# Pricing decisions for power cells considering battery recycling

Guo Xiao

Corresponding author: 202030510177@stu.shmtu.edu.cn

Institute of Logistics Science and Engineering, Shanghai Maritime University, Lin-gang Avenue, Pudong New Area, Shanghai, China

**Abstract:** This paper examines the pricing strategies of four subjects vehicle manufacturers, battery producers, recycling service outlets (with power exchange capabilities), integrated utilization companies, and consumers in a closed supply chain when considering the maximization of their own interests. Exploring the impact of the emergence of the power exchange model on market share and consumer preference for power exchange technology on pricing, the study finds that (1) the emergence of the power exchange model is conducive to reducing the recycling cost of batteries; (2) as the market share of batteries sold increases, the R&D investment in power exchange technology and the rental price of batteries fall rapidly, and the sales price of batteries gradually increases; (3) as consumer preference increases, battery producers (4) With the increase in consumer preference for power exchange technology, the wholesale price, sales price and recycling price of batteries will gradually decrease; (5) With the increase in consumer preference for power exchange technology, the wholesale price, sales price and recycling price of batteries will gradually decrease; the rental price of batteries will show a trend of first down and then up.

**Keywords:** new energy vehicles, power change technology, battery recycling, pricing

## 1. Introduction

Due to the strong support of the state and the continuous reform and innovation of enterprises, the sales of new energy vehicles are increasing, and now the problems of new energy vehicle infrastructure construction and expensive new energy vehicle batteries are becoming prominent. In order not to let new energy vehicles lose users due to charging difficulties, the construction of infrastructure such as charging piles must be strengthened. In addition, in October 2021, the General Office of the Ministry of Industry and Information Technology issued the Notice on the Launching of Pilot Work on the Application of New Energy Vehicle Switching Mode, which will make the charging difficulty of new energy vehicles further solved.

The construction of the power exchange station will further solve the problems of difficult car charging and high battery prices. Under the power exchange model, consumers only use to purchase the car, and the battery is consumed by leasing. At present, Aoduo has already laid out in 25 cities across the country, with a total of over 500 exchange stations (including those under construction); Azera has built 636 exchange stations (including 130 highway exchange stations) in total across the country. In terms of new energy vehicle power storage, the combination of

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charging and power exchange will be common. This article analyses the market in both modes of power exchange charging.

Recycling of used batteries is a long-term and far-reaching task, and in recent years, the volume of used batteries has been increasing year by year. recycling or reuse of used batteries is beneficial to environmental protection and can increase the economic profit of enterprises. Mayyas, Ahmad (2019)[5] showed that raw materials accounted for 50% of the cost of lithium batteries, and the total packaging cost could be reduced by 30% by replacing virgin materials with recycled materials. Gu, Xiaoyu(2018)[3] et al, analyzed the economic benefits of power battery recycling by developing a pricing and decision model for a closed-loop supply chain. Tang, Yanyan (2018)[9] et al. studied the optimal channel selection and battery capacity allocation strategy for battery recycling of electric vehicle manufacturers, and through numerical experiments explored the effects of key parameters on the equilibrium capacity allocation strategy and manufacturer profits. Hong, Xianpei (2015)[4] et al. developed a manufacturer-led closed-loop supply chain battery recycling game model and compared the gains and losses of manufacturer recycling, retailer recycling, and third-party enterprise recycling, and found that the retailer recycling method is the optimal economic efficiency strategy. Nan, Junmin(2005)[6], under the current network construction model, automotive companies prefer to set up some 4S stores authorized by them as specialized repair stores for electric vehicles as the consumer end network for power battery recycling. Jia Chang Dai(2014)[1] conducted research and analysis from seven perspectives: user use, battery maintenance, vehicle operation, grid impact, commercial operation, and station construction, and proposed that under the existing conditions, the centralized charging + power exchange mode is preferable for the electric energy supply of electric vehicles.

