A pricing model of power battery closed-loop supply chain under government subsidies

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Abstract. Government subsidy is a common policy to promote re-manufacturing. In order to explore the pricing and coordination mechanism of power battery production under this policy, a two-period model was proposed. This model combines the supply constraints of partial recovery and full recovery to study the impact of government subsidies on the recovery and fracturing pricing of power battery manufacturers. The study shows that moderate subsidies will increase the recovery rate under both supply constraints. However, high subsidies will increase the output of new power batteries, leading to oversupply, which is not conducive to environmental protection. Therefore, the optimal value of the subsidy is the calculated threshold.

1. Introduction
Since the seven departments jointly issued the "Notice on Doing a Good Job in the Pilot Recycling of New Energy Vehicle Power Storage Battery" in 2018, 17 provinces and municipalities have been selected as pilot areas for power battery recycling. Power battery policies have been introduced in succession, but there is a lack of detailed implementation strategy, and its recycling and reuse still face the bottleneck of low recovery rate and high recovery cost [1-3]. In 2018, Shenzhen City released the "Shenzhen Financial Support Policy for the Promotion and Application of New Energy Vehicles in 2018". Studying the impact of such policies on enterprise production pricing is of great significance for implementing the extended producer responsibility system and promoting the recovery and reuse of power batteries [4-5].

For a long time, research on closed-loop supply chain production has attracted much attention. Scholars believe that enterprises should use waste products for new product manufacturing to reduce environmental pollution [6]. So should the production of power batteries. Besides producing new products through forward supply chain, enterprises should also produce re-manufactured products through reverse supply chain [7]. In terms of the impact of environmental policies on corporate decision-making, scholars mainly studied the impact of recovery rate, subsidies and taxes. In 2015, Muyanfen found that when the recycling rate and recycling rate required by the recycling regulations were low, manufacturers would not improve product quality [8]. Cheng Faxin et al. studied the decision-making problem of the closed-loop supply chain pricing when the quality of waste products is uncertain based on the recycling subsidy policy [9]. In addition, Zhao Xiaomin et al. studied the impact of government financial regulation on the optimal decision-making of WEEE recyclers and producers, including the impact of taxation [10]. The study found that when government rewards and penalties are high, not only do carbon emissions decrease, but supply chain profits increase. However, there are few literatures on the power battery recycling by government subsidy policy at present.
Based on the supply constraints of power battery recovery, a two-cycle model was used to analyze the whole process of manufacturer's production and re-manufacturing. Meanwhile, a profit maximization model was constructed, and the influence of government subsidies on manufacturer's decision-making was analyzed. The results may help governments make policy decisions and manufacturers make production decisions.

2. Model design

2.1. Problem description

At present, China's power battery recycling system is not sound, and policy makers have introduced a policy of subsidy to promote recycling. The closed-loop chain of power battery production and supply consists of manufacturers, policy makers and consumers considering the impact of government policies. The manufacturer takes the lead in the whole process of power battery production, sales, recycling and reuse. Manufacturers produce new power batteries to sell to consumers. The batteries are then recycled from consumers for re-manufacturing and new products are produced. Finally, recycled and new products are produced and supplied to the market. In the process of recycling and using used batteries by manufacturers, government subsidies will affect the production and sales decisions of manufacturers and indirectly affect the recycling of power batteries in the market. The specific process is shown in Figure 1. Parameter explanations are given in Table 1.

![Diagram](image)

Figure 1. The process by which manufacturers recover and re-manufacture under government subsidies.

Table 1. Symbol meaning.

| Symbol | Description                                                                 |
|--------|----------------------------------------------------------------------------|
| $p_{N1}$ | The price of the new battery for sale in phase 1                           |
| $p_{N2}$ | The price of the new battery for sale in Phase 2                           |
| $p_R$   | Phase 2 Sale of re-manufactured battery prices                             |
| $p_A$   | Recycling price of used batteries                                          |
| $q_{N1}$ | Demand for new batteries for Phase 2                                       |
| $q_{N2}$ | Demand for new batteries for Phase 2                                       |
| $q_R$   | Demand for re-manufactured batteries for Phase 2                           |
| $q_A$   | Number of batteries recovered in Phase 1                                   |
### 2.2. Model assumption

Hypothesis 1: The manufacturer fully occupies the market and is a rational decision maker in pursuit of profit maximization with complete information. Its production and sales decisions are forward-looking and can consider the impact on the period 2 when making decisions in the period 1. As the manufacturer monopolized the market, it could be known that the sum of the demand for re-manufactured batteries and new batteries was the demand \( Q \) of the whole market, namely \( q_R + q_{N1} = Q \).

