Closed-Loop Supply Chain Cooperation Decision-Making under Echelon Utilization

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Abstract. This paper introduces the echelon utilization of retired power batteries and constructs a closed-loop supply chain including echelon utilizer. A cooperative mode between echelon utilization merchants and recyclers is established and compared with a non-cooperative mode. The following conclusions are drawn: Manufacturers' strategies and profits are not affected under both modes; compared to non-cooperation. Cooperative enterprises between echelon utilizer and recycler yield greater profits. Therefore, cooperative models can generate both environmental and economic benefits, serving as valuable references for decision-making among all members of the supply chain.

Keywords: Echelon utilization, Closed-loop supply chain, Cooperation of supply chain members

1 Introduction

At present, the number of new energy vehicles in China is surging, and the increase in new energy vehicles will inevitably lead to a large-scale increase in its retired power batteries. Echelon utilization is to use 20%-80% of the residual energy of the power battery for energy storage, communication base stations and low-speed electric vehicles through detection, splitting, repair and reassembly. Some enterprises have laid out the echelon utilization business in advance.

There are studies on the recycling channels of power batteries,Savaskan et al. [1] modeled three common types of recycling entities and found that the retail-led recycling model outperforms those led by manufacturers or third parties. From a supply chain perspective, Li et al. [2] established eight recycling channels, solving and comparing them to conclude. In the realm of electric vehicle battery echelon utilization, Zhang et al. [3] finded that echelon utilization always positively impacts manufacturers' profits. Zhang et al. [4] constructed a closed-loop supply chain model comprising an electric vehicle battery manufacturer, a retailer, and a echelon utilization business.

It was observed that there is limited research on cooperative decision-making among echelon utilization enterprises, and even when available, it often relegates echelon utilization to a final consideration. Therefore, this paper introduces echelon utilizer as integral members of the supply chain and establishes two models — one where echelon

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utilization businesses cooperate with recyclers and another where they do not. Optimal decisions are derived and the comparative analysis of the two models' strengths and weaknesses is conducted. The aim is to offer insights into the decision-making processes of various stakeholders within the closed-loop supply chain of electric vehicle batteries, incentivizing active cooperation among echelon utilization participants, and accelerating the realization of dual carbon goals.

2 Model Description and Basic Assumptions

2.1 Model Description

The closed-loop supply chain of power batteries studied in this paper is composed of manufacturer, consumer market, recycler, echelon utilizer, and echelon utilization market. The manufacturer first decides the unit price of the power battery p_n^i and sells it to the power battery consumer market. Recycler recycle retired power batteries from the consumer market at a price h and decide on the recycling rate τ^i, and the recyclers transfer the high-energy-density batteries in the retired power-batteries to the echelon users at a price g, and the remaining low-energy-density batteries are transferred to the manufacturer at a price f for remanufacturing. Finally, the echelon utilizer determines the price p_t^i of the echelon utilization product and the level m^i of technical input to sell it in the echelon utilization market, and can fully recycle it at the recovery price w and transfer it to the manufacturer.

2.2 Notations

In each decision-making variable and profit π_j^i, $i = b, c$ represents the non-cooperation mode between echelon utilizer and recycler, and the cooperation mode between the echelon utilizer and the recycler. $j = m, r, t, rt$, which represents manufacturer, recycler, echelon utilizer and cooperative enterprise, respectively.

2.3 Basic Assumptions

1) The high-energy-density batteries recycled in the power battery consumer market fully meet the needs of the echelon utilization market [5].

2) The price of the new product is p_n^i, with a demand function of $d_n^i = a - \beta p_n^i$ [6].

3) In this context, both the quality and performance of new products and remanufactured ones are considered equivalent [7].

4) Recyclers recycle old products from consumers at a rate τ_i where $0 < \tau_i \leq 1$, the cost of recycling is $C = \frac{1}{2}A(\tau^i)^2$, where A is the difficulty factor of recycling [8].

5) The unit cost of new products is c_n, while the unit cost of remanufactured products is c_r, $\Delta = c_n - c_r$, In the closed-loop supply chain, $0 < h < f < g$, $f < \Delta$ [9].

6) The demand function of the echelon utilization market for retired batteries is the $d_t^i = k - lp_t^i + \lambda m^i$, λm^i refers to the increase in sales brought about by hard work. $0.5B(m^i)^2$ is the cost of echelon utilization effort [10], where B is large enough.

