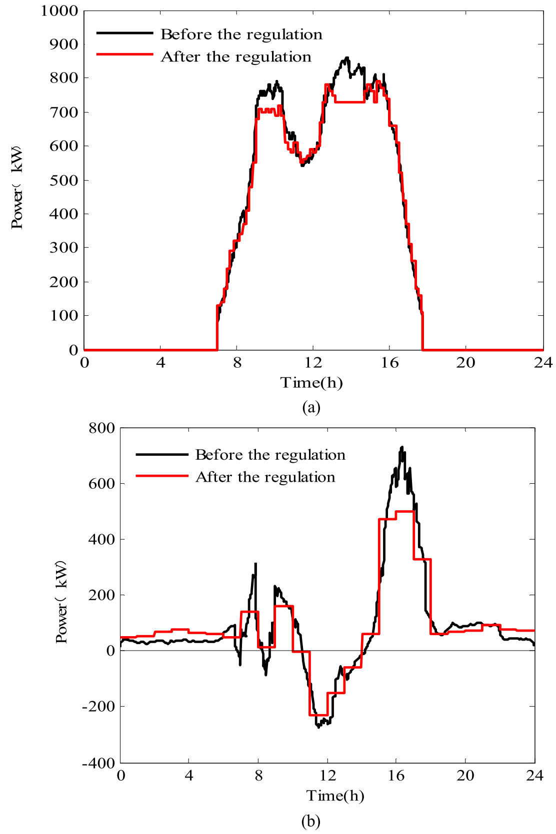

FIGURE 7. The curves of the (a) controlled air conditioning load and the (b) tie line power before and after the optimized regulation.

line power before the regulation (actually the net load curve) fluctuates greatly, and the tie line power satisfies the tie line power limit of the micro-grid system after the regulation. The power and SOC curves of the ESS are shown in Fig.8.

Fig.8(a) shows that the charge and discharge power of the echelon utilization batteries after the regulation is higher than that before the regulation when the electricity price is low; during the daytime peak hours, the charge and discharge power of the echelon utilization batteries is approached before and after the regulation; the purpose of the adjustment is to achieve more charging of the echelon utilization batteries when the electricity price is lower, and more discharge when the electricity price is high. Fig.8 (b) shows the SOC of the echelon utilization batteries changes near 0.5 before the regulation, and the loss of the life and performance of echelon utilization batteries is relatively small, resulting in the waste of the capacity space for the ESS; after the regulation, echelon utilization batteries are charging at the lower price period, the charging speed is improved obviously and the capacity of echelon utilization batteries is more fully utilized.

The parameters of the ABC algorithm are set as follow: the colony size is 100, the number of the nectar source is 50, the threshold is 20, and the number of iterations is 50. By optimizing the rated capacity of the ESS of the micro-grid system in the commercial park is 436.4391kWh and the rated power is 258.3208kW obtained by the ABC algorithm.

