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ELECTRIC VEHICLE BATTERY RECYCLING: SYSTEM DYNAMICS GAME BASED ANALYSIS FOR THE INFLUENCING FACTORS

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Abstract

With the rapid development of electric vehicles (EV), more and more EV batteries will intensively face the retirement. If they are treated improperly, EV batteries might pose a serious threat to human health and environment. Therefore, recycling spent EV battery is full of significance. However, the recycling system and specific policies have not be well established in China. This paper aims to evaluate several recycling subsidy policies being considered and tested in China for their influences on recycling effect and economic benefits. We first establish a system dynamics model with game characteristics to describe and analyse the triple-channel (i.e. manufacturer, retailer, and third-party recycler) recycling system. Recycling subsidy policy and technological progress are then introduced. The game equilibrium and evolution of the system under different scenarios are investigated. Results show that: 1) both recycling subsidy and advancement in technology could improve total recycling rate and profit. 2) Particularly, the former can improve recycling rate of manufacturer while the latter can raise the interest of retailer and third-party recycler in spent EV battery recycling. 3) Even with gradual withdrawal of recycling subsidy, the system could still maintain steady growth as long as the technology advances to a higher level. The results could provide support to manufacturer in managing the multi-channel recycling system and the government agencies in optimizing the recycling policy. The hybrid method, game theory combined with system dynamics, can improve the limitations of these two methods and can be applied to other complex systems with game traits.

Key words: game theory, spent electric-vehicle battery recycling, subsidy policy, system dynamics

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1. Introduction

Over the past few years, air pollution caused widespread concern around the world. As one of the key factors, transportation industry emitted enormous greenhouse gases (Banica et al., 2017; Du et al., 2018a, 2018b). Therefore, government agencies took measures to develop clean energy automobiles especially electric vehicles (EV) (Tang et al., 2017), and China has become the world's largest producer of EV battery.

A rough estimate of EV battery lifespan is projected around 8 to 10 years (Ahmadi et al., 2014; Heymans et al., 2014; Lain, 2001; Marano et al., 2009). Due to the explosive development of EV market since 2012, EV batteries will intensively face the retirement (Tang et al., 2018). According to the estimation, spent EV battery's volume will up to 1160 thousand tons by the year of 2023 in China. Actually, EV battery recycling is of great significance. Firstly, without proper treatment, spent EV batteries might have irreversible and catastrophic consequences for the environment and human health as they contain heavy metals, toxic electrolyte and plastics (Bankole and Lei, 2018; Omar and Rohani, 2015; Ordoñez et al., 2016; Xu et al., 2017; Zeng et al., 2015; Zhang et al., 2016a). Besides, the cobalt resource is scarce in China, which accounts for only 1.8% of the global

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proven reserves, and more than 90% depends upon import. While the large amount of demand will lead to the rise of the resource price. EV battery recycling can significantly reduce the demand for virgin materials. Avoiding significant negative environmental factors occurred from ore mining and processing.

In the initial stage of EV development, the government agencies have realized the importance of EV battery recycling, and successively formulated various policies. "Technology policy for the recycling and utilization of EV battery (2015 edition)" issued in 2016 by Chinese government states that battery manufacturer and automobile manufacturer are mainly responsible for recycling. In 2018, "The new energy vehicle battery recycling pilot scheme" issued by Ministry of Industry and Information Technology and other seven ministries clarify that automobile manufacturer needs to build recycling channels.

Nevertheless, battery manufacturer and automobile manufacturer are reluctant to develop recycling network due to high cost when mandatory regulation and incentives does not exist (Ramoni and Zhang, 2013; Wang and Wu, 2017; Xie et al., 2017; Xu et al., 2017; Zeng et al., 2015; Zhang et al., 2016b). In addition, the lack of technology also hinders the development of spent EV battery recycling industry (Zeng et al., 2015). In practice, the recycling rate of spent EV battery was only 2% in 2015. Moreover, until now, well-developed network system and regulatory mechanisms have not been well established.

Many scholars have conducted a series of studies on recycling channel management. Gao et al. (2014) qualitatively analyzed the current situation of spent EV battery recycling in China, and gave advices to build producer recycling system and leasing recycling system. Liu and Gong (2014) researched matching behavior between vehicle and battery and analyzed the influencing factors of spent EV battery recycling using agent approach. Many scholars studied the decision-making problem of recycling channels by game theory. Savaskan et al. (2004) compared three recycling modes including manufacturer recycling, retailer recycling, and third-party recycling. They found that the efficiency of retailer recycling is highest among the three members because, retailers are in close contact with consumers. Hong et al. (2013) studied manufacturer-retailer recycling, manufacturer-third party recycling, and retailer-third party recycling. They also studied the cooperation mechanism between the channels. Their results showed that manufacturer-retailer recycling mode offers highest efficiency. Liu et al. (2017) further analyzed the intensity of competition between different channels, and later, compared their conclusions with Savaskan et al. (2004) and Hong et al. (2013). Chuang et al. (2014) explored the influence of recycling cost structure and recycling regulations to recycling channel choice based on comparing manufacturer recycling, retailer recycling and third-party recycling. Huang et al. (2015) studied multi-channel selection decisions regarding remanufacturer-leading recycling. While Huang et al. (2017) studied triple recycling channel strategies regarding retailer dominated system. Huang and Wang (2017) studied dual-recycling channel decision with cost disruptions. Li et al. (2017b) explored governance mechanisms of dual-channel reverse supply chain with informal collection channel. They found that both governments and collectors could implement appropriate governance mechanisms to control or utilize the informal collection channel. All the above scholars use game theory to conduct their researches.

In terms of regulatory policies of spent EV battery recycling, quantitative researches are really limited. Wang et al. (2014) compared four kinds of subsidy policy options for auto parts recycling and their reuse including direct subsidy, recycling subsidy, research and development (R&D) subsidy, and product subsidy. Wang et al. (2015a) studied the mechanism of rewards and punishment and its role in implementing the recycling policies under two kinds of power structure separately led by manufacturer and recycler. Results show that the mechanism can improve the recycling rate and efficiently reduce the product price under assigned the responsibility of a reasonable leader. Gu et al. (2017) studied the subsidy mechanism of new energy vehicle and spent EV battery recycling problem. Their results show that spent EV battery recycling rate is positively related to the production of new energy vehicles and negatively related to expected utility. These three researches are also focused on game theory.

The above background suggests that game theory has been widely applied in field of recycling channel strategy and regulatory policy. However, its application remains limited in emerging industries, especially in case of spent EV battery recycling. 1) It is difficult to solve, especially when the income function is higher order function, effective algebraic equilibrium solutions and subsequent game analysis are almost impossible. 2) Finite game problem exists, normally, the optimal solutions are provided through infinite times, which repeat the games. However, recycling policies of spent EV battery are constantly being change. Therefore, absolute same conditions become difficult to maintain for infinite game. Nevertheless, finite game tends to change decision-making behavior (Thaler, 1993).

Considering these challenges, traditional game theory becomes less effective to describe the equilibrium and evolution of spent EV battery recycling system. In contrast, hybrid approach, game theory combined with system dynamics (SD), have more potential to provide satisfactory solution to help to solve the above problems. Some researchers combined game theory and SD – a combination of evolutionary game theory and SD to solve problems including environmental pollution (Wang et al., 2011), green supply chain management (Tian et al., 2014), sustainability of carbon label policies (Zhao et al., 2016, 2018). In addition, Kim and Park (2010) and Cai et al. (2016) built SD model to conduct example analysis based on game model. However, these SD models have failed to depict game characteristics properly. Attempts were made in this paper to combine game theory with SD, 1) changing the limitations of existing SD simulations only for evolutionary game. 2) Based on the "reaction function", the dynamic game is incorporated into the SD model.

