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Optimal Scheduling of Batteries for Electric Vehicle Battery Swapping Stations in Beijing

Guowei Hua[12], Lina Ma[1], Yadong Xu[1*]

[1] School of Economics and Management, Beijing Jiaotong University, Beijing, 100044, China
[2] National Academy of Economic Security, Beijing Jiaotong University, Beijing 100044, China

yadongxu@bjtu.edu.cn (Corresponding author)

Abstract. With the increasing global concern for environmental protection and sustainable development, electric vehicles have become the main development trend in urban transportation. Research on the optimization of battery scheduling for electric vehicle battery swapping stations in Beijing is of great significance for improving the operational efficiency of electric vehicles and reducing carbon emissions in urban transportation. This paper analyses the current situation of electric vehicle battery swapping stations in Beijing, takes the maximum operating profit as the optimization objective, establishes a battery charging and discharging scheduling model considering time-sharing tariffs, and solves the optimal battery scheduling scheme for a certain battery swapping station in Beijing as an example. The results show that the main factors affecting the operating profit of Beijing's battery swapping stations are the service charge and battery ownership. The batteries in the battery swapping stations are not always recharged during tariff-flat hours but are flexibly adjusted within the limits of switching demand and the number of devices. Optimizing the battery utilization and charging/discharging process by taking advantage of the peak-to-valley difference in Beijing's electricity price can effectively reduce the operating cost of the battery swapping station and help to balance the load of the power grid and reduce the pressure at peak hours, thus providing a powerful guide for the development of reasonable and effective operation strategies and battery charging/discharging management for battery swapping stations in Beijing.

Keywords: Electric vehicle, battery swapping station, scheduling optimization, charging and discharging strategies

1. Introduction

In recent years, the problems of insufficient fossil energy reserves and environmental pollution have become increasingly prominent, with the most significant impact on transportation (Tan et al., 2023). Electric vehicles will replace traditional fuel vehicles as the main means of transportation and travel. With the development of electric vehicles, the investment and construction of supporting charging and switching facilities must join the development process (Shi et al., 2023). Beijing attaches great importance to the construction of charging piles and switching stations, and the charging and switching infrastructure for new energy vehicles has made great progress. As of April 2023, the number of battery swapping stations in China amounted to 2,102, of which Beijing ranked first in the country, with 295 battery-swapping stations owned[1]. At present, the business demand for electric vehicle battery swapping stations in Beijing continues to grow. As an important facility for EV energy supply, the battery scheduling optimization problem directly affects the operational efficiency and service quality of the battery swapping station.

In practice, there are three main barriers that constrain the development and promotion of electric vehicles: short vehicle range, long vehicle charging time and high battery acquisition cost. Battery-swapping stations can better control the charging time of batteries and realize staggered power consumption, thus sharing the pressure of the power grid. At the same time, battery-swapping stations can provide rapid and convenient battery replacement services for electric vehicles, which greatly solves the problem of slow battery charging. By centralized management of batteries, the battery-swapping station can also effectively control the decentralization and randomness of EV charging behavior. Therefore, this paper investigates the operation of electric vehicle battery-swapping stations in Beijing, trying to maximize the interests of the operating entities through reasonable equipment configuration and battery charging/discharging management.

Battery charging and discharging scheduling of electric vehicle battery-swapping stations is one of the key factors determining their operational benefits. This paper analyses the operation status of Beijing EVSE under time-sharing tariffs and focuses on the following questions: (1) What factors affect the operational benefits of EVSE in Beijing? (2) How should the operator of EVSE in Beijing arrange the battery charging and discharging strategy to maximize its operational benefits? (3) How should the Beijing government ensure the implementation of the proposed charging and discharging strategies?

This paper discusses the battery scheduling optimization problem of electric vehicle battery-swapping stations in Beijing. By analysing the operation mode of electric vehicle battery-swapping stations in Beijing, and considering factors such as the demand for electric vehicle exchange, the state of charge of batteries, and the charging and discharging capacity of battery-swapping stations, this paper constructs an optimization model of battery scheduling for electric vehicle battery-swapping stations, and solves the optimal scheduling scheme to make the battery The optimal scheduling scheme allows the electric vehicle battery-swapping station to rationally arrange the number of batteries and the time period for centralized charging in operation, and to make full use of the time-sharing tariff mechanism in Beijing to reduce the charging cost and lower the load pressure on the power grid, and to realize the efficient use of batteries and the rapid exchange of electric vehicles. Through the implementation of these programs, the service quality of the battery-swapping station can be effectively improved, and the operation cost can be reduced.

