The impacts of subsidy policies and channel encroachment on the power battery recycling of new energy vehicles

Kai Liu and Chuanxu Wang*
School of Economics and Management, Shanghai Maritime University, 1550 Haigang Avenue, Pudong District, Shanghai 201306, China

Abstract

With the rapid development of new energy vehicles (NEVs), the recycling and reuse of retired power batteries has attracted extensive attention from the society and scholars. In this paper, we establish a closed-loop supply chain model composed of the government, one power battery supplier and one NEV manufacturer. Based on game theory, considering whether the battery supplier encroaches on the power battery recycling channel, we study the optimal decisions of the government and supply chain members under different government subsidy policies (no subsidy, subsidy for the NEV manufacturer and subsidy for consumers) and their impact on profits and social welfare. The results show that, whether the battery supplier encroaches on the recycling channel or not, compared with the no subsidy policy, subsidy for the NEV manufacturer is more conducive to the improvement of enterprise profits and social welfare. In addition, whether the battery collection quantity is constrained by the NEV sales quantity, when the recycling channel cost is lower than a certain threshold, the encroachment is always beneficial to the battery supplier. When the recycling channel cost is within a certain threshold range, the encroachment will achieve a win–win situation; otherwise, win–lose. When the recycling channel cost is higher than a certain threshold, the encroachment behavior has no impact on the NEV manufacturer and the battery supplier. Finally, we investigate the impact of key parameters on the enterprise profits and social welfare through numerical experiments. We also find that the environmental awareness of consumers has significant impacts on social welfare.

Keywords: closed-loop supply chain; government subsidy; recycling channel encroachment; retired power battery; new energy vehicles

1. INTRODUCTION

With the rapid development of the new energy vehicles (NEVs) industry, China has become the world’s largest market of NEVs. According to the data from the China Association of Automobile Manufacturers [1], the production and sales of NEVs reached 1.242 million and 1.206 million, respectively, in 2019, declined by ∼2.3% and 4% year-on-year. By 2020, the cumulative sales of NEVs will exceed 5 million. As a key component of NEVs, the output of power batteries has shown explosive growth since 2014. In 2019, the output of power batteries reached 85.4 GWh (increasing 21% over the previous year) and the future retired scale of power batteries is expected to reach 26.69 GWh and 134.49 GWh in 2020. In addition, the current power batteries are mainly divided into lithium-ion batteries (LIBs) and lithium iron phosphate batteries, both of which contain metal materials, such as Co, Ni, Mn and Li, and have high potential value. However, improper disposal of retired power batteries will cause great harm to the ecological environment and massive waste of resources [2].

Governments around the world are actively responding to the huge challenges brought by power batteries. The European Commission issued the Battery Directive 2006/66/EC in September 2006, requiring that all consumed batteries need to be recycled and battery manufacturers shall assume the costs of recycling and disposal and stipulate the minimum recycling rate should reach 45% in September 2016 [3]. In March 2019, the European Union launched the ‘BATTERY 2030+’ strategy and proposed the future development goal of battery recycling rate reaching at least 75%
and achieving key raw material recycling rate close to 100% [4]. In Korea, the ‘Clean Air Conservation Act’ stipulates that it is the duty of consumers to return end-of-life power batteries and consumers will receive certain subsidies [5]. In January 2018, the Ministry of Industry and Information Technology (MIIT) [6] of People’s Republic of China stipulated that automobile manufacturers shall assume the main responsibility for power battery recycling and relevant enterprises shall perform corresponding responsibilities in all links of power battery recycling and utilization. In the 13th Five-Year period, the Chinese government implemented subsidies for battery electric vehicles, plug-in hybrid electric vehicles and fuel cell vehicles and vigorously promoted the development of the new energy automobile industry, but this also brought huge financial pressure to the government. However, the effective implementation of government subsidy policies is inseparable from the joint participation of governments, enterprises and consumers. Different subsidy modes have other effects on the equilibrium decision and social welfare of each member in the closed-loop supply chain (CLSC). In the existing literature on government subsidies, most scholars only consider one kind of government subsidy mode, such as consumer subsidy [7, 8]. Some scholars compared the differences between government subsidies for manufacturers and consumers [9, 10]. Similarly, in the CLSC of power batteries, we consider two different subsidy methods (subsidy for the NEV manufacturer and subsidy for consumers).

In addition, automobile manufacturers are responsible for power battery recycling, while upstream power battery suppliers should actively participate in the recycling and share the corresponding recycling responsibilities for downstream automobile manufacturers. However, at the present stage, there are two feasible disposal methods for end-of-life power batteries: one is echelon utilization, such as used in energy storage systems and portable power source, and the other is reclamation and reuse, in which the battery is disassembled and the raw materials and metals are extracted for reuse [11]. For power battery suppliers, it is necessary to invest funds to build power battery recycling channels and improve the power battery recycling system. However, the cost of channel construction is substantial, which will also cause channel conflicts and negative effects. Hence, it is particularly important to consider the encroachment behavior of power battery suppliers’ recycling channels. Moreover, considering the maximization of social welfare, which subsidy strategy should the government implement? This paper studies the following four problems: (1) will the power battery supplier encroach on the recycling channel? What are the conditions of its encroachment? (2) For the power battery supplier’s recycling channel encroachment behavior, how about the impact on the profit of the NEV manufacturer and overall supply chain performance? (3) What is the equilibrium result of supply chain members under different government subsidy scenarios and battery supplier encroachment strategies? (4) How would the government subsidy policies and the battery supplier’s recycling channel encroachment strategies affect enterprise profits and social welfare?

For these problems, we consider a three-stage supply chain consisting of the government, a power battery supplier and an NEV manufacturer. We take the scenario without government subsidy as the benchmark model and then extend to the other scenarios in which the government subsidizes the NEV manufacturer or consumer. Considering the encroachment behavior of the battery suppliers’ recycling channel, we adopt the game theory method to characterize the equilibrium decisions under six scenarios (government subsidy and whether the recycling channels encroach or not), namely without encroachment scenarios (no subsidy, subsidy for the NEV manufacturer and subsidy for consumers) and encroachment scenarios (no subsidy, subsidy for the NEV manufacturer and subsidy for consumers). Further, we explore the influence of government subsidy policies and recycling channel encroachment strategies on enterprise profits and social welfare. Besides, we use numerical experiments to study the impact of key parameters on equilibrium strategies, enterprise profits and social welfare.

This paper’s contributions are as follows. (1) In the context of NEVs, we construct a CLSC model for the recycling of retired power batteries and analyze the impacts of government subsidies and the encroachment of recycling channels on the decisions of the enterprises and the government. (2) Considering whether the collection quantity is constrained by the sales quantity, we not only obtain the optimal pricing strategies of enterprises under different scenarios but also obtain the conditions under which battery suppliers adopt the recycling channel encroachment strategy. When battery suppliers choose channel encroachment strategies, it is always beneficial to itself. However, when the channel cost is within a certain threshold range, NEV manufacturers will also benefit. (3) We also obtain the optimal decision of government subsidy under different scenarios and compare the impact of subsidy and recycling channel encroachment strategies on social welfare and present useful insights for enterprises and policymakers. (4) We enrich the research on the recycling of retired power batteries in the context of NEVs and make certain contributions to the CLSC management and other related theories.

The rest of this paper is described below. Section 2 combed the relevant literature from three perspectives. We describe and assume the model in Section 3. Section 4 discusses the optimal strategy of battery supplier with recycling channel encroachment behavior under different subsidy situations. Section 5 compares the optimal results among the different scenarios. In Section 6, we conduct numerical experiments to analyze the influence of related parameters. In Section 7, a summary of this paper and the future research directions are presented. The proofs are provided in the Appendix.

2. LITERATURE REVIEW

Despite the recycling of power batteries in the context of NEVs has attracted increasing attentions, the relationship among government subsidy, supplier recycling channel encroachment and social welfare has hardly been explored. We mainly conduct literature
reviews from the following three categories: Section 2.1 focuses on NEVs battery recycling in a CLSC. And then, we discuss supplier/manufacturer channel encroachment in Section 2.2. In Section 2.3, we discuss the government subsidy in a supply chain.

2.1. NEVs battery recycling in a CLSC
This study is closely related to the literature on power battery recycling, most of which focus on the technical problems in the battery recycling process [12, 13] and economic and environmental analysis of battery recycling and reusing [14, 15]. However, there is little literature on power battery recycling strategies. Based on uncertain market demand, Gu et al. [16] studied the optimal production strategy of the automobile manufacturer under the conditions of government subsidy and battery recycling and found that consumer subsidy and battery recycling can help the electric vehicle manufacturer increase their output. Gu et al. [17] investigated the CLSC of battery recycling by the battery manufacturer and the remanufacturer and found that battery recycling can reduce the consumption of raw materials and reduce the impact on the environment but may not bring economic benefits. Tang et al. [18], based on the reward and punishment mechanism, studied the impact of recycling of waste and scrap electric vehicle batteries on society, economy and environment, and the results show that the reward and punishment mechanism has a greater impact on the recycling rate and social welfare. Based on the recycling of retired power batteries, Zhu et al. [19] explored the optimal channel selection and battery capacity allocation strategy for the electric vehicle manufacturer. Different from the above, based on the CLSC of NEVs, we have studied whether the power battery supplier encroaches on the recycling channel and the influence of different government subsidy policies on the recycling quantities, which fills the research gap for the research of retired power battery recycling and also has certain reference significance for enterprises and policymakers.

2.2. Supplier/manufacturer channel encroachment
Whether the power battery supplier encroaches on the recycling channel and forms a recycling competition relationship with the NEV manufacturer is also a matter of concern. Some scholars have carried out research on the encroachment behavior in the supply chain, and the encroachment behavior of the supplier/manufacturer may cause loss of retailer or supply chain performance [20, 21]. Li et al. [22] explored the impact of supplier encroachment on supply chain information management and found that supplier encroachment is always beneficial to the supplier, but encroachment may be detrimental to supply chain performance. Li et al. [23] studied the phenomenon of supplier encroachment under information asymmetry and nonlinear pricing and found that supplier encroachment may be beneficial or unfavorable to the supplier and the retailer. In some cases, the supplier/manufacturer encroachment can also increase the retailer’s profits [24, 25]. Chiang et al. [26] analyzed the conditions for the introduction of the manufacturer direct channel and their impact on the retailer and found that when consumers’ preference for the direct channel is higher than a certain threshold, the introduction of the direct channel is beneficial to the retailer. Arya et al. [27] found that when the cost advantage of the retailer’s sales channel is large enough, the manufacturer’s channel encroachment is beneficial to the retailer. Zhang et al. [28] explored the impact of manufacturer encroachment and emission reduction strategies on the retailer’s profit under different channel structures, and the results show that manufacturer’s encroachment is always better for itself and manufacturer encroachment will increase the retailer’s profits only when consumer environmental preferences are high. Furthermore, Zhang et al. [29] analyzed the impact of manufacturer encroachment on product quality and the profits of supply chain members and found that the encroachment behavior of the manufacturer is not only beneficial to itself but also beneficial to the retailer. Zheng et al. [30] investigated the effect of manufacturers’ encroachment strategy on the performance of the retailer and supply chain system in CLSC and found that the retailer can benefit if the channel competition is not intense. However, these scholars have not conducted research on the strategy of supplier/manufacturer recycling channel encroachment. Besides, the influence of government subsidy policies on encroachment behavior has also been ignored. Therefore, in the CLSC, we consider different government subsidy policies and supplier recycling channel encroachment behavior to reveal some management insights.

