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Li-ion Traction Battery Recycling: Patent Landscape

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Abstract

This thesis provides a patent landscape analysis of lithium-ion traction battery recycling technologies in the automotive domain. Motivated by the rapid electrification of mobility, the strategic value of battery materials, and tightening regulatory frameworks (such as the EU Batteries Regulation), the study utilizes a reproducible structured search on Lens.org. A final dataset of 1,013 Simple Patent Families was constructed and analyzed. The empirical results reveal a sharp acceleration in patenting activity post-2016 and post-2020, currently dominated by the United States and international (WO) filings. Technologically, while hydrometallurgical and pyrometallurgical routes remain dominant, pre-treatment and direct recycling are emerging as critical niches for process integration and compliance. The organizational landscape is moderately fragmented, indicating that innovation spans the entire multi-step recycling chain. Ultimately, the thesis demonstrates that automotive battery recycling is evolving from a peripheral waste-management task into a strategic, highly regulated industrial capability central to the future of electromobility.

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Chapter 1

Technology Background and Reference Context

This chapter sets out the technological, industrial, and regulatory context of lithium-ion traction battery recycling. It explains why recycling has become a strategic issue in the transition to electric mobility, reviews the main process routes discussed in the literature, and clarifies the specific scope of the thesis. The discussion focuses on passenger-car and light-duty automotive batteries, which constitute the application background of the patent search developed later in Chapter 2.

1.1 Electrification of mobility and the rise of traction batteries

Lithium-ion batteries have become the dominant storage technology in contemporary electric mobility because they combine rechargeability, relatively high energy density, and acceptable safety and performance characteristics. After their initial expansion in portable electronics, they moved into electric vehicles and stationary storage, with EVs now representing the main source of demand. Recent review evidence indicates that EV applications already account for up to 90% of LIB consumption, and overall battery demand is expected to continue growing rapidly during the coming decade (Rezaei et al., 2025). For the automotive industry, this means that the battery is no longer a secondary component, but one of the core technological and economic foundations of the transition away from internal combustion.

The relevance of traction batteries is not only quantitative. In automotive applications, batteries are large, material-intensive, and safety-critical systems composed of cells, modules, pack structures, cooling elements, electronics, current collectors, binders, electrolytes, and active materials. Their end-of-life treatment is therefore more complex than the treatment of small consumer cells, because it must address high voltages, residual state of charge, fire risk, chemical heterogeneity, and the coexistence of multiple cathode chemistries such as NMC, NCA, and LFP (Harper et al., 2019; Wei et al., 2023). As vehicle electrification expands, the growth of installed battery capacity inevitably creates a parallel growth in future end-of-life volumes.

From a strategic perspective, traction batteries also concentrate a large share of the raw-material demand embodied in electric mobility. Lithium, nickel, cobalt, manganese, and graphite are essential inputs for battery production, and their supply is exposed to cost volatility, geopolitical concentration, and environmental pressure associated with primary extraction. Recycling therefore enters the discussion not merely as a waste-management option, but as part of the broader industrial problem of how to scale electromobility without replacing dependence on fossil fuels with a new dependence on critical raw materials (Harper et al., 2019; Rezaei et al., 2025). Figure 1.1 captures both the EV-driven expansion of LIB demand and the long-term decline in battery-pack prices, two dynamics that help explain why traction batteries now sit at the center of industrial strategy.

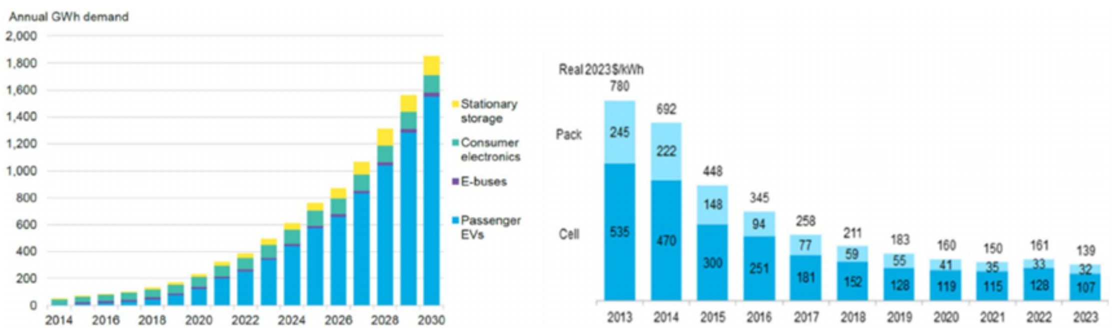

Figure 1.1: Current and projected demand for lithium-ion batteries by application area and evolution of battery-pack prices (adapted from Hayagan et al. (2024)).