The conclusions of this paper are as follows: (1) The revenue obtained from the provision of battery-swapping services by the battery-swapping station is the main source of its operational revenue, so it is necessary to meet the demand for battery-swapping as much as possible to ensure the efficiency of the service to maximize the operational revenue. (2) The batteries of battery-swapping stations are not always charged during the tariff valley, but are flexibly adjusted under the limitations of the demand

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[1] https://www.askci.com/news/chanye/20230609/094714268627523427703566.shtml

for battery-swapping and the number of devices. For example, a proposed charging and discharging strategy for a Beijing battery-swapping station shows that the number of charging batteries is at a high level during the first tariff peak hour, while the number of charging batteries during the first hour of the second tariff peak (17:00-18:00) decreases significantly due to the increase in the number of charging batteries in the tariff flat period (13:00-17:00) prior to that hour. (3) The Beijing Municipal Government can establish a cooperative operation model for the battery-swapping stations with relevant grid companies and operators of the battery-swapping stations so that the battery-swapping stations can participate in grid scheduling as energy storage nodes and realize peak shaving and valley filling.

The contributions of this paper are (1) to construct a battery charging and discharging scheduling model for battery-swapping stations considering time-sharing tariffs; (2) to solve the optimal battery scheduling scheme by taking a certain battery-swapping station in Beijing as an example, and to propose a charging and discharging strategy applicable to a time-sharing tariff mechanism in Beijing; and (3) to optimize the battery utilization and charging and discharging process by taking advantage of the difference between the peaks and valleys of Beijing's tariffs, which can effectively lower the operating cost of the battery-swapping station and provide powerful guidance for the formulation of a reasonable and effective operation strategy and battery charging and discharging management of the battery-swapping station in Beijing.

2. Literature Review

The construction of supporting charging and switching facilities is a necessary path for the development of electric vehicles. Therefore, how to plan and build charging and switching facilities is the focus of current research. Current research mainly focuses on the siting and path optimization of charging and switching facilities. Zhang et al. (2022) proposed a robust model for the design of electric vehicle battery-swapping station siting and capacity determination service network considering the user's choice behavior. Chen et al. (2021) presented a battery replacement station location and routing problem with a time window and a mixed fleet of electric and conventional vehicles (BSS-MF-LRPTW) and developed an HBP-ASS algorithm that combines exact and heuristic strategies. Li et al. (2023) proposed a two-stage heuristic method combining a two-layer genetic algorithm (TLGA) and simulated annealing (SA) based on a two-layer procedure for locating public charging infrastructures and route planning strategies for logistics companies. Mouhcine et al. (2020) proposed a new distributed system for electric vehicle routing based on a novel driving strategy using a distributed ant system algorithm (AS). This distributed architecture minimizes the total driving path of an EV to reach its destination by proposing a set of nearest charging stations and allowing the EV to travel to the charging stations to charge while driving.

However, economic analysis of charging and switching facilities is also key to planning. Making full use of existing charging and switching facilities and grid resources to develop a reasonable scheduling strategy is an important means to improve the profitability of facility operators and enhance the user experience. Zhang et al. (2023) analysed the operation mechanism of BSCS in aggregation mode and proposed a state transition model for electric vehicle batteries. Mohsen et al. (2019) developed a mathematical model for the optimal operation of a BSS under uncertainty constraints that not only meets the stochastic demand of users for fully charged batteries, but also utilized the available batteries and reduces the operating costs through demand shifting and energy sell-back. Ding et al. (2022) proposed a Monte Carlo simulation-based economic scheduling method for battery switching stations, which establishes a multi-objective joint optimization mathematical model for battery switching stations based on B2G technology as a function of operator's revenue, grid load rms and peak-to-valley difference. Zhang et al. (2021) developed a two-stage coordinated decision making (DCD) framework for BSCS configuration with the objective of maximizing the annual revenue of the BSCS using a distributed robust optimization (DRO) approach for multi-timescale battery inventories. Zhang et al. (2016) constructed a centralized charging and switching station battery inventory optimization model by taking the minimization of charging cost, investment cost and battery maintenance cost of the centralized switching station as the objective function, and the charging and discharging capacity of the centralized switching station and the switching demand of electric vehicle users as the constraints.