2.3. Government subsidy in a supply chain
Regarding the government subsidies, the current literature mainly analyzes the impact of different government subsidy objects on the decision and profits of supply chain members, as well as the choice of the optimal subsidy policy. Heydari et al. [31] analyzed the practical significance of government subsidies to manufacturers and remanufacturers’ profits, and the results showed that part of the subsidy should be given to the manufacturer. Ma et al. [7] comparatively analyzed the enterprise equilibrium strategy before and after the implementation of the government subsidy, and the results showed that consumers, manufacturers and retailers could benefit from government subsidies, while e-retailers were not sure whether they could benefit from government subsidies. Xiao et al. [9] compared the impact of remanufacturer subsidy and consumer subsidy on equilibrium strategy and profits and found that remanufacturer subsidy had the best effect. Cohen et al. [32] discussed the effect of consumer subsidies on the government, enterprises and consumers under the condition of uncertain demand. Bian et al. [33] explored the influence of manufacturer subsidies and consumer subsidies on manufacturer’s emissions abatement, enterprise profits and social welfare. However, these studies did not take into account the background of NEVs. Based on the CLSC of NEVs, Zhao et al. [34] compared the impact of different government subsidy objects on enterprise profits and supply chain competitiveness. Sheldon and Dua [35] explored the impact of high/low-income consumer subsidy plan on the purchase behavior and cost-effectiveness of plug-in electric vehicles. Kong et al. [36] used system dynamics to discuss the
effect of other policies on the diffusion model of electric vehicles in the case of subsidy policies ‘fall off’ and found that the cancellation of subsidy will seriously affect the market share of electric vehicles in China (down 40.39%). Different from these studies, for the CLSC of NEVs, we discussed issues related to the government subsidy and the recycling of retired power batteries. Specifically, we compared the impact of three possible government subsidies (no subsidy, subsidy for the NEV manufacturer and subsidy for consumers) on enterprise profits.

In addition, some scholars also discussed the overall social welfare under the government subsidy policy. In the context of NEVs, Shao et al. [37] compared the impact of consumer subsidy plan and price discount plan on the use of electric vehicles and social welfare and found that consumer subsidy plan are more effective. Gu et al. [38] analyzed the impact of subsidy distribution on electric vehicle supply chain profit under incomplete information and found that more subsidies should be allocated to consumers in the early stage of subsidy and the later stage of electric vehicle manufacturers. The difference from the above is that in the context of the CLSC of NEVs, we have considered the impact of different government subsidy policies on social welfare.

In addition, we also focus on the impact of battery supplier recycling channel encroachment on enterprise and social welfare. Table 1 shows the differences between the existing literature and this paper.

### Table 1. Comparison between this study and the related literature.

| Authors            | Consider the NEV supply chain | Manufacturer subsidy | Consumer subsidy | Constraint condition | Channel encroachment | Social welfare |
|--------------------|-------------------------------|----------------------|------------------|----------------------|----------------------|---------------|
| Heydari et al. [31]| √                             |                      |                  |                      |                      |               |
| Ma et al. [7]      |                               | √                    |                  |                      |                      |               |
| Xiao et al. [9]    |                               |                      |                  |                      |                      |               |
| Cohen et al. [32]  |                               |                      |                  |                      |                      |               |
| Bian et al. [33]   |                               |                      |                  |                      |                      |               |
| Zhao et al. [34]   |                               |                      |                  |                      |                      |               |
| Sheldon and Dua [35]|                 |                      |                  |                      |                      |               |
| Kong et al. [36]   |                               |                      |                  |                      |                      |               |
| Shao et al. [37]   |                               |                      |                  |                      |                      |               |
| Gu et al. [38]     |                               |                      |                  |                      |                      |               |
| Our work           |                               |                      |                  |                      |                      |               |

3. PROBLEM DESCRIPTIONS AND MODEL ASSUMPTIONS

We consider a CLSC consisting of the government, one power battery supplier (e.g. CATL) and one NEV manufacturer (e.g. Dongfeng Motor Corporation). In the forward channel, the power battery supplier is responsible for the production of the power batteries and the wholesale price is $w$. The NEV manufacturer assembles NEVs for sale by purchasing power batteries, and the selling price is $p$. In the reverse channel, when the power batteries meet the retired requirements, it can also be used for cascade use (e.g. energy storage) through recycling to obtain economic benefits. We designed two possible channel structures, as shown in Figure 1, namely the CLSC model without channel encroachment (Figure 1a) and the CLSC model under channel encroachment (Figure 1b). The former means that only the NEV manufacturer is responsible for recycling the power battery; the recycling price is $b_m$; and the unit transfer price of the power battery supplier is $t$. The latter indicates that the power battery supplier, as an important participant in battery recycling, decides whether to encroach upon the recycling channel, and the direct recycling price is $b_s$. In these two possible channel structures, we propose three different subsidy scenarios, namely without subsidy, subsidy for the NEV manufacturer and subsidy for consumers.
Table 1 summarizes the notation used throughout this paper and the following are assumed in this paper. First, we assume that all participants are completely rational, risk neutral and make the optimal decision according to their maximum expected profit. However, the government aims to maximize the total social welfare. Second, we assume that the information is symmetric, the power batteries sold and recycled are the same type and there is no difference in quality or function between remanufactured power batteries and the new ones. Third, following the existing literature by Xu et al. [39], we assume that the battery supplier and the NEV manufacturer's production capacity are sufficient to meet the demand of the market or consumers. The market demand function of NEVs is \( D = a - bp \), where \( a, b > 0 \) and are both constant.

Following most previous studies [40, 41], they define the unit cost saving as \( \Delta = c_n - c_r \). Unlike previous researches, following the Tang et al. [42], we consider the echelon utilization of retired power batteries and the unit cost saving can be expressed as \( \Delta = c_n - c_r + \lambda \widetilde{L} \), where \( c_n - c_r \) represents the production cost saving when battery suppliers use recycled battery dismantling materials for remanufacturing and \( \lambda \widetilde{L} \) represents the revenue from the echelon utilization. If the battery supplier open the recycling channel, the unit channel cost is \( c_s^i \) \( (i = N, M, C, NE, ME, CE) \). Obviously, \( c_s^N = c_s^{NE} = 0 \) but \( c_s^M = c_s^C = c_s^{ME} = c_s^{CE} = c_s \) is assumed.

In addition, considering the encroachment behavior of battery supplier, when the power battery supplier does not encroach on the recycling channel, the power battery supplier and the NEV manufacturer have no competition in the recycling channel. Therefore, according to the research of Karakayali et al. [43], the NEV manufacturer's power battery recycling quantity can be expressed as \( R_m(b_m) = L_0 + L_1 b_m \). When the power battery supplier encroaches on the recycling channel, the power battery supplier and the NEV manufacturer are recycling at the same time in the recycling channel and there are channel conflicts. At this point, the automobile manufacturer is closer to the consumer and has the recycling advantage. Only when the power battery supplier's recycling price is higher than the NEV manufacturer, namely \( b_s > b_m \), the consumer will choose to recycle the power battery through the power battery supplier. If the power battery supplier's recycling price is lower than the NEV manufacturer, consumers will choose the NEV manufacturer. The recycling quantity of the NEV manufacturer's and the power battery supplier's power batteries can be expressed as \( R_m(b_m) = L_0 + L_1 b_m - L_2(b_s - b_m) \) and \( R_s(b_s) = L_2(b_s - b_m) \), respectively. Where \( L_0 \) represents the quantities of retired power batteries returned by consumers; \( L_1 \) is the consumer's sensitivity to the NEV manufacturer's recycling price; and \( L_2 \) represents the sensitivity coefficient of the consumer to the difference between the power battery supplier's and the NEV manufacturer's recycling prices.

Maximizing social welfare is widely applied in the CLSC literature, consistent with Jacobs and Subramanian [44], Wang et al. [45] Xu et al. [46] and Zhang et al. [47], the government's objective function, which contains the following four key elements: (1) the sum of firms’ profits \( \pi_i + \pi_m \); (2) the consumer surplus \( CS' = \frac{(a - bp)^2}{2b} \); (3) the environmental benefit \( E' = c(R_m + R_s) \); and (4) the total government subsidy expenditure \( GS' \). Therefore, it can be expressed as \( SW' = \pi_i + \pi_m + CS' + E' - GS' \). In model \( i \), where \( i = \{ N, M, C, NE, ME, CE \} \) respectively represent the case of no encroachment (without subsidy model, NEV manufacturer subsidy model, consumer subsidy model) and the case of recycling channel encroachment (without subsidy model, NEV manufacturer subsidy model, consumer subsidy model). \( m^*, n^* \) and \( \nu^* \) represents the optimal level of government unit subsidies to the NEV manufacturer and consumers, respectively. For illustration purposes, we list all notations in the following Table 2.

### 4. GOVERNMENT SUBSIDIES AND ENCROACHMENT MODELS

In this section, based on whether the battery supplier encroaches on the recycling channel, we get the equilibrium decision of the government, battery supplier and NEV manufacturer under different subsidy models. By comparing the six models, the government’s optimal subsidy strategy and the optimal channel choice of the battery supplier can be determined.

#### 4.1. The CLSC model without channel encroachment

When the CLSC model without channel encroachment, we first consider Scenario N as a benchmark model and then expand and analyze Scenarios M and C. We have obtained the equilibrium decision of the government, power battery supplier and NEV manufacturer under different subsidy models, as well as the government’s optimal subsidy strategy.

##### 4.1.1. Without subsidy model (Scenario N)

In this model, both the power battery supplier and the NEV manufacturer aim to maximize their own profits. The power battery supplier is responsible for producing power batteries and supplying power batteries to the NEV manufacturer; the NEV manufacturer is responsible for the production and assembly of NEVs but cannot produce batteries, so the NEV manufacturer needs to buy batteries from the power battery supplier and recycle the retired power batteries. In the reverse channel, the NEV manufacturer is responsible for collecting retired power batteries from consumers and the unit recycling price is \( b \). It should be noted that, due to the limitations of relevant technologies, the NEV manufacturer could not realize the cascade utilization and the NEV manufacturer must transfer the retired battery to the power battery supplier to realize the cascade utilization of the power battery [19]. Besides, the game order of CLSC under this model is as follows: first, the power battery supplier (Leader) determines the wholesale price \( w \) and the transfer price \( t \) per unit. Then, the NEV manufacturer (Follower) determines the retail price \( p \) and the recycling price \( b \) per unit according to the power battery supplier’s decision. Hence, the battery supplier and the
NEV manufacturer’s profit functions are given as follows:

\[ \pi_s^N (w, t) = (w - c_1) D + (\Delta - t) R_m (b_m) \]  
\[ \pi_m^N (p, b_m) = (p - w - c_2) D + (t - b_m) R_m (b_m) \]  
\[ \text{s.t. } R_m (b_m) \leq a - bp \]  

In Equation (1), the first term represents the profit from selling the power batteries. The last term represents the profits of the recycling of retired power batteries. In Equation (2), the first term represents the profit from selling the NEVs. The last term represents the transfer payment cost that the battery supplier pays to the NEV manufacturer.

To solve the above problems, we can obtain the optimal whole-sell price and transfer price of the battery supplier, the optimal selling price and recycling price of the NEV manufacturer and their own profits. We use the superscript * and \( i = \{ N, M, and C \} \) to denote the optimal solutions in the three subsidy models. We summarize all the equilibrium solutions of Scenario N in Table 3.

