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Global Patent Analysis of Battery Recycling Technologies: A Comparative Study of Korea, China, and the United States

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Abstract: This study provides a comprehensive analysis of global patent trends in battery recycling, focusing on secondary batteries and related technologies across Korea, China, and the United States. The methodology involved collecting data from various patent databases, followed by quantitative analysis to identify technology trends and guide future development. The research employed statistical tools to analyze patent activities, including the frequency and scope of patent filings, and comparative analysis to highlight differences between countries. This study reveals distinct emphases on technologies such as lithium-ion and waste battery recycling, highlighting notable differences in patent activities among key companies and countries. China's large number of patents in battery manufacturing processes contrasts with the USA's focus on electrochemical cell construction and storage systems, while Korea shows significant activity in waste battery technology. The novelty of this paper lies in its detailed comparative analysis of patent trends across these three major economies, providing insights into the technological focuses and priorities of each country. The study also identifies key challenges, such as the need for consistent innovation and broader geographic coverage in Korea, enhancing patent influence and international presence in China, and ensuring high patent quality and fostering innovation in lagging sectors in the United States. Addressing these challenges through enhanced collaboration, increased R&D investments, and supportive policies is crucial for strengthening the global position and driving further innovation in the battery recycling sector.

Keywords: battery recycling; electric vehicle (EV); secondary batteries; patent analysis

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1. Introduction

Electric vehicle sales are increasing rapidly, starting with COVID-19 in 2020 accelerating the spread in the market. According to the International Energy Agency, global electric vehicle sales in 2022 reached over 26 million units, more than eleven times the 2.2 million in 2013 [1]. In 1997, Toyota Motor Corp. launched the world's first hybrid passenger car, the Prius. Since then, companies solely dedicated to producing electric vehicles, like Tesla and Lucid, have emerged. Additionally, traditional automobile OEMs (Original Equipment Manufacturers) are striving to gain a foothold in the rapidly expanding electric vehicle market by introducing diverse electric vehicle models. Notably, in China, the world's largest electric vehicle market, numerous electric vehicle startups such as Xiaopeng, Li Xiang, and Nio have arisen, competing with international electric vehicle brands like Tesla.

The battery, the core of electric vehicles, is one of the most important areas for national economy and technological competitiveness as it is included in the government's national affairs as a future strategic industry [2]. In particular, recent rapid changes in the international political and economic landscape, such as the U.S.-China trade dispute, have heightened concerns about the potential instability of the global value chain (GVC). As a result, there is a clear reshoring movement in major countries such as the United States and the EU to foster and strengthen national strategic industries such as semiconductors and batteries by themselves. In this situation, it is time for Korea to consider policies on how to foster the battery industry.

In particular, demand for battery raw materials has also increased due to inflation and increased supply of electric vehicles after COVID-19, leading to a sharp rise in prices of lithium and nickel [3]. According to a White House report, the demand for lithium and graphite is expected to increase by 4000% by 2040, with China controlling 55% of the world's rare minerals as of 2020 and 85% of the rare mineral renewable sector, therefore China's influence will continue in the future [4]. Korea also needs several strategies for stable supply and demand for electric vehicle battery production in the future, and in this regard, recycling of waste batteries is attracting new attention.

The global demand for lithium-ion batteries is expected to increase up to 4500 gigawatt hours (GWh) by 2030, and the demand for lithium-ion batteries is expected to grow more than 32% annually from 2015 to 2030. In addition, the demand for batteries used for mobility is overwhelmingly high compared to the demand for batteries used in power storage and home appliances [5].

Interest in recycling waste batteries after production of electric vehicle batteries is also increasing. Vehicle batteries can be made into new battery packs after mass production of cells and used in electric vehicles, and old battery packs can be discarded or sent to recycling companies to recycle at a limited capacity or used to produce new batteries after extracting and reprocessing raw materials from waste batteries [6].

Despite the increasing interest in battery recycling, the current literature shows limitations in comprehensively analyzing global patent trends specific to battery recycling technologies. Existing studies often focus on the material technology or overall system and process of battery recycling but lack a detailed comparative analysis of patent trends across different countries. This paper aims to fill this gap by providing an extended analysis of patent trends in Korea, China, and the United States, highlighting the technological focuses and priorities of each country.

The structure of this paper is as follows: Section 2 reviews the relevant literature and highlights key technologies in battery recycling. Section 3 presents the patent analysis methodology and the data sources used. Section 4 discusses the results of the patent trend analysis, comparing the activities in Korea, China, and the United States. Finally, Section 5 concludes with the implications of the findings, the identified challenges, and potential future directions for research and policy.

2. Literature Review

2.1. Key Technologies in Battery Recycling

Key technologies in recycling waste batteries are secondary battery collection and dismantling technology, lithium salt selective extraction technology, metal salt selective extraction technology, battery condition monitoring, recycling material purification technology, and mixing technology between recycled materials and existing materials. If this is extended to the reuse of waste batteries in electric vehicles, related core technologies include secondary battery diagnostic technologies and equipment, reusable waste battery pack separation methods, optimal operation technologies of reusable batteries, and secondary battery pack manufacturing technologies.

2.2. Approaches to Battery Recycling Processes

The papers on battery recycling can be summarized into three main topics: the process of battery recycling (dry, wet, etc.) and recycling materials (lithium-ion metal extraction) and the economic effects of battery recycling and new techniques.

First, the papers on the approach to the battery recycling process are as follows. Focusing on the recycling process of Li-ion batteries, there is a study that comprehensively organizes cutting-edge technologies for lithium-ion battery recycling, focusing on pretreatment, water supply recycling, and direct regeneration of anode materials [7]. Next, it is analyzed from the perspective of battery life cycle and integration into the recycling process [8], and by analyzing the recycling process using a systematic literature review method, it is emphasized that there is a lack of research on lithium-ion battery recycling in the existing literature [9].