The charging scheduling strategy of charging and switching facilities is related to whether it can meet the charging and switching needs of electric vehicles, and the rational planning of battery charging and discharging is the key to improving the operating profit of charging and switching facilities. Some scholars have conducted preliminary investigations on charging and switching station charging scheduling problems. Yang et al. (2023) investigated orderly battery exchange, efficient battery management and rational battery allocation in battery charging station (BSS), focusing on the battery allocation strategy in BSS systems, and proposed a new optimization model for chaotic and irrational battery allocation. Zhang et al. (2023) constructed a bi-objective model of the day-ahead scheduling model for cost-effective and efficient REP consumption and electric cab (ET) switching demand, and used the NSGA-II algorithm to find the optimal policy.

The electric vehicle battery-swapping station operator pursues the maximization of benefits through battery scheduling optimization, but operational factors such as the amount of demand for battery-swapping may change at any time, and the change in these factors will affect the final benefits of the exchange station to different degrees. Asadi and Pinkley (2021) introduced the stochastic scheduling, assignment, and inventory replenishment problem (SAIRP) for battery exchange stations, modeled the operation of a battery exchange station as a stochastic SAIRP, and proposed a Markov Decision Process (MDP) model for determining the optimal strategy for charging, discharging, and replacing the number of batteries. Based on particle swarm optimization, Zhang et al. (2023)[0] proposed a two-stage optimization strategy for electric vehicle charging and discharging considering elastic demand response, which allows users to respond autonomously according to the reference value of charging and discharging demand response, and chose optimization weights autonomously to satisfy their travel and charging needs.

There are currently two main modes of operation for electric vehicle battery-swapping stations: the first is the autonomous operation mode, in which enterprises invest in the construction and operation of battery-swapping stations on their own, which is conducive to enterprises' mastery of the initiative of batteries and improvement of operational efficiency; the second is the cooperative operation mode, in which enterprises cooperate with other organizations in the construction and operation of battery-swapping stations, which expands the coverage of the stations and improves the efficiency of resource utilization. For both models, the key to increasing the operational revenue of the battery-swapping station is to optimize the number of batteries and charging time.

In view of this, this paper analyses the operational characteristics of electric vehicle battery-swapping stations in Beijing, analyses the revenue of battery-swapping stations based on time-sharing tariffs, considers the scheduling of batteries in battery-swapping stations and the matching of battery charging strategies with the time-sharing tariff mechanism of the National Grid, establishes a battery scheduling model of battery-swapping stations aiming at the maximization of the revenue of battery-swapping stations, and then solves the optimal charging and discharging strategies of battery-swapping stations to achieve the reasonable distribution and effective use of electric power resources. allocation and effective utilization of power resources.

3. Model Formulation, Hypotheses and Results

For the convenience of the study, this paper combines the characteristics of the battery-swapping mode itself, and makes the following assumptions about the charging and discharging management of the battery in the battery-swapping station:

(1) It is assumed that the study period is 24 hours a day, and the unit time interval is 1 hour, t=1, 2,..., 24 corresponds to the time periods 8:00-9:00, 9:00-10:00, ..., 7:00-8:00 respectively.

(2) Assuming that the batteries in the exchange station have the same properties, the required charging and discharging time is the same: 1 hour.

(3) Battery charging is continuous. If the battery is in the charging state, charging ends only when it is fully charged. Battery discharge is also continuous. If the battery is in the discharging state, the discharging will end only when it runs out of power.

(4) It is assumed that the demand fulfillment rate of the switching station must be higher than the service level and that unmet demand for switching incurs a shortage cost.