4.1.2. Subsidy for the NEV manufacturer (Scenario M)

To promote the production of energy-saving products, the government provides financial subsidies to manufacturers. For example, on 26 May 2010, the Chinese government issued the ‘Energy Saving Products Benefit People Project’ implementation rules. Chinese automakers have received government subsidies to promote energy-efficient vehicles, with a subsidy standard of 3000 yuan per vehicle. We assume that the government provides a subsidy of \( m \) per unit for NEVs produced by NEV manufacturers and encourages the NEV manufacturer’s to continue to invest in recycling and remanufacturing activities. Hence, the power battery supplier and the NEV manufacturer’s profit function can be expressed as follows:

\[ \pi_s^M (w, t) = (w - c_1) D + (\Delta - t) R_m (b_m) \]  
\[ \pi_m^M (p, b_m) = (p - w - c_2 + m) D + (t - b_m) R_m (b_m) \]  
\[ \text{s.t. } R_m (b_m) \leq a - bp \]  

4.1.3. Subsidy for consumers (Scenario C)

Government agencies often promote the sustainable development of NEVs through direct subsidies to consumers, which helps promote environmental protection upgrades and improve the environment. For example, on 3 March 2020, the Guangzhou Municipal Government promulgated relevant policies to revitalize automobile consumption, giving consumers an annual comprehensive subsidy of RMB 10 000 to purchase NEVs and granted RMB 3000 in subsidies for replacing or purchasing new vehicles of the ‘National VI’. When consumers buy products that meet national policy requirements, the government directly provides financial subsidies. Suppose the government provides subsidies \( v \) per unit to consumers who purchase NEVs and the demand function can be expressed as \( D = a - bp + v \). Hence, the power battery supplier and the NEV manufacturer’s profit function can be expressed as follows:

\[ \pi_s^C (w, t) = (w - c_1) D + (\Delta - t) R_m (b_m) \]  
\[ \pi_m^C (p, b_m) = (p - w - c_2) D + (t - b_m) R_m (b_m) \]  
\[ \text{s.t. } R_m (b_m) \leq a - bp + v \]  

By solving Scenarios M and C, we can obtain the equilibrium solutions, as shown in Table 2.

4.2. The CLSC model with channel encroachment

Manufacturer’s encroachment of recycling channels is common in the electronic product industry. In the context of NEVs, battery supplier recycling channel encroachment decisions will be affected by recycling channel competition and the echelon utilization and reuse efficiency of retired power batteries. Therefore, on the basis of model N, we considered the encroachment of battery suppliers’ recycling channels and obtain equilibrium strategies under different subsidy models. By comparing the different models, we can determine the battery supplier’s recycling channel encroachment strategy and the government’s optimal subsidy level.

4.2.1. Recycling encroachment without governmental subsidy (Scenario NE)

In Scenario NE, both the power battery supplier and the NEV manufacturer aim to maximize their own profits. The power battery supplier is responsible for producing power batteries and supplying power batteries to the NEV manufacturer; the NEV manufacturer is responsible for the production and assembly of NEVs but cannot produce batteries, so the NEV manufacturer needs to buy batteries from the power battery supplier. In the reverse channel, the power battery supplier chose to open the recycling channel to directly recycle the retired power battery, forming a recycling competition with the NEV manufacturer. The game order of Scenario NE is as follows: first, the power battery supplier determines the wholesale price \( w \) and the transfer payment price \( t \) per unit. Then, the NEV manufacturer determines the retail price \( p \) and recycling price \( b_m \) per unit. Finally, the power battery supplier determines the recycling price \( b_s \). Hence, the power battery supplier and the NEV manufacturer’s profit functions are as follows:

\[ \pi_s^{NE} (w, t, b_s) = (w - c_1) D + (\Delta - b_s - c_i) R_s (b_s) \]  
\[ + (\Delta - t) R_m (b_m) \]  
\[ \pi_m^{NE} (p, b_m) = (p - w - c_2) D + (t - b_m) R_m (b_m) \]  
\[ \text{s.t. } R_m (b_m) + R_s (b_s) \leq a - bp \]  

In Equation (7), the first term represents the profit from selling the power batteries. The second term represents the profit available for the power battery supplier to participate in the recycling channel encroachment. The last term represents the profit brought to the power battery supplier by the NEV manufacturer.
These findings highlight the role of demand-side participation in the recycling of retired power batteries. In Equation (8), the first term represents the profit from selling the NEVs. The last term represents the transfer payment cost that the battery supplier pays to the NEV manufacturer. Similarly, we use the superscript * and NE, ME, CE to denote the optimal solutions with the power battery supplier’s recycling channel enroachment in the three subsidy modes. The equilibrium solutions of Scenario NE are shown in Table 4.

### 4.2.2. Recycling enroachment with subsidy for the NEV manufacturer (Scenario ME)

In Scenario ME, the government provides a financial subsidy to the NEV manufacturer, of m per unit; the battery supplier can either directly collect retired power batteries from consumers (unit channel cost is $c_i$) or provide the NEV manufacturer with a uniform transfer price $t$ to collect retired power batteries. In this scenario, the government first sets $m$; then, the manufacturer sets $w, t, b_t$ to maximize its own profits; finally, the NEV manufacturer determines $p, b_m$ to maximize its own profits. Hence, the power battery supplier and the NEV manufacturer’s profit functions are as follows:

$$\pi_s^{ME}(w, t, b_t) = (w - c_1)D + (\Delta - b_s - c_s)R_s(b_s) + (\Delta - t)R_m(b_m)$$

(9)

$$\pi_m^{ME}(p, b_m) = (p - w - c_2 + m)D + (t - b_m)R_m(b_m)$$

s.t. $R_m(b_m) + R_s(b_s) \leq a - bp$

Table 4. Equilibrium solution under different subsidy scenarios (without enroachment).

| Scenario N | Scenario M | Scenario C |
|------------|------------|------------|
| $\phi_m^N < 0$ | $\phi_m^N \geq 0$ | $\phi_m^N \geq 0$ |
| $\phi_m^M < 0$ | $\phi_m^M \geq 0$ | $\phi_m^C < 0$ |
| $\phi_m^C \geq 0$ | $\phi_m^C \geq 0$ | $\phi_m^C \geq 0$ |

Table 3. Equilibrium solution under different subsidy scenarios (without enroachment).

Notation Explanation

| Notation | Explaination |
|----------|--------------|
| $b_m$ | Recycling prices for the NEV manufacturer |
| $b_t$ | Recycling prices for the power battery supplier |
| $p$ | Retail price of NEVs |
| $c_1$ | The unit cost of producing a new power batteries from raw materials |
| $c_2$ | The unit cost of using recycled materials to produce and remanufacture power batteries |
| $c_r$ | The NEV manufacturer’s cost of producing a NEVs excluding battery cost |
| $L$ | The cost of setting up recycling channel for the battery supplier |
| $\Delta$ | The residual capacity for one retired power battery; $L$ is a normal distribution, the mean is $\mu_L$ and the variance is $\sigma^2_L$. |
| $\lambda$ | The net profit of each unit of residual capacity that can be echelon utilized in a retired power batteries |
| $\delta$ | The proportion of the cost of power batteries in the total cost of NEVs |
| $w$ | Wholesale prices of the battery supplier |
| $t$ | The unit transfer price from the NEV manufacturer to the power battery supplier |
| $R_m$ | The collection quantity of retired power batteries by the NEV manufacturer |
| $R_t$ | The collection quantity of retired power batteries by the power battery supplier |
| $L_t$ | The quantities of retired power batteries returned by consumers |
| $L_1$ | The consumer’s sensitivity to the NEV manufacturer’s recycling price |
| $L_2$ | The sensitivity coefficient of the consumer to the difference between the power battery supplier and the NEV manufacturer’s recycling prices |
| $\Phi_m^M$ | T he unit environmental benefit of recycling retired power batteries |
| $\Phi_m^C$ | T he unit environmental benefit of recycling retired power batteries |

Notations and explanations.

- $\phi_m^N < 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
- $\phi_m^N \geq 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
- $\phi_m^M < 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
- $\phi_m^M \geq 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
- $\phi_m^C < 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
- $\phi_m^C \geq 0$: T he NEV manufacturer's cost of producing a NEVs excluding battery cost
Table 4. Equilibrium solution under different subsidy scenarios (with enforcement).

| Scenario | NE | ME | CE |
|----------|----|----|----|
| $\phi_m^{NE} < 0$ | $\phi_m^{NE} \geq 0$ | $\phi_m^{ME} < 0$ | $\phi_m^{ME} \geq 0$ | $\phi_m^{CE} < 0$ | $\phi_m^{CE} \geq 0$ |
| $w^{E*}$ | $a+b\left(c_1-c_0\right)$ | $4\left(a+bc_1-bc_2\right)L_1-bX_1\right)$ | $4\left(a+bc_1-bc_2+bm\right)L_1-bX_1\right)$ | $a+b\left(c_1-c_0\right)$ | $a+b\left(c_1-c_0\right)$ |
| $p^{E*}$ | $2Y_2X_2L_1$ | $4Y_2\left(X_2+bm\right)Y_1+bX_1\right)$ | $4Y_2\left(X_2+bm\right)L_1+bX_1\right)$ | $2Y_2X_2L_1$ | $2Y_2X_2L_1$ |
| $b^{E*}$ | $\left(\frac{Y_1+Y_2}{Y_1+Y_2}\right)X_1Y_1$ | $2\left(X_2+bm\right)Y_1\left(Y_1+Y_2\right)$ | $2\left(X_2+bm\right)L_1+bX_1\right)$ | $\left(\frac{Y_1+Y_2}{Y_1+Y_2}\right)X_1Y_1$ | $\left(\frac{Y_1+Y_2}{Y_1+Y_2}\right)X_1Y_1$ |
| $q^{E*}$ | $\frac{1}{2}X_2$ | $\frac{1}{4}\left(X_2+bm\right)$ | $\frac{1}{4}\left(X_2+bm\right)$ | $\frac{1}{2}X_2$ | $\frac{1}{2}X_2$ |
| $R^{E*}$ | $\frac{Y_2X_2L_1}{B_2}$ | $Y_1Y_2X_1L_1+2L_2X_2L_2$ | $2L_2Y_2\left(X_2+bm\right)L_1+bX_1\right)$ | $Y_1Y_2X_1L_1+2L_2X_2L_2$ | $2L_2Y_2\left(X_2+bm\right)L_1+bX_1\right)$ |
4.2.3. Recycling encroachment with subsidy for consumers
(Scenario CE)

In Scenario CE, the government provides subsidies $v$ per unit to consumers who purchase NEVs and the demand function can be expressed as $D = a - bp + v$. Similarly, the power battery supplier and the NEV manufacturer's profit functions are as follows:

$$\pi_s^{CE} (w, t, b_s) = (w - c_1) D + (\Delta - b_s - c_s) R_s (b_s) + (\Delta - t) R_m (b_m)$$

(11)

$$\pi_m^{CE} (p, b_m) = (p - w - c_2) D + (t - b_m) R_m (b_m)$$

(12)

Solving the optimization models of Scenarios ME and CE, we can obtain the equilibrium solutions summarized in Table 4.

In all scenarios, the optimal wholesale price $w^*$/w$^{ME}$, the optimal transfer price $\pi_s^{ME}$/\$^{CE}$, the optimal retail price $p^*/p^{ME}$, the NEV manufacturer's optimal recycling price $b^*/b^{ME}$, the optimal order quantity $q^*/q^{ME}$, and the battery collection quantity $R^*/R^{ME}$ are all shown in Tables 3 and 4.

5. RESULTS ANALYSIS

Proposition 1. By comparing the wholesale price of batteries and the sales price of NEVs under different subsidy scenarios, the following results are obtained.

