Economic Research on Passenger Vehicle Battery Rental Mode Based on System Dynamics Model

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Abstract. In recent years, the new energy vehicle market has been developing rapidly, in order to further increase the competitiveness of new energy vehicle market, effectively reduce the risk of users and the initial purchase cost, many car companies have launched the battery rental mode of vehicle purchase. Currently, the physical non-interchangeable passenger car occupies a large market share in the battery rental mode, so this paper focuses on the economics of the physical non-interchangeable passenger car in the battery rental mode. From the perspective of consumer cost of ownership, the total cost of ownership (TCO) method is utilized to compare the three options of purchasing a fuel vehicle, purchasing a new energy vehicle as a whole, and purchasing a new energy vehicle in the battery leasing mode, and to obtain the optimal rental pricing range that is a win-win situation for both consumers and battery operators. From the perspective of profitability of battery operators, we establish economic indicators of income and assets, and comprehensively evaluate the economic impacts of rental pricing, residual value of batteries, body scrap ratio, and the ratio of sales volume and model selection. Through the system dynamics model, combined with the perspective of consumers and battery operators, the economic indicators of the battery rental mode are deduced and simulated, and the sensitivity analysis is realized, which can provide a reference for the economic analysis of the battery rental mode.
CCS CONCEPTS • Design • Empirical studies • Estimation

Keywords: Battery rental, System dynamics, New energy vehicles (NEVs), TCO

1 INTRODUCTION

In the context of electrification, the energy power and business model of the automobile industry have begun to be comprehensively reshaped, and new energy vehicles (NEVs) have become the main theme. NEVs are still facing a lot of pain points, such as purchase cost, battery residual value, charging time, etc. [1]

In response to the above pain points, auto companies have launched some innovative battery leasing models: Renault long-term leasing model, NIO BaaS model, Xiaopeng battery rental model. The battery leasing model specifically refers to the separation of the battery and the vehicle in the asset, and consumers can rent the battery or buy the battery for a long time by installment [2]. The main object of this paper is the current market share of unswappable models, that is, the battery can not be quickly disassembled or replaced physically.

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For consumers, the battery rental model can reduce the upfront cost of electric vehicles. For operators, it can maintain control over the battery life cycle and promote efficient resource recovery [3]. Considering consumers and operators, studying the economy of battery rental mode is conducive to promoting diversified services of NEVs.

2 RESEARCH BASIS

At present, many literatures have studied the battery rental mode. Liao et al. conducted a study on consumer preferences [3-4]. Zhang et al. conducted an economic benefit analysis of the power conversion mode in the field of public transportation [5]. Li et al. found that the impact of battery cost on marginal rent of battery leasing is crucial [6]. By analyzing the impact of factors such as battery system price, discount rate, annual charging amount and initial investment in infrastructure on battery operating price, Sun concluded that battery price and battery capacity are the most sensitive factors affecting operating price [7]. Most studies focus on the profit analysis of operators, and few consider the interests of both consumers and operators comprehensively. In the fierce market competition, we must ensure the win-win situation between consumers and operators. Therefore, based on the physical non-exchangeable passenger car models under the battery rental mode, this paper combined with the three-dimensional marginal rent theory of Ouyang Minggao [6], and established the battery rental mode by system dynamics method. On the one hand, starting from the ownership cost of consumers, by comparing the ownership cost of competing Internal Combustion Engine Vehicle (ICEV), BEV and battery rental model of BEV, the optimal rental pricing range acceptable to both consumers and operators is obtained. On the other hand, from the perspective of battery operators' profits, the assets and income indicators of operators are calculated. The important factor "rent" should be within the range of the rent pricing, so that the rent setting of the second part can be followed. Finally, the sensitivity analysis is carried out to study the influence of important factors on the profitability of battery operators. The research framework of this paper is shown in Figure 1.

