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An Optimal Operation Model and Ordered Charging/Discharging Strategy for Battery Swapping Stations

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Abstract: The economic operation of battery swapping stations (BSSs) is significant for the promotion of large-scale electric vehicles. This paper develops a linear programming model to maximize the daily operation profits of a BSS by considering constraints of the battery swapping demand of users and the charging/discharging balance of batteries in the BSS. Based on the BSS configuration and data from electric taxis in Beijing, we simulate the operation situation and charging/discharging load of the BSS in nine scenarios with two ordered charging and discharging strategies. The simulation results demonstrate that the model can achieve the maximum daily profits of the BSS. According to the sensitivity analysis, the battery swapping price for batteries is the most sensitive, followed by the number of batteries in the BSS, while the operation-maintenance costs and battery depreciation costs are least sensitive. In addition, the charging and discharging of batteries in the BSS can be coordinated by increasing the battery quantity of the BSS and formulating the ladder-type battery swapping price.

Keywords: battery swapping station; operation analysis; charging and discharging strategy

1. Introduction

According to statistics from the International Energy Agency, the transportation sector accounted for 28.37% of carbon dioxide (CO_2) emissions from fuel combustion in China [1]. Along with the urbanization development in China, the growth of traditional vehicles is rapid, which will increase the proportion of CO_2 emissions from the transportation sector and lead to the serious air pollution and oil shortage. Electric vehicles (EVs) have prominent advantages of emission reduction and oil conservation in transportation sector. Therefore, many policy measures have been employed to support and encourage the development of EVs in China. Since 2009, China has established 25 pilot cities in batches and popularized EVs in the public domain such as the area of public buses, taxis, sanitation trucks and mail trucks [2]. According to the Global EV Outlook of 2016 [3], by the end of 2015, China had the second largest stock of EVs at 312,290. The large-scale development of EVs depends on the stable and continuous energy supply. The research of Sierzchula [4] shows that constructing one charging station for every 100,000 residents can double the effect on EVs' market promotion compared with providing 1000 dollars directly to every consumer. This demonstrates that the stable energy supply is significant to encourage the market penetration of EVs.

At present, the energy supply mode of EVs mainly includes direct charging mode and battery swapping mode [5]. Direct charging mode refers to the fact that the energy of EVs comes from the direct charging by charge piles and other charging equipment. Battery swapping mode is a way that the batteries of EVs are swapped by full-charged power batteries from centralized charging and swapping stations (CSSs). The swapping mode is applied in many pilot cities of China, such as Hangzhou, Beijing and Haikou. CSSs have the advantage of unified deployment and management for EV battery swapping service. Moreover, it can achieve the economic operation of CSSs and smooth the load of the power grid by unified charging and swapping strategy of batteries and the technology of vehicle to grid (V2G) [6]. Therefore, China had completed construction on 3600 CSSs at the end of 2015 [7]. Moreover, it plans to construct 12,000 centralized CSSs through 2020 [8]. To promote the marketization of charging infrastructure, research on the economical operation of CSSs and the factors influencing operation, as well as the impact on the power grid load, is needed. When the operation of CSSs becomes profitable, more investment will be attracted to the construction of charging infrastructure. The increased number of CSSs can make consumer charging more convenient, which is conducive to the large-scale development of EVs. Thus, many scholars have noted research on the promotion of EV charging infrastructure. Those studies can be divided into two areas: the ordered charging/discharging of EVs and economic operation of CSSs.

The research on the ordered charging and discharging of EVs is concerned with the load forecasting and shifting of EVs. Based on the historical load data of electric bus charging stations, Zhang et al. [9] considered the factors influencing the load of charging stations and forecasted the daily load of charging stations using fuzzy clustering and back propagation neural networks. According to the operating mechanism and charging power curve characteristics of electric bus charging stations, Wang et al. [10] established a general mathematical model to determine the distribution capacity of electric bus charging stations. Shi [11] took the power-demand-side management and electricity price theory into account, and designed a charge and discharge pricing scheme for EVs. To achieve the load-shifting effect of EVs, Li [12] developed an optimization model of demand-side response strategies for EVs using the genetic algorithm. Yao et al. [13] proposed layering and zoning EVs, optimizing the dispatch of regional agents and controlling users' charging and discharging time to realize the objective of peak load shifting. Zhang [14] established an ordered charging and discharging model to maximize the profits of EVs' third-party agents and applied the particle swarm optimization algorithm to attain optimal scheduling results.

The second research area is mainly focused on the analysis of CSSs' economic operation. Zhang et al. [15] shrank the adjustment frequency of thermal power and enhanced the security and economy of the power grid by optimizing the charging and discharging process of battery swapping stations (BSSs). Luo et al. [5] established a two-phase optimization model for battery swapping modes: The first phase is based on the objective of minimizing the charging fee, and the second phase is aimed at minimizing the fluctuation of daily load curves by using the objective of the first phase as the constraint. Deng [16] proposed a bi-level programing approach to coordinate EVs' charging with the network load and electricity price. Soares [17] designed a coordination optimization model to minimize the total costs by considering the new energy generation costs, EV charging costs and discharging incomes. Based on the driving mode of large-scale EVs, Du et al. [18] developed a dynamic economic dispatch model to minimize the generating costs using the traditional mathematical programming method. Sun et al. [19] analyzed the operation mode of BBSs and developed a profit model based on the objective of maximizing the operating profits of BBSs. Additionally, many studies have proposed profitable business modes for CSSs. To achieve a win–win situation for the public sector and market departments, Yang et al. [20] developed a public–private partnership mode based on their long-term cooperation. Robinson et al. [21] designed several models of solar powered charging stations for major entities including industry, the federal and state government, utilities, universities, and public parking. Zhang and Rao [22] developed five commercial modes for a battery swapping and leasing service and analyzed their profits. Other researchers concern on the energy source of EVs.

To increase the participation of renewable energy, Diaz [23] explored the option of coupling EVs as a distributed energy storage system in Tenerife Island and used a model simulator to evaluate the introduction of renewable energy and EVs. Zhang et al. [24] used the linear programming to maximize the sustainability performance of ecology zones.