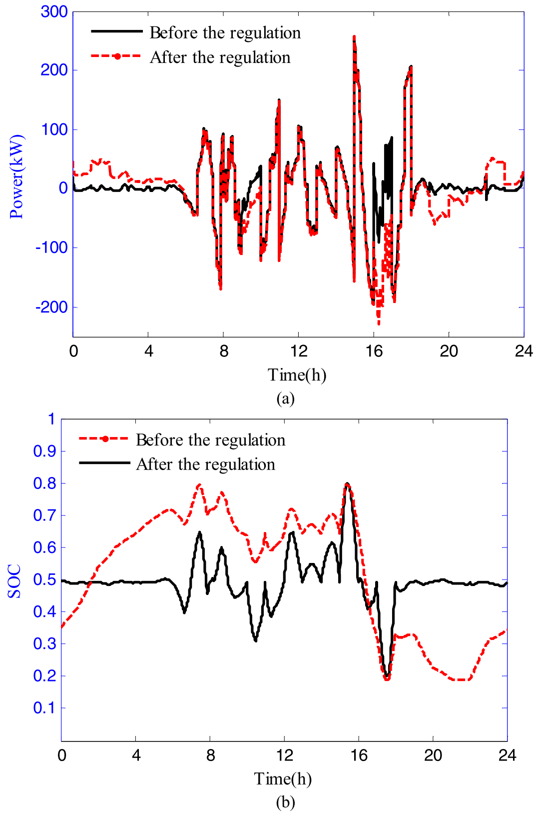

FIGURE 8. The (a) charge and discharge power and (b) SOC curves of the energy storage system before and after the optimal regulation.

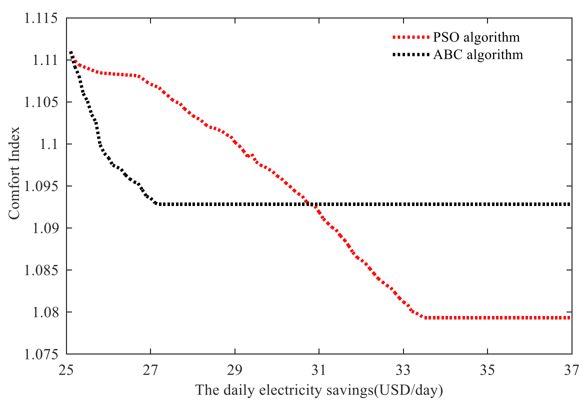

FIGURE 9. The relationship between the user comfort and the daily electricity savings obtained by different optimal algorithms.

The user comfort index is 1.0928 after the regulation control, the purchase electricity cost of the air conditioning users after the regulation control is 786.8486USD/Day, and the daily electricity savings is 25.4577USD.

The relationship of the user comfort and the daily electricity savings obtained by different optimal algorithms is shown in Fig.9 and the calculation results of different optimal algorithms are shown in Table 4.

It can be seen from Table 5 that the fitness level reaches an optimal level when the number of iterations reaches 60 times under the optimization of the PSO algorithm, and the fitness

TABLE 4. The optimal results of the micro-grid system obtained by the PSO and ABC algorithms.

Optimal results	PSO algorithm	ABC algorithm
Optimal capacity (kWh)	422.8301	436.4391
Optimal power (kW)	239.5854	258.3208
User comfort	1.0793<1.1110	1.0928<1.1110
Purchase electricity cost of the users after the regulation (USD)	780.3610	786.8486
Daily electricity savings (USD)	33.7372	27.2496

TABLE 5. The optimal results obtained by PSO and ABC algorithms.

Number of iterations	Comfort index		Daily electricity savings(UDS/day)		Fitness	
	PSO	ABC	PSO	ABC	PSO	ABC
0	1.1110	1.1110	25.0366	25.0366	1.6020	1.6020
10	1.1071	1.1002	26.5219	25.5639	1.5996	1.5986
20	1.1002	1.0989	27.9925	25.9923	1.5978	1.5973
30	1.0919	1.0963	29.2135	26.1315	1.5976	1.5973
40	1.0859	1.0942	30.7923	26.8223	1.5975	1.5973
50	1.0802	1.0928	32.0305	27.2496	1.5974	1.5972
60	1.0793	1.0928	33.7372	27.2496	1.5972	1.5972

level reaches an optimal level when the number of iterations reaches 50 times under the optimization of the ABC algorithm. The convergence speed of the iteration got by the ABC is significantly less than that got by the PSO, and the iterative calculation time takes a long time. Combined with the **Fig.9**, under the same fitness, the daily electricity savings and comfort index of the user obtained by the PSO algorithm are better than that obtained by the ABC algorithm.