1.2 Why battery recycling has become a strategic issue

The first reason why recycling matters is environmental. The rapid diffusion of EVs can support transport decarbonization, but battery production remains resource- and energy-intensive, especially because it relies on mined materials and complex processing chains. In this sense, the environmental performance of electric mobility cannot be judged only at the vehicle-use stage; it also depends on how battery materials are sourced, used, and recovered at end of life. Reviews on EV battery recycling consistently frame recycling as a necessary condition for making the transition to electric mobility more circular and less emissions-intensive.

The second reason is industrial and geopolitical. Spent batteries are increasingly described as a secondary resource or an urban mine, because they contain materials that are already concentrated, processed, and embedded in industrial products. Recycling can reduce pressure on virgin extraction, improve supply security, and foster a more resilient battery value chain. At the same time, the current recycling rate of lithium-ion batteries remains far below the level implied by the expected growth of end-of-life volumes. The strategic problem, therefore, is not whether battery recycling will be needed, but whether collection, treatment, and recovery systems can scale fast enough to match the diffusion of EVs.

A third reason is economic. End-of-life automotive batteries create both costs and opportunities: they generate handling, storage, and treatment burdens, but they also contain recoverable value. However, the economic attractiveness of recycling depends strongly on the recovery route, the chemistry of the feedstock, and the quality of intermediate material streams. For this reason, the literature increasingly moves beyond a simple recycling-versus-no-recycling debate and instead examines which process chains are best suited to preserve material value, reduce costs, and comply with emerging regulatory requirements (Wei et al., 2023; Hayagan et al., 2024; Rezaei et al., 2025). Even when batteries are diverted into second-use applications, recycling is postponed rather than eliminated, because the materials still eventually re-enter the end-of-life stage (Harper et al., 2019).

1.3 Main technological routes for Li-ion battery recycling

The literature does not describe battery recycling as a single, standardized technology. Instead, it presents a process chain in which upstream and downstream operations are tightly connected. Before any metal recovery or active-material regeneration can take place, batteries must generally be made safe, discharged, dismantled or comminuted, and separated into fractions that can be treated further. These early steps are crucial because they affect contamination levels, process safety, and the quality of the material stream often referred to as black mass, that is, the fine fraction containing a mixture of active materials and other battery residues after pretreatment. In other words, downstream recovery performance depends heavily on upstream material preparation, a point that is also reflected in the broader trade-offs summarized in Figure 1.2 (Harper et al., 2019; Wei et al., 2023; Rezaei et al., 2025).

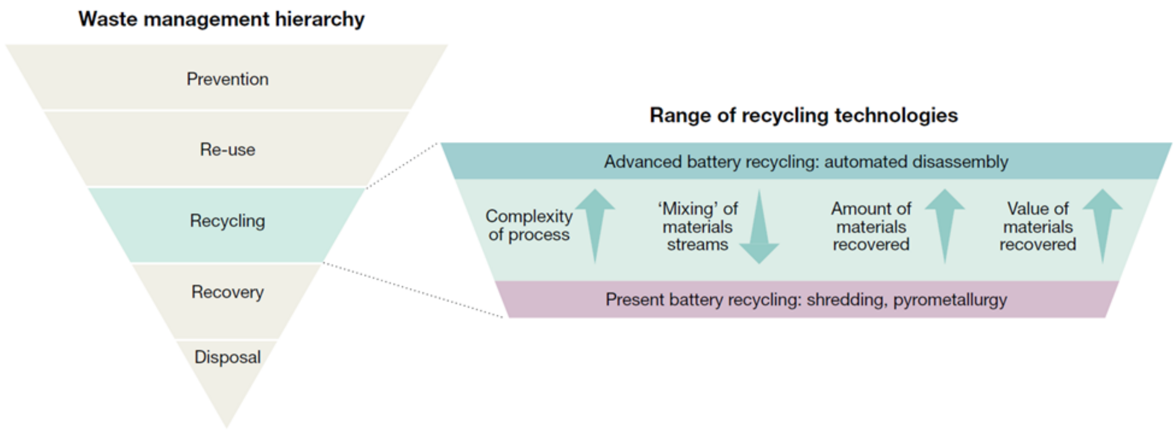

Figure 1.2: Waste-management hierarchy and range of recycling options for electric-vehicle lithium-ion batteries (adapted from Harper et al. (2019)).

Pyrometallurgy remains one of the classical industrial routes. Its main strength is robustness: high-temperature processing can treat heterogeneous and mixed feedstocks and can efficiently concentrate metals such as cobalt, nickel, and copper in metallic or alloy phases. For this reason, pyrometallurgical routes are often regarded as industrially mature and operationally tolerant. At the same time, they are energy-intensive, capital-intensive, and less attractive when the objective is to recover lithium efficiently or to preserve higher-value battery-specific compounds. The literature therefore describes pyrometallurgy as a technically relevant but incomplete solution, especially when applied to chemistries with lower cobalt content or to contexts where circularity targets emphasize broader material recovery rather than only the most valuable metals (Harper et al., 2019; Rezaei et al., 2025).