Second, papers on battery recycled materials are as follows. In the application of mineral treatment for battery recycling, mineral treatment processes such as grinding, sieving, and self-separation are important to recycle lithium-ion batteries, but these processes should pay attention to the loss and high cost of valuable battery parts [10]. Metal extraction and pretreatment for recycling metal from spent lithium-ion batteries are a key part of the recycling process of lithium-ion batteries, and although these methods face challenges such as environmental impact and cost, recycling can be carried out using pyrometallurgy and hydrometallurgy technologies [11].

Third, from the viewpoint of evaluating the life cycle of battery recycling, recycling different cell chemicals in lithium-ion batteries can significantly reduce environmental impact, and the biggest advantage can be seen in recycling lithium nickel manganese cobalt oxide type batteries due to the recovery of cobalt and nickel [12]. And there is a life-cycle analysis for lithium-ion battery production and recycling, underscoring the potential for resource savings [13].

2.3. Economic Effects and New Techniques in Battery Recycling

Economic and environmental aspects of battery recycling have also been extensively studied. For economic advantages, with the recent development of battery recycling technology, recycling of spent batteries, including lead–acid and lithium-ion types, focuses on pro-metallic and hydrometal processes, and the future issues are high cost and secondary pollution [14]. The economic viability of lithium-ion battery recycling in India was studied, emphasizing cost savings and environmental benefits [15]. Recycling of lithium-ion batteries has significant economic and environmental advantages, such as reducing chemical pollution and improving the safety of storage facilities [16].

For innovative techniques, new techniques in battery recycling include bio-leaching using bio-hydrometallurgy, which offers an eco-friendly and cost-effective alternative for recovering metals from spent lithium-ion batteries [17]. These bio-technical approaches have the potential to reduce secondary pollution.

2.4. Patent Analysis in Battery Recycling

The literature review on battery recycling patent analysis reveals a focus on innovative recycling devices and methods, addressing the challenges in recycling various types of batteries. Key insights include advancements in electrolysis methods for recycling, devices for efficient processing of storage batteries, and trends in recycling technologies identified through patent and paper analysis. Previous studies have focused on analyzing patent trends in battery recycling, offering insights into technological innovations and market dynamics.

Previously, in Korea, patent analysis was conducted to analyze patent trends in waste battery recycling. Keywords were battery, electronic cell, patent, and recycling, and 2490 cases were selected from 1971 to 2000 for H01M-006/52 and H01M-010/54 among International Patent Classifications (IPCs), and 871 of them were analyzed through filtering [18].

There has also been multi-country analysis of used battery recycling [19]. This paper analyzes patents and published papers on recycling technologies for used batteries, focusing on the years, countries, companies, and technologies involved. The paper analyzed patents and published papers on recycling technologies for used batteries from 1972 to 2011, focusing on the open patents of the USA (US), European Union (EU), Japan (JP), Korea (KR), and SCI journal articles. The trends of the patents and journal articles were analyzed based on the years, countries, companies, and technologies involved. However, in this paper, there is no analysis for Chinese patents and papers of battery recycling. The 2012 to 2023 period is also missing for battery recycling patent analysis due to when it was published.

For global trends, there is a study that analyzed 90,000 battery patents from 2000 to 2019 [20]. In addition, there is a study that analyzed technologies and trends for recycling lithium-ion batteries [21]. There is also a patent analysis study that reviews patent applications filed by major Japanese battery manufacturers, providing insights into technology development in the Japanese battery industry, which could be relevant for understanding the trends in patenting in the battery recycling sector [22].

Even though there are many academic articles about battery recycling, it is hard to find articles that are about battery recycling patent analysis because most articles focused on material technology [23–25] or the overall system and process of battery recycling [26,27].

Based on the information available, the battery technology patent race is intensifying among South Korea, China, and the USA, with significant developments and strategic moves observed in each country [28]. South Korea and China are particularly competitive in the arena of battery patents, with South Korean companies like LG Energy Solution and Samsung SDI leading in terms of both quantity and quality of patents, especially in areas such as electrode materials, cell processes, and packaging. China, while having the largest market share through companies like CATL, focuses more on lithium–phosphate–iron (LFP) cathode materials and silicon anode materials.

The current trends in battery recycling in the United States are marked by significant developments and investments, driven by the growing demand for electric vehicles (EVs) and the associated need for efficient battery recycling. The US currently employs mainly two methods for battery recycling—hydrometallurgical and pyrometallurgical [29,30]. The hydrometallurgical process involves using an acid-rich solution to extract battery materials, while the pyrometallurgical method uses simpler pretreatments like crushing or shredding. Companies like Redwood Materials and Li-Cycle are scaling up their operations, focusing on innovative recycling processes that recover crucial metals like cobalt, nickel, and lithium from used batteries and manufacturing scrap.

As such, the market and technology for battery recycling in Korea, China, and the United States are fully expanding. However, it is not easy to find a paper that analyzes in-depth battery recycling patents in Korea, China, and the United States. Therefore, through this paper, we will analyze battery recycling patents in the three countries, how to increase battery cycle efficiency through battery recycling, and the differences between the countries through patent trends.

2.5. Gaps and Limitations in Existing Knowledge

Despite extensive research, three gaps and limitations remain. First, for comparative analysis, existing studies often lack a detailed comparative analysis of patent trends across different countries. This paper aims to fill this gap by providing an extended analysis of patent trends in Korea, China, and the United States, highlighting the technological focuses and priorities of each country.

Second, for patent quality and impact, there is a need for more in-depth analysis of patent quality and impact, particularly regarding citations per patent and patent family size. Understanding these metrics can provide insights into the influence and geographic reach of patents.

Third, for emerging technologies, while numerous studies focus on existing technologies, there is limited research on emerging technologies in battery recycling. Future studies should explore innovations in smart technologies and data management systems in recycling operations.

The literature review reveals a robust body of research on battery recycling technologies, processes, and economic impacts. However, gaps in comparative patent analysis and emerging technologies highlight the need for further investigation. This paper aims to address these gaps by providing a comprehensive analysis of patent trends in Korea, China, and the United States, offering insights into technological innovations and strategic directions for future research.

3. Patent Analysis

3.1. Methodology

In relation to secondary batteries, we collect data on patents from Korea, China, and the United States for batteries, secondary batteries, electrorods, lithium-ion, anodes, cathodes, waste, cycle, etc. and analyze patent trends.