This paper intends to answer the following questions: 1) How do relevant factors such as technology advancement affect the recycling of spent EV battery? 2) How could government design effective policies to improve recycling rate of spent EV battery? 3) How do develop a model that can be used to understand the evolution of the recycling system? The results could provide support to automobile manufacturer in managing the multi-channel recycling system and the government agencies in optimizing the recycling policy.

The reminder of this paper is organized as follows. Section 2 describes the problem and builds game model. Section 3 builds and tests SD-game model. Section 4 analyzes the simulation. Section 5 lists conclusion, limitations, and future research directions. All equations used in the model are listed in Appendix.

2. Material and methods

2.1. Problem analysis and game model

We take the spent EV battery recycling system as the research object. Which includes manufacturer (EV battery manufacturer), retailer (4S shop), third-party recycler (TPR), consumers and government agencies. Normally, new EV batteries are available to the consumer through retailer. According to the new regulation, after the product cannot meet the demand of EV, it should be recycled by the manufacturer. Moreover, manufacturer transfer the collected EV battery to a professional processor for subsequent disassembly, etc. Here, manufacturer has several options of collecting channel. The detail is described in Fig. 1.

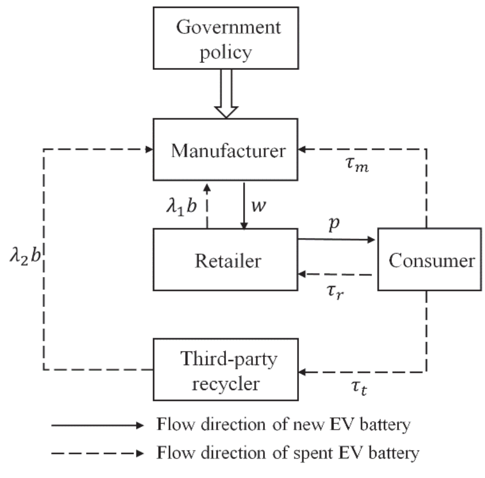


Fig. 1. Recycling system of spent EV battery

Manufacturer has three different collection channels of spent EV battery: one is independent collecting and the other is outsourcing collecting, which includes retailer collecting and TPR collecting.

2.1.1. Notation

The notations, used in the model, are summarized and explained as Table 1:

Table 1. Notations used in the model

Symbol Definition	
ϕ	Potential demand
β	Sensitivity of consumers to price
c_f	Unit cost of new EV battery of manufacturer
b	Unit recycling price of manufacturer
s	Unit recycling subsidy for manufacturer
t	Unit transfer price of spent EV battery of manufacturer
C_m	Scalar parameter of manufacturer, the exchanging coefficient between the recycling rate and the investment
C	Scalar parameter of retailer and TPR
λ_1	Recycling price discount for retailer
λ_2	Recycling price discount for TPR
w	Unit wholesale price
p	Unit price
τ_i	Recycling rate of spent EV battery of channel member i
π_i	The profit of channel member i

Subscript $i \in \{m, r, t, sc\}$ represents to the manufacturer, the retailer, the TPR, and the entire supply chain respectively.

2.1.2. Assumptions

To solve the problems stated in the above subsections, some key assumptions were proposed mainly based on Savaskan et al. (2004).

- The demand function is $D(p) = \phi - \beta p$, in order to ensure $D(p) > 0$, when $p = c_f$, the equation $D(c_f) = \phi - \beta c_f > 0$, $\phi > \beta c_f$ should be satisfied (Savaskan, 2004).
- Manufacturer offers different recycling strategies for its two outsourcing recycling channels, which closely cooperates with retailer in forward supply chain. In order to ensure the profitability of outsourced recycling, recycling price paid to the retailer and TPR should satisfy $0 < \lambda 1b < s + t$ and $0 < \lambda 2b < s + t$, the discount coefficient should satisfy $\lambda 1 < (s + t) / b$ and $\lambda 2 < (s + t) / b$. We distinguish the recycling strategies according to whether $\lambda 1$ or $\lambda 2$ equals to 1. If the parameter equals to 1, the recycling strategy is fair, or else, it is discriminatory (Ding et al., 2013).
- In order to ensure the recycling rate less than 1, $2C > \lambda_1 b (\phi - \beta c_f)$ and $2C > \lambda_2 b (\phi - \beta c_f)$ should be satisfied by referencing the assumption of Savaskan (2004). Moreover, the investment of manufacturer, retailer and TPR in spent EV battery recycling respectively is $C_m \tau_m^2$, $C\tau_r^2$ and $C\tau_t^2$ in reference to Savaskan (2004) and Li et al. (2017a).

2.1.3. Game model

The Stackelberg game, a type of non-cooperative game, in which a decision maker take the lead or the favorable position, and the follower, play the game after the leader. Stackelberg game model was proposed to study the influences of government's subsidy towards environmental-friendly products in a dual-channel supply chain (Li et al., 2018). Stackelberg game model was widely used to study the interactions among manufacturer, retailer, recycler and consumers (Feng et al., 2017; Wang et al., 2015b; Zhao et al., 2017). Moreover, Tang et al. (2018) applied Stackelberg game model to the research of spent EV batteries recycling. Therefore, we adopt the Stackelberg game theory here. Similar to Tang et al. (2018), manufacturer behaving as the Stackelberg leader dominates the system, while retailer and TPR, as the followers, make the best response to the optimal decisions by the manufacturer. The profit functions of manufacturer, retailer, and TPR are as follows (Eqs.1-3):

$$\underset{(w,\ \tau_m)}{Max}\ \pi_m = [w - c_f + (s + t)(\tau_m + \tau_r + \tau_t)](\phi - \beta p) - b(\lambda_1\tau_r + \lambda_2\tau_t)(\phi - \beta p) - C_m\tau_m^2 \quad (1)$$

$$\underset{(p,\ \tau_r)}{Max}\ \pi_r = (p - w)(\phi - \beta p) + \lambda_1 b\tau_r(\phi - \beta p) - C\tau_r^2 \quad (2)$$

$$\underset{(\tau_t)}{Max}\ \pi_t = \lambda_2 b\tau_t(\phi - \beta p) - C\tau_t^2 \quad (3)$$

A non-cooperative game occurs between the retailer and TPR. By the backward induction method, we first calculate the best-response functions of retailer and TPR as Eqs. (4-6):

$$p = (\phi + \beta w - \lambda_1 b\tau_r\beta) / (2\beta) \quad (4)$$

$$\tau_r = (\phi - \beta p)\lambda_1 b / (2C) \quad (5)$$

$$\tau_t = (\phi - \beta p)\lambda_2 b / (2C) \quad (6)$$

Simultaneous Eqs. (4-6), we have the optimal solutions as (Eq. 7):

$$P^* = [2C(\phi + \beta w) - \phi\beta\lambda_1^2 b^2] / [\beta(4C - \beta\lambda_1^2 b^2)],$$
$$\tau_r^* = (\phi - \beta w)\lambda_1 b / (4C - \beta\lambda_1^2 b^2)$$
$$\tau_t^* = (\phi - \beta w)\lambda_2 b / (4C - \beta\lambda_1^2 b^2) \quad (7)$$

Then, we substitute the above Eq. (7) into the profit function of manufacturer so that we can deduce $\boldsymbol{w}$ and $\boldsymbol{\tau_m}$ as Eqs. (8-9):

$$W = \{4C\phi + \beta(4C - \beta\lambda_1^2 b^2)[c_f - (s + t)\tau_m] - K\} / (2\beta L) \quad (8)$$

$$\tau_m = C(s + t)(\phi - \beta w) / [C_m(4C - \beta\lambda_1^2 b^2)] \quad (9)$$

