A system dynamics analysis about the recycling and reuse of new energy vehicle power batteries: an insight of closed-loop supply chain

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Abstract: In order to solve the problem about recycling and reuse of power batteries for new energy vehicles in China, the paper, from the perspective of closed-loop supply chain (CLSC), uses VENSIM software to construct the system dynamics model. By analyzing the degree of cooperation among enterprises in CLSC, the result indicates that through cooperating with foreign excellent enterprises and enhancing the degree of cooperation among enterprises in the CLSC, the development of new energy vehicle power battery recycling can be better promoted. In addition, this paper puts forward some reasonable suggestions on the development of new energy vehicle power batteries.

1. Introduction

With the support of China government, the market of new energy vehicles has gradually grown up[1]. According to statistics, from 2014 to 2017, the annual sales of new energy vehicles in China kept increasing by about 230,000 per year, and especially in 2018 the increase was as high as about 480,000. Although the sales in 2019 was slightly lower than that in 2018, the trend of annual sales was relatively stable, as shown in figure 1[2-3].

With the development of new energy vehicles, the recycling and reuse of power batteries known as the "heart of new energy vehicles", has gradually attracted people's attention. The main reasons are: First, used power batteries contain heavy metals such as nickel and manganese, which will cause heavy metal leakage and pollute the environment If they are not treated properly. Second, Co, Li and other rare metals contained in the used power batteries will bring certain economic value if they can be recycled. Third, most used power batteries still have a capacity of 70% to 80%[4], so if they are scrapped directly, which causes serious waste. If echelon utilization can be realized, resources will be saved, and costs will be reduced. In China's new energy vehicle market, electric vehicles account for about 80%, as shown in figure 2[3] and figure 3[5]. Most of electric vehicles use lithium battery, at present, the lithium battery’s lifespan of China's new energy vehicles is 5-8 years [4], that is to say, during the use of new energy vehicles, power batteries should be replaced and changed at least once. Therefore, it is very important for the development of new energy automobile industry to solve the problem about recycling and reuse of used power batteries.
Currently, scholars use different models and theories to study the recycling and reuse of power batteries of new energy vehicles from different insights. Guo, X. (2015) studied the recycling and reuse of waste power batteries from the perspective of law and proposed to construct a good recycling and reuse system of waste power batteries by means of peculiar legislations[6]. Using the method of game theory, Qiao, F. (2015) studied the subjects in the recycling and reuse of power batteries of pure electric vehicles and believed that the government, enterprises and consumers should form a close linkage to build a good recycling and reuse model[7]. Zhang, D., Wang, J. (2017) analyzed power battery mode of recycling and reuse in the United States, Germany, Japan and other countries. Then proposed corresponding development mode for power battery recycling and reuse in China[8]. Hoyer, C. et al. (2015) established a linear activity analysis model for the closed-loop supply chain of lithium powered batteries to optimize the selection of a given number of production and recycling schemes[9]. Li, X et al. (2018) constructed a mathematical model of government-regulated recovery policies, compared and analyzed the optimal solutions under different scenarios, and discussed the coordination effect on CLSC by adding wholesale price discount contract into the forward supply chain and the recovery efficiency of power batteries under different government subsidy schemes[10]. Li, X et al. (2018) constructed SD-dynamic game model to analyze the optimal multi-channel recycling strategies. It provided a new solution to simulate the multi-channel recycling system of used electric vehicle power battery [11]. Moreover, using SD-dynamic game model, Li, X et al. (2019) also found recycling subsidy and technical advancement could improve recycling rate of used power battery and boost the recycling system’s economic benefit[12].

The followings are the literatures on applying system dynamics to the study of recycling and reuse in CLSC. Wan, Z. et al. (2012) constructed a four-stage CLSC model by using system dynamics, and observed the order rate of products under different recycling rates, remanufacturing rates of recycled products and recycling delays to study the influence of reverse logistics on bullwhip effect[13]. Zhang, Y. (2019) used system dynamics to analyze the influence of repurchase contracts on the CLSC of electronic products[14]. From the insight of CLSC, Yu, Y. (2019) used system dynamics to study the
recycling mode of e-waste[15]. Zhang, Y., Feng, Y. (2019) applied system dynamics to the research on quality control of recycled products in CLSC[16].

Through literatures above, it can be found that few scholars use system dynamics to study the influence of the degree of cooperation among enterprises on the recycling and reuse of new energy vehicles power battery from the insight of CLSC. Therefore, this paper takes the CLSC of new energy vehicle power battery as the research object, and applies system dynamics to analyze the effect of the degree of cooperation among enterprises on the recycling and reuse of new energy vehicles power battery. This paper concludes four parts. In the first part, the research background and problem are explained, and relevant literatures are sorted out. The second part constructs the CLSC system dynamics model of new energy vehicle power battery. The third part analyzes the influence of the degree of cooperation among enterprises in the CLSC on the recycling and reuse of power batteries from two scenarios, independent development and collaborating with excellent enterprises in developed countries. The fourth part summarizes the whole paper and puts forward some suggestions about the development of new energy vehicles power battery.