(1) The battery collection quantity is not constrained by the NEV sales quantity, when $1 < b < \frac{1}{2}$ and $a > b(c_1 + c_2)$, we have $w^{M_s} > w^{CE_s} > w^{NE_s}$, $p^{CE_s} > p^{NE_s} > p^{M_s}$, $b^{M_s} = b^{CE_s} = b^{NE_s}$, $b^{M_s} = b^{CE_s} = b^{NE_s}$, $p^{M_s} > p^{NE_s} > p^{CE_s}$, $b^{M_s} > b^{NE_s} > b^{CE_s}$, $b^{M_s} > b^{NE_s} > b^{CE_s}$, $w^{M_s} > w^{CE_s} > w^{NE_s}$, $p^{M_s} > p^{CE_s} > p^{NE_s}$, $b^{M_s} = b^{CE_s} = b^{NE_s}$, $b^{M_s} = b^{CE_s} = b^{NE_s}$. When the battery collection quantity is constrained by the NEV sales quantity, when $\frac{1}{2} < b < 1$ and $a < b(c_1 + c_2)$, we have $w^{M_s} > w^{CE_s} > w^{NE_s}$, $p^{CE_s} > p^{NE_s} > p^{M_s}$, $b^{M_s} > b^{CE_s} > b^{NE_s}$, $b^{M_s} > b^{CE_s} > b^{NE_s}$, $w^{M_s} > w^{CE_s} > w^{NE_s}$, $p^{M_s} > p^{CE_s} > p^{NE_s}$, $b^{M_s} > b^{CE_s} > b^{NE_s}$, $b^{M_s} > b^{CE_s} > b^{NE_s}$. When $Z_1 = 2L_1(Y_2 - 8Y_1^2) + B_2$.

Proposition 1 shows that, in the forward channel, when the battery collection quantity is not constrained by the NEV sales quantity, the two subsidy plans increase the wholesale price of power batteries. However, for the sales price of NEVs, subsidy for the NEV manufacturer reduces the sales price, which is more beneficial to consumers, while subsidy for consumers raises the sales price. In the reverse channel, when the battery collection quantity is not constrained by the NEV sales quantity, the government subsidy has no effect on the recycling price, while when the battery collection quantity is constrained, the government subsidy increases the recycling price.

Corollary 1. By comparing the impact on the wholesale price of batteries $w$ and the sales price of NEVs $p$ under three different subsidy programs (without and with the battery supplier's encroachment), the following conclusions are obtained.

(1) When the battery collection quantity is not constrained by the NEV sales quantity, $w^{ME_s} = w^{CE_s} = p^{ME_s} = p^{CE_s}$.

(2) When the battery collection quantity is constrained by the NEV sales quantity,

(i) When $c_s > \max \left\{ \frac{bL_0 + (X_c + b) L_1(5L_1 + 4L_2)}{2L_1(b - L_1)(4L_1 + 3L_2)}, \frac{2L_0 + (X_c + b) L_1(7L_1 + 4L_2)}{2L_1(b - L_1) + 4BL_2} \right\}$, $w^{ME_s} > w^{NE_s}$, $p^{ME_s} > p^{NE_s}$.

(ii) When $c_s \leq \min \left\{ \frac{bL_0 + (X_c + b) L_1(5L_1 + 4L_2)}{2L_1(b - L_1)(4L_1 + 3L_2)}, \frac{2L_0 + (X_c + b) L_1(7L_1 + 4L_2)}{2L_1(b - L_1) + 4BL_2} \right\}$, $w^{ME_s} \leq w^{NE_s}$, $p^{ME_s} \leq p^{NE_s}$.

Corollary 1 shows that when the battery collection quantity is not constrained by the NEV sales quantity, whether it encroaches on the recycling channel or not, it has no effect on the wholesale price of batteries and the sales price of NEVs. This is because when the demand is large enough, decisions in the forward and reverse supply chains are independent of each other. When the battery collection quantity is constrained by the NEV sales quantity and the unit channel cost is less than a certain threshold, the wholesale price of the battery under the encroachment of the recycling channel is less than the scenario of no encroachment. This is because the recycling price is a function of output and the increase in remanufacturing cost savings will encourage the power battery supplier to reduce the wholesale price of batteries. When the unit channel cost is greater than a certain threshold, the opposite is true. However, the sales price of NEVs in Scenario ME is more favorable to consumers.
CLSC. The NEV manufacturer is responsible for selling NEVs and is the terminal of the forward supply chain. Meanwhile, as the main body of recycling, the NEV manufacturer is the starting point of the reverse supply chain and is closer to consumers. Also, on the one hand, government subsidies reduce production costs, stimulate consumer demand and affect product sales, and on the other hand, the existence of recycling channel conflict also affects the collection quantity of retired power batteries. The total collection quantity of the recycling channel under the subsidy NEV manufacturer scenario is higher than other scenarios, so the government subsidy for the NEV manufacturer is more effective.

Proposition 3.

(1) When the battery collection quantity is not constrained by the NEV sales quantity, when \( c_s \) satisfies \( c_s^{E1} < N_s^{E1} \), the battery supplier chooses to open the recycling channel, where \( N_s^{E1} = \frac{2(2L_0 + b\Delta L_1 + 4L_1)Y_1}{B_2 - 2L_2 Y_1} \).

(2) When the battery collection quantity is constrained by the NEV sales quantity, when \( c_s \) satisfies \( c_s^{NE2} < N_s^{E2} \), \( c_s^{ME2} < N_s^{E2} \), \( c_s^{CE2} < N_s^{E2} \), the battery supplier chooses to open the recycling channel, where \( N_s^{NE2} = \frac{2(4L_0 + b(X_2 + b\Delta) + b\Delta L_1 + b\Delta Y_1)Y_1}{4L_2 Y_1 + 2L_2 Y_1}, N_s^{ME2} = \frac{2(4L_0 + b(X_2 + b\Delta) + b\Delta L_1 + b\Delta Y_1)Y_1}{4L_2 Y_1 + 2L_2 Y_1}, N_s^{CE2} = \frac{2(4L_0 + b(X_2 + b\Delta) + b\Delta L_1 + b\Delta Y_1)Y_1}{4L_2 Y_1 + 2L_2 Y_1} \).

Corollary 2.

(1) When the battery collection quantity is not constrained by the NEV sales quantity, when \( c_s \) satisfies \( c_s^{E1} \in \{\max(0, N_s^{E1}), N_s^{E1}\} \), the encroachment of recycling channel by the battery supplier is beneficial to the NEV manufacturer, where \( N_s^{E1} = \frac{L_0 + \Delta L_1 + b\Delta Y_1}{b\Delta Y_1 + 2L_2 Y_1 - 1} \).

(2) When the battery collection quantity is constrained by the NEV sales quantity, when \( c_s \) satisfies \( c_s^{NE2} \in \{N_s^{NE2}, N_s^{E2}\}, c_s^{ME2} \in \{N_s^{ME2}, N_s^{E2}\}, c_s^{CE2} \in \{N_s^{CE2}, N_s^{E2}\} \), the encroachment of recycling channel by the battery supplier is beneficial to the NEV manufacturer, where \( N_s^{NE2} = [bL_0 + (X_2 + b\Delta) L_1] A_1, N_s^{ME2} = [bL_0 + (X_2 + b\Delta) L_1] A_1, N_s^{CE2} = [bL_0 + (X_2 + b\Delta) L_1] A_1, \)

From Proposition 3 and Corollary 2, it can be seen that the government subsidy and the channel cost have an impact on the battery supplier's channel decision, while the recycling channel encroachment of the battery supplier may lead to three different situations, namely win–win, win–lose or break-even. Specifically, whether the battery collection quantity is constrained by the NEV sales quantity, when the channel cost is lower than a certain threshold, the battery supplier chooses to open the recycling channel, which is beneficial to itself; when the channel cost is within a certain threshold, the encroachment of the recycling channel is conducive to the increase of the profit of the NEV manufacturer and achieve win–win situation, otherwise a win–lose situation will be formed. When the channel cost is higher than a certain threshold, the battery supplier will not open the recycling channel, namely break-even situation.

Proposition 4.

For the battery supplier (Scenarios NE, M and C), there exists a threshold of the subsidy level:

1. If \( 0 \leq m \leq \min(B_1 - \frac{X_2}{b}, B_1 - X_2) \) and \( c_s < \frac{2(4L_0 + \Delta L_1 + b\Delta Y_1)Y_1}{B_2 - 2L_2 Y_1} \), Scenario NE is more beneficial to the battery supplier (i.e. \( \pi_s^{NE} > \pi_s^{CE} \)).

2. If \( B_1 - \frac{X_2}{b} < m < B_1 - X_2 \) and \( c_s < \frac{2(4L_0 + \Delta L_1 + b\Delta Y_1)Y_1}{B_2 - 2L_2 Y_1} \), Scenario M is more beneficial to the battery supplier (i.e. \( \pi_s^{ME} > \pi_s^{CE} \)).

3. If \( \max(B_1 - \frac{X_2}{b}, B_1 - X_2) < m < \frac{4a - X_2}{b} \), Scenario M is more beneficial to the battery supplier (i.e. \( \pi_s^{ME} > \pi_s^{CE} \)).

where \( B_1 = \sqrt{\frac{X_2}{b}} + L_2 h(Y_1 + Y_2) \).

Proposition 4 reflects when the battery supplier should adopt Scenario NE, M or C. If the level of government subsidies is low, the battery supplier will directly participate in recycling activities. However, with the increase in the level of subsidies, the battery supplier is more inclined to choose the NEV manufacturer to collect retired power batteries separately and Scenario M is more beneficial to the battery supplier.

6. NUMERICAL ANALYSIS

In this section, we perform numerical analysis to study the following three questions: (1) the impact of key parameters on equilibrium decision-making and enterprise profits; (2) the influence of the recycling channel encroachment behavior of battery suppliers on the profits of CLSC system under different subsidy policies; and (3) compare social welfare in different situations. The parameter value settings are as follows.

(1) Considering the parameter values used in Tang et al. [42], when the battery collection quantity is not constrained by the NEV sales quantity, in order to satisfy \( \phi_m^N < 0, \phi_m^M < 0, \phi_m^C < 0, \phi_m^{NE} < 0, \phi_m^{ME} < 0, \phi_m^{CE} < 0 \), we assume \( a = 250000 \) and \( b = 1.1 \). When the collection quantity is constrained by the sales quantity, in order to satisfy \( \phi_m^N \geq 0, \phi_m^M \geq 0, \phi_m^{CE} \geq 0, \phi_m^{NE} \geq 0, \phi_m^{ME} \geq 0, \phi_m^{CE} \geq 0 \), we assume \( a = 210000, b = 1.1 \).

(2) Take Tang EV600 manufactured by BYD as an example, its power battery capacity is 82.8 kWh. According to the '2019 Global Lithium-ion Battery Pack Price Survey Report' released by Bloomberg New Energy Finance, the global average price of LIB packs is 1568/kWh. With the exchange rate of \( 1 = 7.07 RMB \), \( c_n = 82.8 \times 161 \times 7.07 = 91321 RMB \).
The energy density of the power battery of this NEV is 161 Wh/kg, and its weight is $82.8 \times \frac{1000}{161} = 514$ KG. Recycling LIBs can generate a profit of 5013$/ton [48]. Hence, we can get $c_r = 91321 - 5013 \times \frac{514}{1000} \times 7.07 = 73105$ RMB.

According to Madlener and Kirmas [49], the echelon utilization of power batteries can generate 73€/KWh. Furthermore, we assume that when the capacity of the power battery decays below 80%, it can no longer meet the needs of the car and should be used for echelon utilization. With the exchange rate of €1 = 7.62 RMB, $\lambda = 0.8 \times 73 \times 7.62 \times 82.8 = 36847$ RMB. Therefore, $\Delta = c_n - c_r + \lambda L = 36640$ RMB.

In terms of power battery cost, it accounts for $\sim 50\%$ of the total cost. Taking into account technological progress, we assume that this proportion is $\sim 45\%$. Hence, we can get $c_2 = \frac{91321}{0.45} - 91321 = 111615$ RMB.