Through quantitative analysis, multiple technology trends were analyzed based on the effective population searched in the waste battery technology field, setting future technology development directions and future development areas and patent portfolio analysis of major players and market analysis were performed. In quantitative analysis, it is possible to grasp the recent market status of the technology field from various angles through the analysis of the following items, and detailed technology classification is also performed for more detailed technology classification. Through this, we intended to extract major patents and explore the direction of discovering promising technologies in the future.

A patent analysis was conducted based on patent applications for battery recycling in three countries: Korea, China, and the United States. Patents were selected based solely on application and registration criteria. These data were searched with Wintelips (wintelips.com) and Energy Patent House (energypatenthouse.com) that gather patent data.

In this study, the analysis of patents was limited to companies. This is because the purpose of the study was to measure how companies in each country innovate battery recycling technology through the tool of patents. Therefore, the patents of individual researchers were not analyzed in this study. For reference, the proportion of individual patents for battery recycling in South Korea, China, and the United States was not significant. In South Korea, there were 16 out of a total of 65 patents (24.6%), in China, there were 748 out of 3496 patents (21.3%), and in the United States, there were 247 out of 548 patents (45.0%).

Table 1 shows a topic analysis of patent abstracts for each country to identify the top three types of patents for battery recycling in Korea, China, and the United States.

Table 1. Topic Analysis of Battery Recycling Patents.

Country	Topic 1	Topic 2	Topic 3
Korea	Device and method for recycling materials	Separation methods for battery materials	Recycling system for electric vehicle batteries
China	High-nickel ternary cathode materials	Lithium recovery processes	Nickel cobalt manganese recovery methods
US	Battery crushing and recycling plants	Safety mechanisms for recycling processes	Recovery of valuable metals from batteries

In Korea, the primary focus is on devices and methods for recycling materials from used batteries, separation methods for battery components, and systems specifically designed for recycling electric vehicle batteries. Examples include patents on devices and methods for recycling battery materials and systems for separating battery cell components.

In China, patents emphasize the creation and recycling of high-nickel cathode materials, lithium recovery processes, and methods for recovering nickel, cobalt, and manganese from used batteries. This focus reflects China's commitment to developing advanced battery materials to maintain a competitive edge in battery technology.

In the United States, the focus is on patents detailing battery crushing and recycling plants, safety mechanisms for the recycling process, and methods for recovering valuable metals from batteries. The emphasis on safety mechanisms highlights the importance of preventing hazards during the recycling process.

This result provides a concise overview of the top three patent types for each country, highlighting the different technological focuses and priorities in battery recycling patents across Korea, China, and the United States.

3.2. Patent Filing Trend

Figure 1 shows the annual status of battery recycling patent applications in Korea (KR), China (CN), and the United States (US) from 2007 to 2024. Data for the year 2024 were only been found up to March; therefore, they have not been displayed in Figure 1. Korea showed modest and consistent patent activity with a notable increase in 2022. China demonstrated a significant and consistent rise in patent filings over the years, peaking in 2023. The US showed a steady increase in patent filings, peaking in 2022, followed by a decline in subsequent years.

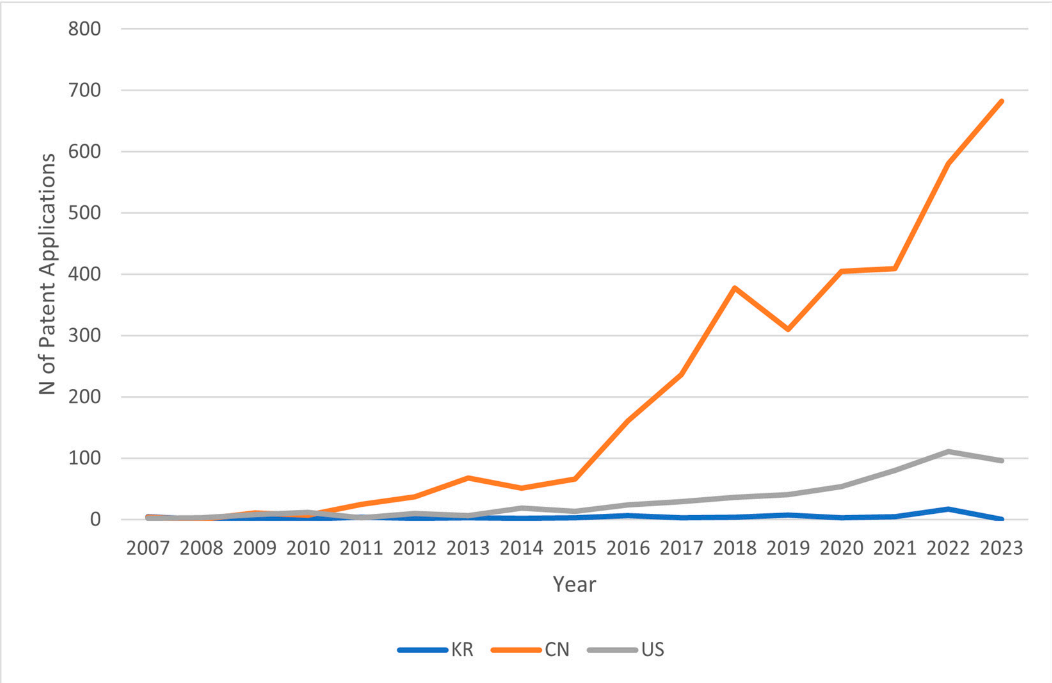

Figure 1. Battery Recycling Patent Volume by year (KR, CN, and US).

Figure 2 presents the data on battery recycling patent filings from 2008 to 2023 across Germany (DE), the European Patent Office (EP), Japan (JP), and the United Kingdom (UK), revealing distinct trends (there were no patents in 2007). The UK shows the most consistent filing activity, with notable filings in 2008, 2014, 2015, and 2018. In contrast, Germany and Japan exhibit minimal and sporadic filings, with Germany having filings only in 2016 and 2023 and Japan showing activity primarily in 2015 and 2020. The EP demonstrates a steady increase in filings, peaking in 2020 with four patents.