3 Model Solution

3.1 Non-Cooperation between Echelon Utilizer And Recycler

In this model, where there is no cooperation among supply chain members, the profit functions of the manufacturer, recycler, and echelon utilizer are as follows:

$$\pi_m^b = (p_n^b - c_n + \Delta\tau^b)d_t^b - f\tau^b d_t^b, \pi_r^b = gd_t^b - h\tau d_n^b + f(\tau^b d_n^b - d_t^b) - 0.5A(\tau^b)^2,$$

$$\pi_t^b = (p_t^b - g + f - w)d_t^b - 0.5B(m^b)^2$$

Theorem 1: there is a unique equilibrium solution:

$$p_n^b = \frac{A(a+\beta c_n) - 2a\beta(\Delta - f)(f-h)}{2\beta[A - \beta(\Delta - f)(f-h)]}, \tau^b = \frac{(f-h)(a-\beta c_n)}{2[A-\beta(\Delta - f)(f-h)]},$$

$$p_t^b = \frac{Bk + (\lambda^2 - Bl)(f-g-w)}{2Bl - \lambda^2}, m^b = \frac{\lambda[k + l(f-g-w)]}{2Bl - \lambda^2}.$$

Proof: ① The solution process is to find the first derivative synonymous solution and revert to the generation to get the above result.

3.2 Cooperation between Echelon Utilizer And Recycler

Under this model, the profit function of the manufacturer and the cooperative enterprise is: $\pi_m^c = (p_n^c - c_n + \Delta\tau^c)d_n^c - f\tau^c d_n^c$

$$\pi_{rt}^c = (p_t^c - w)d_t^c + f\tau^c d_n^c - h\tau^c d_n^c - 0.5A(\tau^c)^2 - 0.5B(m^c)^2$$

Theorem 2: there is a unique equilibrium solution:

$$p_n^c = \frac{A(a+\beta c_n) - 2a\beta(\Delta - f)(f-h)}{2\beta[A - \beta(\Delta - f)(f-h)]}, \tau^c = \frac{(f-h)(a-\beta c_n)}{2[A-\beta(\Delta - f)(f-h)]}$$

$$p_t^c = \frac{Bk + (Bl - \lambda^2)w}{2Bl - \lambda^2}, m^c = \frac{\lambda(k - lw)}{2Bl - \lambda^2}$$

Proof: solution sequence and process are the same as those of the previous model.

4 Comparison and Analysis of Solutions

Based on the equilibrium results obtained in the previous section, a comparative analysis of decision variables and profit functions under different modes leads to the following propositions.

Proposition 1: $p_n^b = p_n^c$, $d_n^b = d_n^c$, $\tau^b = \tau^c$

Proposition 1 indicates that cooperation between echelon utilizer and recycler does not increase the demand for new products and the recycling rate of retired electric vehicle batteries. This is because the amount of recycled power batteries is enough to meet the existing demand of the echelon utilization market.

Proposition 2:

(1)When $B < \frac{\lambda^2}{l}$, $p_t^b < p_t^c$;When $B > \frac{\lambda^2}{l}$, $p_t^b > p_t^c$.(2) $m^b < m^c$.(3) $d_t^b < d_t^c$.

Proposition 2 shows that when the cost coefficient of echelon utilization is small, the price of echelon utilization products is larger under the cooperative mode. The opposite is true when the cost factor is large. The effort level and the demand for echelon utilization products is also higher under the cooperation model.

Proposition 3: $\pi_m^b = \pi_m^c$, $\pi_r^b + \pi_t^b < \pi_{rt}^c$

Proposition 3 shows that the manufacturer's profit is the same in the two models, and the profit of the cooperative enterprise in the cooperative mode is higher than the sum of the profits of the echelon utilizers and the recycler in the non-cooperative mode, so the total profit under the cooperative model is also relatively higher.

Proposition 4:Using MATLAB for analysis, the numerical reference is Hou et al. [8], as shown in the figure 1, the profits of cooperative enterprises under the cooperative model are larger, and the profits gradually decrease with the increase of the recovery difficulty coefficient and the utility cost coefficient of the echelon utilizer.

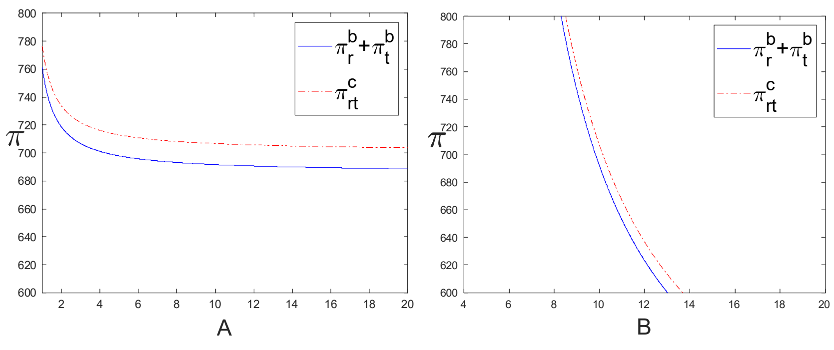

Fig. 1. Numerical analysis

5 Conclusion

This study considers the impacts of cooperation and non-cooperation between recycler and echelon utilizer on supply chain member decisions. Managerial insights include: (1) Manufacturers do not need to consider downstream cooperation, their strategies and profits remain unaffected. (2) Recycler and echelon utilizer should strengthen cooperation to utilize more retired electric vehicle batteries and achieve higher profits.

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