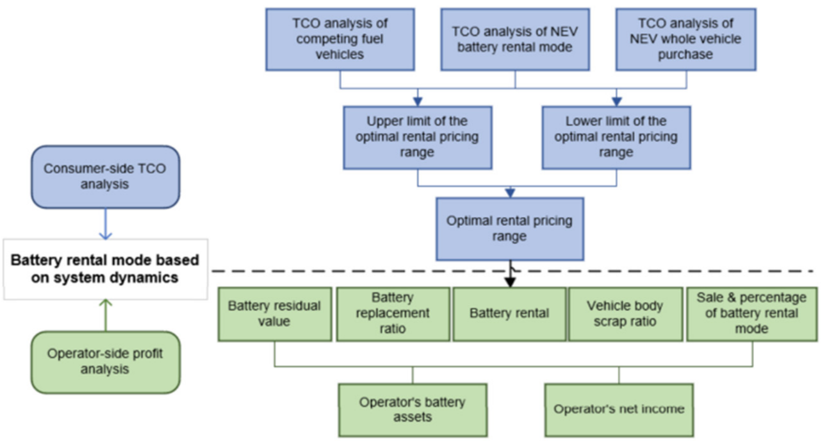

Figure 1 Research framework

3 BATTERY RENTAL MODE BASED ON SYSTEM DYNAMICS

System dynamics uses the feedback, regulation and control principles to design a feedback loop reflecting the system behavior, and then uses the economic and technical principles to establish a dynamic simulation model of the entire system, which can simulate the indicators in the system and fully explore the evolution trend of each body in the system and the interaction characteristics between each body [8]. System dynamics model has been widely used in the economics, energy and environment fields [9]. Various types of variables can be set in the system, including state variables, rate variables, auxiliary variables, constants, etc.

The battery rental model constructed in this paper starts from the consumer side and the battery operator side. Specifically, the consumer side includes the ownership cost of purchasing competitive ICEV, the ownership cost of purchasing BEV, and the ownership cost of battery rental mode for BEV, while the battery operator side includes the average cost, average income and average battery assets of bicycles.

3.1 Battery rental pricing model based on system dynamics

3.1.1 Causality analysis

Causality is the basis of system dynamics, and automobile consumption market conforms to causality.

(1) Ownership cost of competing ICEV

Casual loop diagram of competing ICEV TCO is shown in Figure 2.

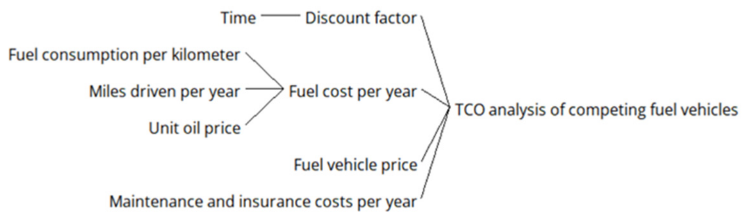

Figure 2 Casual loop diagram of competing ICEV TCO

(2) Ownership cost of purchasing BEV

Casual loop diagram of NEV whole vehicle purchase TCO is shown in Figure 3.

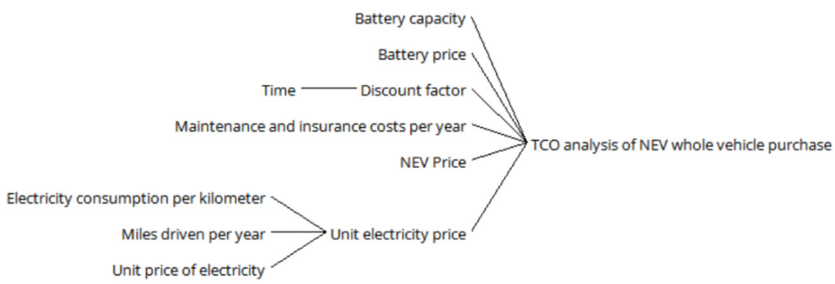

Figure 3 Casual loop diagram of NEV whole vehicle purchase TCO

(3) Ownership cost of battery rental mode is shown in Figure 4.

Casual loop diagram of battery rental mode TCO

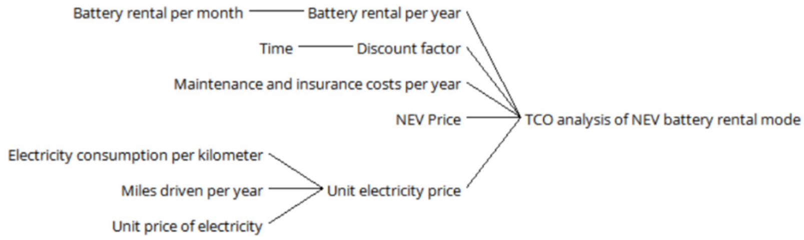

Figure 4 Casual loop diagram of battery rental mode TCO

(4) Average cycle cost of operators

Casual loop diagram of operators' average cost per vehicle is shown in Figure 5.

