Economic Benefit Analysis of NIO Battery-Swap Station based on Regional Service Capacity Model

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Abstract— In recent years, a rising Chinese electric vehicle brand called NIO is striving to build a brand exclusive charging and BS system, and its' goal is to build about 5000 battery-swapping stations (BSSs) around the world by 2025. However, NIO's investment choice has also been questioned. Some consumers generally believe that the huge cost of building the power exchange station will be shared equally in the cost of buying cars. This paper analyzed the construction and operation cost based on existing data from official reports and the relationship between service radius and probability of choosing BS service, along with the Battery as a Service (Baas) promulgated by NIO. And the result shows that regarding the batteries as assets of a single BSS, with the trend of more drivers being willing to take the BS service, the BSS can constantly bring huge profit to the company.

Keywords-Service Radius, Battery-Swapping Station, Battery-Swapping Mode, Electric Vehicle, Battery as a Service

1 INTRODUCTION

In recent years, the environmental pollution problems and shortage of fossil fuels caused by conventional internal combustion engine (ICE) vehicles have aroused the governments' concern, and various preferential policies have been issued to facilitate the development of new energy vehicles. However, the charging time of electric vehicles (EV) is much longer than ICEs, at the same time, the large-scale construction of high-power charging stations will also put great pressure on the urban power grid. As an efficient and fast energy supply mode of new energy vehicles, battery-swapping mode (BSM) has become an alternative method. Rising Chinese electric vehicle brand, NIO has announced a grand plan, which is constructing about 4,000 second-generation battery-swapping stations (BSSs) in the Chinese mainland before 2025, and providing huge BS service concessions for car owners, so as to lower the driving cost and attract more consumers. Whether this magnificent investment in BSM can bring the expected return has aroused controversies. Based on a service radius method (SRM) for quantitative analysis of BSM demand and existed BSSs construction expense model, combining with the scale of NIO EVs, and operation policies published by NIO, this paper will use the cost and revenue analysis method in economics to estimate the return on investment of the NIO BSS. The research results of this paper can help readers understand the construction cost of energy supply infrastructure in the new energy vehicle industry, and provide a reference for investors interested in investing in the construction of BSS.

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2 THE RELATIONSHIP BETWEEN BS NUMBER AND BSM SELECTION PROBABILITY

Different from ICE vehicles, the travel distance of EVs is closely related to the battery performance. If the electric vehicle is in a low battery state for a long time, it may lead to the complete discharge of the battery cell, causing a short circuit and scrapping the battery. Therefore, when the SOC of the battery is low, the electric vehicle will limit the maximum output power to protect the battery's performance and endurance life. Therefore, compared with ICE vehicle drivers, EV drivers are more concerned about the distance between charging stations and cars.

$CF_{class}(t)$ is the ratio of BSS numbers to EV numbers, represents the convenience of getting to BS service. With more BSSs in a certain region, the mileages drivers can use consumed to the BSS is shorter. According to the alarm SOC value, the reference [1] summarize a mathematical programming formulation to illustrate the relationship among SOC, M_{Cha}, M, ρ. The author classifies the charging behavior into two kinds, compulsory charging and unnecessary charging, each behavior corresponds to an equation of charging driving mileage. For compulsory charging, the equation (1-2) is:

$$M_{Cha} = (SOC_{alarm} - SOC_{limit}) * M \tag{1}$$

$$D_1 = M_{Cha}/\rho \tag{2}$$

For unnecessary charging, the equation (3-4) is:

$$D_2 = T * V/\rho \tag{3}$$

$$D = [Min\{D_1, D_2\}] \tag{4}$$

Among them, M_{Cha} is the mileages consumed to the BSS, M is the endurance mileage, ρ is the non-linear coefficient, which takes different values according to different traffic networks, illustrates the condition of the traffic network, D is the service radius of a BSS. According to reference [2], based on the different characteristics of cities' road and geographic situation, there are 4 kinds of traffic networks' non-linear coefficient, grid 1.00~1.41; annular radial 1.1~1.2; freestyle 1.1~2.6; hybrid 1.1~1.4. In equation 3, T is the tolerable time of drivers consumed on the charging way, V is the average speed.