The letter from Eq. (8) and Eq. (9) may be expressed as (Eq. 10):

$$K = \beta\phi[2(s + t)\lambda_1 b - \lambda_1^2 b^2 + 2(s + t)\lambda_2 b],$$
$$L = 4C - (s + t)\lambda_1 b\beta - (s + t)\lambda_2 b\beta \quad (10)$$

Simultaneous the above Eq. (8) and Eq. (9), we can obtain the optimal decisions as (Eq. 11):

$$W^* = \{C_m[\beta c_f(4C - \beta\lambda_1^2 b^2) + 4C\phi - K] - C(s + t)^2\beta\phi\} / [\beta(2C_m L - C(s + t)^2\beta)],$$
$$\tau_m^* = C(s + t)(\phi - \beta c_f) / [2C_m L - C(s + t)^2\beta] \quad (11)$$

Substitute Eq. (11) into Eq. (7), we can derive the optimal decisions as (Eq. 12):

$$P^* = \{2C_m[3C\phi + \beta Cc_f - (s + t)\lambda_1 b\beta - (s + t - \lambda_2 b)\lambda_2 b\beta\phi) - C(s + t)^2\beta\phi]\} / \{\beta[2C_m L - C(s + t)^2\beta]\},$$
$$\tau_r^* = (\phi - \beta c_f)C_m\lambda_1 b / [2C_m L - C(s + t)^2\beta],$$
$$\tau_t^* = (\phi - \beta c_f)C_m\lambda_2 b / [2C_m L - C(s + t)^2\beta] \quad (12)$$

The total recycling rate is as (Eq. 13):

$$\tau_{sc} = (\phi - \beta c_f)[C(s + t) + (\lambda_1 + \lambda_2)bC_m] / [2C_m L - C(s + t)^2\beta] \quad (13)$$

We substitute the optimal solutions (Eqs.16-18) into the profit functions of manufacturer, retailer and TPR, then we have functions of high-order, and it is not easy to analyze the conclusions intuitively. However, SD can provide a good help to solve the problem.

2.2. SD-game model

We analyzed a series of optimal decisions through game theory in the aforementioned part. However, the reality is often much more complex than the above models. In fact, many factors constantly tend to cause the game equilibrium to remain in the state of flux, which includes technical development and dynamic policies. Moreover, these factors even make the equilibrium difficult to achieve. Therefore, we introduced SD to improve the traditional game model. First, we built basic SD model based on Eqs. (4)-(6) and Eqs. (8)-(9). Considering the influence of progress in technology, we introduced STEP function to improve the traditional game analysis and related limitations. Moreover, LOOKUP function is introduced to simulate the dynamic subsidy policy.

2.2.1. The stock and flow diagram of SD model

At the beginning, the government formulates support policies and develops EV battery technology. We took the wholesale price of EV battery as the initial variable of the system, which is affected by recycling subsidy and technology cost. In addition, manufacturer decided recycling rate according to recycling subsidies, transfer price of spent EV battery, and recycling cost. In the same way, retailer used wholesale price and recycling cost to decide the optimum values of price, sales volume, and recycling rate. Likewise, TPR decided optimal recycling rate according to the sales volume and its recycling cost. An increase in recycling rate of spent EV battery would lead to a comparatively lower value of wholesale price. A new round of game decision restart with the change in subsidy policy and advancement in technology. The system achieves game equilibrium and steady state through finite repetitions.

According to above analysis, we established SD-game model by Vensim DSS, and the stock-flow diagram is depicted in Fig. 2 (M is the manufacturer, and R is the retailer).

2.2.2. Data and equations description

We took the "month" as the decision-making time unit in the view of the statistical habit of "The energy saving and new energy vehicle industry development planning (2012-2020)". Then we built a simulation model from the years 2015-2020 of game periods in the reference to the data of "The depth report of EV in 2018" and so on (Table 2).

Main equations of the model are listed in Appendix.

2.2.3. Model test

We simulated traditional game circumstances that ignored recycling subsidy and advancement in technology. Spent EV battery recycling market became steady, when game enter into 38th round (February 2017). We got the values in complete accordance to the theoretical optimal solutions as Eqs. (11)-(12) and listed them in Table 3. The results indicate that the model can fully describe the game process of EV battery recycling system.

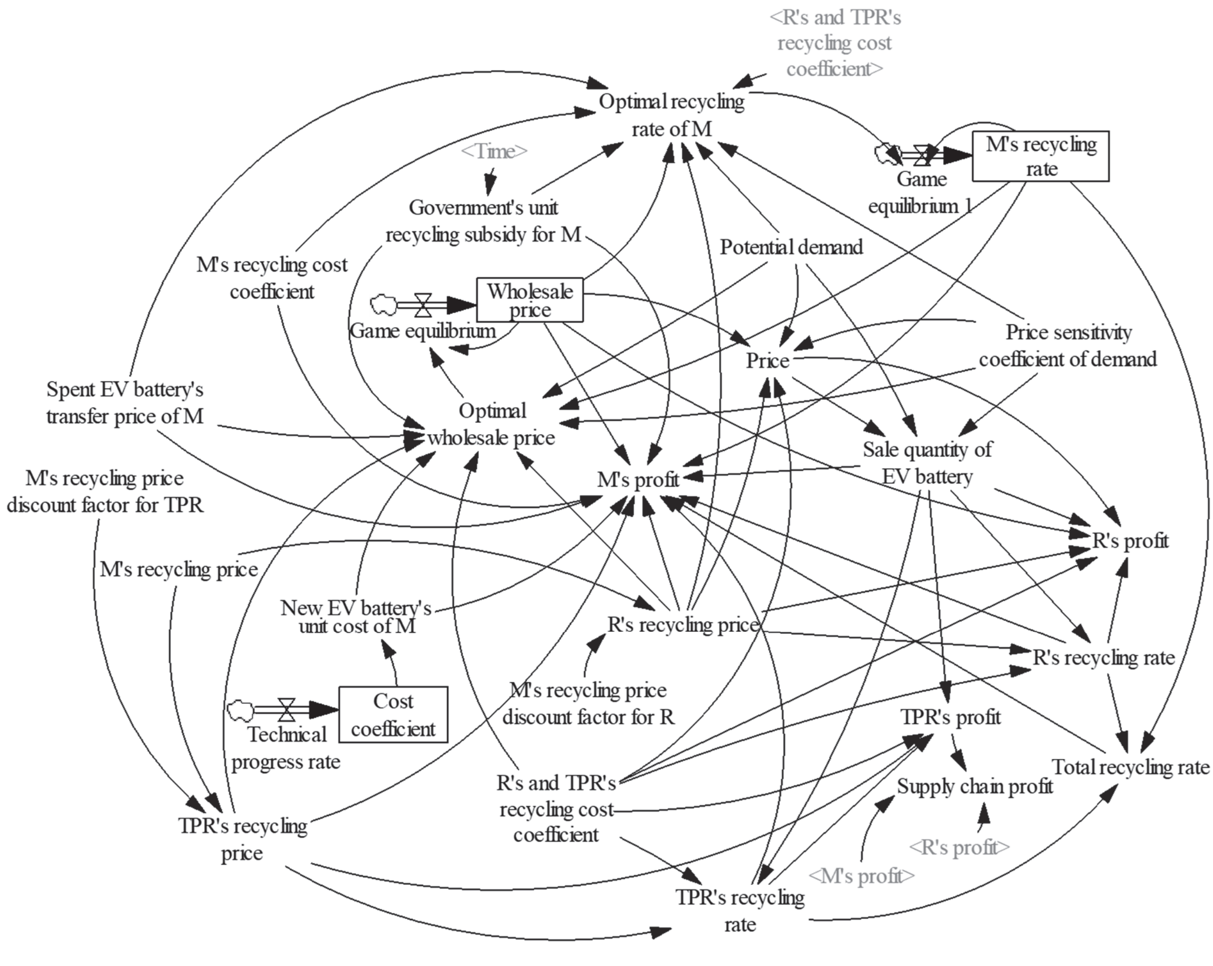


Fig. 2. SD-game model

Table 2. Data in the model

Main parameters	*Value*	*Unit*
b	1000	Yuan / unit
s	1000	Yuan / unit
t	460	Yuan / unit
λ_1	0.9	–
λ_2	0.8	–
β	0.5	–
C	50	million Yuan
C_m	250	million Yuan