2. Model construction and parameter setting

2.1. Model assumption

The model assumptions are as follows:

1. This model includes one power battery producer, one new energy vehicle manufacturer, one echelon utilization enterprise and one scrap dealer.

2. It is assumed that in the recycling and use process, the annual volume of scrapping accounts for 30% of the total battery recycling volume, the annual volume of echelon utilization accounts for 70%.

3. In the procedure of echelon utilization, all power batteries are used for energy storage.

4. The paper assumes mainly metal recycled is the rare metal lithium in power batteries, excluding other metals.

5. As to the technology, it mainly includes battery manufacturing technology, echelon utilization technology, scrapping technology. It is assumed that 70%, 20% and 10% are respectively accounted for by the three.

2.2. Model construction

According to New Energy Vehicle Power Battery Recycling Service Network Construction and Operation Guide, issued by the Ministry of Industry and Information Technology of China in 2019, new energy vehicle manufacturer and echelon utilization enterprise should be mainly responsible for establishing a network about power battery recycling service outlets, in addition, those two entities can cooperate with power battery producer and scrap dealer to build and share the network. Therefore, the closed-loop supply chain system of new energy vehicle power battery constructed in this paper is shown in figure 4.

According to figure 4, the related system dynamics model in this paper is shown in figure 5 and figure 6.
2.3. Parameter settings
The parameters in the model are set, considering these data below:
1. According to the research of Jia, X. et al.[22] and Jiang, X.[23], the unit battery profit rate varies between 0.1458 and 0.2097, while that of new energy vehicles varies between 0.143 and 0.2343.

2. According to the research of Liu, K.[18], the unit battery cost accounts for about 42% of cost of new energy vehicles.

3. In accordance with Subsidy Standards for the Promotion and Application of New Energy Vehicles in 2019-2020, This model sets government subsidy to 60,000 RMB in the first year and the second year, 48,000 RMB in the third year and the fourth year, 36,000 RMB in the fifth year and the sixth year, finally decreases to 0 RMB from the seventh year.

4. According to Miao, X.’s study[19], the lithium content of lithium power batteries is around 3%, the recycling rate is around 85%, moreover, with the development of technology, the rate can be improved, the scrapping cost of power battery is 16,350 RMB/ton, while the market price of Li is about 900,000 RMB/ton.

5. According to Miao, X.[19], Zhen, W.[20], He, Y. et al.[21], set unit echelon utilization cost to 0.7 RMB/ kWh and unit price of echelon utilization to 0.9 RMB/ kWh.

6. According to Feng, W.’s research[17], there is a slightly negative correlation between R&D input on researcher and innovation performance in technology-based enterprises when R&D input on researcher exceed a certain value. Therefore, this paper assumes that in a short period of time, the investment in technology of the whole CLSC can only be realized by increasing R&D input on researcher and the profit of CLSC is positively correlated with the technology progress first, and weakly negatively correlated after reach to the peak value (9,0.02).

Based on data above, the model parameters set in this paper are shown in table 1.

| Table 1. Parameters settings |
|-------------------------------|
| Variables(unit) | Expression/value |
| Initial time, Final time, Time step (year) | 0,9,1 |
| Unit battery cost (ten thousand RMB/pack) | (1-Level of technology*0.7) *10 |
| Battery price (ten thousand RMB/pack) | Unit battery cost*(1+RANDOM NORMAL(0.1458,0.17,0.2097,1,0)) |
| Unit battery profit rate | (Battery price -Unit battery cost)/Unit battery cost |
| Development speed of technology | WITH LOOKUP(Profit of CLSC,[(0,0)-(15,0.2)],(0,0),(6,0.0175),(6.5,0.0178),(7,0.0182),(7.5,0.0186),(8,0.0189),(8.5,0.0193),(9,0.0195),(9.5,0.0198),(10,0.0197),(10.5,0.0196)) |
| Degree of horizontal cooperation | WITH LOOKUP (Profit of CLSC, [(0,0)-(20,0.8)],(0,0),(6,0.2),(6.5,0.25),(7,0.33),(7.5,0.44),(8,0.54),(8.5,0.62),(9,0.69),(9.5,0.75),(10,0.8)) |
| Market demands (ten thousand vehicles) | 3*(1+(15-New energy vehicle price after subsidy)/15) |
| Transformation speed of technology | Degree of horizontal cooperation*(Foreign advanced technology-Level of technology)/3 |
| Extraction rate | WITH LOOKUP (Level of technology,[(0,0)-(1,1)],(0.5,0.85),(0.53,0.86),(0.53,0.88),(0.59,0.87),(0.62,0.9),(0.65,0.91),(0.68,0.92),(0.7,0.93),(0.73,0.95)) |
| Unit new energy vehicle cost (ten thousand RMB/vehicle) | Battery price/0.42 |
| Price of new energy vehicle (ten thousand RMB/vehicle) | Unit new energy vehicle cost*(1+RANDOM NORMAL(0.143,0.18,0.2343,1,0)) |
| New energy vehicle price after subsidy (ten thousand RMB/vehicle) | Price of new energy vehicle -Government subsidy |
| Production of new energy vehicle (ten thousand vehicles) | Market demands*1.01 |
| Annual production of power battery (ten thousand packs) | Production of new energy vehicle*(1+(1-Degree of vertical cooperation) *Unit battery profit rate) |
| Volume of using power battery (ten thousand packs) | INTEG (Annual production of power battery-Annual volume of recycling,0) |
| Annual volume of recycling (ten thousand packs) | DELAY1I(Volume of using power battery*Degree of vertical cooperation,6,0) |
3. Model simulation analysis