Overall, the UK maintains steady activity, while the EP shows a notable upward trend, indicating increased research and development efforts or regulatory changes in recent years. Germany and Japan's low activity suggests less emphasis on battery recycling innovation. These data highlight regional differences in prioritizing battery recycling technology through patent filings.

Based on Figures 1 and 2, the following two points are the results of comparison of patent filing trends in battery recycling technology. The first point is the analysis of patent filings in the UK, EP, Japan, and Germany. The analysis of patent filings in the UK, EP, Japan, and Germany shows distinct trends in the development of battery recycling technology. In the UK, the number of patent filings is minimal, with a few filings each year. The European Patent Office (EP) displays a slightly higher activity level, yet it still remains modest compared to other regions. Japan and Germany also show low but consistent patent filings over the years, reflecting a steady but limited focus on battery recycling technology in these regions. The data indicate that while these countries are involved in battery recycling innovation, the volume of patent filings is not as substantial as in other major players.

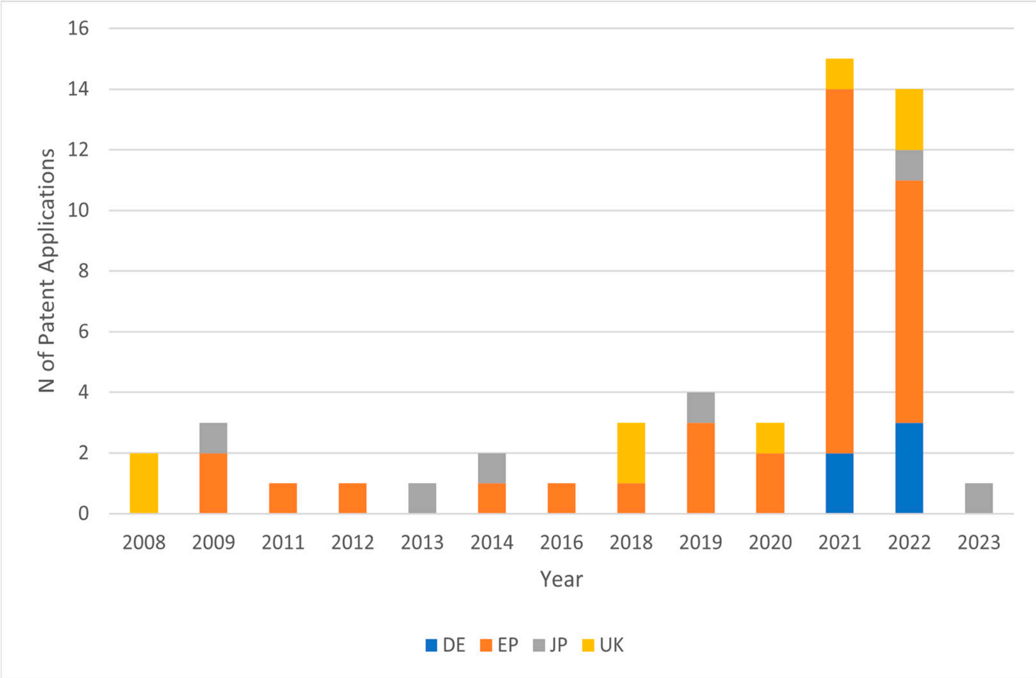

Figure 2. Battery Recycling Patent Volume by year (DE, EP, JP, and UK).

The second point is the comparison with Korea, China, and the USA. When comparing Korea, China, and the USA, the trends show significant differences. China leads in the number of patent filings, with a sharp increase from 2007 onwards, peaking in recent years. This surge indicates China's robust focus and investment in battery recycling technology. Korea, while showing some activity, has fewer filings, suggesting a more moderate approach. The USA exhibits a steady increase in patent filings, particularly from 2010 onwards, reflecting a growing interest and development in this sector. The substantial number of filings in China and the USA highlights a more aggressive stance towards innovation in battery recycling technology compared to the relatively modest numbers seen in the UK, EP, Japan, and Germany.

3.3. Comparative Analysis of Major Players and IP Comparativeness

Table 2 shows a comparison of different companies regarding their intellectual property (IP) holdings, specifically patents, in the context of battery recycling technology. This is a kind of snapshot of the patent landscape among key players in battery recycling technology, which is useful for understanding the competitive environment and innovation trends.

Table 2 presents data on patents related to battery recycling, specifically organized by country (Korea, China, and United States) and the IPC keywords associated with the patents. The analysis reveals a strong emphasis on battery recycling technologies (H01M-010) across various countries and companies, indicating a global trend towards improving battery recycling processes. Companies in Korea and China also show significant interest in metal extraction and material preparation processes, while those in the United States focus on intelligent control systems and data management in recycling. The details of the IPCs in Table 2 can be obtained from the World Intellectual Property Organization (WIPO) [31].

Table 2. Number of patent applications and IPC keywords in technology.

Country (N of Patents)	Player Name	N of Patents	Technology Keywords Based on IPC
Korea (N = 65)	Umicore	9	C22B-003, H01M-010
	Recycle Cooperation	10	H01M-010
	BASF SE	7	H01M-010, B01J-035
	RD Solution	5	H01M-010, B09B-003
	ED Engineering	3	B09B-003
China (N = 3496)	Anhui Nandu Huabo New Material Technology	34	H01M-010, B02C-004
	Anhui Lvwo Recycling Energy Technology	16	H01M-010, B02C-003
	Guizhou Zhongwei Resources Recycling Industry Development	17	H01M-010, C22B-007
	Guangdong Haozhi Technology	8	H01M-010, H01M-004
	Changsha Research Institute of Mining and Metallurgy	19	C22B-007, B02C-018
United States (N = 548)	Strong Force VCN	61	G06Q-010, G05D-001
	Grst International Limited	9	H01M-010
	Guangdong Brunp Recycling Technology	29	H01M-010
	Hunan Brunp Recycling Technology	27	C22B-007
	Worcester Polytechnic Institute	17	H01M-010

In the United States, the keyword H01M-010 shows consistent activity over the years, indicating ongoing research and patent filings in battery recycling technologies. Keywords C22B-003 and C22B-007 also exhibit significant activity, reflecting the importance of metal recovery in the recycling process. The keywords B01J-035, B02C-003, and B02C-004 display variability in trends, with some years showing higher activity related to chemical processes and material crushing. Additionally, G06Q-010 and G05D-001 have noticeable activity in recent years, highlighting the integration of smart technologies in recycling operations.