When it comes to area-related calculations, it is necessary to delimit the scope of the area. Reference [1] provides a method to calculate the minimum number of public facilities in a straight line within constrained conditions. L is the length of the longest line crossing the geometric center of the region, according to the Dijkstra algorithm and network Voronoi diagrams, based on the golden five-minute principle of fire rescue, the reference [3] generating a network-constrained Voronoi diagram is based on the network expansion operation. Using this model, the number of public service facilities in the area can be deduced inversely based on a certain service radius. In this paper, some geographical parameters are used to create a regional service capacity calculation model to estimate the number of cars which need to charge. The following formula demonstrates the relationship among N, the number of service facilities, L and D.

$$[N = \frac{L}{2D} * \pi] \tag{5}$$

Taking Xuhui district of Shanghai as an example, the length of the longest line crossing over the geometric center of the region $L = 6km$, $\rho = 1.4$, $M = 450km$, $SOC_{alarm} = 0.3, SOC_{limit} = 0.25$. T = 15min, set V as 30km/h. According to the data above, it can be calculated that:

$$D_1 = 16km$$

$$D_2 = 5.3km$$

$$D = 5km$$

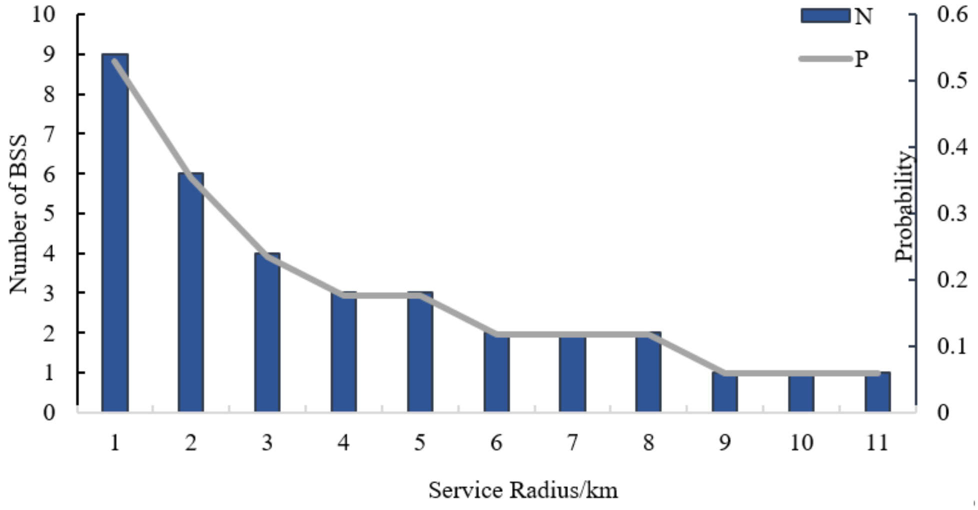

Figure 1. Relationship between BSS number, BSM probability and SR

Due to the high efficiency of BS compared with charging, the relationship between the number of BSSs and service can be approximately expressed as the relationship between the probability of selecting BSSs and the service radius, as shown in Figure.1.

3 COST-REVENUE ANALYSIS OF BATTERY-SWAPPING MODE

The cost in the BSM is mainly composed of the construction cost of BSS in the early phase and the operation cost in a later phase. In order to simplify the calculation model, specification, equipment and operation cost of each BSS stay the same.

For NIO's BSS, the cost of charging equipment accounts for most of the equipment cost, among which the battery is the most important component. The battery cost of each BSS is calculated from the number of batteries N_i and the unit price of batteries C_b. The equipment of battery procurement cost is represented by equation (6).

$$I_{equ\,i} = N_i * C_b \tag{6}$$

According to the reports on NIO's official website, the second-generation BSS will be mainly equipped with 13 battery packs, of which the sales price of a single 100 kwh battery pack is 128,000 yuan. In later calculation, the cost price C_b is set as 100,000 yuan.