## 2. Closed-loop supply chain pricing model

This chapter examines how a closed-loop supply chain consisting of a vehicle manufacturer, a recycling service outlet, a comprehensive utilization enterprise, and a battery manufacturer develops pricing strategies under the influence of consumer preferences after a new energy vehicle manufacturer provides consumers with options for power replacement and charging. In this supply chain, each enterprise considers its own interest maximization, and the recycling service network is operated by the auto manufacturer and the comprehensive utilization enterprise to carry out the new energy vehicle power battery replacement and recycling service, while the auto manufacturer leads the research and development of the battery replacement technology and the comprehensive utilization enterprise is responsible for the battery recycling treatment. Using matlab to derive equations. The model is shown in the following figure 1.

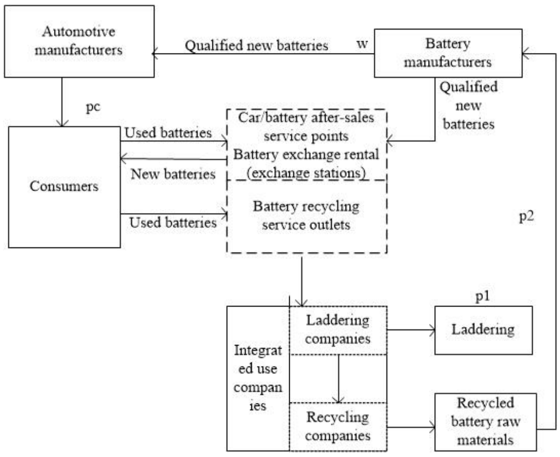


**Figure 1** Battery recovery mode

### 2.1 Model description and parameter setting

Considering that there is an alternative relationship between the two sales methods of new energy vehicle batteries, the market demand functions of batteries are :

$$\begin{cases} q_c = k\alpha - \beta(p_c - b) \\ q_e = (1-\alpha)k - \beta p_e + \delta e \end{cases} \tag{1}$$

Where, $k$ denotes the base demand of new energy vehicle power battery; $\beta$ denotes the sensitivity coefficient of consumers to product price; $\alpha$ denotes the market share of sold batteries; $\delta$ the coefficient of consumers' preference for battery exchange technology; $e$ the level of battery exchange R&D of battery recycling enterprises; $p_c$ denotes the actual price paid for purchasing batteries; $p_e$ denotes the price to be paid for leasing batteries; $q_c$ Market demand for the sale of batteries; $q_e$ Market demand for rental batteries

Profit from the sale of batteries by car manufacturers

$$\pi_r = (p_c - w)\, q_c \tag{2}$$

Profits from recycling service outlets

$$\pi_s = (p_e - w)q_e - (1/2)\, ge^2 \tag{3}$$

Where, $w$ denotes the wholesale price of the battery; $(1/2)\, ge^2$ denotes the R&D input cost of power exchange at the recycling service network, $g$ denotes the R&D cost coefficient of power exchange $(0 < g < 1)$; and $e$ denotes the R&D input of power exchange technology.

For the comprehensive utilization enterprise, assuming that all the recycled batteries can be laddered, the revenue generated by laddering is $p_1$, the revenue from selling raw materials is $p_2$, $p_1 > p_2$, and the profit function of the comprehensive utilization enterprise is

$$\pi_u = (q_c + q_e)(-b + p_1 + p_2) \tag{4}$$

The profit of the battery producer is affected by the number of batteries sold and the cost of battery production. $c_w$ denotes the cost of producing batteries from recycled materials, $c_n$ denotes the cost incurred in the production of batteries, so $c_w = p_2 + c_n$ and the profit function is

$$\pi_m = (q_c + q_e)(w - c_w) \quad (5)$$

**2.2 Model Construction**

First, the new energy vehicle manufacturers decide the battery sales price according to the market reflection; the second step recycling service outlets to ensure their own profit maximization to determine the battery rental price and R & D investment; the third step comprehensive utilization enterprises to decide the battery recycling price; the fourth step battery manufacturers to determine the wholesale price of batteries.