For this NEV, the comprehensive cruising range of New Energy Vehicles is 1040 km in a week, it needs to be deeply charged and discharged twice [50]. It would require 104 recharges per year. Here, we assume that the power battery cycle service life is 1000 times, then the battery service life is 10 years and the unit environmental benefit of recycling retired power batteries is $e = 10 \times 300 = 3000$ RMB.

Therefore, the values of parameters in this paper can be taken as follows: $a = 250000$ or $a = 210000$, $b = 1.1$, $c_1 = 91321$, $c_3 = 91321$, $c_4 = 73105$, $c_2 = 111615$, $\lambda = 36847.7$, $\mu L = 0.5$, $\Delta = 36640$, $e = 3000$, $L_0 = 0$, $L_1 = 0.3$, $L_2 = 0.5$.

6.1. The impact of recycling channel cost on the profits of NEV manufacturer and battery supplier

Figure 2 shows that the unit cost of opening a recycling channel and the level of government subsidies plays a crucial role in the battery supplier’s channel decision. We assume that the government subsidy level is $s = v = 20000$. When the battery collection quantity is not constrained by the NEV sales quantity, we can see from Figure 2a that within a certain threshold, the encroachment of recycling channel under different subsidy scenarios is beneficial to the growth of NEV manufacturers profits (i.e. $c_2^{ME} < (R_2, R_1)$, $i = N, M, C$); otherwise, the encroachment of recycling channel will always be detrimental to the NEV manufacturer. As can be seen in Figure 2b, when the unit channel cost is high enough (i.e. $c_4^{NE} > R_1$, $c_4^{ME} > R_1$, $c_4^{CE} > R_1$), the battery supplier will separately collect the retired power battery through the NEV manufacturer. On the contrary, when the channel cost falls in $R_1$, the battery supplier will open the recycling channel and jointly collect the retired power battery with the NEV manufacturer. When the battery collection quantity is constrained by the NEV sales quantity, the results are similar.

6.2. The impact of recycling channel cost on CLSC profit

As shown in Figure 3, under three different subsidy modes, the encroachment of battery suppliers’ recycling channels has a significant impact on the CLSC profit. Specifically, as shown in Figure 3a, when the battery collection quantity is not constrained by the NEV sales quantity, whether the recycling channel cost $c_s$ is small or large, the CLSC profit with the battery supplier’s encroachment is greater than that without the battery supplier’s encroachment; this means that the battery supplier’s recycling channel encroachment increases the profit of the CLSC. However, when $c_s$ is at an intermediate level, although the encroachment behavior of the battery supplier increases the CLSC profit, the CLSC profit increase incurred by the encroachment behavior of the battery supplier is smaller. Since the profit of CLSC without the encroachment behavior of the battery supplier remains unchanged as the battery supplier’s recycling channel cost $c_s$ changes, when $c_s$ is at an intermediate level, the encroachment behavior of the battery supplier will cause the reduction of the CLSC profit. When $c_s$ is small, the revenue increasing effect resulted from the cost advantage of the recycling channel exceeds the profit reducing effect of the CLSC system caused by channel conflict, which to a certain extent can mitigate double marginalization of the supply chain. Therefore, the battery supplier recycling channel encroachment increases the total CLSC profit. When $c_s$ is large, the increase of the recycling channel cost leads to the gradual decrease of the power battery supplier’s collection quantity, but at this time, he increases the NEV manufacturer’s collection quantity by increasing the transfer payment price, ensuring an increase in total revenue. Hence, the profit of the CLSC increases. When $c_s$ is at an intermediate level, channel conflict intensifies the double marginalization of the supply chain and causes the reduction of the total CLSC profit. As shown in Figure 3b, when the collection quantity is constrained, the difference is that if the government provides subsidy to the NEV manufacturer, the encroachment of recycling channel by the battery supplier will increase CLSC’s profits more significantly.

6.3. The impact of recycling channel cost on social welfare

As shown in Figure 4, the encroachment of recycling channel of the battery supplier under three different subsidy scenarios has a significant impact on social welfare. Suppose $\Delta SW^{i*} (SW^{iME} - SW^{iCE})$ is the difference of social welfare by subtracting the social welfare without the battery supplier encroachment from the social welfare with the battery supplier encroachment under subsidy scenario $i$ ($i = N, M, C$). When the collection quantity is not constrained by the NEV sales quantity, as shown in Figure 4a, under the three subsidy scenarios, the change trend of social welfare difference with and without the battery supplier encroachment of recycling channel is the same. Specifically, as the battery supplier’s recycling channel cost $c_s$ increases, social welfare difference shows a trend of decreasing first and then increasing. This indicates...
that the lower or higher recycling channel cost set by the battery supplier is more conducive to the improvement of social welfare. When the recycling channel cost is at an intermediate level, the social welfare difference will be reduced and it indicates that the social welfare with the battery supplier encroachment of recycling channel is reduced since the social welfare without the battery supplier encroachment of recycling channel keeps unchanged as the recycling channel cost changes. When the collection quantity is constrained by the NEV sales quantity, as shown in Figure 4b, for the scenario of no government subsidy, the increase of social welfare resulted from the recycling channel encroachment of battery supplier is significantly higher than that of the other subsidy scenarios. If the government increases subsidies to the NEV manufacturer or consumers, the encroachment of recycling channels may not always benefit the improvement of social welfare (i.e. $\Delta SW^{Me} > 0$, $\Delta SW^{Ce} < 0$). Therefore, the government subsidy should be set at a reasonable level.

6.4. The impact of consumer’s environmental awareness on social welfare

In the above analysis, we regard consumers as ‘interest careers’ and consumers are more concerned about the recycling price of retired power batteries. However, in real life, some consumers are environmentally conscious and are willing to return power batteries for free, which is similar to recycling end-of-life electronic products [51, 52, 53]. Therefore, according to Tang et al. [42], the quantity of batteries that consumers voluntarily return represents environmental awareness. As environmental awareness of consumers is enhanced, social welfare will gradually improve. When the battery collection quantity is/is not constrained by the NEV sales quantity, Figure 5 shows that under the same subsidy scenario, the social welfare with the encroachment exceeds that without the encroachment, namely $SW^{NE} > SW^{Ns}$, $SW^{ME} > SW^{Ms}$, $SW^{CE} > SW^{Cs}$. In addition, the social welfare promotion effect under Scenario ME is the best. Therefore, the government and enterprises should effectively enhance consumers environmental awareness through financial support or advertising efforts, which will help improve overall social welfare.

7. CONCLUSIONS

In this paper, we apply game theory to develop the CLSC models under three different government subsidy modes (no subsidy, subsidy for the NEV manufacturer and subsidy for consumers),
in which the upstream power battery supplier decides whether or not to encroach the recycling channel. In this case, we compare and analyze the influence of different government subsidy on the optimal strategies of the CLSC members and investigate the changes of collection quantity, enterprise profit and social welfare under different government subsidy scenarios. At the same time, we consider whether the power battery collection quantity is/is not constrained by the NEV sales quantity.

7.1. Main findings

(1) We analyze the optimal strategies, profit and social welfare under different subsidy scenarios with and without the encroachment of the battery supplier’s recycling channel. We find that whether the battery collection quantity is constrained by the NEV sales quantity, the supply chain profits and social welfare with government subsidies (subsidy for the NEV manufacturer or subsidy for consumers) are higher than those without government subsidy. We also analyze the impact of recycling channel cost and consumer’s environmental awareness on enterprise profits and social welfare under different scenarios. The results show that Scenario ME is more beneficial to enterprise profits and social welfare and the consumer's environmental awareness has a positive impact on social benefits.

(2) We also find that the performance of the battery supplier's recycling channel encroachment is better than the independent recycling model of the NEV manufacturer. Here, the battery supplier is taking a leadership in the CLSC, while the NEV manufacturer have a complete sales and recycling channels, the recycling competition may be more conducive to the recycling of retired power batteries. Therefore, the encroachment strategy should be introduced in the recycling activities under certain conditions. Furthermore, by comparing Scenarios NE, M and C, we find that when the government subsidy is relatively low, the battery supplier prefer to choose channel encroachment strategy rather than subsidy strategy.

(3) Whether the battery collection quantity is constrained by the NEV sales quantity, when the cost of the recycling channel is lower than a certain threshold, the encroachment of recycling channel is always beneficial to the battery supplier. And when the cost of the recycling channel is within a certain threshold, the encroachment of the recycling channel by the battery
When the battery collection quantity is not constrained by the NEV sales quantity, different subsidy modes have no influence on the wholesale price of batteries and the sales prices of NEVs, but when the battery collection quantity is constrained by the NEV sales quantity, which is the opposite. In addition, whether the battery collection quantity is constrained by the NEV sales quantity, the incremental profit brought by the battery supplier’s recycling channel encroachment will decrease first and then increase with the increase of recycling channel cost. When the battery collection quantity is constrained by the NEV sales quantity, the incremental profit brought by the battery supplier’s recycling channel encroachment under the Scenario ME is the highest.

7.2. Managerial implications
This research also provides the following management insights for battery suppliers, NEV manufacturers, and policymakers.

(1) From the perspective of battery suppliers, the encroachment strategy of recycling channels and the government subsidy policy have an important impact on the company’s strategic decisions. If the battery supplier’s recycling capacity is insufficient, the NEV manufacturer should directly recycle the retired power batteries; if battery suppliers are more inclined to expand the influence of recycling channels and exploit the market, they should actively participate in the recycling of retired power batteries. For example, it is necessary for some battery suppliers to expand the influence of recycling channels in order to maximize the product remanufacturing value and echelon utilization value, and the company’s recycling channel encroachment strategy is effective.

(2) From the perspective of NEV manufacturers, the participation of the battery supplier does not mean a loss of profit. Under certain conditions, the battery supplier’s encroachment of recycling channels can increase the profits of NEV manufacturers and the strategy of battery suppliers’ encroachment is feasible. Moreover, the NEV manufacturer is also benefit from government financial support.

(3) From the perspective of enterprise profit maximization, battery suppliers should adopt different encroachment strategies to maximize their profits. The encroachment of recycling channels is the best choice for the battery supplier under the scenario of subsidy for the NEV manufacturer.

(4) From the perspective of social welfare, the battery collection quantity and social welfare are higher under the subsidy for the NEV manufacturer. Under certain conditions, the battery supplier’s encroachment on recycling channels also contributes to the improvement of social welfare. The government should actively guide enterprises to carry out recycling activities to improve the efficiency of used resources. In addition, the government should also make full use of newspapers, radio, television, internet, and other news media to vigorously propagate and to improve the public’s awareness of power batteries.

7.3. Future research directions
This research still has some limitations, which can be further expanded in several directions in the future. Firstly, the uncertainty of power battery supply and demand should be considered in the future. Secondly, the uncertainty of the quality of retired power batteries should be also considered in the future research. Thirdly, the model proposed in this paper is limited to one battery supplier and one NEV manufacturer. In fact, the joint participation of third-party recyclers can also be considered in the future research.

Supplementary Materials
The proof for propositions (Supplementary Materials).
REFERENCES

[1] CAAM. Economic Performance of the Auto Industry in 2019. Available online: http://www.caam.org.cn (5 July 2020, date last accessed).

[2] Heelan J, Gratz E, Zheng Z et al. Current and prospective Li-ion battery recycling and recovery processes. JOM 2016;68:2632–8.

[3] European Commission. Disposal of Spent Batteries and Accumulators. 2006. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=13595525065898&qid=1350262537984&uri=CELEX:32006L0066 (8 June 2020, date last accessed).

[4] European Union. Launch of Battery 2030+. 2019. https://battery2030.eu/ (12 June 2020, date last accessed).