The specific data of the construction cost of the BSS is so sophisticated to be accurately captured, but according to the cost information disclosure of the second-generation BSS by NIO, the total construction cost of a single BSS is about 1.5 million yuan. After deducting the battery procurement cost, the construction cost of a single BSS is about 400,000 yuan

The other important construction cost is the land cost. NIO generally rents a site for the construction of BSS rather than purchasing the land. The land cost $I_{land\ I}$ is calculated by rent $R_{land\ I}$ and space $S_{land\ i}$. As equation (7) represents.

$$I_{land\ i} = R_{land\ i} * S_{land\ I} \tag{7}$$

The specification of NIO's second-generation BSS is 10m*6m*3.2m, about four times of standard small vehicle parking space.

For the BSS, the operating cost is a critical component of the total cost. Operating costs include workers' wages, benefits, daily repair costs, power purchase costs, battery attenuation costs, depreciation of fixed assets, etc. Each BSS needs 1-2 workers, workers' wages and benefits of each BSS are set as 150,000 yuan per year.

The replacement standard of NIO's 100kwh battery pack is that the battery capacity is attenuated to 80% of the initial value, correspondingly for BS about 1200 times. Lu Yu summarized the cost of each BS. According to this data, the cost of each BS C_{SW} as equation (8) shows, is nearly about 80 yuan [5].

$$C_{SW} = \frac{C_b}{1200} \tag{8}$$

The charging and BS times T_C can be divided by M_Y, the total annual mileage divided by M_A, the actual synthesized mileage after fully charged.

$$T_C = \frac{M_Y}{M} \tag{9}$$

According to the Beijing transportation development annual report in 2017 [7], the average annual driving mileage of household vehicles in Beijing is about 12000km. The synthesized endurance mileage of NIO ES6 is 500km. Therefore, T_C is near 24 times. Considering the alarm value of SOC and charging behavior, there will be power surplus before each power supplement, the actual charging times in one year, T_{AC} can be calculated by T_C/SOC, as 34 times, which means a charge, or BS once every 10 days on average.

T_{AC} multiply BS selection probability P_{SW}, can calculate the total BS times of a single EV per year, N_{PERSW}. The total BS times of a single BSS, N_{SW}, can get from the ratio of the total number of EVs to the total number of BSSs multiply N_{PERSW}.

$$N_{PERSW} = T_{AC} * P_{SW} \quad N_{SW} = N_{PERSW} * CF_{class}(t) \tag{10}$$

The annual bs cost of a single BSS C_{BS} can be obtained by multiplying the annual BS times by the single BS cost. However, considering the factors of battery depreciation, in order to improve the vehicle maintenance rate, NIO proposed the Battery as a Service (BaaS). Drivers can choose to rent the battery rather than buy out the battery. Therefore, the BS cost is not fully borne by the BSS. According to NIO's report, more than 50% of car owners choose the BAAS, which means that the company only needs to bear about half of the BS cost.

$$C_{BS} = 0.5 * N_{SW} * C_{SW} \tag{11}$$

The power purchase cost C_E depends on the local electricity price P_E of the BSS and the total charging amount N_{SW} of the BSS in one year, and the capacity of the battery B_C. Equation (12) of the power purchase cost is as follows:

$$C_E = P_E * N_{SW} * B_C \tag{12}$$

In order to encourage the development of electric vehicles and promote the construction of charging infrastructure, local governments in China have issued subsidy policies to reduce the purchase cost of new energy vehicles and the construction cost of charging and BS facilities. According to the latest subsidy method for electric vehicle charging and BS facilities in Shanghai, Shanghai provides a power purchase subsidy of 0.3 yuan per kWh for qualified charging and BSS. Therefore, the government subsidy R_S obtained by the BSS every year is as equation (13) represents.

$$R_S = 0.3 * N_{SW} * B_C \tag{13}$$

The BS robot, air conditioner, steering gear and other hardware equipment in the power exchange station will be gradually depreciated in use, and the depreciation cost will also be included in the annual operating cost. Depreciation is calculated using the sum of years method, in which the annual conversion coefficient is r and the service life is y_C. Set the residual value of charging devices in each BSS is 100000 yuan.

