Structural Characteristics of EV Li-ion Batteries Recycling Supply Chain Network

Dong Mu*, Haonan Ni* and Huanyu Ren*.

*School of Economics and Management, Beijing Jiaotong University, Beijing, China.
Address: No.3 Shang Yuan Village, Xizhimen Wai, Haidian District, Beijing, China.
*Corresponding author email: 19113044@bjtu.edu.cn

Abstract. With the rapid increase in the decommissioning of the EV Li-ion batteries (EV-LIBs), the EV-LIBs recycling industry is growing dramatically. Based on the realistic supply relationship data of major firms in the EV-LIBs recycling industry, this paper uses the complex network theory to construct a global firm-level EV-LIBs recycling supply chain (EV-LIBs-RSC) network and analyze the structural characteristics of the EV-LIBs-RSC network from the network level. Specifically, The degree distribution, average degree, overall density, average shortest path length, and community structure of EV-LIBs-RSC network are systematically analyzed. The relevant results can assist the government in proposing appropriate industrial policies.

1. Introduction

With the popularity of electric vehicles worldwide, the industry of electric vehicle Li-ion batteries (EV-LIBs), which are the core components of electric vehicle, has been developing rapidly in recent years. Due to the scarcity of raw materials for the production of EV-LIBs, the recycling of spent EV-LIBs has become a key plate in the entire EV-LIBs industry [1].

At present, major countries are committed to promote the sustainable development of the energy economy [2][3]. Related firms in the EV-LIBs supply chain have successively carried out EV-LIBs recycling businesses and are actively looking for partners. The EV-LIBs recycling industry has continued to develop. According to a report released by Markets and Markets, an international market research organization, the global EV-LIBs recycling market size in 2019 is about USD 1.5 billion and this figure is expected to stably increase to USD 18.1 billion by 20301. The EV-LIBs recycling supply chain (EV-LIBs-RSC) network has taken shape.

With the dramatic increase in the number of spent EV-LIBs, the recycling issue of spent EV-LIBs has received extensive attention in academia. Most previous scholars have studied the recycling of spent EV-LIBs from the perspective of recycling technology[4], while research on the network structure of EV-LIBs-RSC is still lacking.

Complex network theory is an effective method to identify the structural characteristics of the supply chain (SC) network composed of intricate supply relationships[5]. In complex network theory, for a directed SC network, there are a series of network-level metrics to characterize the overall network structure, such as network degree distribution[6], network density[7], network modularity[8]. Among them, network degree distribution is considered to play a central role in network science, because most of the network properties can be obtained by degree distribution calculation[6]. Network density is the ratio of the total number of connections in the network to the number of potential connections, and it indicates the overall connectivity of the SC network[9]. Due to redundancy and flexibility, a high-density SC network has advantages in terms of effective information and material
Network modularity indicates the community structure of the SC network, and SC networks with high modularity contain distinct communities[8][10]. In the SC network, firms located in the same community are more closely connected, i.e., information and materials are exchanged more efficiently[11].

In order to make up for the gap in the research on the structural characteristics of EV-LIBs-RSC network, this paper uses complex network theory to build the firm-level EV-LIBs-RSC network based on the realistic supply relationship data among major EV-LIBs recycling firms. Then we use a series of network-level metrics to explore the structural characteristics of the network.

2. Data Collection and Network Construction

2.1. Data Collection

The data includes the EV-LIBs recycling firms and the supply relationships between these firms. And these data are mainly obtained from the annual reports of the corresponding firms and relevant industry research reports. Specifically, 134 firms and 199 supply relationships were identified to construct the global EV-LIBs-RSC network. Among the 134 firms, 47 firms are auto firms, 26 firms are battery firms, 21 firms are intermediate products firms, 12 firms are recycling firms, 8 firms are echelon utilization firms, and 20 firms are others.

Although the data collected in this paper cannot include all EV-LIBs recycling related firms, the SC network constructed is sufficient to reflect the supply chain characteristics of the EV-LIBs recycling industry because it already covers the major core firms and supply relationships in the industry[12][13].