In summary, previous studies on the ordered charging and discharging of EVs mainly consider the perspective of the power grid's stable operation. The battery swapping mode is an important energy-supply method for EVs [25] by which users can replenish EV batteries in a short time and achieve the load-shifting effect by energy storage. Previous studies on the economic operation of BSSs have focused more on regarding BSSs as a part of the power grid and intended to realize the economical operation of the power grid through the ordered charging of batteries in the BSS, while focusing less on the economical operation of the BSS itself. In China, in particular, the market of constructing and managing BSSs is monopolized by the State Grid and the Southern Power Grid. With the large-scale development of EVs, however, China will gradually open the market to stakeholders [26], and BBS investors will not only be the power grid but also cover private capitalists, battery manufacturers and gasoline enterprises [24].

Therefore, this paper regards the maximization of the BSS's daily profits as the objective value from the perspective of the economic benefits of BSS investors. In addition, it considers the main factors that impact the operational management of BSSs and designs an ordered charging and discharging strategy to make BSSs more profitable. Furthermore, this paper analyzes the load of the BSS and the charging arrangement of the BSS's batteries in different scenarios with ordered charging and discharging strategies based on the electricity price of the peak-valley time-of-use tariff (TOU) and the demand response (DR). There are several major contributions of this study: (1) from the perspective of BSS investors, the operation mode should aim to maximize the daily profits of the BSS; (2) considering the profitable operation of BSSs, we propose the ordered charging and discharging strategies for batteries in BSSs; (3) the optimal operation scheme for BSSs is carried out based on the scenario analysis; and (4) the sensitive factors affecting the operation of BSSs are determined by the sensitivity analysis.

The purpose of this study is to analyze the operation profits of BSSs and proposes an appropriate charging and discharging strategy for BSSs. The work is organized as follows. The operation mode of BSSs is analyzed in Section 2. The optimal operation model is introduced in Section 3. In Section 4, the results of the scenario simulation and sensitivity analysis are discussed, and the effects of two ordered charging and discharging strategies are tested. Section 5 concludes the paper.

2. Operation Mode of the BSS

2.1. Battery Swapping Mode of BSS

In China, BSSs utilize special facilities to charge and swap batteries and to achieve the centralized management and maintenance of batteries. The battery swapping mode is suitable for public buses, taxis, and sanitation trucks, which must be charged immediately. Figure 1 shows the operation mode of a BSS. EVs exchange their batteries in the BSS, and the empty batteries are sent to the empty battery depot. After the empty batteries are fully charged, they will be delivered to the fully charged battery depot. The power grid is the single energy source of batteries in the BSS.

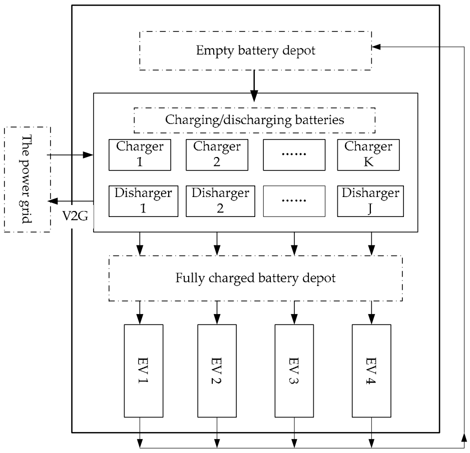

Figure 1. Battery swapping mode of BSS.

2.2. Operation Incomes of BSS

Currently, the main incomes of the BSS come from the business of battery swapping. The two types of battery swap pricing methods are charging by the driving mileage or battery electricity consumption. Thus, battery swapping incomes of the BSS (I_s, yuan) are expressed as:

$$I_s = \sum_{t=1}^{24} \sum_{i=1}^{N(t)} P_s M_i(t), \tag{1}$$

where P_s is the battery swapping price per driving mileage unit or per electricity unit, yuan/km or yuan/kWh; $M_i(t)$ is the driving mileage or battery electricity consumption of EV i at t, km or kWh; and $N(t)$ is the number of EVs for swapping batteries at t.

If the vehicle-to-grid (V2G) technology is mature and the number of EVs is large, BSSs can benefit not only from the battery swapping price but also from the business of feeding electricity into the power grid. This means that BSSs can sell electricity to the power grid by discharging batteries. It supposes that there are J devices to discharge the batteries and the value of the discharging time interval (Δt, h) is one hour. Discharging incomes of the BSS (I_d, yuan) can be described as:

$$I_d = \sum_{t=1}^{24} \sum_{j=1}^{J} P_g(t) p_j(t) \Delta t, \tag{2}$$

where $P_g(t)$ is the feed-in tariff of BSSs at t, yuan/kWh; and $p_j(t)$ is the transmission power of discharging device j, kW; J is the number of discharging devices.

2.3. Operation Costs of BSS

The paper focuses on analyzing BSS's operation status. Therefore, investment and construction costs are not considered here. BSS's operation costs consist of three parts: charging costs, depreciation costs and operation and maintenance costs.

(1) Charging costs (C_c, yuan) are the charging fee that the BSS pays to the grid power, which can be expressed as:

$$C_c = \sum_{t=1}^{24} \sum_{k=1}^{K} P_e(t) p_k(t) \Delta(t), \tag{3}$$

where $P_e(t)$ is the electricity price that the power grid supplies power to the BSS at t, yuan/kW; $p_k(t)$ is the charging power of charger k at t, kW; and K is the number of chargers in the BSS.

(2) Depreciation costs (C_d, yuan) are the depreciation expenses of batteries after charging and discharging. The depreciation costs of a battery (c_c, yuan) after charging can be calculated by dividing the purchase or lease costs by the battery's charging-cycle life. N_c is the number of fully charged batteries in a day. C_d can be defined as:

$$C_d = c_c N_c. \tag{4}$$

With the application of V2G, depreciation costs should consider discharging depreciation costs:

$$C'_d = c_c N_c + c_d N_d, \tag{5}$$

where c_d (yuan) is the depreciation cost of a battery after discharging, which is the value of the purchase or lease costs divided by the battery's discharging-cycle life. N_d is the number of batteries that are fully discharged in a day.

(3) Operation and maintenance costs (C_m, yuan) are related to the equipment configuration of the BSS, including the chargers and batteries, which can be determined by:

$$C_m = f(K, Z), \tag{6}$$

where Z is the number of batteries in the BSS. A higher K and Z lead to a higher C_m.