Table 3. Optimal solutions

Indicator	*Optimal solution*	*Unit*
w	129.7	thousand Yuan
p	174.7	thousand Yuan
Q	22.6	thousand units/Month
τ_m	6%	–
τ_r	20.35%	–
τ_t	18.09%	–
π_m	2.04	billion Yuan
π_r	1.02	billion Yuan
π_t	1.64	million Yuan
π_{sc}	3.07	billion Yuan

We took the value of recycling subsidy as 1000 Yuan / unit in reference to the subsidy policy in Shanghai. Table 3 exhibits that the optimal values of the wholesale price and the price are respectively 129.7 thousand Yuan and 174.7 thousand Yuan. The sale quantity of EV battery is 22.6 thousand units / month. All above optimal solutions are in conformity with actual data of EV battery market. This suggests that the model is fully capable of describing the reality. The recycling rate of retailer and TPR are respectively 20.35% and 18.09%. However, the recycling rate of manufacturer is 6%. The profit of manufacturer and retailer are respectively 2.04 billion Yuan and 1.02 billion Yuan. The profit of TPR is only 1.64 million Yuan.

3. Results and discussions

Based on Section 2, we simulate the impact of subsidy policy and technical progress on recycling activities in this section.

3.1. Simulation and analysis

Three specific indicators-price, recycling rate, and total profit were picked up to analyse the impact of different factors. The reason why we choose these indicators is as follows. The price directly affect the demand market. The recycling rate is an important indicator to reflect the influence on recycling effect. Furthermore, we choose the total profit to reflect the economic benefit. Another point worth to explain is that the following analysis takes the scenario, which leave out the recycling subsidy and technical progress, as the benchmark.

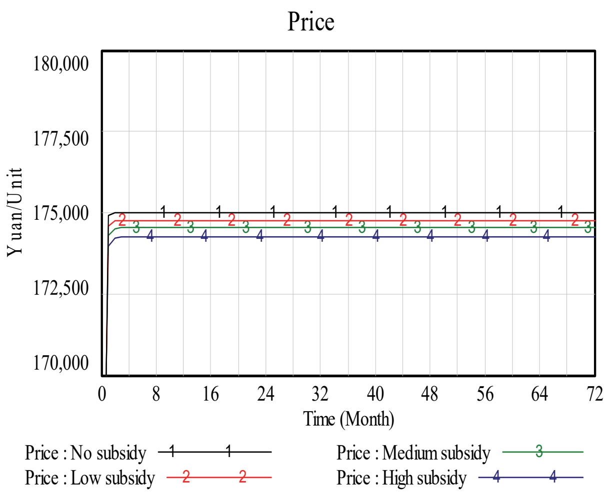
3.1.1. Recycling subsidy policy

We simulate four recycling subsidy standards: 0 Yuan / Unit, 1000 Yuan / Unit, 2000 Yuan / Unit and 3000Yuan / Unit which we refer as "No subsidy", "Low subsidy", "Medium subsidy" and "High subsidy" respectively.

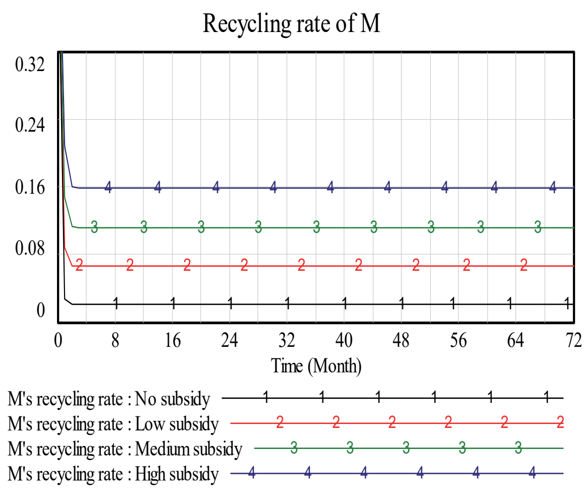
From Fig. 3, it is obvious that the price of battery decrease with the increase of recycling subsidy (Fig. 3a). One possible explanation is that manufacturer pass on recycling subsidy to consumers by lowering price, benefitting consumers and stimulating their demand. The recycling rate of M shows an evident increase in the cases of "Low subsidy", "Medium subsidy" and "High subsidy" (Fig. 3b). Furthermore, recycling rate of M in the case of "High subsidy" is higher than that in the cases of "Medium subsidy" and "Low subsidy". This means that more recycling subsidy means higher interests of manufacturer in recycling spent EV battery. Whereas, the recycling rate of R and TPR shows a slight increase along with the growing recycling subsidy (Fig. 3c, d). In general, the recycling subsidy policy led to an increase in overall recycling rate (Fig. 3e). Moreover, it also improved the total profit (Fig. 3f).

3.1.2. Technical progress

We analyse technical progress of three different speeds: "stagnated technical progress", "Slow technical progress" and "Rapid technical progress" respectively (represent the benchmark, Eq. (20) and Eq. (21) in Appendix separately).



(a)



(b)