2.2. EV-LIBs-RSC Network Construction

A typical EV-LIBs recycling supply chain is mainly composed of five types of firms (see Figure 1). The auto firm is the starting point of the entire recycling supply chain, and as the subject most closely connected to customers, it is mainly responsible for collecting spent EV-LIBs from various outlets and then supplying them to recycling firms for processing. The recycling firm respectively supplies decommissioned EV-LIBs with 20-80% of battery capacity to the echelon utilization firm and end-of-life EV-LIBs with 20% or less of battery capacity to the intermediate products firm. Echelon utilization firms mainly include firms such as grid energy storage, household energy storage, and low-powered electric vehicles. The echelon utilization firm re-transfers the end-of-life EV-LIBs generated after the echelon utilization of decommissioned EV-LIBs to the recycling firm. The intermediate products firm dismantles the recycled end-of-life EV-LIBs by chemical, physical or biological means into intermediate materials that can be reused for EV-LIBs production, and supplies these regenerative battery materials to the battery firm. The battery firm uses these regenerative battery materials to produce new EV-LIBs, and finally resupplies these regenerated batteries to the auto firm for use.

In this paper, based on complex network theory, the related firms are regarded as vertices and the supply relationship between them as the directed edges of suppliers and customers, and then, a directed network is constructed to study the topological structure of the EV-LIBs-RSC network.

![Figure 1](image-url). The basic process of EV-LIBs recycling.
3. Structural Characteristics of Global EV-LIBs-RSC Network

3.1. Network Degree Distribution

According to Albert-László Barabási (2002), the degree distribution is a measure of the probability of the number of other nodes connected by a randomly selected node in the network[6]. In the EV-LIBs-RSC network, the degree distribution represents the probability distribution of the number of partners of each firm. As shown in Figure 2, the degree distribution of the EV-LIBs-RSC network follows a power-law distribution, i.e. \( P_k \sim k^{-\gamma} \), \( k \) is the number of connections a firm has, \( P_k \) is the probability that the number of connections of a firm is \( k \), and \( \gamma \) is the power-law exponent. According to previous empirical research, the power-law exponent of real-world SC networks is mostly around 2. Consistent with the existing research[11][14], the power-law exponent of the EV-LIBs-RSC network constructed in this paper is 1.98.

The fact that the network obeys the power-law distribution indicates that the distribution of EV-LIBs recycling related firms is not balanced. In the EV-LIBs-RSC network, there are a few firms with many partners and the vast majority of firms have only a few partners. For example, CATL is a leading firm in the EV-LIBs industry. It has 30 connections in the network, accounting for 15.1% of the total number of connections.

\[ P_k = k^{-1.98} \]

Figure 2. The degree distribution of EV-LIBs recycling supply chain network.

3.2. Network Average Degree and Network Density

The network average degree and network density describe the connectivity level of the SC network. The higher the average degree and network density, the better the connectivity. For the constructed EV-LIBs-RSC network, the lower network average degree and network density indicate that the average number of supply channels and sales channels of firms in the recycling supply chain network is small, which is not conducive to the transmission of materials and information in the SC network.

In the EV-LIBs-RSC network constructed in this paper, we assume that \( N \) denotes the number of all node firms in the SC network, degree \( k_i \) denotes the number of connections between the \( i^{th} \) firm and all related firms in the network[6]. In view of the fact that the EV-LIBs-RSC network constructed in this paper is a directed network, it is necessary to distinguish in-degree and out-degree. The in-degree \( k_i^{in} \) denotes the number of connections between firm \( i \) and all upstream firms that supply product for it, and the out-degree \( k_i^{out} \) denotes the number of connections between firm \( i \) and all its downstream customers. Assuming that \( \langle k \rangle \) and \( D \) respectively denote the average degree and network density of the network[12], we can get the formula as follows:

\[ \langle k \rangle = \langle k^{in} \rangle = \frac{1}{N} \sum_{i=1}^{N} k_i^{in} = \langle k^{out} \rangle = \frac{1}{N} \sum_{i=1}^{N} k_i^{out} \]

\[ D = \frac{\langle k \rangle}{N-1} \]