Consider a single battery-swapping station with n batteries and L charging/discharging interfaces, which can both charge the batteries from the grid and release the battery power to the grid. At any moment t, the unit price of electricity from the grid is RMB λ_t per kWh, which can represent both the cost when charging the battery and the revenue when releasing electricity from the battery to the grid. d_t denotes the amount of demand for battery-swapping at the battery-swapping station at moment t. Assuming that the rate of satisfaction of the demand for battery-swapping has to be higher than the service level α, and that the unsatisfied demand for battery-swapping generates a shortage cost, the unit shortage cost is β. When the user performs the battery-swapping service, the battery-swapping station collects the battery-swapping service fee and electricity fee, the single battery-swapping service fee is a_0 and does not change in time period T, and the unit price of the electricity fee collected by the battery-swapping station at time t is RMB p_t per kWh. In the battery-swapping station, there are two states of batteries with full charge and deficit, and there are three states of batteries with full charge, which are waiting for, replaced, and discharged to the grid, and two states of batteries with deficit, which are waiting for and charging. At any time t, the variable f_t denotes the number of fully charged batteries; then, $n - f_t$ denotes the number of deficit batteries. The variable s_t denotes the number of batteries exchanged at moment t, and the variables x_t and y_t denote the number of batteries charged and discharged at the exchange station at moment t, respectively. r is the annual discount rate, the unit cost of the batteries is RMB ω per kWh, the battery life is Y years, and E_b denotes the amount of electricity exchanged by charging and discharging a single battery, i.e., the rated capacity of a battery.

The battery charging scheduling model for an electric vehicle battery-swapping station optimizes the battery charging and discharging strategy of the battery-swapping station with the objective of maximizing the daily revenue of the switching station under the premise of satisfying various types of constraints. The revenue is derived from the gains obtained from providing the switching service and discharging to the grid, and the costs include the out-of-stock costs, charging costs and battery depreciation costs. The objective function is as follows:

$$max\sum_{t=1}^{T}[a_0 \times s_t + p_t \times E_b \times s_t - \beta(d_t - s_t) - \lambda_t \times E_b \times (x_t - y_t)] - \omega E_b n \frac{r(1+r)^Y}{365[(1+r)^Y - 1]}$$

s.t.

$$f_1 = n \tag{1}$$

$$f_{t+1} = f_t - s_t + x_t - y_t, t = 1,2,\cdots,T \tag{2}$$

$$x_t \le n - f_t, t = 1,2,\cdots,T \tag{3}$$

$$s_t + y_t \le f_t, t = 1,2,\cdots,T \tag{4}$$

$$x_t \le \mathrm{L}, t = 1,2,\cdots,T \tag{5}$$

$$y_t \le \mathrm{L}, t = 1,2,\cdots,T \tag{6}$$

$$0 \le f_t \le n, t = 1,2,\cdots,T \tag{7}$$

$$s_t \le d_t, t = 1,2,\cdots,T \tag{8}$$

$$s_t \ge \alpha d_t, t = 1,2,\cdots,T \tag{9}$$

$$f_t, s_t, x_t, y_t \in \{Z^+ \cup 0\}, t = 1,2,\cdots,T \tag{10}$$

The objective function is to study the maximization of the operating revenue of the battery-swapping station operator in the whole day, which integrates the switching cost, charging and discharging price and charging and discharging behaviors, the number of batteries in the battery-swapping station, and the charging and discharging capacity of the battery-swapping station. Constraint (1) indicates that the batteries of the battery-swapping station are fully charged at the initial moment; constraint (2) indicates that the number of fully charged batteries at t+1 is equal to the sum of the number of fully charged and charging batteries at t minus the sum of the number of exchanged and discharged batteries; constraint (3) indicates that the number of charging batteries at t should be less than or equal to the total number of batteries of the battery-swapping station minus the number of fully charged batteries; constraint (4) indicates that the number of exchanged batteries and the number of discharged batteries at t cannot exceed the number of fully-charged batteries; constraints (5) and (6) indicate that the number of charging and discharging batteries cannot exceed the number of charging and discharging interfaces; constraint (7) indicates that the number of fully charged batteries cannot exceed the total number of batteries of the exchange station; constraint (8) indicates that the number of exchanged batteries cannot exceed the exchanged demand; constraint (9) indicates that the rate of exchanged demand fulfillment cannot be less than the level of service; constraint (10) indicates that the number of fully charged batteries, the number of switching batteries, the number of charging batteries, and the number of discharging batteries are all positive integers or zero.