3. Operation Model of BSS

3.1. Objective Function

The objective function seeks to maximize the profits of the BSS. Without considering the V2G technology, the function of BSS's profits in a day is expressed as:

$$P = I_s - C_c - C_d - C_m = \sum_{t=1}^{24} \sum_{i=1}^{N(t)} P_s M_i(t) - \sum_{t=1}^{24} \sum_{k=1}^{K} P_e(t) p_k(t) \Delta(t) - c_c N_c - f(K, Z). \tag{7}$$

If the BSS can earn from feeding electricity into the power grid with V2G technology, the function of BSS's profits in a day should be defined as:

$$\begin{aligned} P(V2G) &= I_s + I_d - C_c - C'_d - C_m \\ &= \sum_{t=1}^{24} \sum_{i=1}^{N(t)} P_s M_i(t) + \sum_{t=1}^{24} \sum_{j=1}^{J} P_g(t) p_j(t) \Delta t - \sum_{t=1}^{24} \sum_{k=1}^{K} P_e(t) p_k(t) \Delta(t) - (c_c N_c + c_d N_d) - f(K, Z) \end{aligned}. \tag{8}$$

3.2. Constraint Conditions

We set the following constraints to achieve the operation of BSS:

(1) Constraint of battery swapping demand:

The BSS should meet the battery swapping demand of users, which means that the number of fully charged batteries in the BSS cannot be less than the number of swapping batteries:

$$S(t) \geq \beta N(t), \tag{9}$$

where $S(t)$ is the number of fully charged batteries in the BSS at t, and β is the battery number of one EV. It supposes that EVs are the same model and that they replace all the batteries each time.

(2) Constraint of the number of chargers:

The number of charging batteries at t ($F(t)$) should not be more than the number of chargers (K) in the BSS:

$$F(t) \leq K. \tag{10}$$

(3) Constraint of the number of discharging devices:

The number of discharging batteries ($W(t)$) should not be more than the number of discharging devices (J):

$$W(t) \leq J. \tag{11}$$

(4) Constraint of the number of batteries:

The number of batteries in the BSS is certain. The number of fully charged, empty ($E(t)$), charging and discharging batteries on the charger and discharger should not be more than the total number of batteries. Empty batteries means swapped batteries or discharged batteries:

$$S(t) + E(t) + F(t) + W(t) \leq Z. \tag{12}$$

(5) Constraint of the battery charging process:

It takes T_f hours for empty batteries to be fully charged, and T_f is a positive integer that can be divided into T_f charging stages of 1, 2, ... , T_f. The number of charging batteries in each stage is $F^{(1)}(t)$, $F^{(2)}(t)$, ... , and $F^{(T_f)}(t)$, respectively. The constraint can be expressed as follows:

$$\begin{array}{c} F^{(1)}(t) + F^{(2)}(t) + \ldots + F^{T_f}(t) = F(t) \\ F^{(1)}(t) = F^{(2)}(t+1) \\ F^{(2)}(t) = F^{(3)}(t+1) \\ \ldots \\ F^{(T_f-1)}(t) = F^{(T_f)}(t+1) \end{array} . \tag{13}$$

The number of fully charged batteries in a day can be expressed as:

$$N_c = \sum_{t=1}^{24} F^{(T_f)}(t). \tag{14}$$

(6) Constraint of the battery discharging process:

This presumes that the fully charged batteries take T_w hours to fully discharge. T_w is a positive integer that can be divided into T_w discharging stages of 1, 2, ... , T_w. The number of discharging batteries in each stage is $W^{(1)}(t)$, $W^{(2)}(t)$, ... , and $W^{(Tw)}(t)$, respectively. The constraint can be described as follows:

$$\begin{array}{l} W^{(1)}(t) + W^{(2)}(t) + \ldots + W^{T_w}(t) = W(t) \\ W^{(1)}(t) = W^{(2)}(t+1) \\ W^{(2)}(t) = W^{(3)}(t+1) \\ \ldots \\ W^{(Tw-1)}(t) = W^{(T_w)}(t+1) \end{array} . \tag{15}$$

The total number of discharged batteries in a day is expressed as:

$$N_d = \sum_{t=1}^{24} W^{(T_w)}(t). \tag{16}$$

(7) Constraint of the number of fully charged batteries:

The number of fully charged batteries should maintain a dynamic balance in the BSS:

$$S(t+1) + \beta N(t+1) + W^{(1)}(t+1) = S(t) + F^{(T_f)}(t). \quad (17)$$

(8) Constraint of the number of empty batteries:

The number of empty batteries should maintain a dynamic balance in the BSS:

$$E(t+1) + F^{(1)}(t+1) = \beta N(t) + E(t) + W^{(T_w)}(t). \quad (18)$$

(9) Integer constraint of number of batteries:

$S(t)$, $F(t)$, $W(t)$, $E(t)$, $F^{(i)}(t)$, $W^{(j)}(t)$, $N(t)$, β, K, D, Z are all positive integers. i represents 1, 2, ... , T_f, and j represents 1, 2, ... , Tw.

3.3. Assumptions

The following assumptions simplify the model without affecting the operation of BSS:

(1) Once batteries are put on chargers, the charging power of the chargers is considered as their rated charging power (P_c). Taking account of the charging efficiency of batteries (η_c), the actual charging power can be defined as:

$$P_c' = P_c/\eta_c, \quad (19)$$

where P_d is the rated discharging power of discharging devices, and η_d is the discharging efficiency of batteries. The actual discharging power is expressed as:

$$P_d' = P_d \times \eta_d. \quad (20)$$

(2) A charger can only charge one battery at a time.

