Evolution of Global EV Battery Technology Based on the Main Path of Patent Citation

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Abstract. Based on the patent data collected from European patent database search, this paper firstly analyzes the general situation of electric vehicle battery field in terms of patent application trend, regional distribution and technology field distribution, then constructs patent citation networks in different development stages and identifies the main path of patent citations by SPC algorithm. Finally, the technological evolution process in the field of electric vehicle battery is analyzed by combining visualization mapping and patent texts. The research results show that the evolution direction of electric vehicle battery technology gradually converges, and fuel cell technology is the most critical technology in the whole technology development process.

1. Introduction

The electric vehicle industry has been developing rapidly in recent years in the context of energy conservation and environmental protection. China has taken electric vehicles as a strategic emerging industry and is planning to develop it vigorously, and the "New Energy Vehicle Industry Development Plan (2021-2035)" issued by the State Council proposes that we should adhere to the development direction of electrification, networking and intelligence, focus on integration and innovation, break through key core technologies, and optimize the industrial development Environment. Battery technology as one of the core technologies of electric vehicles, its bottleneck has been a key factor limiting the technological innovation of electric vehicles, and currently enterprises around the world are scrambling to develop new high-efficiency batteries to seize the market and take the lead. Therefore, if companies want to break out in the fierce competition of electric vehicle industry, it is crucial to master the evolution rule of core technology, correctly choose the technology development path, and then focus on R&D objectives and improve R&D efficiency.

Technological innovation is one of the criteria to measure the comprehensive strength of a country. Technology evolution analysis is a preparatory work before conducting technological innovation. Technology evolution path is also called technology main path. It arranges the main technologies of a technology field in chronological order and is used to discover the main technologies and their development directions in that technology field[1]. The method of main path analysis was first proposed by Hummon, who designed three algorithms to extract the main development paths in the citation network[2]. Batagelj optimized his method and proposed the SPC (search path count) method of edge weight counting, which greatly facilitated later scholars to study the citation main paths[3]. Lucioarias, Gwak and others improved the main path analysis method[4-5]. Zhu and Yang conducted an empirical study of different domains using the main path analysis method[6-7]. By analyzing the technological evolution of a domain, the researcher can understand its technological development path,
explore the origin of technology, analyze the current status and development trend of technological activities, and identify emerging technologies in the domain.

Therefore, this paper uses patent measurement, technology main path, visualization and other analysis methods to study the patent technology of the electric vehicle battery industry in the past thirty years, revealing the patent distribution, technology evolution route and development direction in this field, to providing a basis and reference for relevant departments and researchers to formulate relevant strategies and grasp the direction of scientific research.

2. Research design

2.1. Analysis process
According to the World Intellectual Property Organization, more than 90% of global technological innovation is reflected in patent literature. Patent literature is the most reliable source of knowledge reflecting technological progress, so this paper uses patent data for the study. Firstly, the collection of retrieved patents is statistically analyzed to understand the current situation and trend of patent applications in the field of electric vehicle batteries, and the overall situation in the field of electric vehicle batteries is analyzed in terms of patent application trends, regional distribution and technology field distribution. Then, the patent citation network is constructed according to the citation relationship of patents, and the technology main paths in the citation network at different stages are extracted by SPC algorithm. Finally, the process of technology evolution in this field is analyzed in depth by combining visualization mapping and patent texts.

2.2. Data collection
The patent data in this paper were obtained from the European Patent Office. Through extensive literature research, a search strategy combining keywords and IPC classification numbers was determined in this paper to retrieve patent data in the field of electric vehicle batteries between 1985 and 2019. A total of 25,045 patents related to the field of electric vehicle batteries were retrieved. The patent data set with citation relationship among them, totaling 5840 items, was extracted and referred to as the valid patent set.

3. Research results and analysis

3.1. Development status of electric vehicle battery technology

3.1.1. Application trend analysis. By observing the trend of the number of patents over time, the overall level and speed of technology development can be found. The number of patent applications are counted by year, as shown in Figure 1. 25,045 patents were filed in the field of electric vehicle battery technology worldwide from 1985 to 2019, and from 1985 to 2002, the number of patent applications was very small, with no more than 200 applications per year. It indicates that the whole technology field is in the budding stage. between 2002 and 2012, the number of patent applications showed a slow rise. After 2012, the number of patent applications per year increased rapidly, and the electric vehicle battery technology entered a period of rapid development. Therefore, the technology development is divided into three stages: the budding stage before 2002, the slow development period from 2002 to 2012, and the rapid growth period from 2013 to 2019.
Figure 1. Electric vehicle battery technology patent application trend.