The profit function of a new energy vehicle manufacturer Is $\pi_r = (p_c - w)[k\alpha - \beta(p_c - b)]$, $\pi_r$ is a concave function on the sales battery price $p_c$, $\partial^2\pi_r/\partial p_c^2 = -2\beta < 0$, and the first order derivative function $\partial\pi_r/\partial p_c = k\alpha + \beta(b - p_c) - \beta(p_c - w)$ for $p_c$ is made equal to 0, which shows that:

$$p_c^* = k\alpha/2\beta + (b + w)/2 \quad (6)$$

The profit function of the battery recycling service outlet is $\pi_s = (p_e - w)(k(1-\alpha) - \beta p_e + \delta e) - (1/2)ge^2$, the hesian matrix about $p_e$ and $e$ is $\pi_s(p_e, e) = \begin{bmatrix} -2\beta & \delta \\ \delta & -g \end{bmatrix}$, since $|\pi_s(p_e, e)| = 2g\beta - \delta^2$, so that the hesian matrix negative definite when $2g\beta > \delta^2$, that is, when twice the cost coefficient of research and development of power exchange and the consumer's sensitivity coefficient to the price of the product is greater than the coefficient of consumer preference for power exchange technology, $\pi_s$ is a joint concave function about the price of leased batteries $p_e$ and $e$. Substituting equation (6) into the function $\pi_s$, the first order derivative function of $p_e, e$ respectively, to find the most value can be found

$$p_e^* = \frac{g(\beta w - k\alpha + k) - \delta^2 w}{2\beta g - \delta^2} \quad (7)$$

$$e^* = \frac{\delta(-\beta w - k\alpha + k)}{2\beta g - \delta^2} \quad (8)$$

Conclusion 1, the market size of leased batteries is directly proportional to the leasing price of batteries and the level of research and development of power exchange technology, when the market size increases, the leasing price of batteries and the level of research and development of power exchange technology will increase.

The profit function of the integrated utilization enterprise, substituting equation (1) into equation (4), $\pi_u = (\beta b - \beta p_c + \beta p_e + k + \delta e)(-b + p_1 + p_2)$, the integrated utilization enterprise decides the price $b$ of battery recycling, $\partial^2\pi_u/\partial b^2 = -\beta < 0$, $\pi_u$ is a concave function about the price $b$ of battery recycling and there exists the optimal value of $b$. $\partial\pi_u/\partial b = (\beta(p_1 + p_2) + k\alpha + \beta w)/2 + \beta p_e - k - \delta e - \beta b$, so that $\partial\pi_u/\partial b = 0$, then $b = (\beta(p_1 + p_2) + k\alpha + \beta w - 2k)/2\beta + p_e - \delta e/\beta$, and substituting equation (7) and (8) yields

$$b^* = (p_1 + p_2 + w)/2 + \delta^2 k\alpha - 6kg\beta \quad (9)$$

and substituting equation (9) into equation (6) yields

$$p_c^* = \frac{p_1+p_2+3w+2\delta^2 k\alpha}{4} - 3kg\beta + \frac{k\alpha}{2\beta} \quad (10)$$

Conclusion 2, the degree of consumer preference for power exchange technology will affect the recycling price of comprehensive utilization enterprises and the selling price of batteries of automobile manufacturers. Under the condition that other influencing factors remain unchanged, when consumer preference for power exchange technology increases, comprehensive utilization enterprises will increase the recycling price of batteries, while automobile manufacturers will increase the selling price of batteries; the increase of the cost coefficient of power exchange R&D will reduce the recycling price of batteries and the selling price of batteries.