According to Article 60 of the regulations for the implementation of the enterprise income tax law of the people's Republic of China, the minimum depreciation period for production equipment or equipment related to production and business activities is 5-10 years, which is determined by the service life. The depreciation life of BS equipment on the market is mostly about 10 years, so the depreciation rate r of fixed assets is 10%. The annual depreciation amount C_D within 5 years is shown in Tab.1 below.

TABLE 1. DEPRECIATION VALUE OF A SINGLE BSS

Year	Depreciation rate	Depreciation value
1	0.18	54545.45
2	0.16	49090.91
3	0.15	43636.36
4	0.13	38181.82
5	0.11	32727.27

The calculation of power purchase cost is more complex, and the time-of-use price policy widely implemented at present should be taken into account. The TOU price of industrial power in Shanghai is shown in Table.2.

TABLE 2. TOU PRICE OF INDUSTRIAL POWER IN SHANGHAI

Period of time	Time of use tariff(yuan/kwh)	Period of time	Time of use tariff(yuan/kwh)
1	0.358	13	0.697
2	0.358	14	0.697
3	0.358	15	0.697

4	0.358	16	0.697
5	0.358	17	0.697
6	0.358	18	0.697
7	0.697	19	1.192
8	0.697	20	1.192
9	1.192	21	1.192
10	1.192	22	1.192
11	0.697	23	0.358
12	0.697	24	0.358

The annual operation cost is as equation (14) represents:

$$I_{Tot} = C_D + I_{land\ i} + C_{BS} + C_E - R_S \quad (14)$$

4 OPERATION INCOME

At the beginning of its establishment, NIO put forward the slogan of household enterprise, and try to achieve the purpose of attracting users by providing preferential BS service to customers. NIO provided the first NIO car owner with free BS service up to 6 times per month, at the same time, car owners also have the right to use the unique fast-charging pile of the brand for free. When the BS times exceed 6 times per month, NIO charges for 180 yuan per BS service from car owners. According to the estimation of actual vehicle endurance mileage and the current construction scale of the BSSs, the proportion of paid BS service is not high, which is difficult to bring benefits that can match the construction cost of the BSSs.

The data released by NIO also proves this. From May 2018 to June 2020, NIO has built 135 first-generation BSSs, providing more than 570,000 BS services for car owners, including no more than 100,000 paid services, which means no more than 20% BS service can generate revenue. However, with the rapid growth of the number of BSSs, more drivers will select the BSM rather than charging. In 2021, NIO publish the second-generation BSS, which can store more battery packs than the first-generation BSS, also the design of the BS robot is optimized, the BS process is simplified, and the efficiency of the BSS is greatly improved. The upper limit of BS times per day is less than 80 times to more than 300 times from the first-generation BSS, therefore, the profit prospect of NIO BSS is optimistic in the long term. Set the rate of paid BS service r_p as 0.2, the BS income R_{sw} of each BSS in one year is:

$$R_{sw} = 180 * r_p * N_{SW} \quad (15)$$

Due to the existence of BaaS, nearly 50% drivers need to pay for the rent of batteries. NIO's official pricing for the rental price of 100kwh battery pack is 17760 yuan a year, so the formula of rental income is:

$$R_r = 0.5 * 17760 * N_{SW} * 365/(34 * P_E) \quad (16)$$

It can be seen from the above that the annual income formula of each BSS is:

$$R = R_r + R_{sw} \quad (17)$$

5 CASE ANALYSIS

Combing with the charging behavior analysis of Shanghai citizens, the reference [4] proposed a mathematical model to analyze the influence of multiple parameters on the total social cost of a single BSS. In this case, the Xuhui District of Shanghai is selected as the research object. Xuhui District is one of the central urban areas of Shanghai, with developed transportation and large vehicle ownership. In particular, thanks to the protection policy of Shanghai for the development of EVs, the construction of charging stations in Xuhui District is relatively intensive. NIO has established three BSSs in Xuhui. Therefore, Xuhui District is suitable to be the research object of this paper.