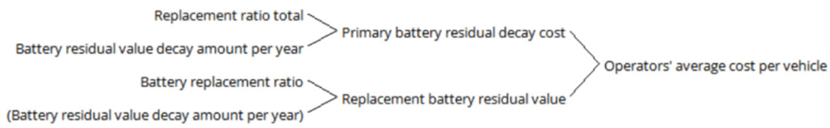

Figure 5 Casual loop diagram of operators' average cost per vehicle

(5) The average revenue per vehicle of operators

Casual loop diagram of operators' benefit per vehicle is shown in Figure 6.

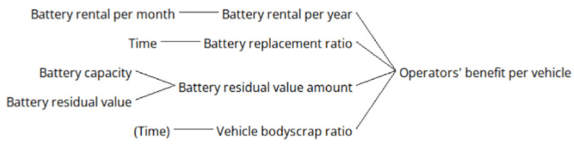

Figure 6 Casual loop diagram of operators' benefit per vehicle

(6) The average unit battery assets of operators

Casual loop diagram of operators' battery assets per vehicle is shown in Figure 7.

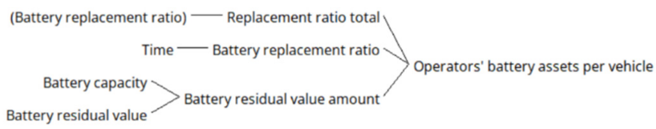

Figure 7 Casual loop diagram of operators' battery assets per vehicle

3.1.2 System flow diagram

The system flow diagram not only shows the logical structural relationship between stock and flow, but also distinguishes the nature of each variable. It could grasp the mutual promotion or mutual constraints of the whole system elements from a macroscopic perspective, and deepen the quantitative relationship among the factors at the same time. Besides, it is able to engage stakeholders throughout the modelling process [10]. System flow diagram of system dynamics model is shown in Figure 8.

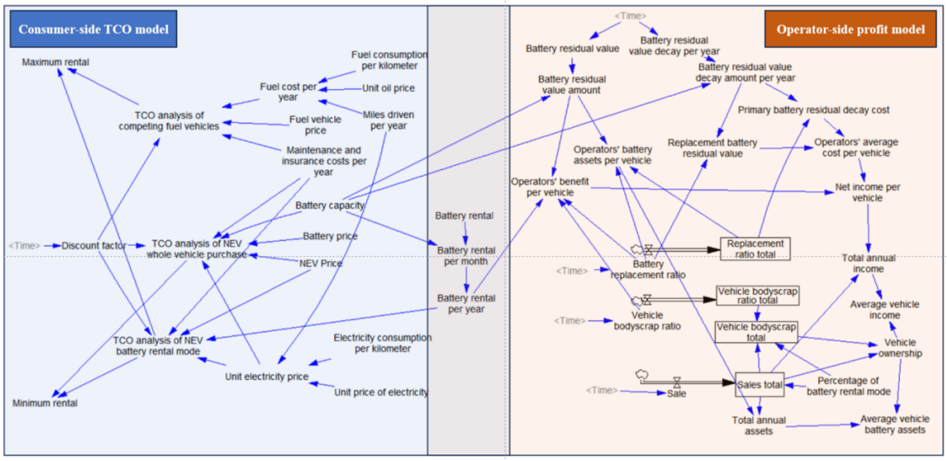

Figure 8 System flow diagram of system dynamics model

3.2 Cost of ownership economics analysis on consumer sides

Table 1 Description of the main symbols of the model

Notation	Meaning	Notation	Meaning
C_1	TCO of competing fuel vehicles	Pnc	NEV Price
C_2	TCO of NEV whole vehicle purchase	e	Electricity consumption per kilometer
C_3	TCO of NEV battery rental mode	Pe	Unit price of electricity
Picv	Fuel vehicle price	x	Battery rental
g	Fuel consumption per kilometer	Cv	Average cost per vehicle
Pg	Unit oil price	Pv	Average net income per vehicle
Pr	Maintenance and insurance costs per year	Pe	Average battery assets per vehicle
TD	Miles driven per year	So	Primary battery residual value
a	Discount factor	Sn	Replacement battery residual value
α	Discount rate	ε	Battery replacement ratio
Pb	Battery price	σ	Vehicle bodyscrap ratio
E	Battery capacity		

The description of the main symbols of the model is shown in Table 1.