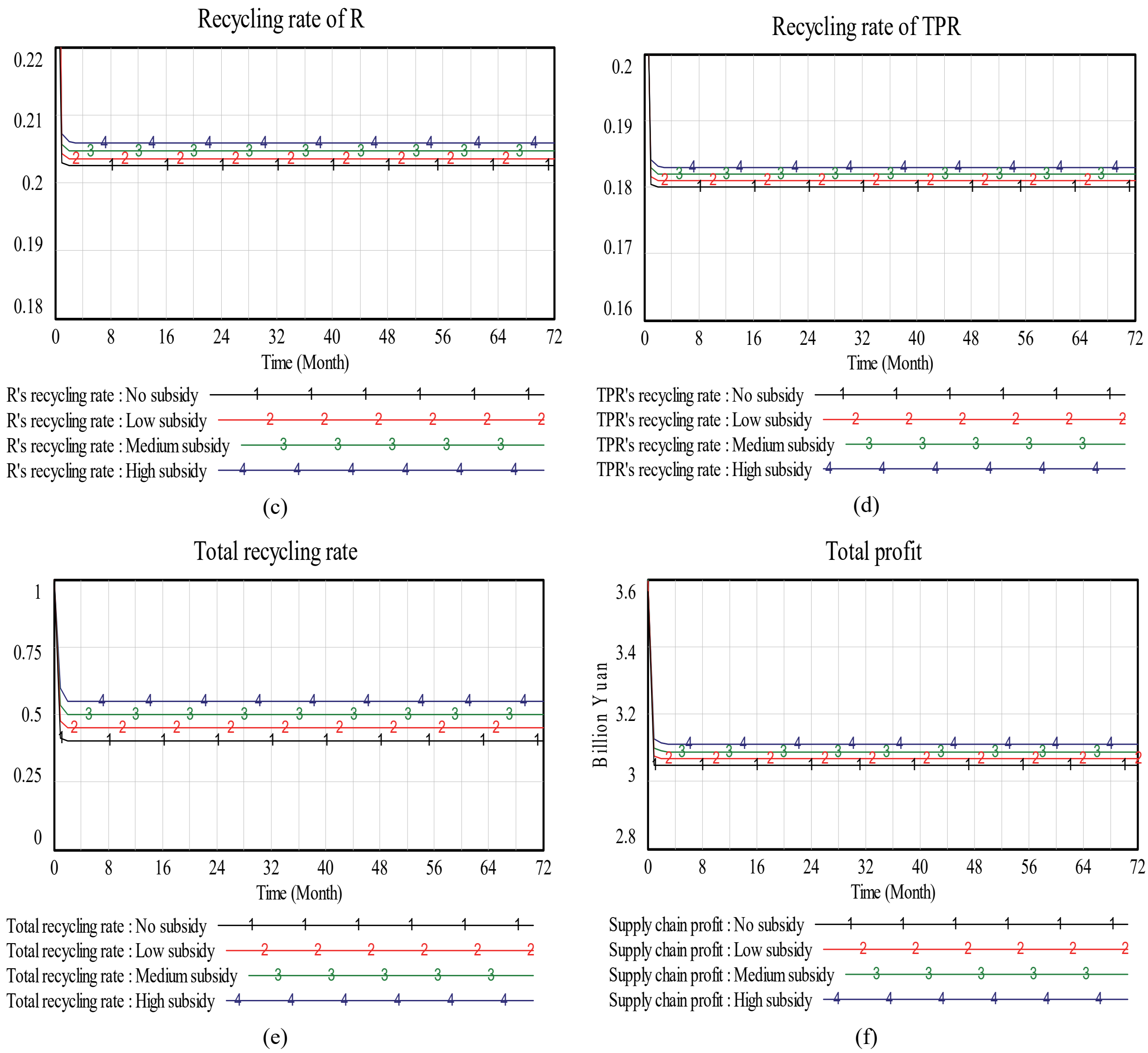


Fig. 3. Influences of subsidy policy on (a) price; (b) recycling rate of M; (c) recycling rate of R; (d) recycling rate of TPR; (e) total recycling rate; and (f) supply chain profit

As is shown in Fig.4, advancement in technology also led the price down (Fig. 4a). Differently, it has hardly any effect on the recycling rate of M (Fig. 4b). However, technical progress bring a substantial rise in recycling rate of R and TPR (Fig. 4c,d). Moreover, under rapid technical progress, the recycling rate of R and TPR is higher than under slow technical progress. Similar to provision of recycling subsidy, technological advance can result in an increase in overall recycling rate and total profit (Fig. 4e,f).

3.1.3. Subsidy policy combined with technical progress

To analyse the comprehensive influence of mixed-factors, we choose two recycling subsidy policies - “Low subsidy”, “High subsidy” to combine with “Slow technical progress” and “Rapid technical progress”. The “Low subsidy”, “High subsidy”, “Slow technical progress” and “Rapid technical progress” are abbreviated as LS, HS, ST and RT respectively.

Combining these abbreviations such as LS + ST represents a mixed-case of low subsidy and slow technical progress. In total, there are four combinations, and the other three combinations are similar. Fig. 5 shows price, recycling rate of each agent and overall, as well as total profit under four combinations. Relative to the scenario without any policy, it is evident that combination of high recycling subsidy and rapid technical progress could significantly decline the price (Fig. 5a). Fig.5b, c, d, e clearly show us this comprehensive measure can greatly increase the recycling enthusiasm of each member, therefore, the total recycling rate has a positive rise.

Further from Fig. 5e, comparing curve 2 and 3, curve 4 and 5, we can see that total recycling rate evidently increased when the recycling subsidy raised. That means providing recycling subsidy is more effective than technical advancement in improving recycling rate. Certainly, the effect of combination measure on total profit is positive (Fig. 5f).

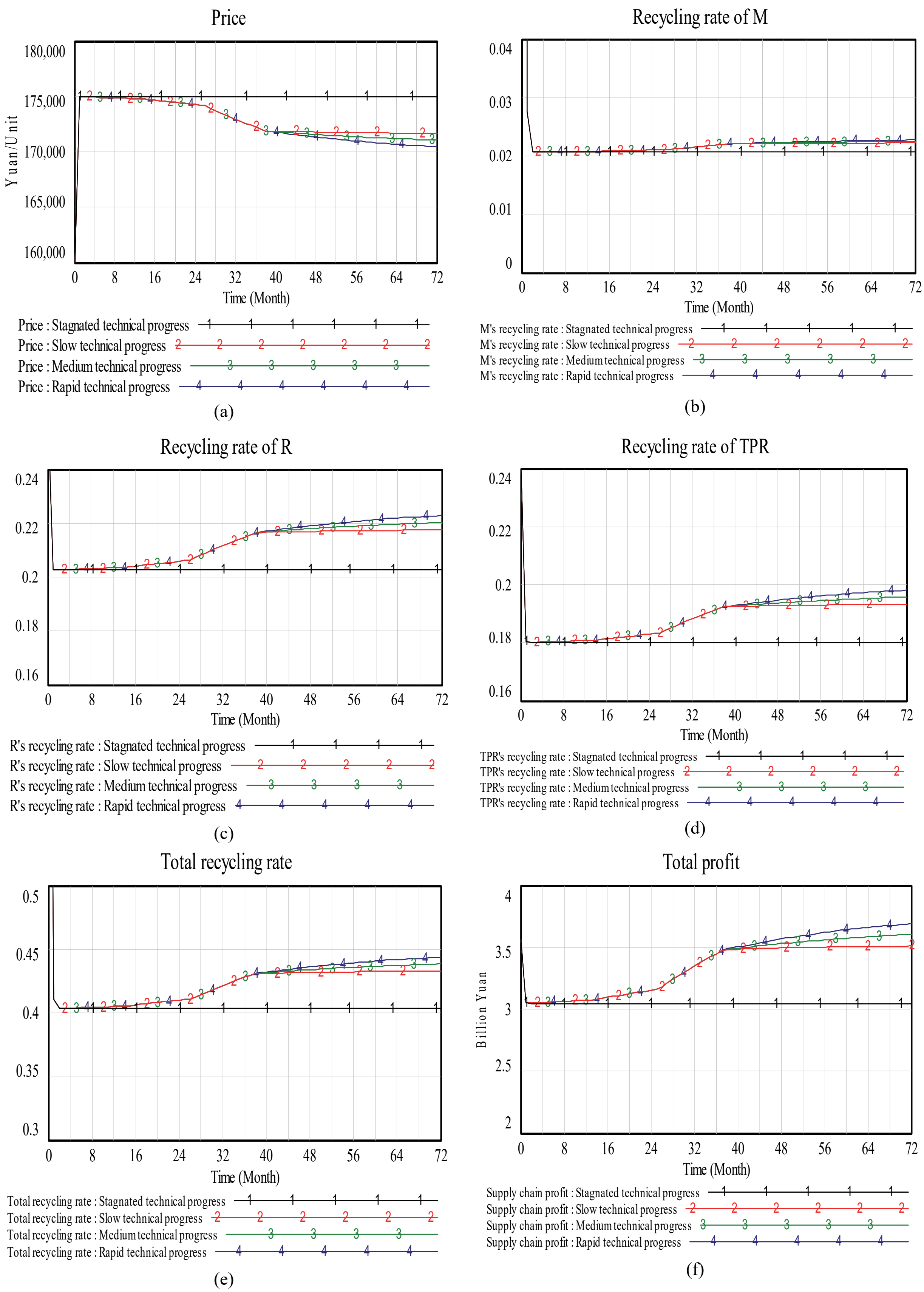


Fig. 4. Influences of technical progress on (a) price; (b) recycling rate of M; (c) recycling rate of R; (d) recycling rate of TPR; (e) total recycling rate; and (f) supply chain profit