(3) The time that a mechanical arm swaps batteries for EVs and puts them on the charger is between four and six minutes, a much shorter period than the charging or discharging period of one hour. It can therefore be ignored here. Based on the previous assumption conditions, Equation (7) can be simplified as follows:

$$P' = \sum_{t=1}^{24}\sum_{i=1}^{N(t)} P_s M_i(t) - \sum_{t=1}^{24} P_e(t)F(t)P_c' - c_c \sum_{t=1}^{24} F^{(T_f)}(t) - f(K,Z). \quad (21)$$

Taking account of the discharging of BSS, Equation (8) can be expressed as:

$$P'(V2G) = \sum_{t=1}^{24}\sum_{i=1}^{N(t)} P_s M_i(t) + \sum_{t=1}^{24} P_g(t)W(t)P_d' - \sum_{t=1}^{24} P_e(t)F(t)P_c' - c_c \sum_{t=1}^{24} F^{(T_f)}(t) - c_d \sum_{t=1}^{24} W^{(T_w)}(t) - f(K,Z) \quad (22)$$

Since there are many parameters in the papers, the nomenclature of the parameters are shown in Table A1 (Appendix A).

4. Empirical Analysis

4.1. Basic Data

A Beijing BSS and BAIC Motor EV200 (BAIC BJEV, Beijing, China) are used as the examples for analysis. The parameters of BSS [27] and BAIC Motor EV200 [28] are shown in Tables 1 and 2, respectively. The electricity price of BSS in Beijing is the industrial TOU [29] shown in Table 3.

Table 1. Operation parameters of the BSS.

Index	Parameter	Unit
Number of batteries	1104	unit
Number of chargers	1044	unit
Charge power of chargers	15	kW
Charging efficiency of batteries	95	%
Total investment of BSS	2100	Ten thousand yuan
Equipment maintenance rate	5	%
Operation time of equipment	365	day

Table 2. Technical parameters of BAIC Motor EV200.

Index	Parameter	Unit
Battery lifetime (charging cycle frequency)	≥2000	/
Electric quantity of batteries	30.4	kWh
Number of batteries in an EV200	4	/
Mileage	200	km

Table 3. Industrial peak-valley time-of-use tariff of Beijing.

Time		Price (Yuan/kWh)
Valley hours	00:00–08:00	0.365
Peak hours	*08:00–12:00* *17:00–21:00*	*0.869*
Average hours	12:00–17:00 21:00–24:00	0.687

The battery swapping price of BSS is 0.6 yuan/km, which is charged by driving mileage. In addition, the battery depreciation costs of a battery after a single charging session is 9 yuan [19]. Batteries take 2 h to fully charge or discharge (T_f = 2 h, T_w = 2 h). Since there are no dischargers in the BSS, the number of dischargers is assumed as 500 units in the paper. Table 4 shows the number of EVs for swapping batteries and the average driving mileage ($\overline{M_i(t)}$), which are obtained by fitting the battery-swapping-demand data of battery electric taxis to a South China BSS.

Table 4. Battery swapping demand and average driving mileage.

T	$N(t)$	$\overline{M_i(t)}$	T	$N(t)$	$\overline{M_i(t)}$
1	26	100	13	28	109
2	16	110	14	16	110
3	8	120	15	18	111
4	4	112	16	36	103
5	4	107	17	32	108
6	5	108	18	28	109
7	4	106	19	14	113
8	6	113	20	18	115
9	16	115	21	20	105
10	24	120	22	22	102
11	20	106	23	24	112
12	20	117	24	12	114

4.2. Scenario Simulation

The total equipment investment and daily maintenance costs of BSS are related to the number of chargers and batteries. BSS income originates from two main sources: battery swapping service and discharging. Therefore, we design nine scenarios based on the different number of chargers and batteries, charging optimization or not, and discharging or not. The discharging price is also the TOU shown in Table 3. In addition, the increased device investment in the discharge process will not be considered here because it would not affect the overall operation analysis of the model.

Charging optimization means that the BSS applies the charging strategy by considering the electricity price, number of batteries and number of chargers instead of charging the batteries as soon as they are swapped. Scenario 1 (S1) uses the basic data of the Beijing BSS without the charging optimization, which means that the swapped batteries are put on the chargers once they are swapped from EVs. S2–S9 are optimized by the charging optimization model in Section 3. Besides, the corresponding model and the equations of S2–S9 are shown in Table A2. The equipment investment and daily maintenance costs in S2–S9 are obtained by the arithmetic descending of those in S1. It shows the device configuration, investment scheme, and operation mode of BSSs in Table 5.

Table 5. Device configuration, investment scheme and operation mode of the BSS.

S	Number of Chargers	Number of Batteries	Device Investment (Ten Thousand Yuan)	Daily Maintenance Fee (Yuan)	Optimization	Discharge
S1	1044	1104	2100	2487	No	No
S2	1044	1104	2100	2487	Yes	No
S3	200	1104	1383	1894	Yes	No
S4	200	800	1079	1478	Yes	No
S5	1044	800	1796	2460	Yes	No
S6	1044	1104	2100	2487	Yes	Yes
S7	200	1104	1383	1894	Yes	Yes
S8	200	800	1079	1478	Yes	Yes
S9	1044	800	1796	2460	Yes	Yes

4.3. Operation Analysis

Based on the data in Table 5, we use the linear programming method to solve the optimized model in Section 3. Table 6 shows BSS income and costs for nine scenarios.

Table 6. Incomes and costs analysis of the BSS (yuan).

S	Charging Costs	Depreciation Costs	Operation and Maintenance Costs	Battery Swapping Service Incomes	Discharging Incomes	Profits
S1	36,821.4	15,156	2487	27,657.6	0	−26,806.8
S2	10,686.5	5508	2487	27,657.6	0	8976.1
S3	10,686.5	5508	1894	27,657.6	0	9569.1
S4	17,999.2	8244	1478	27,657.6	0	−63.6
S5	17,447.1	8244	2460	27,657.6	0	−493.5
S6	10,686.5	5796	2487	27,657.6	626.5	9314.7
S7	10,686.5	5796	1894	27,657.6	626.5	9907.7
S8	17,999.2	8532	1478	27,657.6	626.5	274.9
S9	17,447.1	8532	2460	27,657.6	626.5	−155

As shown in Table 6, because the number of EVs for swapping batteries is stable over a period, the battery swapping service incomes of BSSs would not change under the particular demand of Table 2. Maintenance costs are related to the equipment configuration of the BSS. Therefore, the increased number of chargers and batteries will directly affect investment, operation, and maintenance costs of the BSS. Compared with S1 and S2, if the BSS does not apply the charging optimization strategy, it will see a loss of 26,806.8 yuan and increase the battery depreciation costs. As shown in Table 6, because of the lack of ordered charge optimization in S1, the charging cost of S1 is 26,134 yuan, which is more than that of S2. The combination of S1 and S3, reducing the number of chargers, will not affect the normal operation of the BSS under the current battery swapping demand and the equipped number of batteries. In contrast, it will reduce the equipment investment and maintenance costs and make the BSS more profitable. When there are not enough chargers, however, if the number of batteries decreases to 800, the BSS will take a loss in S4 and S5. Compared with S3 and S4, when there are 200 chargers, the possibility of valley charging will increase with the increased number of batteries. This results in reducing the charging costs and increasing profits. Unlike in S1–S5, the profits of discharging are considered in S6–S9. As shown in Table 5, the number of chargers and batteries in S6–S9 are equal to that in S2–S5. According to the statistics in Tables 3–6, in the case of the same device configuration, if discharging is taken into account, it will enhance the profits of the BSS.

