Research on the influence of consumers' environmental preference and government policy on EV battery recycling

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Abstract. According to Chinese government, the first peak period of EV battery recycling will come soon. Improper disposal of EV batteries will cause a serious damage on the environment. So, reverse supply chain of EV battery recycling should be established. As one of the main bodies of reverse supply chain, consumers play an important role in the recycling of EV batteries. Government policy can regulate EV battery recycling. These factors will have a direct impact on EV manufacturers recycling strategy. To discuss how these factors, influence the recycling strategy exactly, a mathematical is established. Results shows that compared with the government's reward-penalty mechanism, consumers' environmental preference is the fundamental driving force for EV manufacturers to recycle EV batteries.

1. Introduction
EV battery is the core component of EV. As the capacity of EV battery will decline with time, and its average useful life is about 8 years [1]. If the battery capacity of EV declines to 70% - 80% of normal capacity, it needs to be replaced. Otherwise, the safety and stability of EV cannot be guaranteed [2]. On the one hand, if the replaced old EV battery cannot be properly handled, the chemical substances contained in it will have a great damage on the environment [3]; on the other hand, the raw materials of EV battery contain some precious metals, and their prices will rise with the increase of EV demand, which is not conducive to the promotion of EVs [4]. In addition, although the old EV batteries can not meet the needs of EVs, they can still be used for other purposes including energy storage stations [5].

Since 2012, the number of EVs in China began to grow explosively. According to the average service life of EV battery, China is about to usher in the first peak period of EV battery recycling. The recycling of EV batteries will become an important issue soon.

Consumers play an important role in the recycling of EV batteries and government regulation is necessary. In this paper, the influence of these two factors on EV battery recycling is discussed.

2. Notations and hypothesis
The definition of notations involved in the model is shown in Table 1.

The hypothesis in the model is as follows:
1) The information is symmetric and the participants are risk neutral and completely rational.
2) The demand for EVs is basically equal to the number of batteries to be recycled.
3) According to the technology management model [6], the relationship between the recycling rate and the investment of EV battery is quadratic.
(4) The market capacity of EVs is 1.

| Table 1. Notations |
|--------------------|
| Notations | Definition |
| \( \xi_g \) | Minimum recycling rate of EV battery stipulated by the government |
| \( \theta \) | The value of EV purchased by consumers |
| \( t \) | Government's reward and penalty coefficient for EV manufacturers |
| \( e \) | Environmental effect coefficient of unrecycled EV battery per unit |
| \( k \) | Consumers' environmental preference |
| \( \beta \) | R&D cost coefficient |
| \( \xi \) | Actual EV battery rate of EV manufacturers |
| \( r \) | Consumers' profit when EV manufacturers recycle electric batteries from consumers |
| \( p \) | Retail price of EV |
| \( c \) | Production cost of EV |
| \( q \) | Market demand of EV |
| \( W \) | Government subsidies to electric vehicle manufacturers |
| \( U \) | Consumer utility when buying EVs |
| \( \Pi \) | Profit of EV manufacturers |
| \( E \) | Environmental effects of unrecycled EV batteries |

3. Mathematical model

3.1. Model establishment

Consuming the value of EV purchased by consumers is \( \theta \sim U(0,1) \) [7], the net utility of consumers buying EV and participating in EV battery recycling is as follows:

\[
U = [1 + k(\xi - \xi_g)] \theta + \xi r - p
\]

If and only if \( U > 0 \), consumers will purchase EVs, and the corresponding value of \( \theta \) is:

\[
\theta_0 = \frac{p - \xi r}{1 + k(\xi - \xi_g)}
\]

Considering \( p - \xi r > 0 \), when the consumer's environmental preference \( k \) is large enough and the EV manufacturers' recycling rate \( \xi \) is lower than minimum recycling rate \( \xi_g \), that is \( 1 + k(\xi - \xi_g) < 0 \), consumers will not purchase EVs due to environmental preference.