Taking a certain battery-swapping station in Beijing as an example, the proposed model is used to optimize its battery charging and switching strategy. Referring to the average number of visits to gas stations in real life, the demand for battery-swapping d_t in time period T is set to obey a Poisson distribution with a mean value of 15, and a set of samples with a capacity of 24, i.e., the value of d_t, generated by random sampling using MATLAB, is shown in Table 1.

Table 1: Demand for battery-swapping at the battery-swapping station

t	d_t value	t	d_t value
1	15	13	14
2	15	14	12
3	22	15	11
4	18	16	11
5	17	17	10
6	23	18	9
7	17	19	9
8	15	20	8
9	14	21	9
10	16	22	11
11	12	23	12
12	15	24	13

The values of some of the parameters of the electric vehicle exchange stations and batteries are given in Table 2:

Table 2: Parameters of the battery-swapping station[2]

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[2] Parameters of the nio es8 power pack in nio app

Parameter	Value
Battery service life (years)	8
Battery unit cost/(RMB/kWh)	933
Rated battery capacity/kWh	75
Unit out-of-stock cost/RMB	5
Discount rate/per cent	6

At present, Beijing adopts time-of-use tariffs to smooth out the electricity load, dividing the tariffs into three stages: peak, usual period and trough. If the battery-swapping station can reasonably arrange the charging time and move the charging to the valley section, it can save considerable charging costs. The time-sharing electricity price in Beijing in September 2023 is taken as λ_t, see Table 3. Corresponding to grid pricing, the exchange electricity price charged to users by some of the battery-swapping stations in Beijing is also time-sharing pricing. Take the selected battery-swapping station as an example, the electricity fee charged to users is shown in Table 4.

Table 3: Electricity tariffs for industrial and commercial users of Beijing Electric Power Company purchasing electricity on behalf of the company[3]

Segmentation	peak hour	nonpeak period	low valley time interval
time period	10:00-13:00 17:00-22:00	7:00-10:00 13:00-17:00 22:00-23:00	23:00-07:00
tariff /（RMB/kWh）	0.929165	0.681301	0.433437

Table 4: Electricity charges for battery-swapping stations [4]

Segmentation	peak hour	nonpeak period	low valley time interval
time period	10:00-13:00 17:00-22:00	7:00-10:00 13:00-17:00 22:00-23:00	23:00-07:00
tariff/（RMB/kWh）	1.31	0.99	0.69

The model is solved to analyse the sensitive relationship between parameters such as the number of batteries n, the number of charging and discharging interfaces L, the single switching service fee a_0, and the battery-swapping service level α of the battery-swapping station to the operation revenue as well as the charging and discharging arrangement of the batteries of the battery-swapping station in each time period. Let n be 40, 50, 60, and 70; α be 30, 35, 40, and 45; and α be 0.8, 0.85, 0.9, and 0.95. Assuming that the number of charging and discharging interfaces L of the battery-swapping

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[3] http://www.bj.sgcc.com.cn/html/main/col40274/2023-08/28/20230828203246860461178_1.html

[4] Pricing of the Beijing Dazhongsi Lanjinglijia battery-swapping station in nio app

station is half of n [5], L is 20, 25, 30, and 35. Service fee α, and switching service level α on the operating revenues of the switching station and determine the sensitivity of each factor. The corresponding operating revenues under different parameters are shown in Figs. 1, 2, 3 and 4.