The profit function of the battery producer is $\pi_m = (\beta b - \beta p_c + \beta p_e + k + \delta e)(w - c_w)$, and substituting equations (7)(9)(10) yields $\pi_m = (\frac{\beta w(2\beta g-7\delta^2)}{4(2\beta g-\delta^2)} - \frac{3\delta^2(k\alpha+k)}{2(2\beta g-\delta^2)} + \frac{\beta(p_1+p_2)}{4} + \frac{\delta^2 k\beta\alpha}{2} - 3kg\beta^2 + 3k/2 - k\alpha)(w - c_w)$,the battery producer determines the wholesale price of the battery $w$, $\frac{\partial^2 \pi_m}{\partial w^2} = \frac{2\beta(2\beta g-7\delta^2)}{-4\delta^2+8g\beta}$, if there exists a maximum value point of the function, i.e., $\frac{\partial^2 \pi_m}{\partial w^2} < 0$. Therefore, it is necessary that $2\beta g - 7\delta^2 < 0$ and $-4\delta^2 + 8g\beta > 0$. Therefore, when $(2/7)\beta g < \delta^2 < 2\beta g$, $\pi_m$ is a concave function on the wholesale price of batteries and there exists a point of great value for $w$, $\frac{\partial \pi_m}{\partial w} = -\frac{\beta c_w(2\beta g-7\delta^2)}{4(2\beta g-\delta^2)} - \frac{3\delta^2(k\alpha+k)}{2(2\beta g-\delta^2)} + \frac{\beta(p_1+p_2)}{4} + \frac{\delta^2 k\beta\alpha}{2} - 3kg\beta^2 + \frac{3k}{2} - k\alpha + \frac{\beta w(2\beta g-7\delta^2)}{2(2\beta g-\delta^2)}$ such that the first-order derivative function equals zero:

$$W^* = \frac{c_w}{2} - \frac{(p_1+p_2)(2\beta g-\delta^2)}{2(2\beta g-7\delta^2)} + \frac{(2k\alpha-3k)(2\beta g-\delta^2)}{\beta(2\beta g-7\delta^2)} + \frac{(6kg-\delta^2 k\alpha)(2\beta g-\delta^2)}{2\beta g-7\delta^2} \quad (11).$$

Conclusion 3, when $2\alpha + 6\beta g - \delta^2\beta\alpha > 3$, the battery demand and wholesale price are positively proportional, otherwise, the battery demand and wholesale price are inversely proportional.

## 3. Example analysis

In relation to the above model, in order to gain a clearer understanding of the inter-quantitative relationships, the influence of the parameters on each decision variable was analysed in excel, this paper mainly considers the influence of the coefficient of consumer preference for the switching technology, $\delta$, and the market share of the sold batteries. Considering the actual situation, the initial parameters are taken as follows: {k, $c_w$, $p_1$, $p_2$, $\beta$, g, $\alpha$ }={1500, 200, 1500, 150, 0.3, 0.4, 0.4, 0.5}, and it is known that $(2/7)\beta g < \delta^2 < 2\beta g$, and when $\beta$, $g$ is determined, it is known that $0.185164 < \delta < 0.489897$.

Figure 2 analyzes the impact of consumers' preference for power exchange technology on the profits of enterprises. With the increase of consumers' preference, the profits of both battery manufacturers and vehicle manufacturers gradually decrease, and for comprehensive utilization enterprises and recycling service outlets, the profits show a trend of first decreasing and then increasing. As shown in the figure, the revenue of comprehensive utilization enterprises reaches the minuscule point when δ∈(0.246,0.266); the recycling service outlets have the minuscule point when δ∈(0.296,0.346).

Figure 3 shows the effects of consumer preference for power exchange technology on the sales price, lease price, R&D investment in power exchange, wholesale battery price and battery recycling price of batteries. With the increase of consumer's preference for power exchange technology, the wholesale price, sales price and recycling price of battery gradually decrease; the lease price of battery shows a trend of first down will then up, and there is a minimal value at $\delta \in (0.326, 0.336)$; the R&D investment of power exchange technology gradually increases with the increase of consumer's preference for power exchange technology, and when the consumer's preference is greater than 0.316, the power exchange technology is worth investing.