In Korea, H01M-010 shows a steady increase in activity, reflecting a growing focus on battery recycling technologies. Keywords C22B-003 and C22B-007 show some activity, indicating efforts in metal recovery from recycled materials. The keywords B01J-035 and B09B-003 exhibit variable trends, suggesting an interest in chemical processes and waste disposal technologies. B02C-003 and B02C-004 are less prominent but still present, indicating activities related to material crushing and preparation.

In China, the keyword H01M-010 shows significant and increasing activity, demonstrating a strong focus on battery recycling. Keywords C22B-003 and C22B-007 show high activity, highlighting extensive efforts in metal recovery. The keywords B01J-035, B09B-003, B02C-003, and B02C-004 exhibit substantial activity, indicating a broad approach to recycling involving chemical processes and material crushing. Additionally, H01M-004 has a notable presence, suggesting innovations in primary cell technologies.

All three countries show strong and consistent activity in battery recycling (H01M-010), with China leading in the number of patents. Significant efforts in metal recovery (C22B-003, C22B-007) are observed in the US and China, with Korea also contributing. Chemical processes and material crushing show variable but present trends in all three countries, indicating ongoing research in optimizing recycling processes. Smart technologies (G06Q-010, G05D-001) have a more recent focus, particularly in the US, reflecting the integration of data processing and control systems in recycling.

Table 3 reveals varying levels of patent activity and impact across the three countries from 2007 to 2024. CPP stands for "citations per patent" and represents the average number of times a patent is cited by other patents or publications. It is a metric used to assess the impact and influence of a company's or institution's patents on further research and technological development. CPP is calculated by dividing the total number of citations by the total number of patents.

Table 3. CPP, PII, TS, and PFS by players in Korea, China, and United States (2007–2024).

Country	Player Name	CPP	PII	TS	PFS
Korea	Umicore	0.7	0.34	6.0	2.22
	Recycle Cooperation	2.8	1.41	28.0	3.00
	BASF SE	0.7	0.36	5.0	2.14
	RD Solution	0.4	0.20	2.0	2.00
	ED Engineering	2.7	1.34	8.0	2.67
China	Anhui Nandu Huabo New Material Technology	0.4	0.22	15.0	1.32
	Anhui Lvwo Recycling Energy Technology	0.4	0.22	7.0	1.56
	Guizhou Zhongwei Resources Recycling Industry Development	0.3	0.18	6.0	1.29
	Guangdong Haozhi Technology	0.1	0.06	1.0	1.25
	Changsha Research Institute of Mining and Metallurgy	4.5	2.25	85.0	3.16
United States	Strong Force VCN	3.6	1.82	220.0	2.46
	Grst International Limited	0	0.00	0.0	1.00
	Guangdong Brunp Recycling Technology	1.0	0.52	30.0	1.72
	Hunan Brunp Recycling Technology	0.4	0.13	7.0	1.00
	Worcester Polytechnic Institute	6.9	3.50	118.0	3.53

- CPP = Total Citation/Total Patents

A high CPP indicates that the patents are frequently cited, suggesting that the technology is innovative and significantly contributes to the field. Conversely, a low CPP implies that the patents are less frequently cited, which could mean they are less influential, newer, or not yet widely recognized. For example, if a company has filed 10 patents and these patents have been cited 50 times, the CPP would be 5. Thus, CPP serves as a vital indicator of the qualitative impact of patents.

China leads in the number of patents, particularly in battery recycling and metal recovery, though the citation impact (CPP) varies significantly among players. Korea shows a growing focus on battery recycling, with some companies demonstrating high CPPs indicating influential patents. The United States exhibits strong activity in both the number and impact of patents, particularly in smart technologies and data processing related to recycling operations.

In Korea, Umicore has a moderate number of patents (9) with a relatively low citation count (6), resulting in a CPP of 0.7. Recycle Cooperation stands out with a higher CPP of 2.8 from 10 patents and 28 citations, indicating that their patents are well-regarded and frequently referenced. BASF SE shows similar characteristics to Umicore with seven patents and a CPP of 0.7. RD Solution, with five patents and a CPP of 0.4, shows lower impact, while ED Engineering, despite having only three patents, has a high CPP of 2.7, suggesting highly regarded contributions.

In China, Anhui Nandu Huabo New Material Technology leads with 34 patents but has a low CPP of 0.4 from 15 citations, indicating extensive patenting activity with limited citation impact. Anhui Lvwo Recycling Energy Technology and Guizhou Zhongwei Resources Recycling Industry Development have similar profiles, with moderate patent activity and low CPPs of 0.4 and 0.3, respectively. Guangdong Haozhi Technology has the lowest CPP of 0.1 with eight patents and one citation. However, Changsha Research Institute of Mining and Metallurgy stands out with a high CPP of 4.5 from 19 patents and 85 citations, indicating highly influential patents.

In the United States, Strong Force VCN shows substantial patent activity with 61 patents and a high CPP of 3.6 from 220 citations, indicating influential patents. Grst International

Limited has nine patents but no citations, resulting in a CPP of 0. Guangdong Brunp Recycling Technology has 29 patents and a balanced CPP of 1.0 from 30 citations. Hunan Brunp Recycling Technology has a moderate number of patents (27) with a low CPP of 0.4 from seven citations. Worcester Polytechnic Institute exhibits the highest CPP of 6.9 with 17 patents and 118 citations, highlighting their significant contributions to recycling technologies.