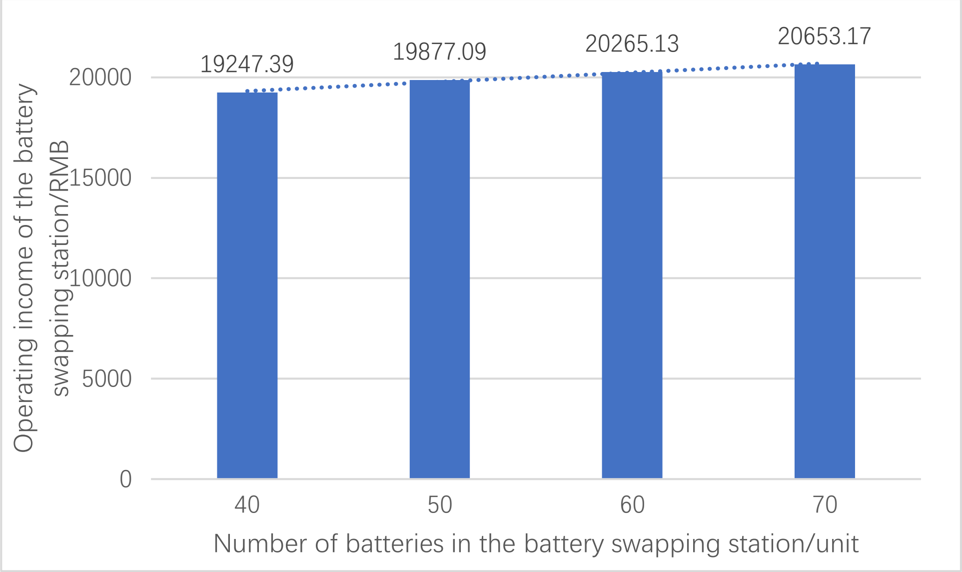

Fig.1: Operating revenues corresponding to different numbers of batteries in the battery-swapping station, L=20，a_0=30，α=0.95

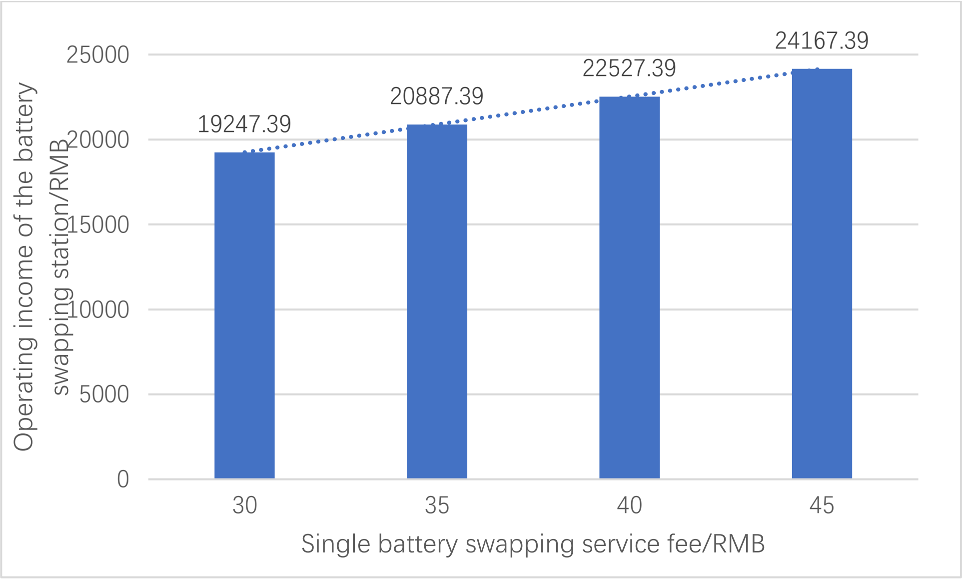

Fig.2: Operational returns corresponding to different battery-swapping service fees, n=40，L=20，α=0.95

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[5] Liu Z, Miao R et al. (2016). Battery swapping station operation revenue model and strategy. *Industrial Engineering*, 19(03), 85-89.