The cost of ownership for a consumer purchasing a competing fuel vehicle over N years is C_1, which is calculated by the formula:

$$C_1 = Picv + g \cdot Pg \cdot TD \cdot a + Pr \cdot a \tag{1}$$

The cost of ownership for a consumer buying a pure electric vehicle in its entirety for N years is C_2, which is calculated as:

$$C_2 = Pb \cdot E + Pnc + e \cdot Pe \cdot TD \cdot a + Pr \cdot a \tag{2}$$

The cost of ownership for consumers through the battery leasing model in N years is C_3, which is calculated by the following formula:

$$C_3 = Pnc + x \cdot E \cdot a + e \cdot P \cdot TD \cdot a + Pr \cdot a \tag{3}$$

The N-year discount factor is calculated as:

$$a = \left(1 + \frac{1}{\alpha}\right) \cdot (1 - \frac{1}{(1+\alpha)^N}) \tag{4}$$

Constraints:

From the consumer's perspective, the cost of ownership of the battery rental model in N years, C_3, should not exceed the cost of ownership of a competing fuel vehicle in N years, C_1; from the battery operator's perspective, the cost of ownership of the battery rental model in N years, C_3, should not be lower than the cost of ownership of the entire EV purchase in N years, C_2. In summary, battery rental pricing has subtle bilateral constraints, and must meet the requirements of both parties in order to promote the sustainable development of the battery rental business.

$$C_2 \leq C_3(x) \leq C_1 \tag{5}$$

Set the boundary conditions:

$$C_1 = C_3(x1) \qquad C_2 = C_3(x2) \tag{6}$$

Therefore, the optimal rental pricing x for the battery rental model is between x1 and x2.

3.3 Economic analysis of profitability on the battery operator-side

According to 3.1.1 causality, the average vehicle cost per vehicle is expressed as the battery residual value decay without a new battery versus the battery residual value decay value with a new battery.

$$Cv_{kj} = (So_{j-1} - So_j) \cdot (1 - \sum_{i=1}^{i=j-k+1} \varepsilon_i) + \sum_{t=0}^{t=j-k} (Sn_{j-1} - Sn_j) \cdot \varepsilon_t \tag{7}$$

Where: k is the sales year; j is the target year; and t is the battery replacement year.

Average single-vehicle income is expressed as the sum of annual rent and the residual value of batteries that need to be replaced in the current year. Average single-vehicle battery assets are expressed as the sum of the residual value of batteries that have not been exchanged for new batteries and the residual value of batteries that have been exchanged for new ones.

$$Pv_{kj} = x \cdot E + (\varepsilon_{j-k+1} + \sigma_{j-k+1}) \cdot So_j \tag{8}$$

$$Pe_{kj} = So_j \cdot (1 - \sum_{i=1}^{i=j-k+1} \varepsilon_i) + \qquad \sum_{t=0}^{t=j-k} \left(Sn_j \cdot \varepsilon_t\right) \tag{9}$$

The target total annual net income and total assets are found by averaging the vehicle income and vehicle assets, where the total annual net income needs to be subtracted from the costs:

$$TotalPv_j = \sum (Pv_{kj} - Cv_{kj}) \tag{10}$$

$$TotalPe_j = \sum Pe_{kj} \tag{11}$$

4 RESULTS ANALYSIS

4.1 Rental range determination based on cost of ownership at the customer-side

4.1.1 Key variable setting

Based on our research on the relevant OEMs, we have determined the price of a brand of pure electric vehicle bare car and battery price. Competitor fuel car prices are dealer prices (including purchase tax). Other variables are obtained from related industry research. The specific key variable settings are shown in Table 2.