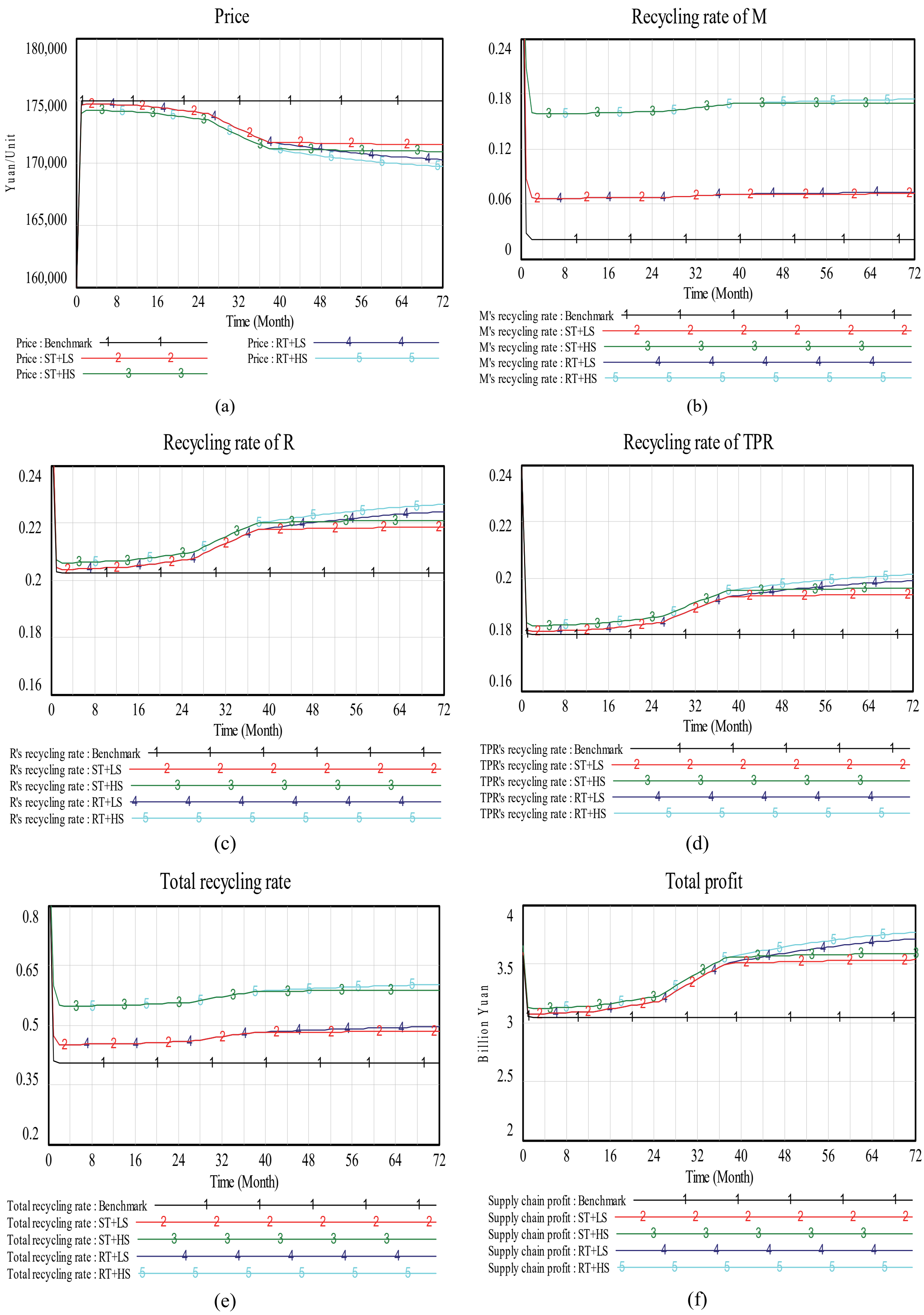


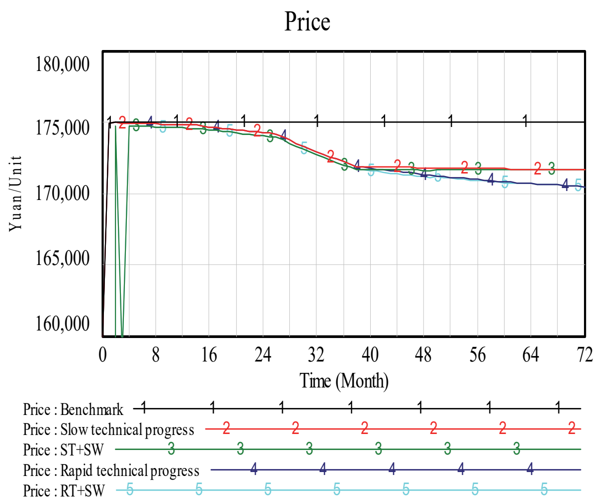
Fig. 5. Influences of subsidy policy and technical progress on (a) price; (b) recycling rate of M; (c) recycling rate of R; (d) recycling rate of TPR; (e) total recycling rate; and (f) supply chain profit

3.1.4. Subsidy withdrawal in the context of technical progress

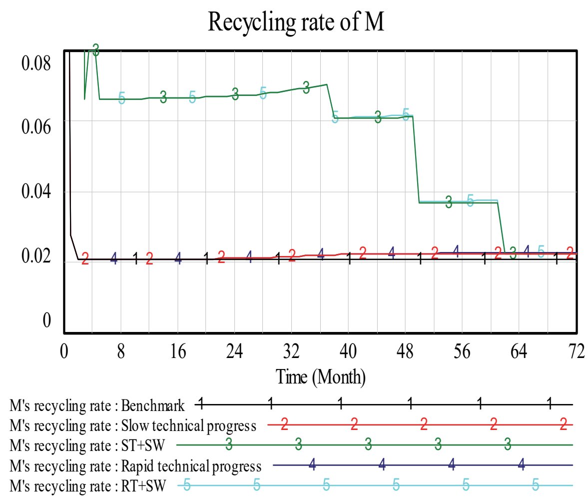
In this section, we analyse the case which considering the subsidy withdrawal in the context of technical advancement. We take the initial recycling subsidy as 1000 Yuan / Unit based on the actual situation in Shanghai and simulate the gradual decline in subsidy (as shown in Eq. (23) in Appendix). We abbreviate subsidy withdrawal as "SW". Two scenarios are simulated in which ST+SW and HT+SW represent considering subsidy withdrawal in the context of slow technical progress and high technical progress separately.

From Fig. 6 we can clearly see that a decline in recycling subsidy efficiently decrease the recycling rate of M (Fig. 6b). Whereas, it can hardly affects the price, recycling rate of R and TPR, total recycling rate and profit in the long run (Fig. 6a, c, d, e, and f). Although the recycling rate of M has decreased (Fig. 6b), the increase in the recycling rate of R and TPR could make up the decline (Fig. 6c, d). Overall, the total recycling rate has not decreased (Fig. 6e). Comparing curve 4 and 5 in Fig. 6f, we can indicate that even if the recycling subsidy fall back, as long as the technology keep advancing to a higher level, it still can boost the total profit.