In terms of rent cost, the data previously disclosed by NIO shows that the floor area of each second-generation BSS is 60 square meters. The land rental price of the open square in the area is difficult to obtain. Therefore, according to the average rental price of shopping malls and parking spaces in Xuhui District, that is, about 70 yuan per square meter per day. According to the rent formula, the annual rent of the second-generation BSS is nearly about 130,000 yuan per year.

The weekly average business data of a BSS in Xuhui District are selected for research, as shown in Figure.2. The noon period is the peak period of BS, and there is less demand for BS in the morning and evening, which is suitable for charging the battery.

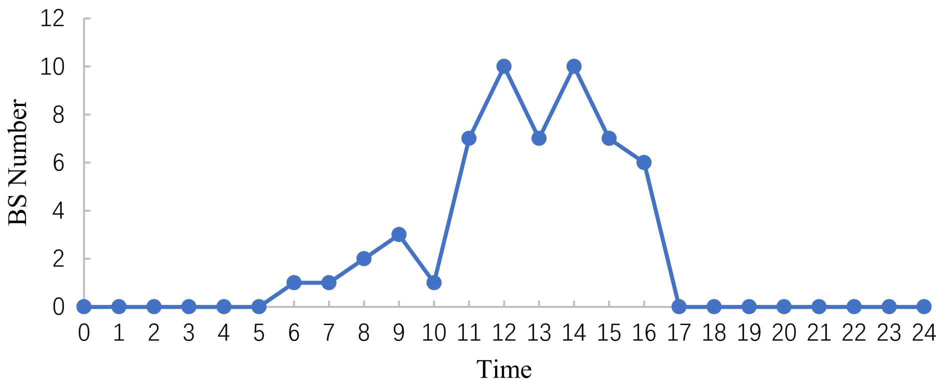

Figure 2. BS Number Variation in one day

According to the above data, the total BS number in one day is 55, after reducing the government subsidies, it is calculated that the charging cost of a BSS in one day is about 2,400 yuan. The daily cost of electricity is shown in Table.3. Therefore, the annual power purchase cost of each BSS C_E is about 887,000 yuan. Correspondingly, the annual BS cost is 1.6 million yuan.

TABLE 3. DAILY ELECTRICITY COST

BS number	Power purchase unit prices	Price after subsidize	Cost of Electricity
0	0.358	0.058	0

0	0.358	0.058	0
0	0.358	0.058	0
0	0.358	0.058	0
0	0.358	0.058	0
0	0.358	0.058	0
1	0.697	0.397	39.7
1	0.697	0.397	39.7
2	1.192	0.892	178.4
3	1.192	0.892	267.6
1	0.697	0.397	39.7
7	0.697	0.397	277.9
10	0.697	0.397	397
7	0.697	0.397	277.9
10	0.697	0.397	397
7	0.697	0.397	277.9
6	0.697	0.397	238.2
0	0.697	0.397	0
0	1.192	0.892	0
0	1.192	0.892	0
0	1.192	0.892	0
0	1.192	0.892	0
0	1.192	0.892	0
0	0.358	0.058	0
0	0.358	0.058	0

From the relationship of the probability of BS selection with the number of BSSs, the P_E is 0.28, Xuhui District covers an area of 55 square kilometers, and the service radius of a single BSS is currently 3 kilometers, the BS interval is 10 days. Reference [6] using Agent-Based Modeling to demonstrate the evolution pattern of EVs under different scenarios. As shown in Figure.3, the main direction of encouraging the development of EVs is stable. According to its' conclusion, set the growth rate of N_V as 20%, the variation of BS number per day can be speculated.