Hypothesis 2: All recycled old batteries are used for re-manufacturing, i.e. \( q_N = q_A \). Government subsidies for recycling can be seen as government subsidies for manufacturers to re-manufacture. A unit re-manufacturing subsidy is a unit recovery subsidy \( \eta \).

Hypothesis 3: There is no significant difference between the cost performance of recycled batteries and that of new products. Both intrinsic values are the same and provide the same level of satisfaction to the consumer.

Hypothesis 4: We assume that the unit re-manufacturing cost is less than the unit new product manufacturing cost in order to match the actual manufacturer's purpose of re-manufacturing activities to make profits. It is profitable to recycle batteries.

### 2.3. Profit model and solution

#### 2.3.1. Profit model.

Two-cycle model is introduced to analyze the production process, which has been widely used in literature [11]. In the first phase, the environmental protection policy is introduced, and the manufacturer decides the price of the new production power battery. In the second phase, the manufacturer sets the recovery price, determines the amount of recovery, re-manufactures the battery price and receives government subsidies. According to the above process, the demand function, recovery function and supply constraint are established as follows:

- **Demand function:** Market demand is a linear function of price. To simplify the demand function, the first phase of the new battery demand function was set as \( q_{N1} = 1 - p_{N1} \); the second phase demand is evenly distributed between \([0, 1]\). The demand function is \( q_R = 1 - p_R, q_{N2} = 1 - p_{N2} \). Since the manufacturer is in full possession of the market, it can be inferred that \( q_R + q_{N1} = 1 \). Contacting the demand function established earlier, we infer \( p_{N2} = 1 - p_R \).

- **Recovery function:** In practice, more waste batteries must be recycled at a higher cost. Thus, the recovery quantity is treated as a linear function of the recovery price, namely \( q_A = \alpha p_A \) (\( \alpha > 0 \)). And the recovery cost function is \( p_A q_A = k p_A^2 \).

- **Supply constraint:** The supply constraint is \( q_A \leq \epsilon q_{N1} \). It indicates that the number of recycled batteries in the second phase is less than the number of recycled batteries in the new batteries produced in the first phase. The \( \epsilon q_{N1} \) measures the government re-manufacturing subsidy and the corporate profit function is as follows:

\[
\Pi = (1 - p_{N1})(p_{N1} - c_n) + (1 - p_{N2})(p_{N2} - c_n) + (1 - p_R)(p_R - c_R) - k p_A^2 + \eta (1 - p_R)
\]

- **Supply constraint:** \( q_A \leq \epsilon q_{N1} \)

- **Complete market coverage:** \( p_{N2} = 1 - p_R \)

Substituting the recovery function and the \( q_{N1} \) demand function into the supply constraint, we can obtain \( k p_A + \epsilon p_{N1} \leq \eta \). In case 1, the profit function satisfies \( k p_A + \epsilon p_{N1} < \eta \) (constraint 1). Under
this constraint, the manufacturer recovers part of the old battery and re-manufactures it. In case 2, the profit function satisfies $k p_A + \varepsilon p_{N1} = \eta$ (constraint 2). This constraint represents the manufacturer's recycling of all available used power cells and the re-manufacturing of all recycled batteries. It can find that the difference between the two constraints is whether to recycle all recyclable old batteries. The optimal solutions of the profit function under two constraints are discussed respectively below.