Furthermore, Table 3 provides PII, TS, and PFS information of players in Korea, China, and the United States. The patent impact index (PII) is a measure that compares the average number of citations per patent of a specific entity to the average number of citations per patent of all entities in a given dataset. It is calculated as follows:

- PII = CPP of the entity/average CPP of all entities

A higher PII indicates that an entity's patents are cited more frequently compared to the average, suggesting a greater impact or influence in the field.

Technology strength (TS) quantifies the overall impact of an entity's patent portfolio. It is calculated as the product of the number of patents and the average number of citations per patent (CPP):

- TS = total patents $\times$ CPP

A higher TS indicates a stronger technological position, reflecting both the quantity and the quality (impact) of the patents.

Patent family size (PFS) indicates the average number of countries in which a patent is filed within the same patent family. It is calculated as follows:

- PFS = total number of family members/total patents

A larger PFS suggests that the patents have wider geographical coverage, which can imply broader market protection and greater potential for commercialization.

In Korea, Umicore has a moderate patent count with a low patent impact index (PII) of 0.34, reflecting less impact compared to the average, and a technology strength (TS) of 6.0, with an average patent family size (PFS) of 2.22. Recycle Cooperation, however, shows significant impact with a high PII of 1.41, a TS of 28.0, and a broad geographic coverage indicated by a PFS of 3.00. BASF SE has a low PII of 0.36 and a TS of 5.0, indicating moderate technology strength, with a PFS of 2.14. RD Solution has minimal impact with a PII of 0.20 and low technology strength (TS of 2.0), with a PFS of 2.00. ED Engineering shows strong impact with a high PII of 1.34, a TS of 8.0, and good geographic coverage (PFS of 2.67).

In China, Anhui Nandu Huabo New Material Technology and Anhui Lvwo Recycling Energy Technology both have a low PII of 0.22, indicating limited impact, with TS values of 15.0 and 7.0, and narrow geographic coverage with PFS values of 1.32 and 1.56, respectively. Guizhou Zhongwei Resources Recycling Industry Development also has a minimal impact with a PII of 0.18 and low TS of 6.0, with a PFS of 1.29. Guangdong Haozhi Technology has very limited impact with a PII of 0.06, minimal TS of 1.0, and narrow geographic coverage (PFS of 1.25). In contrast, Changsha Research Institute of Mining and Metallurgy has significant impact with a high PII of 2.25, strong TS of 85.0, and good geographic coverage indicated by a PFS of 3.16.

In the United States, Strong Force VCN shows significant impact with a high PII of 1.82, very strong technology strength (TS of 220.0), and broad geographic coverage (PFS of 2.46). Grst International Limited has no impact, as indicated by a PII of 0.00, no technology strength (TS of 0.0), and narrow geographic coverage (PFS of 1.00). Guangdong Brunp Recycling Technology shows moderate impact with a PII of 0.52, a TS of 30.0, and narrow geographic coverage (PFS of 1.72). Hunan Brunp Recycling Technology has limited impact with a low PII of 0.13, low technology strength (TS of 7.0), and narrow geographic coverage (PFS of 1.00). Worcester Polytechnic Institute, on the other hand, has significant impact with a high PII of 3.50, very strong technology strength (TS of 118.0), and broad geographic coverage (PFS of 3.53).

Figure 3 shows a scatter plot and this provides a clear picture of patent influence (CPP) and geographic coverage (PFS) across key players in Korea, China, and the United States. Players like Worcester Polytechnic Institute, Changsha Research Institute of Mining and Metallurgy, and Recycle Cooperation are leaders in terms of influential patents with wide geographic coverage. Conversely, some players in China and the US exhibit lower influence and narrower coverage, highlighting areas for potential improvement or strategic focus.

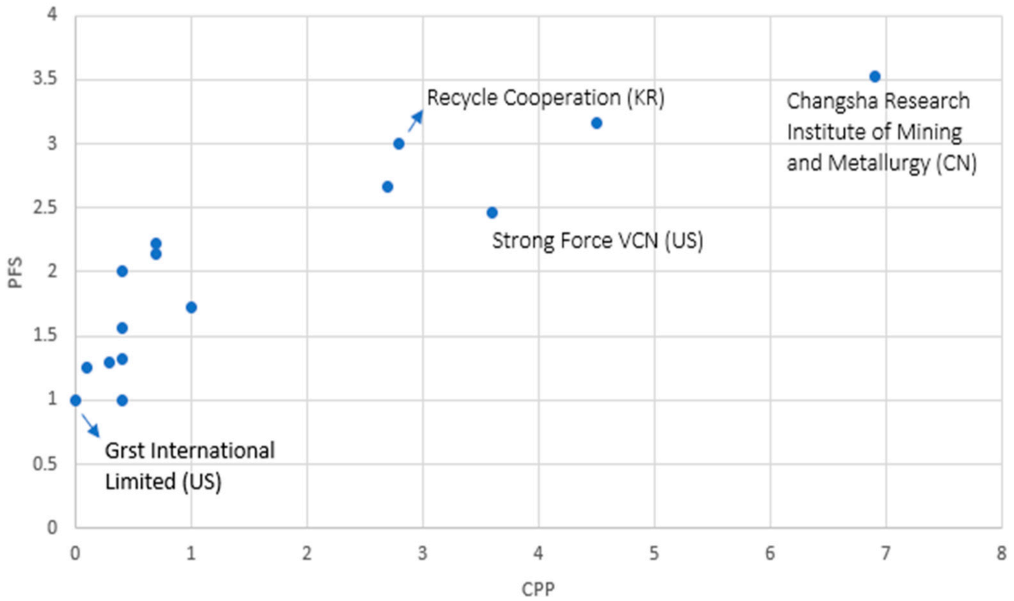

Figure 3. CPP and PFS Scatter Plot.

Korea exhibits a diverse range of patent influences across its key players, with a general trend towards moderate to high influence and decent geographic coverage. Notably, Recycle Cooperation and ED Engineering stand out for their exceptional citations per patent (CPP) and large patent family size (PFS). Recycle Cooperation, with a CPP of 2.8 and a PFS of 3, demonstrates substantial influence in the field, indicating that their patents are both highly impactful and widely recognized across different regions. Similarly, ED Engineering, with a CPP of 2.7 and a PFS of 2.67, shows a strong patent influence and good geographic reach, underscoring their significant contributions to battery recycling technologies. Other players like Umicore and BASF SE maintain a steady presence with moderate CPP values of 0.7, reflecting a consistent, if not outstanding, impact in the field. RD Solution, with a lower CPP of 0.4 and a PFS of 2, indicates less influential patents, suggesting room for growth in both impact and reach.