3.1.2. Patent regional distribution. The analysis of which countries the patent holders in the field are distributed in gives an idea of the technological positions occupied by different countries in the field technology, and the results are shown in Figure 2. Most of the major patent holders are from Japan, which indicates that Japan is in the leading position in this battery field. The next in line are China, Germany and the United States. Although China's electric vehicle industry started late, it is developing fast. Now it has surpassed Germany, the United States and other manufacturing powerhouses in the number of patent applications, which shows the importance China attaches to this industry of electric vehicles.

Figure 2. Electric vehicle battery technology patent regional distribution

3.1.3. Technology field distribution. The distribution of technology focus in the field can be grasped by counting the distribution of the number of patents on the IPC classification number. In the overall patent data of battery technology for electric vehicles, the top 10 subcategories of patent applications under this category are selected as representative patents to reflect the technology level and research focus, and the statistical results are shown in Figure 3. The five sub-categories with the largest proportions are H01M10/44, H01M8/04, H01M10/48, H01M8/00, H01M2/10. It accounts for about 70% of all patents. It indicates that the main research direction of battery technology in the past thirty years or so lies in fuel cells and the corresponding auxiliary technologies.

Figure 3. Distribution of technical fields of electric vehicle battery technology
3.2. Analysis of the technological evolution in the field of electric vehicle batteries

According to the development trend of electric vehicle battery technology, the patent citation network is constructed in three stages. Then the SPC algorithm is used to extract the main paths separately and visualize the main paths of each stage. The patents on the main path of the technology are analyzed through the patent text to identify the key patents in the technology evolution and reveal the inner development pattern and evolution trend of the technology in each technology stage, so as to study the evolution process of electric vehicle battery technology.

Figure 4. Patent citation network main path from 1985-2002

The first phase has two main paths containing 10 branching paths and 14 nodes. Patent US5332630 is the starting point of the first evolutionary path, it is a fuel cell assembly for powering an electric motor in an electric vehicle. The three patents US5678647, US5991670, and US5771476 that evolved afterwards are all fuel cell-related battery reactor and control system structures, while US6276473, US6662891B2, and US2001030069A1 at the end of the path are in-depth developments of fuel cell control systems that refine the fuel cell application system and its electric motor. Patent EP0539269 is the starting point of the second technology path. Unlike the first path, the patent technology based on this patent is mainly developed along the direction of battery cover, battery box and other auxiliary devices, such as patents US5513721, US6085854, US6188574.

Figure 5. Patent citation network main path from 1985-2012

There is only one main path of technology left in the second phase, the path starting with patent EP0539269 disappears. The technology evolves in two different directions starting with the nodal patent US5678647. Patent US5858568 is a power supply system for enhancing the efficiency of battery transmission. Patent US6378637 is for improving efficiency by changing the way fuel cell components are arranged. The subsequent patents US2004101725, patent US7374001, and patent US2008230288 are all optimization solutions for fuel cell systems. This path is derived from the first stage of the first path. Patent US6380637 relates to the power exchange system used in vehicle power systems, and the technological evolution after this follows a technological divergence along the direction of fuel cells. From patent US6516905 to patent US2007166584 are studies of fuel cell related applications such as internal combustion engines, battery packs, and electric power systems. As can be seen, up to this stage, fuel cells are still the focus of research into battery technology for electric vehicles.
The path of the third stage combines the two paths in the second stage into a single path through patent US2006040160 and patent US7726429. Patent US7726429 is a fuel cell vehicle that uses electricity generated by a fuel cell to drive an electric motor. Patent US2015027796 is a treatment of a fuel cell battery reactor and its placement. As can be seen from the changes in technology evolution in the three stages, the most critical technology in the entire development process is that related to fuel cells. Through the three development stages, the technology has undergone a development process of continuous in-depth research, gradually merging the branching paths on the technology evolution path into a single critical main path.

4. Conclusions
A comparison of the technology paths of the three stages shows that the whole technology evolution process is deeply developed along the field of fuel cell technology. The first stage of research focused on the discovery of the basic principles of fuel cells, such as the principle of converting chemical energy into electrical energy. The second phase focused on improving the conversion efficiency of fuel cells. Researchers began to realize that the development of new cells had encountered bottlenecks, while the fuel cell itself still had a large potential to be explored. By the third stage, the discovery of new technologies and emerging materials all marked the maturity of fuel cell technology, and people began to explore new directions of technology development.

Acknowledgments
This research was financially supported by Postgraduate Research & Practice Innovation Program of Jiangsu Province (NO. SJCX20_0139), and the Ministry of Education of Humanities and Social Science Project(NO. 19YJA870015).

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