Hydrometallurgy has become the dominant reference route in much of the recent literature because it enables selective recovery at lower temperatures. By using aqueous leaching and subsequent purification or separation stages, hydrometallurgical processes can recover lithium, nickel, cobalt, and manganese with higher selectivity than smelting-based approaches. This route is therefore attractive when the goal is to reconstruct material streams with higher purity. However, its advantages come with their own trade-offs: reagent consumption, wastewater generation, and the need to manage selectivity carefully across different chemistries and impurity profiles. The route is flexible and powerful, but not environmentally neutral by default; its performance depends heavily on the choice of leaching agents and on the design of the entire process chain (Rezaei et al., 2025).

Direct recycling, finally, has received growing attention because it aims to preserve more of the embedded value of battery materials. Instead of breaking cathode materials down completely into elemental constituents, direct recycling seeks to recover and regenerate components such as cathodes, and in broader formulations even electrolytes and anodes, for re-use in battery manufacturing. This route is particularly appealing because it can reduce energy use and greenhouse-gas emissions compared with purely metallurgical approaches, while potentially producing higher-value outputs (Wei et al., 2023; Hayagan et al., 2024; Rezaei et al., 2025). Yet the same literature stresses that direct recycling is much more sensitive to feedstock purity, chemistry sorting, and process control. Its promise is high, but it is not a universal drop-in substitute for all other routes.

In practice, these routes are not mutually exclusive. Commercial and pre-commercial systems often combine pretreatment, thermal steps, mechanical separation, and chemical recovery in hybrid process chains. For this reason, the relevant analytical question is often not which single route prevails, but how different routes are combined to handle specific chemistries, contamination levels, regulatory constraints, and value-recovery objectives. This complexity is important from a patent-landscape perspective, because it implies that innovation can emerge at many points along the recycling chain, from safe discharge and dismantling to selective leaching, binder removal, cathode regeneration, and process integration.

Table 1.1: Indicative comparison of the main technological routes in Li-ion battery recycling.

Route	**Core logic**	**Main strengths**	**Main constraints**
Pretreatment / black mass	Safe discharge, dismantling, shredding, and separation generate intermediate fractions for later recovery.	Determines feed quality, safety, and downstream efficiency.	Labor intensity, automation challenges, and contamination risks.
Hydrometallurgy	Target metals are leached and then separated through precipitation, extraction, or related steps.	High selectivity and strong recovery potential at relatively low temperature.	Chemical consumption and wastewater management.
Pyrometallurgy	Thermal treatment or smelting concentrates target materials into downstream-recoverable streams.	Robust with mixed or contaminated feed and industrially mature.	High energy demand; lithium is often not fully recovered without extra steps.
Direct recycling	Cathode functionality is preserved or regenerated through relithiation and related treatments.	Potentially lower energy use and higher value retention.	Requires clean, well-sorted feedstocks and tighter process control.

Source: author synthesis based on Harper et al. (2019), Wei et al. (2023), Hayagan et al. (2024), and Rezaei et al. (2025).

Table 1.1 shows that hydrometallurgy and pyrometallurgy remain the two established industrial reference routes, whereas direct recycling is emerging as a potentially higher-value complement rather than a universal substitute. The table also makes clear why pretreatment and black-mass conditioning cannot be treated as peripheral tasks: they are enabling steps that influence safety, contamination, route choice, and final recovery performance. This is why recent reviews place so much emphasis on automated dismantling, better sorting, and more controlled pretreatment as enabling conditions for next-generation recycling systems.

1.4 Bottlenecks, recent developments, and the role of regulation

A recurring conclusion across the literature is that the main bottlenecks of EV battery recycling are not limited to downstream chemistry. Upstream stages such as safe discharge, disassembly, sorting, and separation are often decisive because automotive battery packs are not designed primarily for easy deconstruction. Adhesives, composite layers, pack-architecture diversity, and incomplete information on chemistry or state of health all complicate industrial-scale treatment. This is why the quality of black mass and other intermediate fractions becomes so important: when the feedstock is contaminated or chemically mixed, the efficiency of hydrometallurgy and especially direct recycling deteriorates.

The literature on recent developments therefore moves in two directions at once. One concerns better recovery chemistry, including greener or more selective leaching, improved cathode-relithiation routes, and broader direct-recycling strategies that extend from electrolyte recovery to electrode regeneration. The other concerns better control of the input stream, through automation, robotic disassembly, improved sorting technologies, and design choices that make batteries more compatible with future reclamation and material recovery. This second direction is especially important because a process with excellent chemistry can still perform poorly if the incoming feedstock is heterogeneous, badly labeled, or excessively mixed.