3.1. Independent development

Under this Scenario, enterprises in the CLSC do not cooperate with Foreign excellent enterprises, so the variable, Foreign advanced technology, is set to 0. Then the value of the variable, Degree of vertical cooperation, is respectively 0.2, 0.4, 0.5, 0.6 and 0.8 (indicating a very low degree of cooperation, a low degree of cooperation, a moderate degree of cooperation, a high degree of cooperation and a very high degree of cooperation). The corresponding lines, a, b, c, d, e, are shown in figure 7 to figure 12. It can be seen from figure 7 that different degrees of vertical cooperation have no significant impact on the Level of technology. On the contrary, from figure 8 to figure 12, it can be seen that Profit of CLSC, Total profit of echelon utilization, Total profit of scrapping, Annual volume of recycling, Annual volume of echelon utilization and recycling volume of rare metal vary significantly, and they increase with the increase of Degree of vertical cooperation. In conclusion, under the scenario of independent development, the degree of cooperation among the enterprises in CLSC has no significant effect on related technology of power battery (battery manufacturing technology, echelon utilization technology, scrapping technology), but through a good cooperation can better dig out reverse chain's profit of power battery, thus the CLSC can achieve better profits.
3.2. Cooperating with foreign excellent enterprises
In this scenario, the enterprises in the CLSC cooperate with foreign excellent enterprises, so the variable, Foreign advanced technology, is set as IF THEN ELSE (Time<3, 0.6, IF THEN ELSE (Time<6, 0.7, 0.8)). The Degree of vertical cooperation is assigned as same as that in 3.1 (0.2, 0.4, 0.5, 0.6 and 0.8). Corresponding lines, a1, b1, c1, d1, e1, are shown in figure 13 to figure 18. A result different with the one in 3.1 can be seen, Degree of vertical cooperation has a significant impact on the
Level of technology. While the Profit of CLSC, Total profit of echelon utilization, Total profit of scrapping, Annual volume of recycling, Annual volume of echelon utilization and recycling volume of rare metal are also significantly affected, and still grow with the increase of Degree of vertical cooperation. In conclusion, under this scenario, strengthening the cooperation among enterprises can significantly improve the related technologies of power batteries, and make the whole CLSC get more profits.
3.3. Comparison analysis

Compare the final results of 3.1 and 3.2, as shown in table 2, it can be seen that, in the case of the withdrawing government subsidies, cooperating with foreign excellent enterprises and enhancing the degree of cooperation among enterprises in the CLSC can better promote the development of the recycling and reuse of new energy vehicle power batteries.

Table 2. The results comparison

| Line                              | a   | a1  | b   | b1  | c   | c1  | d   | d1  | e   | e1  |
|-----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Level of technology               | 0.6694 | 0.6628 | 0.6736 | 0.6979 | 0.6753 | 0.7116 | 0.6758 | 0.7215 | 0.6769 | 0.7322 |
| Recycling volume of rare metal    | 0.0074 | 0.0074 | 0.0135 | 0.0138 | 0.0160 | 0.0165 | 0.0182 | 0.0189 | 0.0217 | 0.0227 |
| Annual volume of echelon utilization | 1.475 | 1.477 | 2.602 | 2.624 | 3.045 | 3.080 | 3.414 | 3.461 | 3.944 | 4.011 |
| Annual production of power battery | 2.989 | 2.955 | 2.922 | 3.042 | 2.886 | 3.063 | 2.845 | 3.064 | 2.762 | 3.019 |
| Market demands                    | 2.614 | 2.584 | 2.632 | 2.741 | 2.640 | 2.801 | 2.642 | 2.846 | 2.647 | 2.893 |
| Profit of CLSC                    | 6.968 | 6.953 | 8.345 | 8.416 | 8.942 | 9.047 | 9.478 | 9.612 | 10.39 | 10.56 |
| Total profit of echelon utilization | 0.9065 | 0.9078 | 1.599 | 1.612 | 1.871 | 1.892 | 2.097 | 2.126 | 2.423 | 2.464 |
| Total profit of scrapping         | 0.2624 | 0.2621 | 0.4742 | 0.4833 | 0.5622 | 0.5795 | 0.6389 | 0.6642 | 0.7612 | 0.7973 |
| Unit battery cost                 | 5.313 | 5.360 | 5.284 | 5.114 | 5.272 | 5.018 | 5.268 | 4.949 | 5.261 | 4.874 |
| New energy vehicle price after subsidy | 16.92 | 17.07 | 16.83 | 16.29 | 16.79 | 15.99 | 16.78 | 15.76 | 16.76 | 15.53 |