4.4. Sensitivity Analysis

Section 4.3 analyzes the operation status of the BSS in different scenarios and indicates that the number of chargers and the number of batteries greatly influence the operation income of the BSS. To determine the sensitivity factors that impact BSS profits, we change the value of a single factor to test its sensitivity. We use the profits of BSSs as the sensitivity evaluation index and the incomes of a day in S2 as the target value of the technology scheme. According to the optimized functional formula, the main factors that influence the profits of the BSS include the battery swapping price, battery depreciation costs, operation and maintenance costs, and number of chargers and batteries. Because the electricity price is very stable in China, it will not be considered in the sensitivity analysis.

Figure 2 shows the sensitivity of various factors. The sensitivity of the battery swapping price and number of batteries is greater than that of the other factors, while the sensitivity of the operation and maintenance costs and battery depreciation costs is much lower. The gain-loss balance point of the BSS should be 8587.1 yuan. When the battery swapping price is less than 0.4137 yuan/km, the BSS will take a loss. When there are fewer than 828 batteries, the BSS will earn negative income. Therefore, it should formulate a reasonable price for battery swapping service and equip a suitable number of batteries for the BSS.

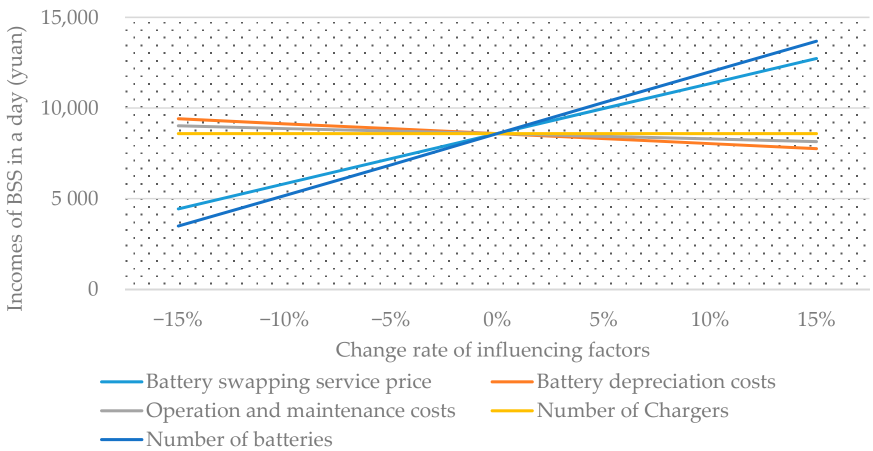

Figure 2. Single factor sensitivity analysis of various factors.

When the number of chargers varies the amplitude between −15% and 15%, the profits of the BSS are unchanged. This means that the amplitude between −15% and 15% of the number of chargers would not affect the profits of the BSS. If the number of chargers is decreased, however, it can reduce the investment costs and operation and maintenance costs, which results in gaining more profits for the BSS. To further analyze the impact of the number of chargers, we describe the profit trend of the BSS with a decreasing number of chargers. In Figure 3, when the number of chargers is reduced from 1044 to 150, the profits of the BSS begin to diminish. This demonstrates that the relationship between the number of chargers and daily profits of the BSS is not increasing monotonically; rather, there exists a balance point. After the number of chargers reaches a certain threshold, even if it increases, the profits of the BSS will not increase. Therefore, finding the reasonable battery swapping price and suitable number of chargers and batteries are important to maximize the economic benefits of the BSS.

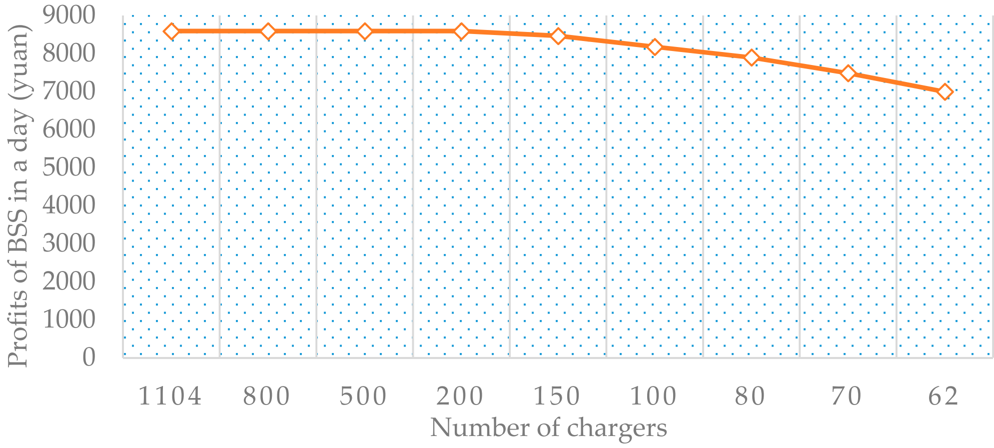

Figure 3. Relationship curve of chargers' number and BSS's profits.

The daily profit of the BSS is 6994 yuan when there are 62 chargers. Chargers can simultaneously charge no more than 62 batteries, as shown in Figure 3. To meet the demand of battery swapping, the BSS should be equipped with 1104 batteries. Doing so, however, would increase the fixed asset investment costs in the initial period when there are 62 charging batteries. Moreover, it is not conducive for the BSS to participate in the load shifting of the power grid. When $K < 62$, the BSS cannot meet the battery swapping demand and the model has no optimal solution. Thus, it is necessary to determine the appropriate number of chargers to achieve the benefits of the BSS.