[5] Choi Y, Rhee SW. Current status and perspectives on recycling of end-of-life battery of electric vehicle in Korea (Republic of). Waste Manag 2020;106:61–70.

[6] MIIT. Interim Measures for the Management of Recycling and Utilization of Power Battery for New Energy Vehicles. 2018. http://www.miit.gov.cn (6 July 2020, date last accessed).

[7] Ma W, Zhao Z, Ke H. Dual-channel closed-loop supply chain with government consumption-subsidy. Eur J Oper Res 2013;226:221–7.

[8] Han X, Yang Q, Shang J et al. Optimal strategies for trade-old-for-remanufactured products: receptivity, durability, and subsidy. Int J Prod Econ 2017;193:602–16.

[9] Xiao L, Wang X, Chin K et al. Competitive strategy in remanufacturing and the effects of government subsidy. J Syst Sci Eng 2017;26:417–32.

[10] Yu J, Tang C, Shen Z. Improving consumer welfare and manufacturer profit via government subsidy programs: subsidizing consumers or manufacturers? Manuf Serv Oper Manag 2018;20:752–66.

[11] Souh. Energy Storage is One of the Key Reuse Areas for Retired Batteries. 2020. https://www.souh.com/a/365009372_115863 (13 July 2020, date last accessed).

[12] Yun L, Linh D, Shui L et al. Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles. Resour Conserv Recycl 2018;136:198–208.

[13] Chen M, Ma X, Chen B et al. Recycling end-of-life electric vehicle lithium-ion batteries. Aust Dent J 2019;64:2622–46.

[14] Heymans C, Walker SB, Young SB et al. Economic analysis of second use electric vehicle batteries for residential energy storage and load-leveling. Energy Policy 2014;71:22–30.

[15] Mazzeo D. Nocturnal electric vehicle charging interacting with a residential photovoltaic-battery system: a 3E (energy, economic and environmental) analysis. Energy 2019;168:310–31.

[16] Gu H, Liu Z, Qing G. Optimal electric vehicle production strategy under subsidy and battery recycling. Energy Policy 2017;109:579–89.

[17] Gu X, Ieromonachou P, Zhou L et al. Developing pricing strategy to optimise total profits in an electric vehicle battery closed loop supply chain. J Clean Prod 2018;203:376–85.

[18] Tang Y, Zhang Q, Li Y et al. The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism. Appl Energy 2019;251:113313. https://doi.org/10.1016/j.apenergy.2019.113313.

[19] Zhu M, Liu Z, Li J et al. Electric vehicle battery capacity allocation and recycling with downstream competition. Eur J Oper Res 2020;283:365–79.

[20] Liu Y, Zhang Z. Research note the benefits of personalized pricing in a channel. Mark Sci 2006;25:97–105.

[21] Li T, Xie J, Zhao X. Supplier encroachment in competitive supply chains. Int J Prod Econ 2015;165:120–31.

[22] Li Z, Gilbert SM, Lai G. Supplier encroachment under asymmetric information. Manag Sci 2013;60:449–62.

[23] Li Z, Gilbert SM, Lai G. Supplier encroachment as an enhancement or a hindrance to nonlinear pricing. Prod Oper Manag 2015;24:89–109.

[24] Tsay AA, Agrawal N. Channel conflict and coordination in the e-commerce age. Prod Oper Manag 2009;13:93–110.

[25] Yan W, Xiong Y, Chu J et al. Clicks versus bricks: the role of durability in marketing channel strategy of durable goods manufacturers. Eur J Oper Res 2018;265:909–18.

[26] Chiang WK, Chhajed D, Hess JD. Direct marketing, indirect profits: a strategic analysis of dual-channel supply chain design. Manag Sci 2003:49:1–20.

[27] Arya A, Mittendorf B, Sappington DE. The bright side of supplier encroachment. Mark Sci 2007;26:651–9.

[28] Zhang LH, Yao J, Xu L. Emission reduction and market encroachment: whether the manufacturer opens a direct channel or not? J Clean Prod 2020;269:121932. https://doi.org/10.1016/j.jclepro.2020.121932.

[29] Zhang J, Li S, Zhang S. Manufacturer encroachment with quality decision under asymmetric demand information. Eur J Oper Res 2019;273:217–36.

[30] Zheng B, Yu N, Jin L. Effects of power structure on manufacturer encroachment in a closed-loop supply chain. Comput Ind Eng 2019;137:106062. https://doi.org/10.1016/j.cie.2019.106062.

[31] Heydari J, Govindan K, Jafari A. Reverse and closed loop supply chain coordination by considering government role. Transp Res D Transp Environ 2017;52:379–98.

[32] Cohen MC, Lobel R, Perakis G. The impact of demand uncertainty on consumer subsidies for green technology adoption. Manag Sci 2016;62:1235–58.

[33] Bian J, Zhang G, Zhou G. Manufacturer vs consumer subsidy with green technology investment and environmental concern. Eur J Oper Res 2020;287:832–43.

[34] Zhao J, Zeng D, Che L. Research on the profit change of new energy vehicle closed-loop supply chain members based on government subsidies. Environ Technol Innov 2020;19:100937. https://doi.org/10.1016/j.eti.2020.100937.

[35] Sheldon TL, Dua R. Effectiveness of China’s plug-in electric vehicle subsidy. Energy Econ 2020;88:104773. https://doi.org/10.1016/j.eneco.2020.104773.

[36] Kong D, Xia Q, Xue Y. Effects of multi policies on electric vehicle diffusion under subsidy policy abolishment in China: a multi-actor perspective. Appl Energy 2020;266:114887. https://doi.org/10.1016/j.apenergy.2020.114887.

[37] Shao L, Yang J, Zhang M. Subsidy scheme or price discount scheme? Mass adoption of electric vehicles under different market structures. Eur J Oper Res 2017;262:1181–95.

[38] Gu X, Ieromonachou P, Zhou L. Subsidising an electric vehicle supply chain with imperfect information. Int J Prod Econ 2019;211:82–97.

[39] Xu L. Analysis for waste collection and management of closed-loop supply chain with dual-channel forward logistics. Int J Ind Eng-Theory Pract 2020;27:124–39.

[40] Xu L, Wang CX, Zhao JJ. Decision and coordination in the dual-channel supply chain considering cap-and-trade regulation. J Clean Prod 2018;197:351–61.

[41] Xu L, Shi J, Chen JH. Pricing and collection rate for remanufacturing industry considering capacity constraint in recycling channels. Complexity 2020;1–13.

[42] Tang Y, Zhang Q, Li Y et al. Recycling mechanisms and policy suggestions for spent electric vehicles’ power battery—a case of Beijing. J Clean Prod 2018;186:388–406.

[43] Karakayali I, Emirfarinas H, Akcali E. An analysis of decentralized collection and processing of end-of-life products. J Oper Manag 2007;25:1161–83.

[44] Jacobs BW, Subramanian R. Sharing responsibility for product recovery across the supply chain. Prod Oper Manag 2011;21:85–100.

[45] Wang CX, Wang W, Huang RB. Supply chain enterprise operations and government carbon tax decisions considering carbon emissions. J Clean Prod 2017;152:271–80.

[46] Xu L, Wang CX, Miao Z et al. Governmental subsidy policies and supply chain decisions with carbon emission limit and consumer’s environmental awareness. RAIRO Oper Res 2019;53:1675–89.
A.1. PROOF OF SECTION 4.1

Proof 4.1.1. The profit function in Equation (2) is concave in $p^N$ and $b^N_m$. Therefore, for the NEV manufacturer, the first-order conditions are given as follows: \[
\frac{\partial \pi^N_{m}}{\partial p^N} = a + b(-2p + w) + bc_2 = 0, \quad \frac{\partial \pi^N_{m}}{\partial b^N_m} = -L_0 + (t - 2b_m)L_1 = 0.
\]
Further, the first-order conditions lead to the optimal reactions: \[p^N = \frac{a + bw + bc_2}{2b}, \quad b^N_m = \frac{t - L_0}{L_1}.\] We plug these best responses into battery supplier's profit function and take the first- and second-order derivatives of it with respect to $w^N$ and $t^N$ and obtain that \[H^N_{2}(w, t) = \begin{bmatrix}
\frac{\partial^2 \pi^N_{m}}{\partial w^2} & \frac{\partial^2 \pi^N_{m}}{\partial w \partial t} \\
\frac{\partial^2 \pi^N_{m}}{\partial t \partial w} & \frac{\partial^2 \pi^N_{m}}{\partial t^2}
\end{bmatrix} = \begin{bmatrix}
-b & 0 \\
0 & -L_1
\end{bmatrix}.\] According to the Hessian matrix, we get $H^N_{1} = -b < 0$ and $H^N_{2} = bL_1 > 0$. Therefore, the Hessian matrix for the battery supplier's profit is negative definite.

Next, we introduce Karush–Kuhn–Tucker conditions to characterize the optimality condition and model a Lagrangian function of supply chain profit as $\pi^N = \pi^N_{s} + \lambda_1[D - R_1(b_m)]$, where $\lambda_1$ is the multipliers. Further, combining and solving the KKT conditions, we easily obtain the following.

a. When the battery collection quantity is not constrained by the NEV sales quantity, $\lambda_1 = 0$, namely $\phi^N_{m} = -a + bc_1 + bc_2 + L_0 + \Delta L_1 < 0$. Equating the first-order conditions to zero and solving the KKT conditions, we have \[w^N_{s} = \frac{-a + bc_1 + bc_2}{2b}, \quad t^N_{s} = \frac{1}{L_1}(\Delta - L_0).\]

b. When the battery collection quantity is constrained by the NEV sales quantity, $\lambda_1 = \frac{-a + bc_1 + bc_2 + L_0 + \Delta L_1}{b + L_1}$, namely $\phi^N_{m} = -a + bc_1 + bc_2 + L_0 + \Delta L_1 \geq 0$. Equating the first-order conditions to zero and solving the KKT conditions, we have \[w^N_{s} = \frac{(a - bL_1 - bc_2)L_0 + 2a - 2bL_1 - L_0}{2(b + L_1)}, \quad t^N_{s} = \frac{(X_2 + b)L_1 - L_0(2b + L_1)}{2L_1(b + L_1)}.
\]

Substituting the $w^N_{s}$ and $t^N_{s}$ into the optimal reactions, we can get the optimal retail price and the optimal recycling price for the NEV manufacturer $p^N_{s}$ and $b^N_{m}$. Because the solution processes of other models are similar to the above case, to avoid repetition, it is not described in this article.

The social welfare function of Scenario N can be expressed as follows: \[\pi^N = \frac{1}{8}[\frac{a - b(c_1 + c_2)}{b} + \frac{(L_0 + \Delta L_1)^2}{L_1} - \frac{1}{4}e(L_0 + \Delta L_1)], \quad C^N = \frac{1}{32b}[\frac{a - b(c_1 + c_2)}{b} + \frac{(L_0 + \Delta L_1)^2}{L_1} - \frac{1}{4}e(L_0 + \Delta L_1)].\]

The third-order condition leads to the optimal reactions: \[p^N_{s} = \frac{(bL_0 + X_2 + bL_1)L_1}{2bL_0(2b + L_1)}, \quad E^N = \frac{32b(b + L_1)}{4bL_0(2b + L_1)}.
\]

Proof 4.1.2 and 4.1.3. The proofs of government decision in Scenarios M and C are similar to that in Scenario N. Therefore, we just provide the existential conditions of optimal solutions. The expressions of social welfare in Scenarios M and C can be given respectively by the following.