4. Conclusions, propositions and limitations

4.1. Conclusions

The conclusions of this paper are as follows:

1. Under the scenario of independent development, strengthening cooperation among enterprises in the CLSC can't significantly improve related technologies of power battery (battery manufacturing technology, echelon utilization technology, scrapping technology), but it can benefit for the development of power battery recycling and reuse, and can make the whole CLSC obtain more profits.

2. Under the scenario of cooperating with foreign excellent companies, enhancing the cooperation among enterprises can significantly improve the related technologies of power batteries, at the same time, it is also productive for the development of the recovery and reuse of power batteries, and can bring more profits for the whole CLSC.

3. Cooperating with foreign excellent enterprises and enhancing the degree of cooperation among enterprises in the CLSC can better promote the development of the recycling and reuse of new energy vehicle power batteries.

4.2. Propositions

Based on current situation of new energy vehicle power batteries in China, the following suggestions are proposed:

1. Reinforce the cooperation among enterprises. Since the development of the CLSC in China is not yet mature, the cooperation between upstream and downstream enterprises is relatively low. This leads to a small scale-economy for power battery recycling and reuse. In addition, the characteristics of the used power battery determine the particularity of its recycling, reuse and storage mode. If the batteries with different attenuation levels are used together, not only the battery lifespan will be shortened, but also some safety risks will be brought. Therefore, the upstream and downstream enterprises should strengthen cooperation, build a new energy vehicle power battery management platform, and ensure the safety and traceability of the whole procedure from production to scrapping of power batteries through offline standardizing operation and online sharing accurate information. So as to realize better recycling and reuse of used power batteries.

2. Actively promote technology progress. Facing with the new lower government subsidy in 2019, the power battery industry has to suffer a severe period, many power battery producers have been forced to withdraw from the market because they cannot produce batteries that can meet the subsidy
conditions. Obviously, this means the technology development of the whole power battery industry has not reached expectation. So, for the sake of a more rapid and more robust development of power batteries and relevant technologies, the government should strengthen supervising and controlling the profit level of the CLSC while using subsidies to force the whole CLSC to make technology progress. Meanwhile, power battery producers should take more aggressive steps to get rid of the dependence of government subsidy. For example, cooperating with enterprises that has absolute strength in power battery in South Korea, Germany and other countries to speed up the breakthrough of key technologies and produce high-quality batteries. The echelon utilization enterprise and the scrap dealer should do well in technology development which is suitable for the battery technology, so as to better increase the profit of reverse chain.

3. Perfect the relevant regulation. Compared with Germany, Japan and other countries, China's new energy vehicle power battery CLSC’s development is not very sufficient[4]. At present, the recycling and reuse of new energy vehicle power battery is only carried out in pilot cities, such as Shenzhen, so the regulation and the measure are not perfect. However, China can combine the actual situation with successful experience of other countries so that formulate scientific and effective regulations to standardize the recycling and reuse process procedure. In addition, the government should take more diverse measures to fully mobilize the enthusiasm of all parties in the CLSC.

4.3. Limitations
In this paper, the system dynamics theory is used, while the paper still exists some shortcomings due to the diversity of participants and the complexity of comprehensive factors:

1. Although the system dynamics model of the CLSC of new energy vehicle power battery is constructed in this paper, some details are not considered enough. For example, in the echelon utilization, the recycled power batteries are only considered to be used for energy storage, in fact these power batteries can also be used in low-speed electric vehicles and other domains.

2. This paper reflects the causal relationship among the activities in the CLSC, but the interaction among the enterprises in the CLSC is not sufficiently revealed. Therefore, the model can be optimized by adopting game theory and other methods.

3. The quantitative researches about new energy vehicle power battery recycling and reuse are less, so it more or less brings difficulty to data collection. When determining the relevant parameter value, the value is mostly supported by literature analysis and assumptions in studies rather than a large number of actual data, therefore the site investigation, questionnaire survey, etc. can be used to obtain data.

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