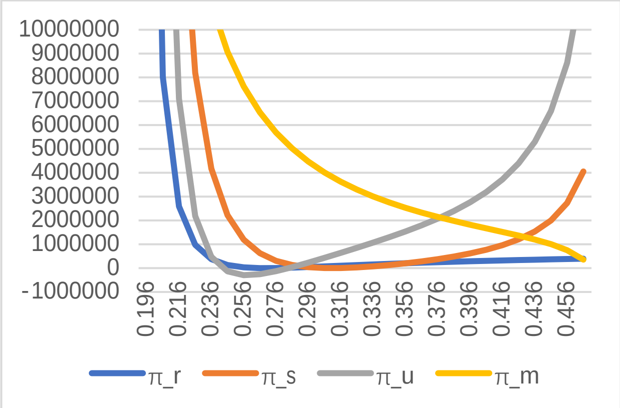


**Figure 2** Effect of $\delta$ on profit

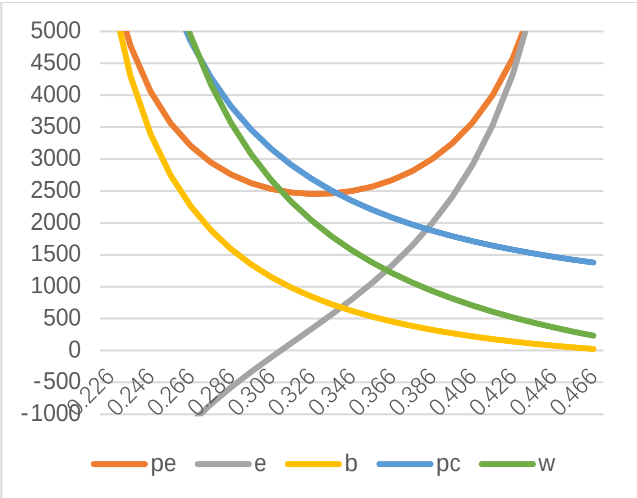


**Figure 3** Effect of $\delta$ on $p_c^*$ $p_e^*$ $e^*$ $b^*$ w*

## 4. Concluding remarks

This paper has practical implications for the development of the closed-loop supply chain new energy vehicle industry. In practice, the model of power exchange + charging is more conducive to the profitability of enterprises; however, there are limitations in considering fewer influencing factors for comprehensive utilization enterprises, and subsequent consideration can be given to the consideration of comprehensive utilization enterprises to increase factors related to battery recycling and treatment costs and income from gradual utilization.

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## Appendix

```
clear all;

clc;

syms pc w x y  pe  b k z e g xx qc qe p1 p2 c % Creation of symbolic scalar variables, functions and matrix variables (scale variables)

rr =(pc-w)*{k*x-y*(pc-b)};

df1=diff(rr,pc,1);

df2=diff(rr,pc,2);

pretty(df1)%On the first and second order derivatives of pc
```

```
pretty(df2)
rs=(pe-w)*{(1-x)*k-y*pe+z*e}-0.5*g*e^2;
J=jacobian(rs,[pe;e]);
H=jacobian(J,[pe;e]);
pretty(H)%Hessian Matrix
df3=diff(rs,e,1);
df4=diff(rs,pe,1);
pretty(df3)
pretty(df4)
A=g*(y*w-k*x+k)-(z^2)*w;
B=2*y*g-z^2;
C=A/B;
e=z*(pe-w)/g;
E=subs(e,pe,C);
pretty(E)
ru=(qc+qe)*(-b+p1+p2);
QC=x*k-y*(pc-b);
QE=(1-x)*k-y*pe+z*e;
ru1=subs(ru,qe,QE);
ru2=subs(ru1,qc,QC);
D=(k*x+y*b+y*w)/(2*y);
ru3=subs(ru2,pc,D);
df5=diff(ru3,b,2);
df6=diff(ru3,b,1);
pretty(df5)
pretty(df6)
ru4=subs(ru3,pe,C);
ru5=subs(ru4,e,E);
pretty(ru5)
```