4.5. Ordered Charging and Discharging Strategy for BSS

The electricity price, discharging price and battery swapping price are related to the interest of multiple stakeholders, including the power grid, EV users, charging and swapping facility operators and battery manufacturers. Figure 4 shows the definition of the battery swapping price. The power grid uses the general industrial TOU to charge for the electric power that it transmits to the BSS. The discharging price is applied to calculate the electricity fee when the power grid purchases the electricity from the BSS. The BSS utilizes the battery swapping price to determine the battery swapping service fee of EV users.

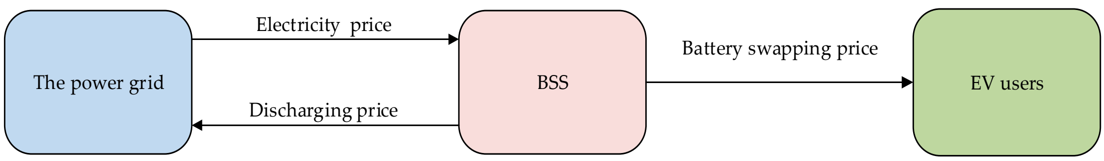

Figure 4. Definition of battery swapping price for the BSS.

The example above aims to maximize profits of the BSS, while the impact of the battery charging arrangement on the power grid's load is not researched. Thus, in Section 4.5.1, we propose two ordered charging and discharging strategies to analyze their effects on the BSS's profits and load shifting on the power grid.

4.5.1. Ordered Charging and Discharging Strategy Based on the Electricity Price of TOU

The electricity price and discharging price are the electricity price of TOU, and the battery swapping price is 0.6 yuan/km according to the existing fee standard of the BSS. We analyze the effects of the ordered charging and discharging strategy based on the electricity price of TOU (C1) with data from the BSS of Beijing in the nine scenarios. Equation (21) is the objective function of programming model, and Equations (9)–(18) with the Constraint (9) are the constraint conditions. We use the linear programming method to solve the number of charging batteries and the power and efficiency of charging and discharging. Figure 5 shows the load distribution of the BSS in different scenarios.

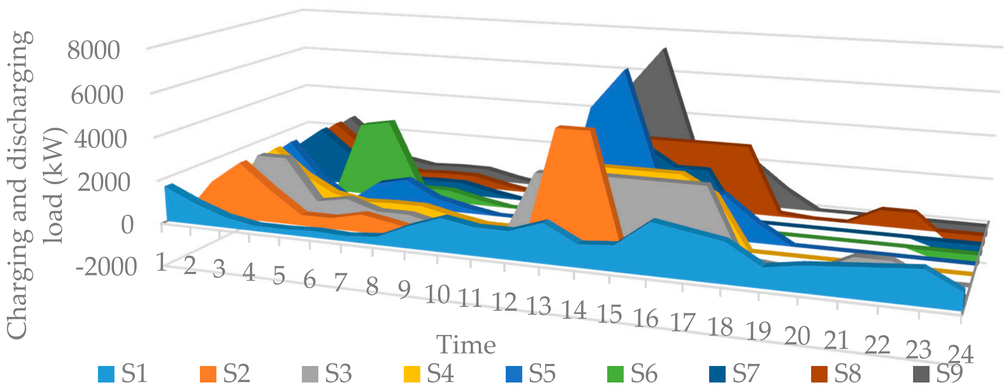

Figure 5. BSS' load distribution of different scenarios under C1.

The figure shows that the load of the BSS is concentrated in the valley period from 00:00 to 06:00 and the average period from 12:00 to 16:00 in Figure 5. There is a small amount of battery charging in the peak period of 08:00–12:00 and 17:00–21:00, which demonstrates that the proposed model can not only guarantee the economic operation and battery-swapping demand of the BSS but also respond to the load-shifting demand of the power grid according to TOU. The results of the scenario simulation show that it can concentrate more charging load during the valley period when the number of batteries and chargers is sufficient. Because there are more batteries in S6 than in S9, the charging load of S6 is higher than that of S9 in the valley period from 00:00 to 08:00. Because the battery stock of S9 is inadequate, the BSS must charge batteries from 12:00 to 17:00 to meet the battery swapping demand. In fact, the aim of the ordered charging and discharging strategy is to arrange the number and charging/discharging times of BBS batteries in each period. Table 7 shows the charging arrangement of the BSS batteries in S1 and S2. $F_1(t)$, $F_1{}^{(1)}(t)$, $F_1{}^{(2)}(t)$ and $E_1(t)$ represent the number of charging batteries, the number of batteries in the first charging stage, the number of batteries in the second charging stage, and the number of empty batteries in S1, respectively. $F_2(t)$, $F_2{}^{(1)}(t)$, $F_2{}^{(2)}(t)$ and $E_2(t)$ represent those in S2.

Table 7 shows that, due to the appropriate arrangement of batteries in the BSS, charging costs decrease after charging optimization. C1 can not only meet the demand of battery swapping but also achieve concentrated charging in the low price phase from 2:00 to 9:00. Therefore, the reasonable arrangement can improve the profitability of the BSS.

Table 7. Comparison of the number of charging batteries in S1 and S2 under C1.