C. THE ECONOMICAL COMPARISON OF THE ABOVE TWO ENERGY STORAGE SYSTEMS

Based on the calculation of the equivalent cycle life of echelon utilization batteries described in Section III.A, the equivalent full charge and discharge times of the battery in the typical day can be calculated according to the SOC, $N_{day} = 1.4021$; If the capacity retention rate of the energy storage battery entering or exiting the energy storage application stage takes 0.8 or 0.7 respectively, the calendar life of echelon utilization batteries is 7.5033 year calculated by (12) and (13); The unit capacity operation and maintenance cost of echelon utilization batteries calculated by (17) is 0.0290USD/kWh; From the point of the use value produced by echelon utilization batteries as the energy storage equipment, the purchase price of the unit capacity of echelon utilization batteries estimated by (16) is 254.1635USD/kWh. The economical comparison results of conventional energy storage batteries and echelon utilization batteries are given in Table 6 in which the cost of the ESS is converted to day and the exchange rate is 0.145 on May 5, 2017.

It can be seen from Table 6 when the purchase cost of the unit capacity of echelon utilization batteries C_E is equal to 254.1635USD/kWh, the purchase cost of echelon utilization batteries74.8380 USD/day is lower than that of conventional energy storage batteries 74.9180USD/day.

TABLE 6. Economical comparison of the two energy storage systems.

Battery cost (USD/day)	Conventional energy storage batteries	Echelon utilization batteries			
	C_E=362.6080 (USD/kWh)	C_E=254.1635 (USD/kWh)	C_E=254.5391(USD/kWh)	C_E=217.5650 (USD/kWh)	C_E=145.043 2(USD/kWh)
Purchase cost	73.9050	72.7508	72.8310	49.9590	37.9850
Operation and maintenance cost	2.0617	2.0872	2.0872	2.0872	2.0872
Total cost	74.9180	74.8380	74.9180	52.0600	40.0867

The operation and maintenance cost is slightly higher than that of conventional energy storage batteries; When C_E is equal to 254.5391USD/kWh, the total cost configured by echelon utilization batteries 74.9180USD/day is the same as that configured by conventional energy storage batteries; When C_E is equal to 217.5650USD/kWh and 145.0432USD/kWh respectively, the total cost configuring the echelon utilization batteries is much lower than that of conventional energy storage.

VI. CONCLUSIONS

Although the REVBs can't meet the requirement in the field of the electric vehicles, it still plays a role in the field of EESs. Based on the characteristics of ''Source-Load'' in the micro-grid system of a commercial park and the optimal response mode of the controlled air-conditioning load, the controlled air-conditionings as ''virtual energy storage'' equipment are combined with echelon utilization batteries to realize the effects of the load shifting. The optimal configuration model of the micro-grid system in a commercial park is established. The conclusions are drawn as follows:

1) Taking the user comfort and fairness of the air conditioning control into consideration, the economy of air conditioning users is improved by the optimal regulation of the controlled air-conditioning load. The optimal response mode of the air-conditioning equipment as ''virtual energy storage'' to participate in demand side management is explored. The optimized regulation not only improves the users' comfort, but also reduces the users' cost of purchasing electricity from the grid.

2) The optimal capacity configuration model of the ESS for the micro-grid system in the commercial park is respectively resolved by the PSO and ABC algorithms. Under the premise of ensuring the user comfort index, the capacity configuration of the micro-grid in the commercial park obtained by the PSO algorithm has better economic than that obtained by the ABC algorithm. The optimal capacity of the EUESS obtained by the PSO algorithm is equal to 239.5854kW/422.8301kWh, and the optimal capacity of the EUESS obtained by the ABC algorithm is equal to 258.3208 kW/436.4391kWh.

3) Taking the economy of the micro-grid system into account, when the unit capacity purchase price of echelon utilization batteries C_{E} is less than 254.5391USD/kWh, the economy of the micro-grid system with the echelon utilization batteries is better than that with the conventional energy storage batteries. The impact of the business model and the robustness of the proposed method will be further analyzed.

REFERENCES

[1] S. Xiaoqing, C. Weiguo, R. Shanrong, and C. Haibing, ''Demonstration research on air conditioning load shaving power grid peak orderly,'' *Elect. Eng.*, vol. 15, no. 1, pp. 47–51, Jan. 2014.