When \( 0 < \theta_0 < 1 \), the demands for EV are:

\[
q = 1 - \theta_0
\]

Government subsidies to electric vehicle manufacturers are as follows:

\[
W = t(\xi - \xi_g)q
\]

The profits of EV manufacturers and environmental effects are as follows:

\[
\Pi = (p - c - \xi r)q + W - \frac{1}{2} \beta \xi^2
\]

\[
E = e(1 - \xi)q
\]

3.2. Model solution

According to formula (5), the first derivative of the recycling price of EV battery, the recycling price rate of EV battery and the price of EV are calculated respectively and solved simultaneously, and the stagnation point can be obtained:

\[
\begin{aligned}
\left\{ r^* &= r(p^*, \xi^*) \\
p^* &= 0 \\
\xi^* &= \xi(r^*, p^*)
\end{aligned}
\]
According to formula (7), it is obvious that \( p = 0 \) does not conform to the actual situation. So there is no extremum. For continuous bounded functions, if there is no extremum in the definition domain, the maximum value of the function is obtained at the boundary of the definition domain. Therefore, when \( \xi = 0 \) or 1, the EV manufacturer obtains the maximum profit, that is EV manufacturer will recycle all the EV batteries or not recycle any EV batteries at all. Combined with formula (2), proposition as follows can be drawn:

Proposition 1: When consumers’ environmental preference is large enough, EV manufacturers will recycle all EV batteries.

If consumers’ environmental preference is not large enough, let \( \Pi_0 \) and \( \Pi_1 \) correspond to \( \xi = 0 \) and \( \xi = 1 \) respectively.

\[
\Pi_0 = (p - c - t\xi_g)(1 - \frac{p}{1-k\xi_g})
\]

\[
\Pi_1 = [p - r - c + t(1 - \xi_g)][1 - \frac{p-r}{1+k(1-\xi_g)}]
\]

For formula (8), the first and second derivatives of \( p \) are obtained respectively.

\[
\frac{d\Pi_0}{dp} = -2p+c+(t-k)\xi_g+1
\]

\[
\frac{d^2\Pi_0}{dp^2} = -2 < 0
\]

The maximum profit of EV manufacturers when \( \xi = 0 \) is:

\[
\Pi_0^* = \begin{cases} 
0 & 1-k\xi_g < 0 or 1-c-(k+t)\xi_g < 0 \\
\frac{(1-c-(k+t)\xi_g)^2}{4(1-k\xi_g)} & 1-k\xi_g > 0 and 1-c-(k+t)\xi_g > 0
\end{cases}
\]

For formula (9), let \( \delta = p - r \), the first and second derivatives of \( p \) are obtained respectively.

\[
\frac{d\Pi_1}{d\delta} = -2\delta+c+(t-k)(1-\xi_g)+1
\]

\[
\frac{d^2\Pi_1}{d\delta^2} = -2 < 0
\]

The maximum profit of EV manufacturers when \( \xi = 1 \) is:

\[
\Pi_1^* = \frac{(1-c+(k+t)(1-\xi_g))^2}{4(1+k(1-\xi_g))}
\]

When \( \Pi_1^* > \Pi_0^* \), that is:

\[
k(t+k)^2\xi_g^2 + [2k\beta -(k+2)(t+k)^2]\xi_g + (t+k)^2
\]

\[-2(t+k)(c-1) - k(c-1)^2 > 0
\]

4. Numerical Experiments

Combined with the actual data and reference [7], suppose \( c = 0.5, \beta = 0.05, t = 0.02, e = 0.1 \). Assume that the government’s reward and penalty coefficient have been determined.

The simulation results of the influence of consumers’ environmental preference on EV battery recycling rate and environmental effects are shown in Fig 1 and Fig 2 respectively.

Fig 1 shows that as consumers’ environmental preference becomes larger, EV manufacturers are more willing to recycling EV batteries. When consumers’ environmental preference is large enough, all EV batteries will be recycled even with no government subsidy.
Fig. 1 Influence of consumers' environmental preference and minimum recycling rate on EV battery recycling

Fig 2 shows that as consumers' environmental preference or minimum recycling rate becomes larger, environmental effects of unrecycled EV batteries can be reduced.

Fig. 2 Influence of consumers' environmental preference and minimum recycling rate on environmental effects

5. Conclusion
This paper mainly discussed the influence of consumers' environmental preference and minimum recycling rate of EV battery stipulated by the government on EV battery recycling. According to numerical experiments, conclusions as follows is obtained:

(1) Consumers' environmental preference is the fundamental driving force for EV manufacturers to recycle EV batteries. When consumer preferences are large enough, EV manufacturers will recycle all EV Batteries without any other incentives. Therefore, in the long run, improving consumers' awareness of environmental protection is the fundamental way to solve the problem of EV battery recycling.

(2) When the EV battery recycling situation is not ideal, improving consumers' environmental preference or minimum recovery rate can help to reduce the environmental effect; otherwise, the minimum recovery rate should be increased cautiously.

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