When $\phi^M_{m} < 0$, we can obtain the social welfare in Scenario M as follows: \[SW^M = \pi^M_{s} + \pi^M_{m} + CS^M(m) + E^M(m) - G^M(m) = \frac{1}{8}[\frac{(X_2 + bL_1)^2}{b} + \frac{(L_0 + \Delta L_1)^2}{L_1} - \frac{1}{4}e(L_0 + \Delta L_1) - \frac{1}{2}(2bL_0 + X_2 + bL_1)].\] When $\phi^M_{m} \geq 0$, we can obtain the social welfare in Scenario M as follows: \[SW^M = \pi^M_{s} + \pi^M_{m} + CS^M(m) + E^M(m) - G^M(m) = \frac{32b(b + L_1)^2}{8bL_0(2b + L_1)} + \frac{32b(b + L_1)^2}{16bL_0(2b + L_1)}.
\]

By taking the second-order derivative of $SW^M$ with respect to $m$, resulting in \[\frac{\partial^2 SW^M}{\partial m^2} = -\frac{k}{16} < 0, \quad \frac{\partial^2 SW^M}{\partial m^2} = \frac{k}{16} \left[\frac{b^2}{(b + L_1)} - 1\right] < 0,\] which means that the government subsidy in Scenario M exists a unique optimal solution. When $\phi^M_{m} < 0$, we obtain the optimal conditions:

\[p^M_{s} = \frac{(bL_0 + X_2 + bL_1)L_1}{2bL_0(2b + L_1)}, \quad E^M = \frac{32b(b + L_1)}{4bL_0(2b + L_1)}.
\]

When $\phi^M_{m} \geq 0$, we can obtain the social welfare in Scenario M as follows: \[SW^M = \pi^M_{s} + \pi^M_{m} + CS^M(m) + E^M(m) - G^M(m) = \frac{32b(b + L_1)^2}{8bL_0(2b + L_1)} + \frac{32b(b + L_1)^2}{16bL_0(2b + L_1)}.
\]

By taking the second-order derivative of $SW^M$ with respect to $m$, resulting in \[\frac{\partial^2 SW^M}{\partial m^2} = -\frac{k}{16} < 0, \quad \frac{\partial^2 SW^M}{\partial m^2} = \frac{k}{16} \left[\frac{b^2}{(b + L_1)} - 1\right] < 0,\] which means that the government subsidy in Scenario M exists a unique optimal solution. When $\phi^M_{m} < 0$, we obtain the optimal conditions:

\[p^M_{s} = \frac{(bL_0 + X_2 + bL_1)L_1}{2bL_0(2b + L_1)}, \quad E^M = \frac{32b(b + L_1)}{4bL_0(2b + L_1)}.
\]
subsidy as \( m_1 = \frac{3a}{b} - 3c_1 - 3c_2 \); when \( \phi_M \geq 0 \), it can be derived that \( m_2 = \frac{3L_1(x_2 + \Delta b) + 46L_1 + b_0}{4L_1 - 4b_0 + b_0} - \frac{4(x_2 + \Delta b) + 46b - 2La}{2b + L_1} \).

The proofs of government subsidy in Scenario C are similar to that in Scenario M. Therefore, we just provide the existential conditions of optimal solutions. The expressions of social welfare in Scenario C can be given by. When \( \phi_M^C < 0 \), \( SW^C = \pi^C_0(v) + \pi^C_m(v) + CS^C(v) + E^C(v) - G^C(v) = \frac{1}{8} \left( \frac{[v_1 + v_2 + c_1 + c_2]}{b} \right)^2 + \frac{1}{8} \left( \frac{[v_1 + v_2 + c_1 + c_2]}{b} \right)^2 + \left( \frac{a + v - b c_1 - b c_2}{b} \right)^2 + \frac{1}{8} v(a + v - b c_1 - b c_2), \) when \( \phi_M^C \geq 0 \), \( SW^C = \pi^C_0(v) + \pi^C_m(v) + CS^C(v) + E^C(v) - G^C(v) = \frac{b L_0 + (x_2 + \Delta b + v) L_1^2}{16 b L_1 (b + L_1)^2} + \frac{b L_0 + (x_2 + \Delta b + v) L_1^2}{32 b (b + L_1)^2} + \frac{2 b L_0 + (x_2 + \Delta b + v) L_1^2}{(b + L_1)^2} - \frac{v(b_0 + (x_2 + \Delta b + v) L_1^2)}{4(b + L_1)} \).

### A.2. PROOF OF SECTION 4.2

Proof 4.2.1. According to Equation (7), \( \frac{\partial \pi^NE}{\partial b} = (t + b m - 2b s - c_2) L_2 \), we can get \( b_N^E = \frac{1}{2} (t + b m - c_2) \). We plug \( b_N^E \) optimal response into the profit function of the NEV manufacturer. Then, the profit function in Equation (8) is concave in \( p^NE \) and \( b_N^M \).

Therefore, for the NEV manufacturer, the first-order conditions are given as follows:

\[
\frac{\partial \pi^NE}{\partial b} = a + b (-2p + w) + b c = 0 \quad \text{for} \quad b = \text{max} \left( \frac{1}{7} \left[ 3 - 4L_1 + \sqrt{9 + 16L_1(2 + L_1)} \right] \right)
\]

Further, the first-order conditions lead to the optimal reactions \( p^N = \frac{a + b w + b c}{2b} \) and \( b_N^M = \frac{-2a + 2L_1 + (2 + c_2)L_2}{2(2L_1 + L_2)} \). Substituting \( b_N^M \) into \( b_N^E \), and we get \( b_N^E = \frac{-2a + 2L_1 + (4 + 4c_2)L_2}{4L_1 + b_0} \).

We plug the best responses into battery supplier's profit function and take the first- and second-order derivatives of it with respect to \( w^NE \) and \( t^NE \), resulting in \( H^NE (w, t) = \left[ \frac{\partial^2 \pi^NE}{\partial w^2} \right] \) and \( \left[ \frac{\partial^2 \pi^NE}{\partial t^2} \right] \) as:

\[
\begin{bmatrix}
-\frac{b}{2} & 0 \\
0 & \frac{\partial^2 \pi^NE}{\partial t^2}
\end{bmatrix}
\]

According to the Hessian matrix, we get \( H^NE = -b < 0 \) and \( \frac{\partial^2 \pi^NE}{\partial t^2} = \frac{b L_0 (8L_1^2 + 11L_1 L_2 + 4L_2^2)}{2(2L_1 + L_2)^2} > 0 \).

Therefore, the Hessian matrix for the battery supplier's profit is negative definite.

Next, similar to the proof process of 4.1.1, we introduce Karush–Kuhn–Tucker conditions to characterize the optimality condition and model a Lagrangian function of optimization problem in the profit for supply chain as \( \pi^NE_s = \pi^NE_s + \lambda_2 [D - R_m (b_m) - R_s (b_s)], \) where \( \lambda_2 \) is the multipliers. Further, combining and solving the KKT conditions, we easily obtain the following.

a. When the battery collection quantity is not constrained by the NEV sales quantity, \( \lambda_2 = 0 \), namely \( \phi_M^{NE} = 8(L_0 + \Delta L_1)(L_1 + L_2)^2 - a - b (c_1 + c_2) )/2L_0 (4L_1^2 + 5L_1 L_2 + 2L_2^2) \).

Equating the first-order conditions to zero and solving the KKT conditions, we have \( w^{NE} = \frac{a + b c_1 - b c_2}{2b}, \) \( t^{NE} = 4\Delta L_1 (L_1 + L_2) (2L_1 + L_2) - 2L_0 (4L_1^2 + 5L_1 L_2 + 2L_2^2) + c_1 L_1 L_2^2 / 2L_1 B_2 \).

b. When the battery collection quantity is constrained by the NEV sales quantity, \( \lambda_2 = 8(L_0 + \Delta L_1)(L_1 + L_2)^2 - a - b (c_1 + c_2) )/2L_0 (4L_1^2 + 5L_1 L_2 + 2L_2^2) \).

Equating the first-order conditions to zero and solving the KKT conditions, we have \( w^{NE} = 4 \left( a - b \Delta + b c_1 - b c_2 \right) L_1 - b L_0 \) \( t^{NE} = 4 \Delta L_1 (L_1 + L_2) (2L_1 + L_2) / [8 b L_0 (L_1 + L_2)^2 + b (2L_1^2 + 5L_1 L_2 + 2L_2^2)] + c_1 L_1 L_2 b L_2 + 8 L_1 (L_1 + L_2) / [2 b L_0 B_2 + 16 \Delta L_1 (L_1 + L_2)^2] \).

Substituting the \( w^{NE} \) and \( t^{NE} \) into the optimal reactions, we can get the optimal retail price and the optimal recycling price for the NEV manufacturer \( p^{NE} \) and \( b_N^{NE} \). Because the solution processes of other models are similar to the above case, to avoid repetition, it is not described in this article.

The social welfare function of Scenario N can be expressed as follows: when \( \phi_M^N < 0 \), we can obtain the social welfare in Scenario N as follows:

\[
\text{SW}^{NE} = \pi^NE + \pi^NE + 8L_0 (L_0 + \Delta L_1)(L_1 + L_2)^2 - a - b (c_1 + c_2) )/2L_0 (4L_1^2 + 5L_1 L_2 + 2L_2^2) + \frac{a (b c_1 - b c_2)^2}{16 b} + \frac{e \left( 4L_0 (L_1 + L_2) (L_1 + L_2)^2 - c_1 L_1 L_2 (2L_1 + L_2)^2 \right)}{2b L_0}
\]

When \( \phi_M^N \geq 0 \), we can obtain the social welfare in Scenario N as follows:
K. Liu and C. Wang

\[ SW^{NE} = \sum_{i} e^{iNE} + \sum_{j} C_{j}^{NE} + E^{NE} - G^{NE} = \]

\[ = 4b(l_0 + (X_0 + b + \Delta L)l_2)(l_1 + l_2)^2 - 2bc_l_1[l_0 + (X_0 + b + \Delta L)l_2](4l_1 + 3l_2) + b_2 l_2 c_2^3[l_2(2l_1 + 2l_2)^2 + b(8l_2^2 + 7l_1l_2 + l_2^2)] + \]

\[ 8b(l_1 + l_2^2)(2l_2 + l_2)[l_0 + (X_0 + b + \Delta L)l_2 + c_2 b_2 l_2](l_1 + l_2)^2 + 4b(l_0 + (X_0 + b + \Delta L)l_2)(l_1 + l_2)^2 - b_2 c_2 l_2(4l_1 + 3l_2)^2 \]

By taking the second-order derivative of \( SW^{ME} \) with respect to \( m \), resulting in \( \frac{\partial^2 SW^{ME}}{\partial m^2} = -\frac{b}{b_m^2} < 0 \), we obtain the optimal solution. When \( \phi_m^{ME} < 0 \), we obtain the optimal...
Considering government subsidy in scenario CE, we have

\[ \phi_m^{ME} = \frac{3a}{b} - 3c_1 - 3c_2; \quad \text{when } \phi_m^C \geq 0, \text{ it can be} \]

derived that \( m_2^{ME} = \frac{3L_1(X_2+\Delta)+4bL_1+4bL_2 - 4(X_2+\Delta)+4c_2 - 2L_2}{2b+L_1}. \)

Considering government subsidy in scenario CE, we have

\[ \frac{\partial^2 W^{CE}}{\partial v^2} = -\frac{1}{2} \frac{7}{18b} \quad \frac{\partial^2 W^{CE}}{\partial v^2} = -\frac{2L_1(L_1+L_2)^2 [4b(4b-3) L_1^2 + b(2b-13)L_1 L_2 + 4(b-1)L_2^2 + 2L_1(1b-7)(L_1+L_2)^2]}{b(L_1(L_1+L_2)^2+bL_2)^2}. \]