At the same time, regulation is changing the innovation environment. Regulation (EU) 2023/1542 (European Parliament and Council of the European Union, 2023) transforms battery recycling from a peripheral end-of-life issue into a compliance field with explicit performance requirements. According to the regulation, lithium-based batteries must meet a minimum recycling-efficiency target of 70% by 2030, while material-recovery targets for cobalt, nickel, and lithium become progressively stricter between 2027 and 2031. The same framework introduces traceability instruments such as the QR label and the digital battery passport, thereby connecting end-of-life treatment to information transparency and life-cycle data.

The delegated regulation adopted in 2025 (European Commission, 2025) adds another important layer by specifying how recycling efficiency and recovery of materials must be calculated and documented. In particular, it clarifies the distinction between input, output, and intermediate fractions and states that black mass is an intermediate fraction rather than a final recovered output in itself. This is highly relevant from both an industrial and a patent perspective. It implies that first-stage pretreatment alone is not enough to claim full recovery performance; actual credit is attached to the point at which target materials are recovered in a form that can substitute primary materials. Consequently, process chains that deliver auditable mass balances, cleaner intermediate streams, and higher final recovery rates become more strategically valuable.

These developments suggest that innovation in battery recycling is increasingly shaped by the interaction of technology, industrial scale-up, and regulation. The issue is no longer only whether metals can be extracted, but whether they can be recovered at sufficiently high yield, with acceptable cost and environmental burden, and within a regulatory framework that demands traceability and verifiable performance. This broader pressure helps explain why patenting in the field is not limited to metallurgy alone, but extends to sorting, pretreatment, binder removal, regeneration, and process integration.

1.5 Research scope and objective of the thesis

Against this background, the objective of this thesis is to analyze innovation dynamics in lithium-ion battery recycling through a patent-landscape approach focused on the automotive domain. The interest of the topic lies in the fact that battery recycling is currently situated at the intersection of three forces: the rapid expansion of electric mobility, the strategic importance of battery materials, and the tightening of regulatory and industrial requirements for circularity. Patent data are particularly useful in this context because they make it possible to observe how organizations seek to protect process knowledge, where they prioritize jurisdictions, and which actors appear most active across different segments of the technological chain.

The thesis does not attempt to cover every battery type or every possible end-use application. Instead, it is positioned around the context of passenger-car and light-duty EV traction batteries, while the empirical dataset developed later is more precisely defined, in methodological terms, as an automotive-related subset of lithium-ion battery recycling patents. This distinction is important and is discussed in Chapter 2, because recycling patents do not always specify end use in the most searchable patent fields. The final dataset is therefore designed to capture patents that are strongly related to automotive battery recycling, even if not all documents are limited to passenger-car traction batteries in a strict and exhaustive sense.

Within this scope, the thesis examines how patenting activity evolved over time, which jurisdictions are most important for protection, which organizations are building sustained positions, and how different technological routes, especially pretreatment/black mass, hydrometallurgy, pyrometallurgy, and direct recycling, can be used as analytical lenses for interpreting the retrieved patent space. In this sense, the patent landscape is not intended to replace the engineering literature, but to add an innovation-system perspective to the technological debate.

Building on this technological and regulatory background, Chapter 2 describes the methodological approach used to construct and analyze the patent dataset. Chapter 3 presents the empirical results of the patent landscape, and the concluding chapter synthesizes the main findings and discusses their broader implications for the evolution of lithium-ion traction battery recycling.

Chapter 2

Methodology

2.1 Research design and unit of analysis

This thesis applies a patent landscape approach to characterize innovation in recycling technologies for lithium-ion batteries, with a focus on the automotive domain. Patent documents provide structured information on the timing of inventions, the organizations involved, and the jurisdictions where protection is sought. To avoid multiple counting of the same invention filed in different jurisdictions, the unit of analysis is the patent family; all descriptive statistics are computed on Simple Patent Families as defined in Lens.org, which group documents sharing a common priority and represent one underlying invention.

2.2 Data source and tools

Patent data were retrieved from Lens.org using the Structured Search interface, which allows explicit control of the searched fields and fully reproducible query strings. After retrieval, results were exported from Lens and processed in Microsoft Excel. The data extraction was performed on December 17th 2025.

The decision to perform the descriptive analyses in Excel (rather than relying exclusively on Lens built-in analytics) was motivated by the need to consistently operate at the family level, because platform charts may aggregate at the publication level and can inflate counts when the same invention has multiple publications.