[2] L. Tianyang, Z. Xingwang, and X. Wenju, ''Regulation technology of air-conditioning load in commercial buildings for balance of power grid peak and valley,'' *Automat. Electr. Power Syst.*, vol. 39, no. 17, pp. 96–102, Sep. 2015.

[3] P. Siano, and D. Sarno, ''Assessing the benefits of residential demand response in a real time distribution energy market,'' *Appl. Energy*, vol. 167, pp. 33–551, Jan. 2016.

[4] B. Shen, G. Ghatikar, Z. Lei, J. Li, G. Wikler, and P. Martin, ''The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges,'' *Appl. Energy*, vol. 130, pp. 814–823, Oct. 2014.

[5] N. Lu and Y. Zhang, ''Design considerations of a centralized load controller using thermostatically controlled appliances for continuous regulation reserves,'' *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 914–921, Jun. 2013.

[6] W. Chengshan, L. Mengxuan, and L. Ning, ''A tie-line power smoothing method for microgrid using residential thermostatically controlled loads,'' *Proc. CSEE*, vol. 32, no. 25, pp. 36–43, Sep. 2012.

[7] M. Liu, W. Liang, Y. Zhang, J. Liu, and K. Li, ''Cooperative generation-load optimal dispatching model considering air-conditioning load group control,'' *Power Syst. Technol.*, vol. 41, no. 4, pp. 1230–1236, Apr. 2017.

[8] N. Lu, ''An evaluation of the HVAC load potential for providing load balancing service,'' *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1263–1270, Sep. 2012.

[9] N. Lu *et al.*, ''An evaluation of the NaS battery storage potential for providing regulation service in California,'' presented at the IEEE/PES Power Syst. Conf. Exposit., Phoenix, AZ, USA, Mar. 2011.

[10] Y. Zhang and N. Lu, ''Parameter selection for a centralized thermostatically controlled appliances load controller used for intra-hour load balancing,'' *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2100–2108, Dec. 2013.

[11] M. Alizadeh and A. Scaglione, ''Least laxity first scheduling of thermostatically controlled loads for regulation services,'' presented at the IEEE Global Conf. Signal Inf. Process., Austin, TX, USA, Dec. 2013.

[12] S. Bashash and H. K. Fathy, ''Modeling and control of aggregate air conditioning loads for robust renewable power management,'' *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 4, pp. 1318–1327, Jul. 2013.

[13] T. Ruijun, ''Research on key technology of power lithium battery echelon use,'' *Bus Coach Technol. Res.*, no. 3, pp. 30–32, Jul. 2014.

[14] J. Wenna. *The Recycling Standards Need to 'Charge' of the Electric Vehicle on the Road*. Accessed: Dec. 12, 2014. [Online]. Available: http://www.ceh.com.cn/ceh/ztbd/jnjp/124945.shtml

[15] J. Neubauer and A. Pesaran, ''The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications,'' *J. Power Source*, vol. 196, no. 23, pp. 10351–10358, Dec. 2011.

[16] V. V. Viswanathan and M. Kintner-Meyer, ''Second use of transportation batteries: Maximizing the value of batteries for transportation and grid services,'' *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 2963–2970, Sep. 2011.