Table 2 Key variable settings

Variable	Unit	Value
Pb	RMB/kWh	950
Pnc	RMB	175000
Picv	RMB	240000
E	kWh	84
e	kWh/km	0.18
g	L/km	0.075
Pe	RMB/kWh	0.8
Pg	RMB/L	7.5
TD	km	13000
Pr	RMB/year	8700
α		3%

4.1.2 Calculation of optimal rental pricing range

According to the existing research base, the ownership cost of the NIO BaaS model will exceed the purchase of the whole vehicle in 6-7 years, so in this paper, the number of years for comparing the ownership cost of the competitor's fuel vehicle, the purchase of the whole vehicle of the tram, and the lease of the tram's batteries, N, is chosen as 7. When the boundary condition $C_1 = C_3(x1)$ is applied, x1 = 185.35RMB/(kWh-year); when the boundary condition $C_2 = C_3(x2)$ is applied, x2 = 148.04RMB/(kWh-year) When the boundary condition is reached, the monthly rent is 1297 yuan/month and 1036 yuan/month respectively. Economy analysis of battery operator side

4.1.3 Key variable setting

According to the causality analysis of the operator's vehicle income and assets in section 3.1.1, the battery residual value, the battery replacement ratio, the body scrap ratio, the sales of new energy vehicles and the ratio of choosing the battery rental mode are all important influencing factors, so the important variables in the research timeframe are firstly predicted.

(1) Battery residual value

The prediction of battery residual value refers to the decreasing trend of power battery cost in the comprehensive analysis of pure electric and fuel cell vehicle economics by Qiu et al. [11]

(2) Body scrap ratio

Based on the normal distribution probability model, the proportion of bodywork scrapping is fitted. Through the nonlinear curve Gaussian fitting, the fitting curve is shown in the Figure 9 below, the adjusted R2 is 0.91 close to 1, the fitting effect is good.

(3) Percentage of sales volume and choice of battery rental mode

Referring to the study of Xu et al. [12] on the forecasting of new energy vehicle sales, it is pointed out that the cumulative sales of new energy vehicles in China can be better fitted by using the Bass model. Combining the Bass model with the past sales data of the studied models, the cumulative sales for 2023-2037 are forecasted as Figure 10.

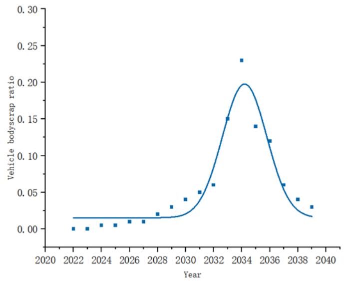

Figure 9 Fitted curve of body scrap ratio

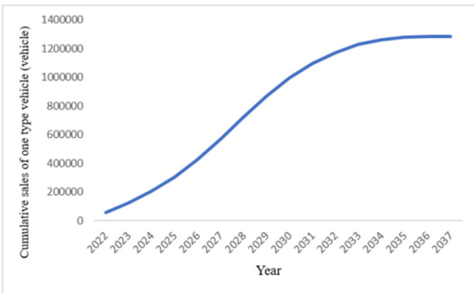

Figure 10 Curve of cumulative sales

4.1.4 Analysis of asset and income results on the battery operator-side

Based on the key variables and parameter settings, the benchmark scenario is simulated and extrapolated using Vensim software to obtain the operator's total net revenue and total assets, average unit revenue and average unit battery assets for the target year, as shown in the following Figure 11 and Figure 12.

Under this rent pricing, total assets rise each year for the first ten years, peaking at about 6.1 billion RMB in 2032, then decline each year, and the rate of decline in total battery assets intensifies in the target year as the battery round of replacements ends. Total net income grows at a slower rate in the initial phase, i.e., until 2030, and then increases significantly from 2030-2032, which is somewhat related to the high level of retention in that phase, and peaks at about 3.3 billion RMB in 2033.

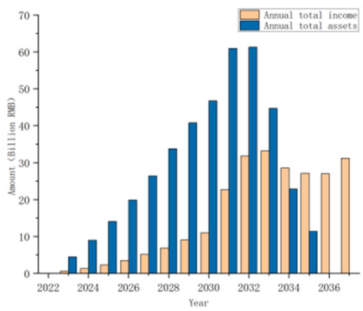

Figure 11 Trends in total net income and total assets

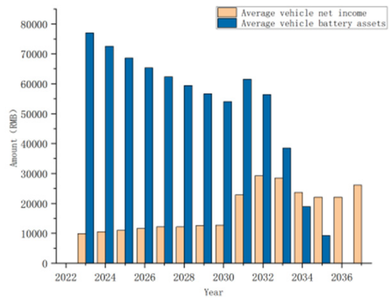

Figure 12 Trends in average net income and average assets per vehicle

Under this rent pricing, the average single-vehicle battery asset declines steadily for the first eight years, then rises abruptly to 62,000 RMB in 2031, and then declines at a faster rate after that. The average single-vehicle revenue is about 12,000 RMB from 2023-2030, increases markedly in 2031, and stays at a high level with an average single-vehicle revenue of about 25,000 RMB from 2031-2036.The average single-vehicle battery asset is about 1,000 RMB per vehicle in the first eight years, and then increases to about 1,000 RMB per vehicle in 2030.This is the same as the average single-vehicle battery asset.