2.3 Search strategy and dataset construction

The search strategy was designed using a funnel approach. First, a broad, process-based pool of lithium-ion battery recycling patents was constructed; second, an automotive context filter was applied to derive an automotive-related subset. This two-step approach reflects the methodological direction that emerged during the query-design phase. In the first meeting, the search strategy was developed through Lens Structured Search with explicit attention to the searched fields and to the need to document each query together with its result count. In the subsequent feedback exchange, it was further clarified that patents on battery-recycling processes often do not explicitly specify the end-use of the batteries in the title, abstract, or claims; as a consequence, a broader recycling set had to be built first and then filtered with an automotive-related condition applied to broader patent fields.

Step 1 (core technology pool) combined lithium-ion keywords and recycling/material-recovery keywords searched in title, abstract, and claims. This step returned 7,259 Simple Patent Families. Step 2 (automotive-related subset) extended the core query by adding automotive and electric-vehicle-related keywords searched across any patent field, including the description. This step returned 1,013 Simple Patent Families. In this thesis, the dataset is therefore presented as an automotive-related subset of lithium-ion battery recycling patents, rather than an exhaustive set of automotive traction-battery recycling patents. The exact final Lens Structured Search string used to construct the final dataset was the following:

```
(title:("lithium-ion" OR "Li-ion" OR "lithium ion") OR abstract:("lithium-ion" OR
"Li-ion" OR "lithium ion") OR claim:("lithium-ion" OR "Li-ion" OR "lithium ion"))
AND
(title:(recycl* OR recover* OR reclamation OR "black mass") OR abstract:(recycl* OR
recover* OR reclamation OR "black mass") OR claim:(recycl* OR recover* OR
reclamation OR "black mass"))
AND
("electric vehicle" OR automotive OR vehicle OR traction OR car OR "hybrid vehicle"
OR BEV OR PHEV)
```

The recycling/material-recovery block was intentionally broader than the single term recycling. In particular, the term black mass was retained because it is a standard process term in lithium-ion battery recycling and refers to the mixed material generated after mechanical pre-treatment steps such as crushing and grinding. Since many recycling inventions concern pre-treatment and separation rather than only downstream metallurgical recovery, including this term improved the retrieval of patents focused on the upstream stages of the recycling chain. Recent literature explicitly describes black mass as the product generated by comminution-based pre-treatment and as a technically meaningful intermediate for subsequent recovery processes.

The term reclamation was retained as a complementary retrieval term within the broader material-recovery bundle. The reason is methodological rather than taxonomical: patent and technical language does not always rely on the word recycling alone, and some relevant documents use reclamation or related wording when referring to the recovery of valuable materials from spent batteries. This is also visible in the technical literature, where formulations such as "metal reclamation from spent lithium-ion battery cathode materials" are used. For this reason, reclamation was included to improve recall across vocabulary variants, together with recycl and recover, rather than to define a separate technological category.

To explore technological heterogeneity within the final dataset, four exploratory sub-clusters were also generated from the Step 2 result. These are not mutually exclusive and therefore do not partition the sample; rather, they provide analytical lenses for interpreting the results. The sub-clusters are: hydrometallurgy (765 families), pyrometallurgy (622 families), pre-treatment/black mass (304 families), and direct recycling (72 families). They are reported in Appendix A and will be used in the interpretation of the empirical results rather than as alternative dataset definitions.

2.4 Data preparation and cleaning

The query results were set to Simple Patent Families and exported from Lens. The exported data include bibliographic fields (title, abstract, priority, application and publication dates, jurisdictions, CPC/IPC codes), organizational information (applicants/owners), and citation indicators (backward and forward patent citations). The analytical dataset used in Chapter 3 contains N = 1,013 Simple Patent Families.

Two additional processing steps were applied to prepare the dataset for descriptive analysis. First, a refined date was computed to support temporal analyses: the application date was used; if missing, the publication year was used as a fallback. The application year (derived from the refined date) was then used as the time reference for the trend analysis. Second, assignee names were normalized manually to mitigate fragmentation caused by spelling variants, abbreviations, and subsidiaries. A cleaned assignee field was created to enable robust ranking of the main innovators.

2.5 Variables and indicators

The empirical analyses in Chapter 3 are based on four sets of indicators. Temporal trends are measured using the number of Simple Patent Families by the application year. Geographical distribution is measured using the publication jurisdiction as a proxy for target markets. Key innovators are identified based on the number of families per cleaned assignee. Finally, an optional "quality versus quantity" proxy is computed as the average number of forward patent citations per family for the main assignees.

2.6 Limitations and robustness considerations

No date filter was applied during data retrieval in Lens. For the time-series analysis, the observation window was restricted to the application years 2010-2024 in Excel, in order to focus on the period relevant to modern EV diffusion and to avoid distortions from sparse early records and incomplete very recent years.