S	S1				S2			
T	$F_1(t)$	$F_1^{(1)}(t)$	$F_1^{(2)}(t)$	$E_1(t)$	$F_2(t)$	$F_2^{(1)}(t)$	$F_2^{(2)}(t)$	$E_2(t)$
1	104	104	0	0	0	0	0	0
2	168	64	104	0	104	104	0	0
3	96	32	64	0	168	64	104	0
4	48	16	32	0	96	32	64	0
5	32	16	16	0	32	0	32	16
6	36	20	16	0	32	32	0	0
7	36	16	20	0	52	20	32	0
8	40	24	16	0	36	16	20	0
9	88	64	24	0	16	0	16	24
10	160	96	64	0	0	0	0	88
11	176	80	96	0	0	0	0	184
12	160	80	80	0	0	0	0	264
13	192	112	80	0	344	344	0	0
14	176	64	112	0	344	0	344	112
15	136	72	64	0	0	0	0	176
16	216	144	72	0	0	0	0	248
17	272	128	144	0	0	0	0	392
18	240	112	128	0	0	0	0	520
19	168	56	112	0	0	0	0	632
20	128	72	56	0	0	0	0	688
21	152	80	72	0	0	0	0	760
22	168	88	80	0	0	0	0	840
23	184	96	88	0	0	0	0	928
24	144	48	96	0	0	0	0	1024

4.5.2. Ordered Charging and Discharging Strategy Based on DR

The power grid coordinates the charging and discharging of batteries in the BSS by the electricity price of TOU in Section 4.5.1. The method by which the power grid guides the BSS to charge and discharge in an orderly fashion is called the price-based DR. Similarly, it can be applied to the battery swap pricing between BSS and EV users. The battery swapping price is fixed under C1 in Section 4.5.1. Thus, in Figure 5, it can be seen that the BSS charges the batteries not only in the valley price period but also in the average price period. Unlike Section 4.5.1, the battery swapping price here is based on TOU instead of the fixed price under the ordered charging and discharging strategy based on DR (C2). Combined with Beijing's electricity price of TOU and the existing driving characteristic of electric taxis, Table 8 shows that the tiered battery swapping price fluctuates between −10% and 10% on the basis of the initial battery swapping price (0.6 yuan/km).

Table 8. Tiered battery swapping price.

Time	Battery Swapping Price (Yuan/kWh)
00:00–08:00	0.54
08:00–17:00	0.66
17:00–00:00	0.60

To reduce the battery swapping costs, price-sensitive users will choose to swap batteries in the valley price period. N is the number of EVs whose users would like to respond to the tiered battery swapping price and swap their batteries in the valley price period. N is the number of EVs coming to the BSS to swap batteries. It can determine the degree of DR with the user transfer proportion (σ) [30], which can be described as:

$$\sigma = \frac{n}{N}. \quad (23)$$

We use the basic data in Tables 1 and 2 for the parameters of the BSS and EVs. In Table 9, the battery swapping demand and average driving mileage of EVs are based on the data from a BSS in South China, and σ is assumed to be 0.3.

Table 9. Battery swapping demand and average driving mileage of EVs under C2.

T	$N(t)$	$\overline{M_i(t)}$	T	$N(t)$	$\overline{M_i(t)}$
1	26	100	13	10	109
2	20	110	14	12	110
3	24	120	15	14	111
4	24	112	16	16	103
5	22	107	17	10	108
6	20	108	18	12	109
7	23	106	19	14	113
8	18	113	20	18	115
9	10	115	21	23	105
10	8	120	22	25	102
11	12	106	23	24	112
12	15	117	24	22	114

The objective function is Equation (21), and the constraint conditions are Equations (9)–(18). The number of chargers and the power and efficiency of charging and discharging are found using the linear programming method, and the results showing the BSS load under different scenarios appear in Figure 6. The BSS load is mainly concentrated in the 00:00–08:00 and 13:00–16:00 periods, and there is little BSS load from 17:00 to 19:00. Because there is a large number of chargers and batteries in S2 and S3, there are no excess batteries that need to be charged during the stage of high battery swapping demand between 14:00 and 18:00. Due to the lower number of chargers and batteries in S5 and S9, however, the BSS generates the peak charging load in the period between 14:00 and 18:00. Comparing Figure 6 with Figure 5, the BSS can arrange more batteries to be charged in the valley period between 00:00 and 08:00 by stimulating the user responding to the incentive price. Moreover, there are few batteries charging in the peak period of 08:00–12:00 and 17:00–21:00. This demonstrates that the proposed operation model can not only meet the battery swapping demand but also respond to the load-shifting demand of the power grid.

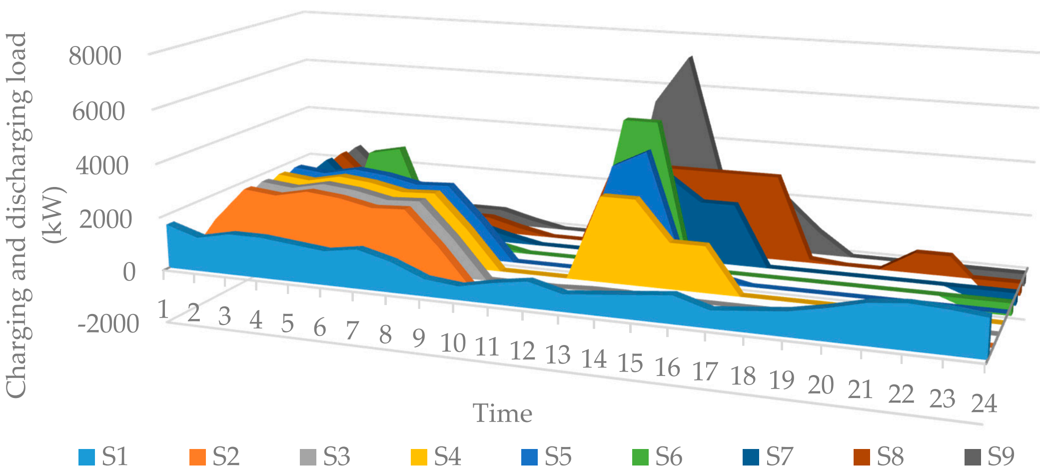

Figure 6. BSS's load distribution of different scenarios under C2.

The number arrangement of charging and discharging batteries is shown in Table 10. The positive number represents the number of charging batteries, and the negative number indicates the number of discharging batteries.

Table 10. Battery charging and discharging arrangement over 24 h in the BSS.