Thus, provision of a vigorous support is necessary in initial developmental stages of spent EV battery recycling industry. However, a long-term dependence on subsidy is not a good strategy for sustainable development. The cost of new EV battery will show a downward trend along with the advancement in technology. In addition, the subsidy policy could gradually withdraw. Then the industry of spent EV battery recycling could achieve smooth pattern relying on market forces and their adjustments



(a)



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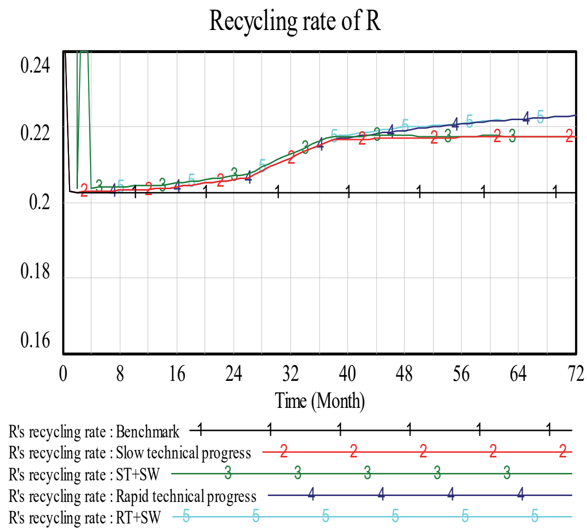
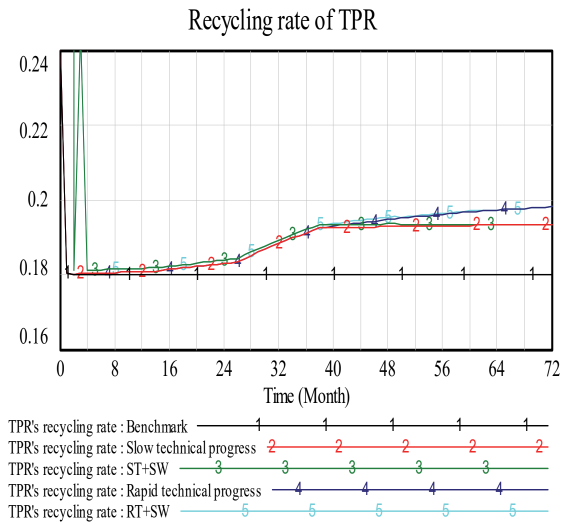


(c)



(d)

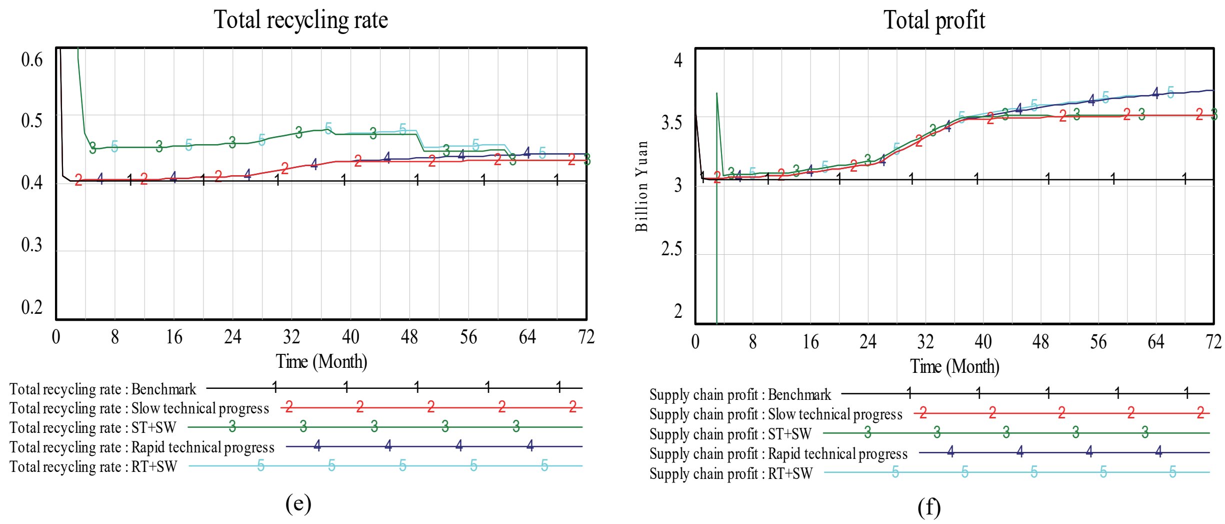


Fig. 6. Influences of technical progress and recycling subsidy withdrawal on (a) price; (b) recycling rate of M; (c) recycling rate of R; (d) recycling rate of TPR; (e) total recycling rate; and (f) supply chain profit

3.2. Discussions

Through above simulation, it is obvious that both provision of recycling subsidy policy and advancement in technology are of great significance in promoting the development of EV battery industry. This paper aims to evaluate the effectiveness of subsidy policy and technical progress on EV batteries recycling based on SD-game model and by simulating Chinese EV battery industry, which is a typical emerging recycling industry. The main results are as follows.

First, under recycling subsidy policy, the increase in total recycling rate mainly comes from manufacturer. The effect of subsidy policy on retailer and third-party recycler is very limited. Whereas, accompanied by technological advances, the interest of retailer and third-party recycler in EV battery recycling is stimulated. Second, it is obvious that the combination of subsidy and technical progress has better positive effects on improving the development of EV battery recycling than single policy. For example, the combination of high subsidy and rapid technical progress has the best positive effects on recycling promotion but involves high cost. Last, according to our simulation, in the long run, the technology advances to a higher level, even if the recycling subsidy policy gradually withdraws, the EV battery recycling industry still can maintain a stable development.

Therefore, in the initial phase, the government should provide recycling subsidy to manufacturer. As a leader, the manufacturer actively take part in EV battery recycling. Actually, it is a wise choice for manufacturer to outsource recycling work to retailer and third-party recycler. Furthermore, the manufacturer shift the focus on technology development, which is beneficial for not only manufacturer but also the entire system.

The impacts of subsidy policy for recycling were previously studied (Aksen et al., 2009; Chang et al., 2016; Chen, 2005; Liu et al., 2016, 2018; Sheu et al., 2005). Results showed that the provision of subsidy can pose a positive effect on recycling rate (Jia et al., 2017; Liu et al., 2018; Mitra and Webster, 2008; Wang et al., 2014; Wojanowski et al., 2007). Similar results were observed in this paper, different from existing papers, we further simulate the situations of technological progress and subsidy withdrawal.

Besides, in China, government support in terms of incentive policies such as subsidy measures and mandatory rules for recycling spent EV batteries should be developed to further promote the market behaviour (Hichkle, 2014; Lee et al., 1998; Wang, 2017; Zhang et al., 2016b; Zhou et al., 2007). However, there are more qualitative research than quantitative research regarding the above issue. Based on the actual background of spent EV battery recycling in China, this paper quantitatively analyse the impacts of subsidy policy in the context of technical progress, the proposed policy suggestions are more practical to the government agencies.

The other focus of this paper is to combine game theory with SD to simulate the subsidy policy and technical progress. The existing papers mainly conduct their researches using game theory (Hong and Ke, 2011) as well as two bi-level programming models (Aksen et al., 2009). We attempted to apply SD-game method to solve the problem. Based on the reaction function, establishing the SD model not only solves the difficult problem of high-order function solving in game theory, but also overcomes the subjectivity of SD modelling to some extent. This method provides a reference for solving similar problems.