The dataset is built using keyword-based searches, which may generate both false positives (documents mentioning automotive terms but not directly related to automotive traction batteries) and false negatives (recycling inventions relevant to EV batteries but not mentioning an automotive context in the text). For this reason, results should be interpreted as patterns within an automotive-related subset. Assignee normalization requires manual judgment and may affect rankings if alternative grouping rules are used. Finally, temporal analyses based on application years can still be affected by patent publication lag, particularly for the most recent years.

Chapter 3

Empirical Analysis and Results

This chapter reports the empirical results of the patent landscape analysis for an automotive-related subset of lithium-ion battery recycling patents. The dataset used throughout the chapter is extracted from Lens.org and curated in Excel. It contains 1,013 simple patent families in total. The Lens search was performed without a date filter; for the time-series analysis in Section 3.1, a 2010-2024 application-year window is applied in Excel (904 families), while the full dataset is retained for the jurisdictional and assignee-level views. The following sections discuss (i) the evolution of patenting activity over time, (ii) the geography of protection, (iii) leading assignees, and (iv) a forward-citation proxy for portfolio impact.

3.1 Evolution of Patenting Activity (Trends)

Figure 3.1 reports the annual number of simple patent families in the automotive-related subset by application year (2010-2024; N = 904). Beyond the upward trend, the data show two clear accelerations: a first step-up in 2016-2018 and a second, stronger surge after 2020, culminating in a peak of 150 families in 2023.

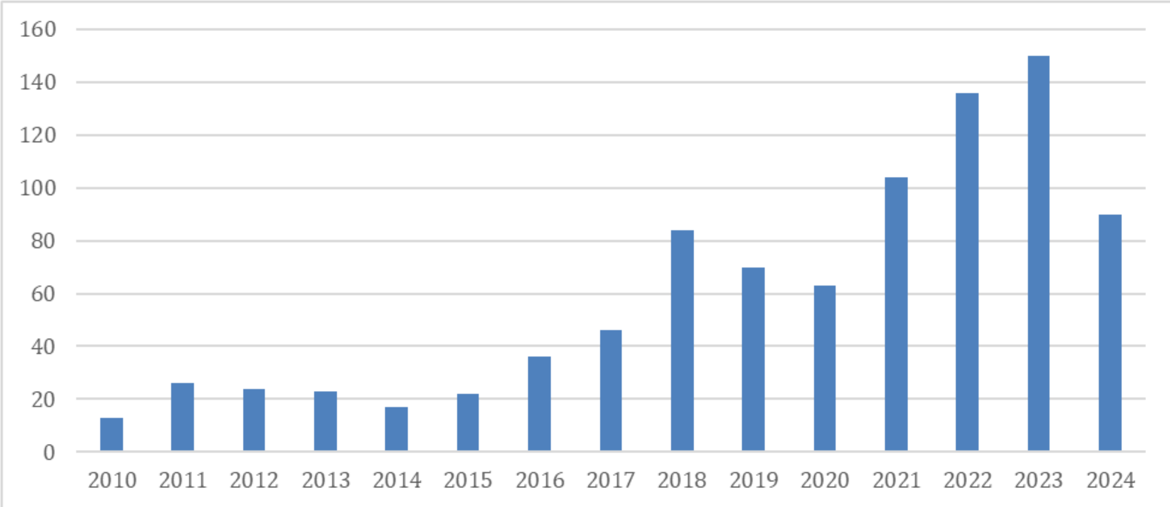

Figure 3.1: Evolution of patent applications for automotive Li-ion battery recycling (2010-2024).

The first acceleration starts in 2016-2018, rising from 36 families (2016) to 84 (2018). A plausible interpretation is that this period captures the transition from exploratory R&D to more industrially oriented development, as EV deployment and end-of-life planning began to translate into process scale-up efforts. Importantly, recycling innovation is not limited to downstream pyrometallurgy or hydrometallurgy: reviews emphasize that upstream steps (safe discharge, dismantling, and mechanical separation) are often rate-limiting and can determine the quality of intermediates such as black mass, which in turn affects downstream recovery performance (Harper et al., 2019; Rezaei et al., 2025).

A second acceleration occurs after 2020, with filings increasing from 63 families (2020) to 104 (2021), 136 (2022), and 150 (2023). This step-change is consistent with two concurrent dynamics. First, the economic and technical attractiveness of recycling routes is increasingly shaped by cathode chemistry shifts (e.g., lower cobalt contents or the growth of LFP), which motivate higher-value recovery strategies such as cathode regeneration (direct recycling) and create incentives for better sorting and separation to avoid mixed-chemistry feedstocks (Wei et al., 2023; Hayagan et al., 2024; Rezaei et al., 2025). Second, in Europe, the Batteries Regulation introduced binding targets for recycling efficiency and material recovery (including lithium) and traceability requirements (battery passport); the 2025 delegated act further specifies how recycling efficiency and material recovery must be calculated, documented, and verified (European Parliament and Council of the European Union, 2023; European Commission, 2025). Together, these drivers can increase the strategic value of patents not only on extraction chemistry, but also on process control, mass-balance accounting, and compliant treatment of intermediate fractions.