In China, the range of patent influences varies widely among the key players. The standout performer is Changsha Research Institute of Mining and Metallurgy, which boasts a remarkable CPP of 4.5 and a PFS of 3.16. This indicates that their patents are highly influential and enjoy extensive geographic coverage, making significant contributions to the industry. On the other end of the spectrum, companies like Guangdong Haozhi Technology exhibit a very low CPP of 0.1 and a narrow PFS of 1.25, reflecting minimal impact and limited geographic reach. Other Chinese players, such as Anhui Nandu Huabo New Material Technology and Anhui Lvwo Recycling Energy Technology, maintain low CPP values of 0.4 with varying geographic coverage, indicating that while they have a presence in the market, their patents are less influential. Guizhou Zhongwei Resources Recycling Industry Development, with the lowest CPP of 0.3, further underscores the disparity in influence among Chinese companies, highlighting a broad spectrum from highly influential to minimally impactful patents.

The United States features a wide range of patent influences, from very high to virtually nonexistent. Worcester Polytechnic Institute is the leader, with an impressive CPP of

6.9 and a PFS of 3.53, indicating exceptional influence and extensive geographic coverage. This demonstrates that their patents are not only highly impactful but also widely recognized and adopted across different regions. Strong Force VCN also shows a strong presence with a CPP of 3.6 and a PFS of 2.46, reflecting significant influence and good geographic reach. In contrast, Grst International Limited exhibits no patent citations, resulting in a CPP of 0 and a PFS of 1, indicating that their patents have no discernible impact or geographic reach. Guangdong Brunp Recycling Technology and Hunan Brunp Recycling Technology fall in the middle, with CPP values of 1.0 and 0.4, respectively, and varying PFS, showing moderate influence and geographic coverage. This wide range illustrates the diversity in patent influence among US players, from leading innovators to those with minimal impact.

Overall, Korea, China, and the United States each display distinct characteristics in their patent influences and geographic coverages. Korea's key players generally exhibit moderate to high influence with decent coverage, with standout performers like Recycle Cooperation and ED Engineering. China's landscape is more varied, with Changsha Research Institute of Mining and Metallurgy leading in influence, while other players lag significantly. The United States presents a broad spectrum, with Worcester Polytechnic Institute achieving exceptional influence and others like Grst International showing no impact, reflecting a diverse range of patent efficacy and reach.

3.4. Patent Transaction Analysis

Figure 4 shows that the trends in patent transactions in Korea (KR), China (CN), and the United States (US) from 2007 to 2024. China has shown a significant and consistent increase in patent transactions over the years, especially from 2014 onwards, with the number of transactions peaking in 2023. This suggests that China has been rapidly intensifying its patent activities, indicating a strong focus on intellectual property.

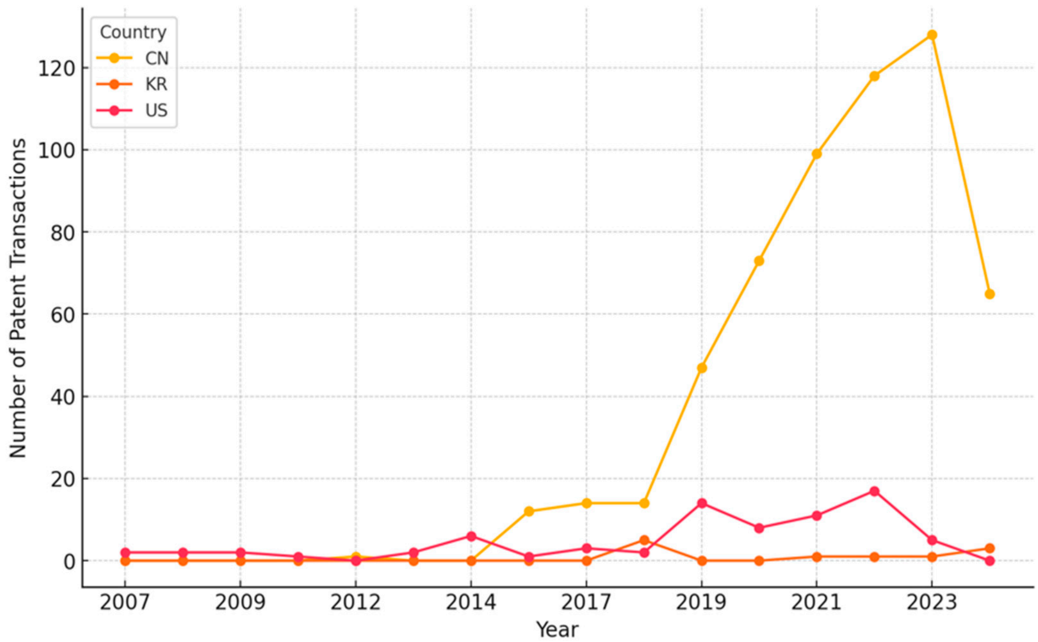

Figure 4. Transaction Volume of Battery Recycling Patent by year (KR, CN, and US).

Korea, in contrast, has had relatively fewer patent transactions compared to China and the US, with notable activity starting from 2018. The highest number of transactions in a single year was five in 2018, showing moderate activity with a slight increase in recent years. This indicates that while Korea is engaged in patent transactions, its activity level is more modest.

The United States displays a steady but less pronounced increase in patent transactions, with occasional peaks, the highest being 17 transactions in 2022. This steady level of activity reflects an ongoing but stable approach to patent transactions, indicating a consistent engagement in maintaining and managing intellectual property without significant fluctuations.

Based on the analysis of patent transactions, several key insights emerge regarding the most frequently traded patents. The patent titled "METHOD FOR COMPOSITE DELAMINATION" appears the most frequently, with seven transactions. This suggests a high market interest in technologies related to the delamination process, which is crucial in the recycling and recovery of composite materials from batteries.