According to the formula (1) and (2) of these two metrics, we can derive that the network average
degree is 1.47 and the network density is 0.011. The results can be explained by the current development status of the EV-LIBs recycling industry. At present, the global EV-LIBs recycling market as a whole is in the exploration and development stage, especially the domestic EV-LIBs recycling market has just started, the overall industry chain has not been fully formed, most EV-LIBs manufacturers and intermediate products manufacturers are currently only relying on the existing EV-LIBs production partners in the positive supply chain to carry out recycling business. In addition, most of the current recycling firms are start-ups, which have not yet formed a close upstream and downstream recycling supply relationship with battery firms, intermediate product firms and echelon utilization firms.

3.3. Network Average Path Length

The network average path length is the average of the shortest paths between any two nodes in the network. A longer average path length means that the relationship between firms is getting farther apart. And the long path length of the material flow must pass through a potentially large number of intermediaries[11].

For the EV-LIBs-RSC network constructed in this paper, we define $\langle d \rangle$ as the average path length of the network and $d_{ij}$ as the shortest path between company i and company j. Then, for a directed network containing $N$ companies, we can get the formula as follows:

$$\langle d \rangle = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} d_{ij}$$

(3)

By formula (3), the average path length of the constructed network is 3.961. The average path length of the network constructed in this paper is relatively small, indicating that the distance between EV-LIBs recycling related firms is small, and the transfer of material and information between firms does not need to rely on too many intermediary firms. This means that the efficiency of business communication and product delivery between firms is higher. Like social networks, the EV-LIBs-RSC network presents the network characteristics of a small-world phenomenon.

3.4. Network Community

In a SC network, a group of firms that come together through similar interests or functions is called a network community. Firms located in the same community are more closely connected to each other, i.e., the flow of materials and information is more efficient[11]. For a SC network, a larger number of communities means a more distinctive modularity of the SC network. Obviously, this is not conducive to the rapid flow of materials and information throughout the entire SC network, but it is beneficial for the SC network to resist large-scale risks.

As can be seen in Figure 3, the EV-LIBs-RSC network constructed in this paper consists of a total of seven communities, including three large communities and four small communities. As the current EV-LIBs recycling industry is in the exploration and development stage, most firms only form small-scale recycling supply relationships based on existing partnerships in other business aspects, and recycling related firms in different countries rarely develop cooperative relationships. This inevitably leads to a large number of communities in the entire recycling SC network, which makes the network present a more obvious modular characteristic.

In addition, the three large communities in the network are mainly located in China. The largest community is composed of 83 firms with CATL, Green Eco, Xiamen Tungsten, CNGR, Huayou Cobalt, and Umicore as the core firms, followed by the second largest community of 27 firms with Beijing Saidemei and GHTECH as the core firms, and the third largest community of 16 firms with China Tower and Gotion High-tech as the core firms. Most of these core firms are battery firms and intermediate products firms, while there are only a few recycling firms and echelon utilization firms. On the one hand, it shows that currently in the EV-LIBs recycling industry, recycling firms have not yet developed, and their influence in the recycling supply chain network is relatively weak. On the other hand, it also reflects that the domestic EV-LIBs recycling business model is dominated by battery manufacturers and intermediate products firms. The reasons for this mainly include economic driving factors such as reducing production costs and improving bargaining level as well as social responsibility factors required by the extended production responsibility system.
Each of the four small communities in the network consists of only two firms. Among them, a small community consisting of Southern Power Grid and BAK is distributed in China, and the other three small communities respectively consisting of Remondis and Mercedes-Benz, EDF and Mitsubishi, ABB and GM are distributed abroad. Each of these four communities has an echelon utilization firm: Southern Power Grid in China, Remondis in Germany, EDF in France, and ABB in Switzerland. Obviously, foreign countries, especially countries in Europe and the United States, are more inclined to use decommissioned EV-LIBs in the energy storage system.

Figure 3. Visual representation of the EV-LIBs-RSC network community.