[17] H. Ding, Z. Hu, and Y. Song, "Value of the energy storage system in an electric bus fast charging station," *Appl. Energy*, vol. 157, pp. 630–639, Nov. 2015.
[18] H. Catherine, S. B. Walker, S. B. Young, and M. Fowler, "Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling," *Energy Policy*, vol. 71, pp. 22–30, Aug. 2014.
[19] Z. H. Jinguo, J. I. Dongsheng, and W. A. Xiaojun, "Analysis on economic operation of energy storage based on second use batteries," *Power Syst. Technol.*, vol. 38, no. 9, pp. 2551–2555, Sep. 2014.
[20] A. Keeli and R. K. Sharma, "Optimal use of second life battery for peak load management and improving the life of the battery," present at the IEEE Int. Electr. Vehicle Conf., Greenville, SC, USA, Mar. 2012.
[21] L. Yuyan, "Research on the characteristic and model of air conditioner load," M.S. thesis, Dept. College Energy Elect. Eng., Hohai Univ., Nanjing, China, 2004.
[22] W. Chengshan, L. Mengxuan, and L. Ning, "A tie-line power smoothing method for microgrid using residential thermostatically-controlled loads," in *Proc. CSEE*, vol. 32, no. 25, pp. 36–43, Sep. 2012.
[23] C. Cheng, "Research on hybrid energy storage control strategy for renewable energy power generation grid-connected technology," M.S. thesis, School Control Comput. Eng., North China Electr. Power Univ., Beijing, China, 2014.
[24] Z. Hua *et al.*, "Control strategy and economic analysis of energy storage system based on bidirectional complementary," *Electr. Power Construct.*, vol. 37, no. 8, pp. 96–101, Aug. 2016.
[25] J. Tianming, "Data mining and optimal control on PV-storage hybrid generation system," M.S. thesis, School Control Comput. Eng., North China Electr. Power Univ., Beijing, China, 2015.
[26] L. Xinjing *et al.*, "Research progress of calendar life of lithium-ion battery," *Chin. J. Power Sources*, vol. 39, no. 8, pp. 1777–1779, Aug. 2015.
[27] C. Russell Eberhart and Y. Shi, "Particle swarm optimization: Developments, applications and resources," present at the Congr. Evol. Comput., Seoul, South Korea, May 2001.
[28] J. Qiu, J. Zhao, H. Yang, and Z. Y. Dong, "Optimal scheduling for prosumers in coupled transactive power and gas systems," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1970–1981, Mar. 2018.
[29] C. Shijun and Z. Lizi, "Energy storage capacity optimization for wind power generation system," in *Proc. CSU-EPSA*, vol. 27, no. 3, pp. 71–75, Mar. 2015.
[30] R. Akbari, R. Hedayatzadeh, K. Ziarati, B. Hassanizadeh, "A multi-objective artificial bee colony algorithm," *Swarm Evol. Comput.*, vol. 2, no. 1, pp. 39–52, Feb. 2012.
[31] R. A. Kumar, K. Asokan, and S. R. Kumar, "Optimal scheduling of generators to maximize GENCOs profit using LR combined with ABC algorithm in deregulated power system," present at the Int. Conf. Comput. Power, Energy, Inf. Commun. (ICCPEIC), Chennai, India, Apr. 2014.
[32] M. A. Yiping, "Hybrid energy storage capacity optimization configuration for micro-grid considering EV scheduling," *Power Syst. Protection Control*, vol. 45, no. 23, pp. 98–107, Dec. 2017.

XIAOJUAN HAN was born in Jilin, China, in 1970. She received the B.S. and M.S. degrees from the Northeast Electric Power College, in 1993 and 1996, respectively, and the Ph.D. degree in thermal engineering from North China Electric Power University, Beijing, China, in 2002, where she has been teaching and researching, since 1996. Her research interests include renewable energy power generation technology, information fusion, and modern detection technology. She has certain academic influence in the field of energy storage control technology.

FENG WANG was born in Yunnan, China, in 1996. He received the B.S. degree from the School of Control and Computer Engineering, North China Electric Power University, Beijing, China, in 2017, where he is currently pursuing the M.S. degree. His research interests include application research of large-scale energy storage technology and control strategy of renewable energy generation.

MENGJIAO CHEN was born in Hebei, China, in 1995. She received the B.S. degree from the School of Control and Computer Engineering, North China Electric Power University, Beijing, China, in 2017, where she is currently pursuing the M.S. degree. Her research interest includes economic evaluation of energy storage systems.