4. Conclusions

This paper adopted game theory to build decision model with subsidy policy firstly. Then, considering game model facing many application difficulties such as solving the high-order function, finite gaming, and change of key parameters, attempts were made to combine game theory with SD. Hence, the SD-dynamic game model is proposed to simulate the game equilibrium and evolution of spent EV battery recycling system.

Through the simulation, we can concluded that 1) both, providing recycling subsidy and technical advancement, could improve recycling rate of spent EV battery and boost the system's economic benefit. 2) Furthermore, the former is capable of enhancing the recycling rate of manufacturer. While, the latter can effectively raise the enthusiasm of retailer and third-party recycler in recycling. 3) Moreover, with the gradual withdrawal of recycling subsidy, spent EV battery recycling market could maintain a steady development, as long as, the technology keep advancing to a higher level.

Additionally, this paper used the actual data of EV battery industry to analyse and evaluate the effectiveness of recycling subsidy policy and technical progress. Therefore, we could offer some practical and feasible insights for policy makers and manufacturer. In the coming years, spent EV battery recycling is about to face a large number of retirement, in this initial stage, the government should provide support to the leading manufacturer, introducing it actively take part in recycling. Of cause, combination of recycling subsidy and technical advancement could positively promote the recycling but of high cost. In the long run, manufacturer should outsource the recycling to retailer and third-party recycler and donate itself to develop the technology. Only in this way, the technology could advance to a high level and the EV battery could maintain a steady development even recycling subsidy decline gradually.

The main contribution of this paper is that we organically combine game theory and SD. This hybrid method 1) change the limitations of existing SD simulations only for evolutionary game. In addition, 2) make full use of the advantages of conditional function, STEP function and LOOKUP function in SD to expand the game analysis. This method can be applied to other complex systems with game traits. Nevertheless, many aspects need to be improved: 1) Expand data collection to get data that are more accurate. 2) Consider other recycling channels or other types of recycling policies.

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Appendix. Summary of main equations

(1) Potential demand = 100000 Units;

(2) Sale quantity of EV battery = Potential demand − Price sensitivity coefficient of demand * Price;

(3) Wholesale price = INTEG ((1 + Game equilibrium) * Wholesale price − Wholesale price, Initial Value= 60000 Yuan);

(4) Game equilibrium = (Optimal wholesale price − Wholesale price) / Wholesale price, the equation reflects whether the new game is balanced;

(5) Optimal wholesale price = (Price sensitivity coefficient of demand * (4 * R's and TPR's recycling cost coefficient − R's recycling price^2 * Price sensitivity coefficient of demand) * (New EV battery's unit cost of M − (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M) * M's recycling rate) + Potential demand * (4 * R's and TPR's recycling cost coefficient − 2 * (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M) * Price sensitivity coefficient of demand * R's recycling price + Price sensitivity coefficient of demand * R's recycling price^2 − 2 * Price sensitivity coefficient of demand * TPR's recycling price * (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M − TPR's recycling price))) / (2 * Price sensitivity coefficient of demand * (4 * R's and TPR's recycling cost coefficient − (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M) * Price sensitivity coefficient of demand * R's recycling price − Price sensitivity coefficient of demand * TPR's recycling price * (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M − TPR's recycling price)));

(6) M's recycling rate = INTEG ((1 + Game equilibrium 1) * M's recycling rate − M's recycling rate, Initial Value=80000 Yuan);

(7) Game equilibrium 1 = (Optimal recycling rate of M − M's recycling rate) / M's recycling rate;

(8) Optimal recycling rate of M = (R's and TPR's recycling cost coefficient * (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M) * (Potential demand − Price sensitivity coefficient of demand * Wholesale price)) / (M's recycling cost coefficient * (4 * R's and TPR's recycling cost coefficient − Price sensitivity coefficient of demand * (R's recycling price)^2));

(9) Price = (2 * R's and TPR's recycling cost coefficient * (Potential demand + Price sensitivity coefficient of demand * Wholesale price) − Potential demand * Price sensitivity coefficient of demand * (R's recycling price)^2) / (Price sensitivity coefficient of demand * (4 * R's and TPR's recycling cost coefficient − Price sensitivity coefficient of demand * (R's recycling price)^2));

(10) New EV battery's unit cost of M = Cost coefficient;

(11) M's profit = (Wholesale price − New EV battery's unit cost of M + (Government's unit recycling subsidy for M + Spent EV battery's transfer price of M) * Total recycling rate) * Sale quantity of EV battery − R's recycling price * R's recycling rate * Sale quantity of EV battery − TPR's recycling price * TPR's recycling rate;

(12) R's recycling price = M's recycling price * M's recycling price discount factor for R;

(13) R's recycling rate = R's recycling price * Sale quantity of EV battery / 2 / R's and TPR's recycling cost coefficient;

(14) R's profit = (Price − Wholesale price) * Sale quantity of EV battery + R's recycling price * R's recycling rate * Sale quantity of EV battery − R's and TPR's recycling cost coefficient * (R's recycling rate) ^ 2;

(15) TPR's recycling price = M's recycling price * M's recycling price discount factor for TPR;

(16) TPR's recycling rate = TPR's recycling price * Sale quantity of EV battery / 2 / R's and TPR's recycling cost coefficient;

(17) TPR's profit = TPR's recycling price * TPR's recycling rate * Sale quantity of EV battery-R's and TPR's recycling cost coefficient * (TPR's recycling rate) ^ 2;

(18) Total recycling rate = M's recycling rate + R's recycling rate + TPR's recycling rate;

(19) Supply chain profit = (M's profit + R's profit + TPR's profit) / 1e + 009, Billion Yuan;

(20) Technical progress rate = (STEP(0.00167, 0) + STEP(0.00375, 13) + STEP(0.01793, 25) − STEP(0.0187, 37) − STEP(0.00083 , 49) − STEP(0.00083 , 61)), this formula reflects rapid technical progress;

(21) Technical progress rate = (STEP(0.00167, 0) + STEP(0.00375, 13) + STEP(0.01793, 25) − STEP(0.02205, 37) − STEP(0.00042 , 49) − STEP(0.00042 , 61)), this formula reflects slow technical progress;

(22) Cost coefficient = INTEG ((− Technical progress rate * Cost coefficient), Initial Value= 40000 Yuan), this formula reflects the decline trend of EV battery's cost coefficient, same with the change trend of advancement in technology, rapid declines then slightly declines, and the cumulative reduction up to 50% by 2020;

(23) Government's unit recycling subsidy for M = WITH LOOKUP (Time, ([(0,0) − (80,2000)], (0, 1000), (1, 1000), (2, 1000), (3, 1000), (4, 1000), (5, 1000), (6, 1000), (7, 1000), (8, 1000), (9, 1000), (10, 1000), (11, 1000), (12, 1000), (13,1000), (14,1000), (15,1000), (16,1000), (17,1000), (18,1000), (19,1000), (20,1000), (21,1000), (22,1000), (23,1000), (24,1000), (25,1000), (26,1000), (27,1000), (28,1000), (29,1000), (30,1000), (31,1000), (32,1000), (33,1000), (34,1000), (35,1000), (36,1000), (37,800), (38,800), (39,800), (40,800), (41,800), (42,800), (43,800), (44,800), (45,800), (46,800), (47,800), (48,300), (49,300), (50,300), (51,300), (52,300), (53,300), (54,300), (55,300), (56,300), (57,300), (58,300), (59,300), (60,300), (61,0), (62,0), (63,0), (64,0), (65,0), (66,0), (67,0), (68,0), (69,0), (70,0), (71,0), (72,0))), this equation reflects the dynamic change progress of recycling subsidy, starting from scratch, then withdrawing gradually.

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