2.3.2. Optimal solution under constraint 1. Known conditions are as follows:

\[
\begin{cases}
    p_{N2} = 1 - p_R \\
    q_A = q_R \iff p_A = (1 - p_R)/k
\end{cases}
\]

By substituting all known conditions, the profit function is obtained as follows:

\[
L_1 = \max_{p_{N1}, p_R} \Pi_1 = (1 - p_{N1})(p_{N1} - c_N) + p_R(1 - p_R - c_N) \\
+ (1 - p_R)(p_R - c_R) - \frac{(1 - p_R)^2}{k} + \eta(1 - p_R)
\]

To solve the profit function, the partial derivatives of $p_{N1}$ and $p_R$ were obtained by using the above functions, and the formula was as follows:

\[
\frac{\partial L_1}{\partial p_{N1}} = 0 \iff p_{N1} = \frac{1 + c_N}{2}
\]

\[
\frac{\partial L_1}{\partial p_R} = 0 \iff p_R = \frac{k(2 + c_R - c_N - \eta) + 2}{4k + 2}
\]

The result shows that the function feasibility set is convex. Therefore, there is an optimal solution, and the above first derivative is the optimal solution.

2.3.3. Optimal solution under constraint 2. Known conditions are as follows:

\[
\begin{cases}
    p_{N2} = 1 - p_R \\
    q_A = q_R \iff p_A = (1 - p_R)/k \\
    \varepsilon q_{N1} = q_A \iff p_{N1} = (\varepsilon - 1 + p_R)/\varepsilon
\end{cases}
\]

As constraint 1, the function form is as follows:

\[
L_2 = \max_{p_R} \Pi_2 = \left(1 - \frac{\varepsilon - 1 + p_R}{\varepsilon}\right)\left(\frac{\varepsilon - 1 + p_R}{\varepsilon} - c_N\right) + p_R(1 - p_R - c_N) \\
+ (1 - p_R)(p_R - c_R) - \frac{(1 - p_R)^2}{k} + \eta(1 - p_R)
\]

The partial derivative of $p_R$ with the above function is obtained as follows:

\[
\frac{\partial L_2}{\partial p_R} = 0 \iff p_R = \frac{\varepsilon^2 k(2 + c_R - c_N - \eta) + \varepsilon k(c_N - 1) + 2\varepsilon^2 + 2k}{2(\varepsilon^2 k + k + \varepsilon^2)}
\]

Similarly, the value of $p_R$ in the above formula is the optimal solution of the function under constraint two.

3. Result analysis

Table 2 shows the optimal decisions of manufacturers under government subsidies. Under constraint 2, the optimal solution of $p_{N1}$ is $(\varepsilon - 1 + p_R^*)/\varepsilon$ where $p_R^*$ represents the optimal solution of $p_R$ under this constraint.
Table 2. The manufacturer's optimal decision.

| Constraint | $P_{N1}$ | $P_R$ |
|------------|----------|--------|
| Constraint 1 | $\frac{1 + c_N}{2}$ | $\frac{k(2 + c_R - c_N - \eta) + 2}{4k + 2}$ |
| Constraint 2 | $\frac{\varepsilon - 1 + p_R^*}{\varepsilon}$ | $\frac{\varepsilon^2 k(2 + c_R - c_N - \eta) + \varepsilon k(c_N - 1) + 2\varepsilon^2 + 2k}{2(2\varepsilon^2 k + k + \varepsilon^2)}$ |

According to the table 2, even if the manufacturer recovers all the used power batteries, the government subsidy will influence the decision. Regardless of the conditions one or two, government subsidies are inversely proportional to the price of manufacturers selling recycled batteries. In other words, if the company does not recycle all power batteries, then higher subsidies will produce more re-manufactured products. Small subsidies do not affect prices of phase 1. If the subsidy value is high, companies will produce too many new batteries in the phase 1 to ensure that more products can be recycled and re-manufactured in the phase 2, which is not environmentally desirable. At the same time, it can be seen from the calculation that, under the condition of satisfying constraint 1, the necessary and sufficient conditions for obtaining the optimal profit solution are as follows:

$$\eta < \eta^* = \frac{\varepsilon(2k + 1)(1 - c_N) - k(2 - c_R + c_N)}{k}$$

This suggests that government subsidies have a threshold value of $\eta^*$. Above this threshold, all recyclable batteries will be recycled. If government subsidies fall below the threshold, increasing them will produce more recycled batteries. Above the threshold, companies will recycle all available used power batteries for hefty government subsidies. Thus, appropriate government subsidies are necessary.

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