4.1.5 Battery Operator Income Sensitivity Analysis

(1) Rent - target total net income

The growth rate of the target annual total net income is calculated under the scenarios of 10%, 20%, and 30% rent increase, and the results are shown in Figure 13.

During the period 2023-2030, the growth rate of total net income in the target year exceeds the corresponding rental growth rate. After 2030, on the other hand, the growth rate of total net income in the target year is much less than the growth rate of rents in the corresponding years. Therefore, increasing rents in the rental guest range before 2030 has a significant effect on the accumulation of battery operators' revenues, while after 2030, downward rent adjustments can reduce the cost of user access without significantly affecting battery operators' total income. Rental control means should be adjusted with the change of time stage, combined with the total number of car models to make timely adjustments, which is the future direction of the development of diversified battery rental services.

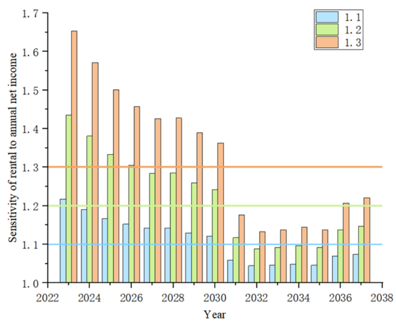

Figure 13 Rental annual net income sensitivity analysis

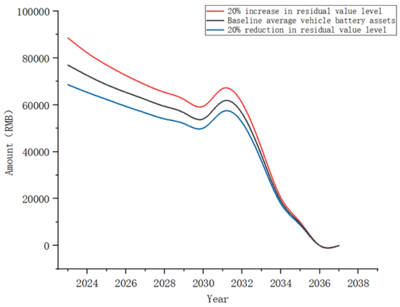

Figure 14 Battery residual value- battery asset sensitivity analysis

(2) Battery residual value - single-vehicle battery assets

As shown in Figure 14, residual value levels are strongly correlated with single-vehicle battery assets. A 20% increase in the overall residual value level results in an increase of about 15% in battery assets in 2023 at the beginning and only 6% in 2036 at the end. It can be seen that as time evolves, the impact of higher battery residual values on battery assets becomes less. This result is also reflected in the case of a 20% reduction in residual value levels. Therefore, improving the residual value rate of new energy vehicles and slowing down the decay of battery cost is important for battery operators to increase their battery assets, especially for the protection of the residual value of new vehicles.

5 CONCLUSION

In this study, we constructed a scenario simulation model of the market change of the unswappable battery rental mode using system dynamics from the perspectives of both consumers and battery operators. Combined with a brand of new energy vehicles for sale, the impact of rent on consumer spending and battery operator revenue is analyzed, and battery operator revenue is analyzed economically, with the following conclusions:

(1) Rental pricing affects the spending on the consumer side and the revenue on the battery operator side. The optimal rental pricing range for the 84 kWh battery of the model studied in this paper is 1036-1297 RMB/month. Combined with other battery leasing cases, rental pricing is approximately linearly correlated with battery capacity.

(2) Battery rental mode rent increase and battery operator side revenue is not a simple linear relationship, this paper studies the model after 2030 even if the increase in rent for the overall revenue enhancement effect is still not significant. Therefore, a flexible rental program should be introduced at the right time in conjunction with the current market situation.

(3) The battery residual value rate is closely related to the battery assets of a single vehicle, showing a positive correlation. From the perspective of the full life cycle of new energy vehicles, the initial battery residual value rate has a more significant impact on battery assets. Battery is the core hub device in the entire new energy ecosystem, and improving the residual value rate of new energy vehicles is crucial to increasing the battery assets of battery operators, especially focusing on improving the residual value rate of new vehicles.

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