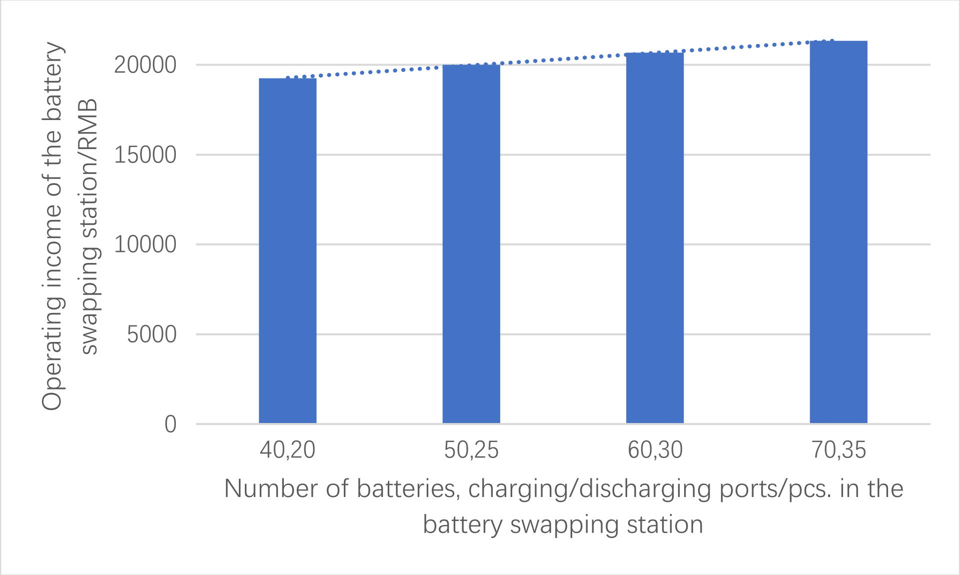

Fig.3: Operational revenue corresponding to different numbers of batteries and charging/discharging interfaces in the battery-swapping station, a_0=30， α=0.95

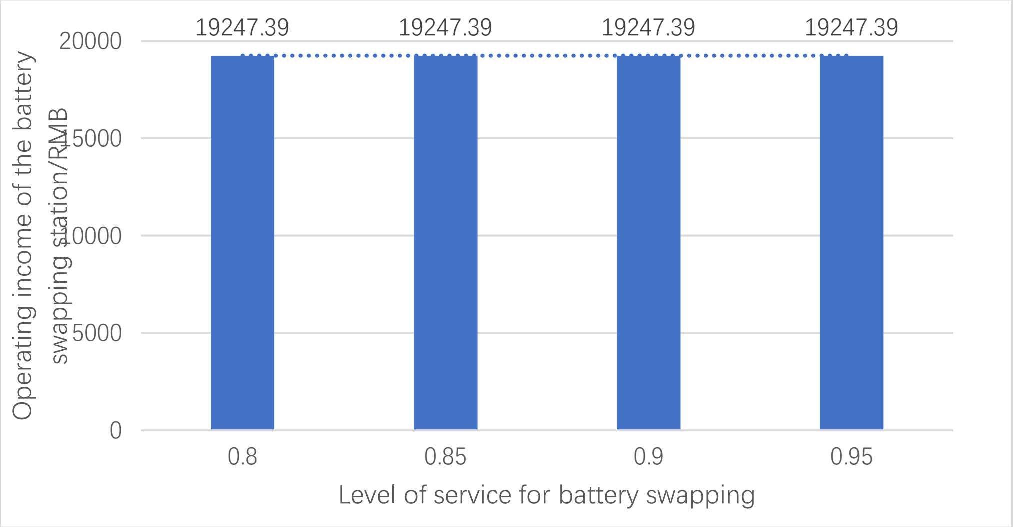

Fig.4: Operational revenue corresponding to different battery-swapping service levels, n=40， L=20， a_0=30

From Figures 1, 2, and 3, it can be seen that with the increase in battery ownership n, charging interfaces L, and switching service charge a_0 of the battery-swapping station, the operating income increases, but the increase rate is different, which means that the sensitivity of the operating income to the change in different parameters is different, and the sensitivity is in the order of switching service charge a_0, battery ownership n, and charging interfaces L. The switching service charge shows the highest sensitivity because the battery-swapping demand is relatively fixed in a short period of time, which leads to an obvious increase in the income of the battery-swapping station after the increase in the switching service charge. The highest sensitivity is because the demand for battery-swapping is relatively fixed for a short period of time, which leads to a significant increase in the revenue of the battery-swapping station after the increase in the battery-swapping service fee. The relatively low sensitivity of the number of batteries in the battery-swapping station is because the demand is basically satisfied, and the increase in the number of batteries has very little impact on the revenue of the battery-swapping part, mainly causing the revenue of the discharging part to increase. Figure 3 indicates the change in the revenue of the battery-swapping stations when the number of battery-swapping stations and charging/discharging interfaces increases synchronously because the increase in revenue is mainly generated by discharging to the grid when the demand for battery-swapping is basically satisfied. The change in the level of service of the battery-swapping does not lead to a change in the operational revenue, which indicates that the battery-swapping strategy can satisfy the demand for battery-swapping.