The apparent decline in 2024 (90 families) should be interpreted with caution: patent datasets typically undercount the most recent year because of publication delay and incomplete indexing. Accordingly, 2024 is treated as a partial observation rather than evidence of a structural downturn.

3.2 Geographical Distribution of Patent Protection

The geographical distribution of filings provides a first indication of where innovators consider protection strategically important. Because patent rights are territorial, jurisdiction counts can be interpreted as a proxy for target markets and regulatory environments (rather than the origin of invention). Figure 3.2 reports the top jurisdictions associated with the patent families in the dataset (N = 1,013). The United States is dominant with 537 families (about 53% of the dataset). The second-largest share is represented by PCT applications (WO, 253 families; about 25%), followed by European filings (EP, 102 families; about 10%) and Chinese filings (CN, 88 families; about 9%). Japan (JP, 17 families) and Korea (KR, 8 families) appear with smaller counts in this subset.

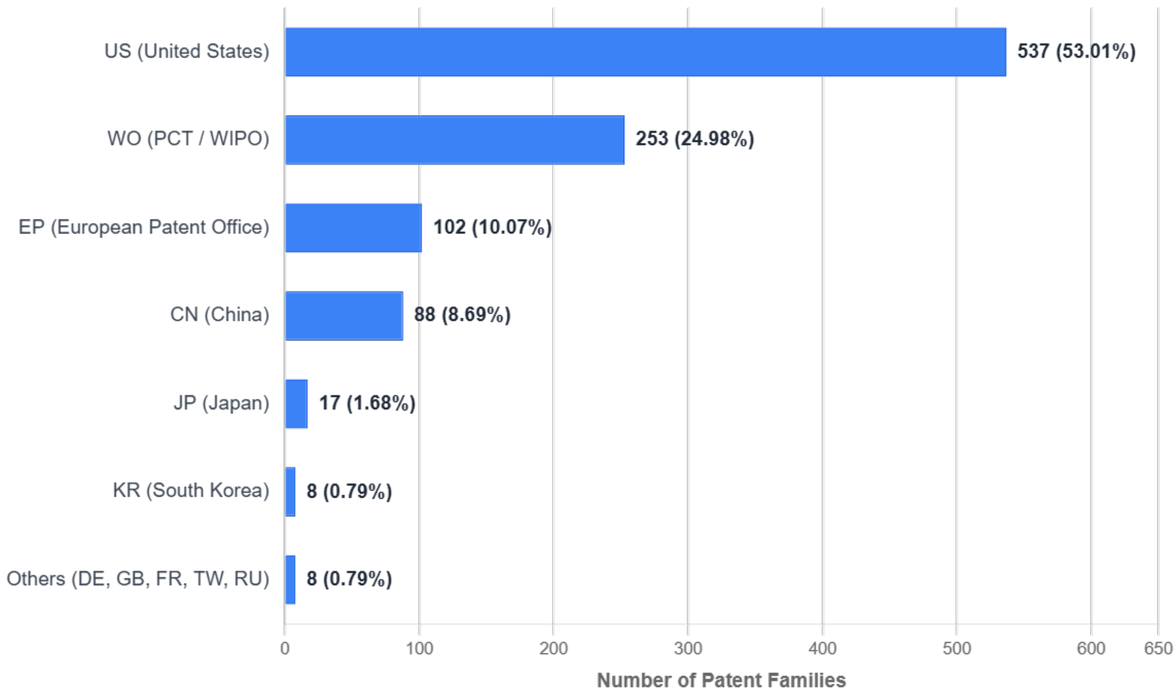

Figure 3.2: Top jurisdictions for automotive Li-ion battery recycling patent families.

The strong US presence indicates that the US is a core jurisdiction in the protection strategy for this topic in our dataset. The large share of WO/PCT filings is also meaningful: a PCT application is not a final market in itself, but a mechanism to preserve the option to enter multiple national jurisdictions while postponing cost-intensive national-phase decisions. Therefore, the WO share is best interpreted as a signal of perceived international relevance and uncertainty over the final set of target markets.

European filings (EP) can also be discussed in light of the tightening EU regulatory framework on batteries and waste batteries. In particular, the regulation introduces recycling-efficiency and material-recovery targets and new traceability requirements, while the delegated act specifies calculation points and verification rules (European Parliament and Council of the European Union, 2023; European Commission, 2025). This compliance regime can increase the strategic value of IP related to high-yield recovery and auditable process chains. Finally, jurisdictional counts depend on filing routes and do not directly measure where inventions originate; they primarily reflect protection strategies.