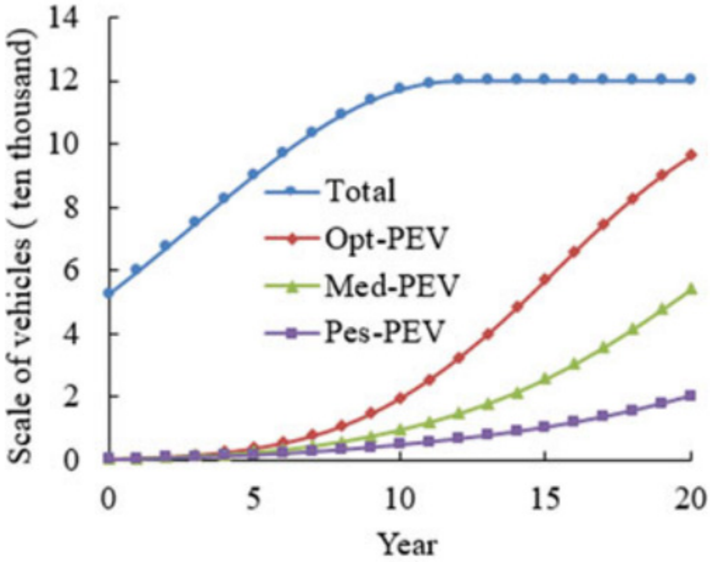

Figure 3. Prediction of PEV Sales

Furthermore, the annual total cost in five years can also be calculated in Table.4.

TABLE 4. COST SUMMARY

Year	Depreciation value	Cost of BS	Cost of Electricity	Fixed Cost	Total Cost
1	54545.45	803000.00	887315.00	280000.00	2024860.45
2	49090.91	999288.89	1104214.22	280000.00	2432594.02
3	43636.36	1241973.33	1372380.53	280000.00	2937990.23
4	38181.82	1850112.00	2044373.76	280000.00	4212667.58
5	32727.27	2466816.00	2725831.68	280000.00	5505374.95

In this paper, we regard the battery as the asset of the BSS, so the income from battery leasing is included in the income of the BSS. According to the above formula, we can also predict the income of the BSS in Xuhui District in the next five years. The data is represented in Table.5

TABLE 5. INCOME SUMMARY

Year	Rent Income	BS Income	Total Income
1	19418954.25	722700	20141654.25
2	23302745.1	899360	24202105.1
3	27963294.12	1117776	29081070.12
4	33555952.94	1665100.8	35221053.74
5	40267143.53	2220134.4	42487277.93

Combing the Income and Cost table, we can calculate the net revenue of each BSS, as shown in Table.6:

TABLE 6. REVENUE SUMMARY

Year	Total Cost	Total Income	Net Revenue
1	2024860.45	20141654.25	18116793.79
2	2432594.02	24202105.1	21769511.08
3	2937990.23	29081070.12	26143079.89
4	4212667.58	35221053.74	31008386.16
5	5505374.95	42487277.93	36981902.98

It can be seen from the table that due to the huge rental income brought by battery leasing, when a BSS can maintain stable passenger flow, the asset profitability of each BSS is very considerable, and the profitability of the BSS is positively correlated with the number of batteries contained in the BSS.

6 CONCLUSION

The scheme of BSS was put forward very early, but it has not been promoted as the main charging facility of new energy vehicles due to high construction cost, difficulty to unify battery standards and limited-service capacity. Many automobile manufacturers have tried to build BSSs to enhance the brand attraction, but in the end, only NIO insisted, and NIO innovatively put forward the battery rental service scheme, including the battery into the company's assets to provide rental income. According to the analysis of this paper, the scheme of BSS and battery leasing can bring huge returns to the company. However, this paper also has some shortcomings. In fact, the probability of BS selection is more complex, limited by the level of knowledge, the research on location planning is relatively rough. At the same time, the increasing number of car owners subscribing to BaaS services is not being taken into account, resulting in low actual estimated cost and income, which affects the accuracy of the results.

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