When \( b > \max \left\{ \frac{1}{\sqrt{9+16L_1(2+L_1)}}, \frac{1}{\sqrt{9+16L_1(2+L_1)}} \right\} \), we can get \( \frac{\partial^2 W^{CE}}{\partial v^2} < 0, \quad \frac{\partial^2 W^{CE}}{\partial v^2} < 0 \), which indicate that each
government subsidy exists a unique optimal solution. When

\[ \phi_m^{ME} < 0, \quad \phi_m^C < 0, \text{ we obtain the optimal subsidy as} \]

\[ m_1^{ME} = \frac{3a}{b} - 3c_1 - 3c_2, \quad \nu_1^C = \frac{7b - (a-b+c_2)}{8b - 2}, \]

respectively; \( \text{when } \phi_m^{ME} > 0, \phi_m^C > 0 \) it can be derived that \( m_2^{ME} = \frac{3L_1(X_2+\Delta)L_1[3(L_1+L_2)^2+b(2L_1+L_2)]+2b(8L_1(L_1+L_2)^2+2bL_2) + \frac{1}{2}[4b^2L_1(L_1+L_2)+bL_2(4L_1-L_1-L_2)]}{2b^2(4L_1^2+bL_1L_2+bL_2^2)+4bL_1(L_1+L_2)^2} \),
\[ \nu_2^{CE} = \frac{4(3L_1+L_2)^2[4bL_1+bL_2+8L_1(L_1+L_2)^2+B_0(8L_1(L_1+L_2)^2+2bL_2) + \frac{1}{2}[4b^2L_1(L_1+L_2)+bL_2(4L_1-L_1-L_2)]}{4bL_1(L_1+L_2)^2+bL_2^2} \]

\[ L_1^2 + 13L_1L_2 + 4L_2^2 \] The proofs of the government subsidy

problems in the three cases with the encroachment are completed in

Section 4.2.

A.3. PROOF OF PROPOSITION 1

Proof. 1. When the battery collection quantity is not constrained by

the NEV sales quantity, the difference of the optimal wholesale

government price in different scenarios can be calculated as follows.

a. Without the battery supplier’s encroachment, we can obtain

\[ w^{CE} - w^{NE} = \frac{(7b - (a-b+c_2))}{2b(4b - 2)} > 0; \quad w^{ME} - w^{Ca} = \frac{14b(4b - 2)}{2b(4b - 2)} > 0, \]

then we can obtain \( w^{ME} > w^{Ca} > w^{NE}, \nu^{ME} > \nu^{NE} \), \( p^{ME} > p^{Ca} > p^{NE} \), \( \frac{\nu^{ME} - \nu^{Ca}}{\nu^{ME} - \nu^{NE}} > 0, \]

\( \frac{p^{ME} - p^{Ca}}{p^{ME} - p^{NE}} > 0, \) \( \text{which also indicates that } \nu^{ME} > \nu^{Ca} > \nu^{NE}, \nu^{ME} > \nu^{Ca} > \nu^{NE} \), \( p^{ME} > p^{Ca} > p^{NE} \).

b. With the battery supplier’s encroachment, we can obtain

\[ \nu^{ME} > \nu^{CE} > \nu^{NE}, \nu^{ME} > \nu^{NE}, \nu^{ME} > \nu^{NE} \]

\[ p^{ME} > p^{CE} > p^{NE}, p^{ME} > p^{NE}, p^{ME} > p^{NE} \]

2. When the battery collection quantity is constrained, according to the optimal wholesale price and retail price, the difference can be calculated as follows.

a. Without the battery supplier’s encroachment, we can obtain

\[ w^{ME} - w^{NE} = \frac{m(2b+L_1)}{2b(4b - 2)} > 0, \quad w^{Ca} - w^{NE} = \frac{1}{2} \left( \frac{1}{2b+L_1} \right) > 0, \]

\( \nu^{ME} - \nu^{Ca} = \frac{mL_1}{2b(4b - 2)} > 0; \quad p^{ME} - p^{Ca} = \frac{mL_2}{2b(4b - 2)} < 0, \)

\( p^{ME} - p^{Ca} = \frac{-mL_2}{4b - 2} < 0, \quad \nu^{ME} - \nu^{Ca} = \frac{1}{2} \left( \frac{1}{2b+L_1} \right) > 0, \)

\( \frac{p^{ME} - p^{Ca}}{p^{ME} - p^{NE}} > 0, \) \( \text{which also indicates that } \nu^{ME} > \nu^{Ca} > \nu^{NE}, \nu^{ME} > \nu^{Ca} > \nu^{NE} \), \( p^{ME} > p^{Ca} > p^{NE} \).

b. With the battery supplier’s encroachment, we can obtain

\[ 0 < w^{ME} - w^{NE} = \frac{mL_1(L_1+L_2)^2+2bL_2}{bL_1(L_1+L_2)^2+bL_2^2} \]

\[ > 0; \quad \nu^{ME} - \nu^{Ca} = \frac{(b^2(4b - 2))}{bL_1(L_1+L_2)^2+bL_2^2} > 0, \]

\( \text{which also indicates that } w^{ME} > w^{Ca} > w^{NE}, w^{ME} > w^{Ca} > w^{NE} \)

A.4. PROOF OF COROLLARY 1

Proof. When the battery collection quantity is not constrained by

the NEV sales quantity, it is easy to prove \( w^{ME} = w^{ME}, \nu^{ME} = \nu^{ME}, \nu^{ME} = \nu^{ME}, p^{ME} = p^{ME}, p^{ME} = p^{ME}, p^{ME} = p^{ME} \).

When the battery collection quantity is constrained by

the NEV sales quantity, according to the optimal wholesale

government price and retail price under the same subsidy condition

(when and without the battery supplier’s encroachment), we can calculate the following difference: \( w^{NE} - w^{NE} = \frac{2bL_1(2L_1+L_2)(4L_1+3L_2)L_1(L_1+L_2)^2}{(2L_1)(4L_1+3L_2)^2} \)

\( \nu^{ME} - \nu^{Ca} = \frac{2bL_1(L_1+L_2)^2(4L_1+3L_2)}{(2L_1)(4L_1+3L_2)^2} \), \( \nu^{ME} - \nu^{Ca} = \frac{2bL_1(L_1+L_2)^2(4L_1+3L_2)}{(2L_1)(4L_1+3L_2)^2} \), \( \nu^{ME} - \nu^{Ca} = \frac{2bL_1(L_1+L_2)^2(4L_1+3L_2)}{(2L_1)(4L_1+3L_2)^2} \),
\[ w^{ME} > w^{Ne}, \text{ } w^{ME} > w^{Ne}, \text{ } w^{ME} > w^{Ne}, \text{ } w^{ME} > w^{Ne}, \text{ } w^{ME} > w^{Ne}, \text{ } w^{ME} > w^{Ne}. \]

Similarly, we can get other results.
A.5. PROOF OF PROPOSITION 2

Proof. Without the battery supplier’s encroachment, when the battery collection quantity is not constrained by the NEV sales quantity, it is easy to prove $\pi^M_s \succ \pi^C_s \succ \pi^N_s$, $\pi^M_m > \pi^C_m > \pi^N_m$, $\pi^M_i > \pi^C_i > \pi^N_i$. When the battery collection quantity is not constrained, $\pi^M_s - \pi^N_s = \frac{2mL_0 + m(2X_s + 2b\Delta + bm)L_1}{8(b + L_1)} > 0$, and $\pi^M_m - \pi^N_m = \frac{2mL_0 + m(2X_m + 2b\Delta + bm)L_1}{8(b + L_1)} > 0$, $\pi^M_i - \pi^N_i = \frac{2mL_0 + m(2X_i + 2b\Delta + bm)L_1}{8(b + L_1)} > 0$. Therefore, we can get $\pi^M_s > \pi^C_s > \pi^N_s$, $\pi^M_m > \pi^C_m > \pi^N_m$, $\pi^M_i > \pi^C_i > \pi^N_i$. With the battery supplier’s encroachment, whether the battery collection quantity is constrained by the NEV sales quantity, it is easy to prove $\pi^M_s > \pi^C_s > \pi^N_s$, $\pi^M_m > \pi^C_m > \pi^N_m$, $\pi^M_i > \pi^C_i > \pi^N_i$, and we can prove that $\pi^M_s > \pi^C_s > \pi^N_s$.

A.6. PROOF OF PROPOSITION 3

Proof. The conditions for the battery supplier to open the recycling channel are as follows: when the battery collection quantity is not constrained by the NEV sales quantity, the real root of equation $R^*_E = 0$ represent the upper bound of the battery supplier’s choice of recycling channel encroachment, namely when $c^*_E < N^*_E = \frac{2(L_0 + \Delta L_1)(L_1 + L_2)}{B_2 - 2L_2(L_1 + L_2)}$, the battery supplier chooses to open the recycling channel; when the battery collection quantity is constrained by the NEV sales quantity, similarly, when $c^*_E < N^*_E = \frac{2(bL_0 + \Delta L_1)(L_1 + L_2)}{4L_1(L_1 + L_2)(2L_1 + L_2) + b(b - 2L_1(L_1 + L_2))}$, the battery supplier chooses to open the recycling channel. Other scenarios are similar to the proof.

A.7. PROOF OF COROLLARY 2

Proof. The boundary conditions that are beneficial to the NEV manufacturer when the battery supplier open recycling channels are as follows: the real root of equation $\pi^N_m - \pi^N_s = 0$ represent the lower bound that the encroachment of battery supplier recycling channel is beneficial to the NEV manufacturer. When the battery collection quantity is not constrained by the NEV sales quantity, when $c^*_E \in [N^*_E, N^*_E)$, the encroachment of recycling channel by the battery supplier is beneficial to the NEV manufacturer; when the battery collection quantity is constrained by the NEV sales quantity, when $c^*_E \in [N^*_E, N^*_E)$, the encroachment of recycling channel by the battery supplier is beneficial to the NEV manufacturer, where $N^*_E = \frac{L_0 + \Delta L_1}{B_2} - 1$, $N^*_E = \frac{bL_0 + \Delta L_1}{B_2} - 1$. Therefore, we can get $\pi^M_s > \pi^C_s > \pi^N_s$, $\pi^M_m > \pi^C_m > \pi^N_m$, $\pi^M_i > \pi^C_i > \pi^N_i$, and we can prove that $\pi^M_s > \pi^C_s > \pi^N_s$.

A.8. PROOF OF PROPOSITION 4

Proof. By comparing the profits of battery suppliers in Scenarios NE, M and C, we can have $\pi^N_E - \pi^C_s = \frac{2(4L_0 + \Delta L_1)^2(L_1 + L_2)^2 - 2c_1L_1(L_0 + \Delta L_1)L_2(4L_1 + 5L_2) + c_1^2L_1L_2(8L_1 + 7L_2)}{L_1B_2}$, $v = bB_1 - X_2$, where $B_1 = \frac{X^2_2}{b^2} + \frac{L_2(2Y_1 + Y_2) + c_1(Y_2 - 2X_1)B_1}{B_2L_2}$. Similarly, $\pi^N_E - \pi^C_s$, by solving $f(m) = 0$, we can get $m = B_1 - X_2$. Further, when $m = v$, if $0 < m \leq \min(B_1 - \frac{X_2}{b}, bB_1 - X_2)$ and $c_1 < \frac{2(4L_0 + \Delta L_1)Y_1}{B_2 - 2L_2Y_1}$, $\pi^N_E > \pi^M_s$, $\pi^M_m > \pi^C_s$, $\pi^M_i > \pi^C_i$, $\pi^N_E > \pi^M_s > \pi^C_s$, $\pi^M_m > \pi^C_m > \pi^N_s$, $\pi^M_i > \pi^C_i > \pi^N_i$. The proof of Proposition 4 is completed.