T	S1	S2	S3	S4	S5	S6	S7	S8	S9
1	104	0	0	0	0	0	0	0	0
2	80	104	104	104	104	0	104	104	104
3	96	184	184	184	184	0	168	168	168
4	96	176	176	176	176	0	96	96	96
5	88	192	192	192	192	216	48	48	48
6	80	184	184	184	184	232	32	32	32
7	92	168	168	168	168	36	36	36	36
8	72	172	172	172	172	36	36	36	36
9	40	92	92	92	92	16	16	16	16
10	32	0	0	0	0	0	0	0	0
11	48	0	0	0	0	0	0	0	0
12	60	0	0	0	0	0	0	192	0
13	40	4	4	200	252	344	200	200	344
14	48	4	4	200	292	344	200	200	456
15	56	0	0	108	56	0	144	200	176
16	64	0	0	108	16	0	144	200	136
17	40	0	0	0	0	0	0	200	128
18	48	0	0	0	0	0	0	8	56
19	56	0	0	0	0	0	0	0	0
20	72	0	0	0	0	0	0	0	0
21	92	0	0	0	0	0	0	48	0
22	100	0	0	0	0	0	0	48	0
23	96	0	0	0	0	−32	−32	−32	−32
24	88	0	0	0	0	−32	−32	−32	−32

5. Conclusions

The large-scale development of EVs requires not only the support of mature battery technology but also the construction of a complete charging infrastructure. Ensuring the benefits of charging infrastructure and encouraging individuals to participate in the safe operation of the power grid can help to achieve the ordered charging and discharging of EVs, which is of great significance to the large-scale development of EVs. Based on the analysis of BSS's operation modes, this paper develops a linear programming model that aims to maximize the daily profits of the BSS. This paper uses the parameters of BSSs and battery-operated electric taxis of Beijing as the basic data source. Moreover, on the premise of satisfying the battery swapping demand of EVs, this model mainly considers the constraint conditions of the number of batteries, number of chargers, and battery charging power. Based on the multi-scenario simulation and sensitivity analysis, we analyze the economical operation of the BSS. Furthermore, this paper simulates the charging and discharging load of BSSs in different scenarios under two charging and discharging strategies based on the electricity price of TOU and DR, respectively. The research results and conclusions are as follows:

(1) The scenario simulations prove that the proposed model can maximize the profits of BSS operators by effectively deploying batteries and chargers to work. If the BSS applies the method of charging the swapped batteries simultaneously; however, it will cause serious losses because of the greatly increasing charging costs and battery depreciation costs.
(2) The sensitivity analysis determines the factors influencing BSS profits. The sensitivity of the battery swapping price is the greatest, followed by the sensitivity of the number of batteries. The sensitivity of operation and maintenance costs and battery depreciation costs is small. It is worth noting that the relationship between the number of chargers and BSS's profits is not increasing monotonically. There is a balance point. When the number of chargers reaches a certain threshold, the profits of the BSS will not improve even if the number of chargers is increased. Therefore, it is important for the BSS to formulate a reasonable battery swapping price and be equipped with

the appropriate number of chargers and batteries. In addition, reducing the depreciation costs of batteries is beneficial to BSS and EV users.

(3) To achieve greater profits, the BSS should charge the batteries in the valley and average load periods. The battery swapping demand of users is more concentrated in the average period than in the valley period, however, which will cause a loss in revenue. The charging and discharging strategy based on DR can provide the incentive price to both BSSs and users. The empirical example shows that the incentive price is conducive to the economic operation of BSSs and the stability of the power grid load.

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Author Contributions: In this paper, Yanni Liang carried out the operation mode, established the operation model for the BSS, and wrote Sections 2 and 3; Xingping Zhang analyzed the results of the scenario simulation and sensitivity analysis; Jian Xie tested the effect of the charging and discharging strategy for the BSS and wrote Section 4; and Wenfeng Liu collected the related data and basic parameters for the BSS operation model and wrote Section 5.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of main parameters.

Parameters	Description of Parameters	Unit
I_s	Battery swapping incomes of the BSS in one day	yuan
P_s	Battery swapping price per driving mileage unit or per electricity unit	yuan/kWh
t	Time interval of a day	h
$M_i(t)$	Driving mileage or battery electricity consumption of EV i at t, km or kWh	km or kWh
$N(t)$	Number of EVs for swapping batteries at t	-
I_d	Discharging incomes of the BSS in one day	yuan
$P_g(t)$	Feed-in tariff of BSSs at t	yuan/kWh
$P_j(t)$	Transmission power of discharging device j	kW
J	Number of discharging devices	-
C_c	Charging costs of BSS in one day	yuan
$P_e(t)$	Electricity price that the power grid supplies power to the BSS at t	yuan/kW
$P_k(t)$	Charging power of charger k at t	kW
K	Number of chargers in the BSS	-
C_d	Depreciation costs of BSS in a day	yuan
c_c	Depreciation costs of a battery after charging	yuan
N_c	Number of fully charged batteries in a day	-
C'_d	Discharging depreciation costs of BSS with the application of V2G in a day	yuan
c_d	Depreciation cost of a battery after discharging	yuan
N_d	Number of batteries that are fully discharged in a day	-
C_m	Operation and maintenance costs of BSS in a day	yuan
Z	Total number of batteries in the BSS	-
P	BSS's profits in a day	yuan
$P(V2G)$	BSS's profits with V2G technology in a day	yuan
$S(t)$	Number of fully charged batteries in the BSS at t	-
β	Battery number of one EV	-
$F(t)$	Number of charging batteries at t	-
$W(t)$	Number of discharging batteries at t	-
$E(t)$	Number of empty batteries at t	-
T_f	Hours for empty batteries to be fully charged	h
T_w	Hours for fully charged batteries to fully discharge	h
P_c	Rated charging power of the chargers	kW
P'_c	Actual charging power when batteries are put on chargers	kW
η_c	Charging efficiency of batteries	-
P_d	Rated discharging power of discharging devices	kW
P'_d	Actual discharging power when batteries are put on discharging device	kW
η_d	Discharging efficiency of batteries	-
P'	BSS's profits in a day based on the assumptions	yuan
$P'(V2G)$	BSS's profits with V2G technology in a day based on the assumptions	yuan

Table A2. S1–S9 and their relevant equations.

Scenarios	Objective Functions	Constraints	Remarks
S1	/	/	No optimization. Batteries are put on the chargers once the batteries are swapped from EVs.
S2–S5	Equation (21)	Equations (9), (10), (12), (13), (17), (18) and Constraint (9)	Batteries are arranged by the optimization model but discharging is not considered in these scenarios.
S6–S9	Equation (22)	Equations (9)–(13), (15), (17), (18) and Constraint (9)	Batteries are arranged by the optimization model and discharging is considered in these scenarios.

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