Taking a set of parameters n=40, L=20, a_0=30, and α=0.9, the detailed analysis of the solution results of the model under this parameter and the results of the analysis are shown in Table 5, which shows the number of batteries that should be charged and discharged at the battery-swapping station in each time period, and the arrangement of such a strategy can make the most reasonable utilization of resources and the maximization of the operational revenue. Therefore the model in this paper can also be good for battery charging and discharging management, which provides a scientific basis for the operation of the battery-swapping station.

Table 5: Number of batteries exchanged, charged, discharged, and fully charged at different times in the battery-swapping station

t	d_t	S_t	x_t	y_t	f_t
1	15	15	0	0	40
2	15	15	15	0	25
3	22	22	15	0	25
4	18	18	20	0	18
5	17	17	20	0	20
6	23	23	17	0	23
7	17	17	20	0	17
8	15	15	15	0	20
9	14	14	20	0	20
10	16	16	2	0	26
11	12	12	20	0	12
12	15	15	14	5	20
13	14	14	12	0	14
14	12	12	11	0	12
15	11	11	11	0	11
16	11	11	10	0	11
17	10	10	9	0	10
18	9	9	9	0	9
19	9	9	8	0	9
20	8	8	9	0	8
21	9	9	11	0	9
22	11	11	20	0	11
23	12	12	20	0	20
24	13	13	0	15	28

4. Conclusion

With the large-scale promotion and popularization of electric vehicles, it is extremely important to formulate a reasonable battery scheduling optimization strategy for battery-swapping stations to achieve their economic operation. In this paper, based on the study of the operating characteristics of electric vehicle exchange stations in Beijing, we explore the operation optimization problem of exchange stations based on the time-sharing tariff mechanism, and establish an optimization model with the goal of maximizing the operating revenue of exchange stations. The conclusions of this paper are as follows:

(1) The operating revenue of Beijing's battery-swapping stations is affected by the market price of batteries, the pricing of battery-swapping services, and the number of configured batteries and charging/switching interfaces, with the main influencing factors being the charge of battery-swapping services and the ownership of batteries. For the operation of the battery-swapping station, the revenue obtained from the provision of battery-swapping services is the main source of revenue, so it is necessary to meet the demand for battery-swapping as much as possible to ensure the efficiency of the service to maximize the operating income.

(2) The battery of the battery-swapping station is not always recharged during the tariff valley, but is flexibly adjusted under the limitations of the demand for battery-swapping and the number of devices. The proposed battery charging/discharging strategy of the battery-swapping station can satisfy all the demand of battery-swapping in one day, and can discharge to the grid to gain certain benefits while sharing the load of the grid. This scheduling optimization scheme can take into account the peak-to-valley difference in electricity price and the demand for EVs, which can make the most reasonable use of resources, effectively reduce the charging cost and balance the load on the grid.

(3) In view of the development trend and future demand of electric vehicle battery-swapping stations in Beijing, we make corresponding suggestions to the Beijing Municipal Government. For example, a battery-swapping station can be used as an energy storage node to supply power to the outside world during the peak period of electricity consumption, helping to balance the load of the power grid and ensure the stable operation of the power grid. The management system of battery-swapping stations should be promoted, the battery-swapping model should be promoted, and the peak and valley electricity price difference should be utilized to reduce the charging cost to solve the charging difficulty problem in old neighborhoods. The government, relevant power grid companies and battery-swapping station operators can jointly establish a cooperative operation mode for battery-swapping stations, forming a customer-centered benefit-sharing mechanism.

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