Note: The size of a vertex is proportional to its degree, and the color denotes different network communities, i.e., the purple, light green, blue, orange, black, pink, and dark green respectively denote seven different network communities.

4. Conclusion
Taking the complex network theory as the basis of research, this paper uses a series of network-level metrics to analyze the structural characteristics of the firm-level EV-LIBs-RSC network, and finally we draw some conclusions as follows. From the network level, the current EV-LIBs-RSC network has the characteristics of a complex network with relatively decentralized and scale-free distribution, and presents the network characteristics of a small world phenomenon. In addition, the number of network communities is large, and the network presents a relatively obvious modular feature. Network communities vary in size, with large communities being very large and small communities consisting of only two firms.

The topology of the EV-LIBs-RSC network is only analyzed from a static perspective in this paper. In fact, in the context of the rapid development of the EV-LIBs recycling industry, the number of recycling firms is increasing, and new cooperative relationships are being established between firms. Therefore, future research can further explore the structural changes of the EV-LIBs-RSC network from a dynamic perspective and analyze the reasons for these changes.

5. Acknowledgments
Financial support was provided by the Fundamental Research Funds for the Central Universities (2020YJS052) and the National Natural Science Foundation of China (72172012).
6. References

[1] Li X., Mu D., Du J., et al. Game-based system dynamics simulation of deposit-refund scheme for electric vehicle battery recycling in China[J]. Resources, Conservation and Recycling, 2020, 157:104788-1047793.

[2] Du J., Sun Y., Ren H., The Relationship of Delivery Frequency with the Cost and Resource Operational Efficiency: A Case Study of Jingdong Logistics, Mathematics and Computer Science. Vol. 3, No. 6, 2018, pp. 129-140. doi: 10.11648/j.mcs.20180306.12

[3] Du J., Qiao F., Yu L., Temporal characteristics and forecasting of PM2.5 concentration based on historical data in Houston, USA[J]. Resources Conservation and Recycling, 2019, 147:145-156.

[4] Harper G. S.R., Kendrick E, Driscoll L, Slater P, Stolkin R, et al. (2019). Recycling lithium-ion batteries from electric vehicles. Nature(575), 75-86.

[5] Mu, D., and Yue, X. 2021. "Heterogeneity and Environmental Preferences Shape the Evolution of Cooperation in Supply Networks." Complexity, 2021, 8894887.

[6] Albert, R. & Barabasi, A.L. (2002). Statistical mechanics of complex networks. Reviews of Modern Physics, 74(1), 47-97.

[7] Sheffi Y, R.J.J. (2005). A supply chain view of the resilient enterprise. MIT Sloan Manag Rev, 47(1), 41.

[8] Newman ME, G.M. (2004). Finding and evaluating community structure in networks. Phys Rev E, 69(2), 026113.

[9] Kim, Y., Choi, T.Y., Yan, T. & Dooley, K. (2011). Structural investigation of supply networks: A social network analysis approach. Journal of Operations Management, 29(3), 194-211.

[10] Perera, S., Bell, M.G.H. & Bliemer, M.C.J. (2017). Network science approach to modelling the topology and robustness of supply chain networks: a review and perspective. Applied Network Science, 2(1).

[11] Hearshaw, E.J.S. & Wilson, M.M.J. (2013). A complex network approach to supply chain network theory. International Journal of Operations & Production Management, 33(3-4), 442-469.

[12] Supun Perera,Michael G.H. Bell,Michiel C.J. (2017). Bliemer. Network science approach to modelling the topology and robustness of supply chain networks: a review and perspective[J]. Applied Network Science, 2(1).

[13] Potter, A. & Wilhelm, M. (2020). Exploring supplier–supplier innovations within the Toyota supply network: A supply network perspective. Journal of Operations Management, 66(7-8), 797-819.

[14] Shi, X.Q., Long, W., Li, Y.Y., Deng, D.S., Wei, Y.L. & Liu, H.G. (2020). Research on supply network resilience considering random and targeted disruptions simultaneously. International Journal of Production Research, 58(21), 6670-6688.