Another highly traded patent is "Battery recycling system for electric vehicle," which appears four times. This reflects the growing importance of developing efficient recycling systems specifically tailored for electric vehicle batteries. The transition to electric vehicles has heightened the need for effective recycling technologies to manage the increasing volume of used batteries.

Additionally, patents related to comprehensive battery management and recycling systems also appear, such as "Secondary battery module, battery information management device, battery information management system, secondary battery reuse system, secondary battery recovery and sales system, secondary battery reuse method, and secondary battery recovery and sales method," which appears four times. This indicates significant interest in integrated systems that handle the entire lifecycle of secondary batteries, from usage to recycling and resale.

Furthermore, patents focusing on specific materials recycling, such as "RECYCLING OF LEAD- AND TIN-BASED MATERIALS," show a focused interest in recovering valuable materials from batteries. Other frequently traded patents include those related to non-aqueous electrolyte secondary batteries and lithium battery recycling equipment, reflecting ongoing advancements in battery technology and safety mechanisms during the recycling process. Overall, the data highlight the market's priority on innovations that enhance the efficiency, safety, and comprehensiveness of battery recycling systems, particularly for electric vehicle batteries.

Analysis of frequently sold patents reveals several key technology trends in the battery recycling sector. There is a significant focus on delamination processes, which are essential for efficiently separating and recovering materials from batteries. Additionally, specialized recycling systems for electric vehicles are highly sought after, reflecting the industry's emphasis on developing sustainable solutions for the increasing number of electric vehicle batteries.

Comprehensive battery management and recycling systems are also prevalent, indicating a trend towards integrated solutions that cover the entire lifecycle of batteries, from use to recycling and resale. Material-specific recycling technologies, such as those for lead, tin, and lithium, highlight the market's interest in efficient recovery of valuable materials. Safety mechanisms during the recycling process, particularly in handling non-aqueous electrolyte secondary batteries and protection during crushing, are crucial areas of innovation.

Overall, the analysis shows that the market prioritizes technologies that enhance the efficiency, sustainability, and safety of battery recycling processes. These trends align with broader industry goals of improving resource recovery and reducing environmental impact.

4. Discussion

These are the challenges and strategies for policy makers in order to promote battery recycling technology and related industry.

Korea faces the challenge of maintaining consistent innovation across all its players. While companies like Recycle Cooperation and ED Engineering exhibit high CPP, others like Umicore and RD Solution show moderate to low CPP, highlighting the need for more impactful R&D efforts. To address this, fostering collaboration between industry and academia, increasing R&D investments, and implementing innovation-friendly policies are crucial. Additionally, expanding the geographic coverage of patents is essential, as companies like RD Solution have room for improvement in international patent family size. Encouraging global patent filings and partnerships with international entities can help Korean companies enhance their market influence.

China's primary challenge is increasing the patent influence of many of its companies. Firms like Guangdong Haozhi Technology and Guizhou Zhongwei Resources Recycling Industry Development have low CPP, indicating less impactful patents. Improving patent quality through better R&D practices and focusing on innovative technologies can help increase their influence. Moreover, there is a significant disparity in patent influence among Chinese companies, with Changsha Research Institute of Mining and Metallurgy leading significantly. Bridging this gap by supporting smaller or less advanced companies through subsidies, tax incentives, and access to advanced research facilities is essential. Enhancing international presence is also crucial, as some companies have limited international patent coverage. Facilitating international patent applications and collaborations can help strengthen their global presence.

The United States exhibits a wide range of patent influences, from highly impactful (Worcester Polytechnic Institute) to minimal or none (Grst International Limited). Ensuring high patent quality across all players by strengthening review processes and providing support for companies with lower CPP can help maintain high standards. Addressing variability in geographic coverage is also important, as some companies have limited reach. Encouraging broader geographic patent filings and international collaborations can help expand US companies' influence globally. Additionally, fostering innovation in lagging sectors through targeted support and incentives can stimulate innovation and increase overall patent influence.

To address these challenges, promoting enhanced collaboration between academia, industry, and government can lead to more innovative and impactful patents. Increasing R&D investments by both governments and private sectors is crucial to boost innovation. Encouraging companies to file patents internationally can enhance their global presence and market influence. Implementing supportive policies, such as tax incentives, subsidies for R&D, and easier access to patenting processes, can further help overcome these challenges. By addressing these key challenges, Korea, China, and the United States can strengthen their positions in the global patent landscape and drive further innovation in the battery recycling sector.

5. Conclusions

This study conducted a comprehensive global patent analysis on battery recycling technologies, focusing on secondary batteries across Korea, China, and the United States. The findings reveal significant differences in patent activities and technological focuses among these countries. Korea exhibits a mix of moderate to high patent influence with decent geographic coverage, with standout companies like Recycle Cooperation and ED Engineering. China shows a wide range of patent influences, with Changsha Research Institute of Mining and Metallurgy leading significantly, while other companies lag. The United States displays a broad spectrum of patent influences, from highly impactful patents by Worcester Polytechnic Institute to minimal influence from companies like Grst International Limited. Addressing the identified challenges—such as maintaining consistent innovation in Korea, increasing patent influence and reducing disparity among companies in China, and ensuring high patent quality in the United States—can significantly enhance the global competitiveness of these nations in battery recycling technologies.

Moreover, several additional analyses could further strengthen this study. Economic impact assessments of patent activities could reveal cost savings from recycling and the economic benefits of enhanced technologies. Environmental impact assessments could evaluate the reductions in resource extraction and waste generation. Developing a technological roadmap could identify future trends and emerging technologies in battery recycling, guiding strategic planning and investment decisions. Conducting detailed case studies of leading companies would provide deeper insights into their strategies and contributions.

Additionally, examining national policies and their impact on battery recycling technologies could offer recommendations for policy improvements. Finally, analyzing market trends and forecasting future demand for battery recycling technologies, considering the rapid growth of the electric vehicle market, would provide valuable insights into the industry's future directions.

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