3.3 Leading Assignees and Organizational Profiles

Assignee analysis helps identify which organizations are building sustained portfolios in automotive battery recycling. Figure 3.3 shows the most prolific assignees in the dataset (assignee names were normalized to reduce duplication across spelling variants). The top assignees include Nanotek Instruments (61 families), Global Graphene Group (40), Ascend Elements (36), and Sumitomo Metal Mining (34). Toyota (19), BASF (18), Dowa (18), Umicore (16), and Toshiba (15) appear as additional major players, while UT Battelle, CATL, and Lyten each hold 11 families.

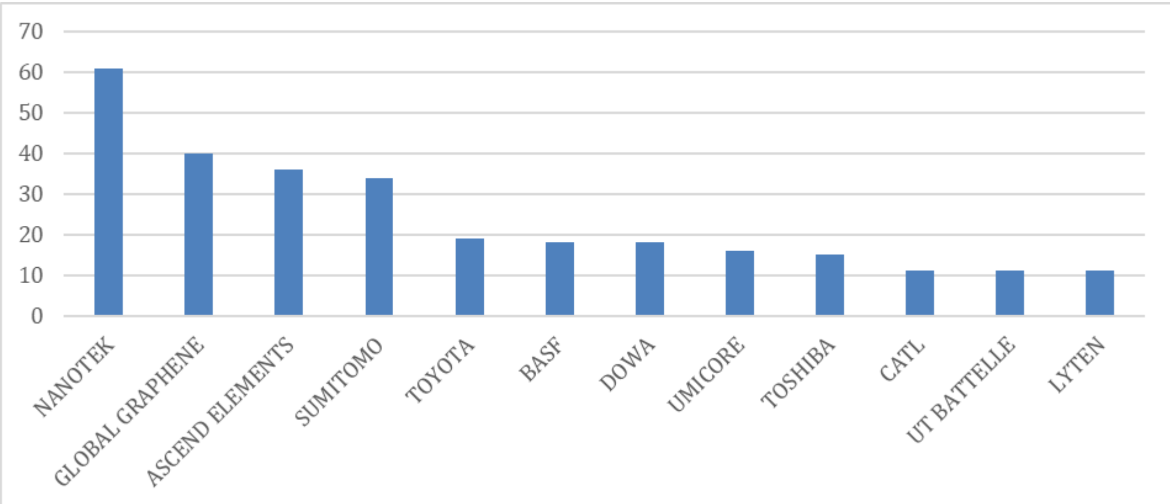

Figure 3.3: Top assignees by number of patent families in the automotive-related subset.

Two structural features stand out. First, the concentration is moderate: even the top 12 assignees together account for 290 families (about 29% of the dataset), meaning that the remaining about 71% of patent families are distributed across a long tail of other organizations. This fragmentation is consistent with a technology field in which innovation can emerge in different stages of a multi-step process chain (pretreatment, mechanical separation, and downstream recovery routes) (Harper et al., 2019; Rezaei et al., 2025).

Second, the assignee ranking becomes more informative when read qualitatively rather than only as a count of families. Patent titles suggest that several leading portfolios are strongly oriented toward industrial recovery and recycled-material valorization. Ascend Elements repeatedly appears with families on lithium recycling, impurity control, graphite roasting, and recycled cathode materials. Umicore, Dowa, and Sumitomo likewise show recurring emphasis on recovering valuable metals/materials from spent lithium-ion batteries and, in some cases, on converting recovered streams into positive-electrode materials. By contrast, Toyota and CATL appear with smaller but visible portfolios that include capacity-recovery or activity-recovery methods and production-related inventions, suggesting that the corporate landscape is not limited to classical end-of-life metallurgy but also includes regeneration- and manufacturing-interface solutions. UT Battelle stands out as a more diversified portfolio, spanning black-mass recovery, solvent-based separation, membrane extraction, and direct regeneration. Overall, the leading assignees do not represent one single organizational profile; rather, they reflect different positions along the broader recycling and battery-material loop.

This interpretation also helps bring the exploratory sub-clusters into the empirical narrative. As shown in Figure 3.4, the hydrometallurgy (765 families) and pyrometallurgy (622) sub-clusters are substantially larger than the pre-treatment/black mass (304) and direct recycling (72) sub-clusters, although these groups are overlapping and not mutually exclusive. This pattern suggests that the present patent space is still weighted toward established recovery routes, while pre-treatment and especially direct recycling remain more focused niches. Read in this light, the company landscape is coherent with a multi-step process chain: some leading portfolios are concentrated on metal recovery and purification, whereas others are positioned closer to black-mass treatment, cathode-material regeneration, or production-loop integration.

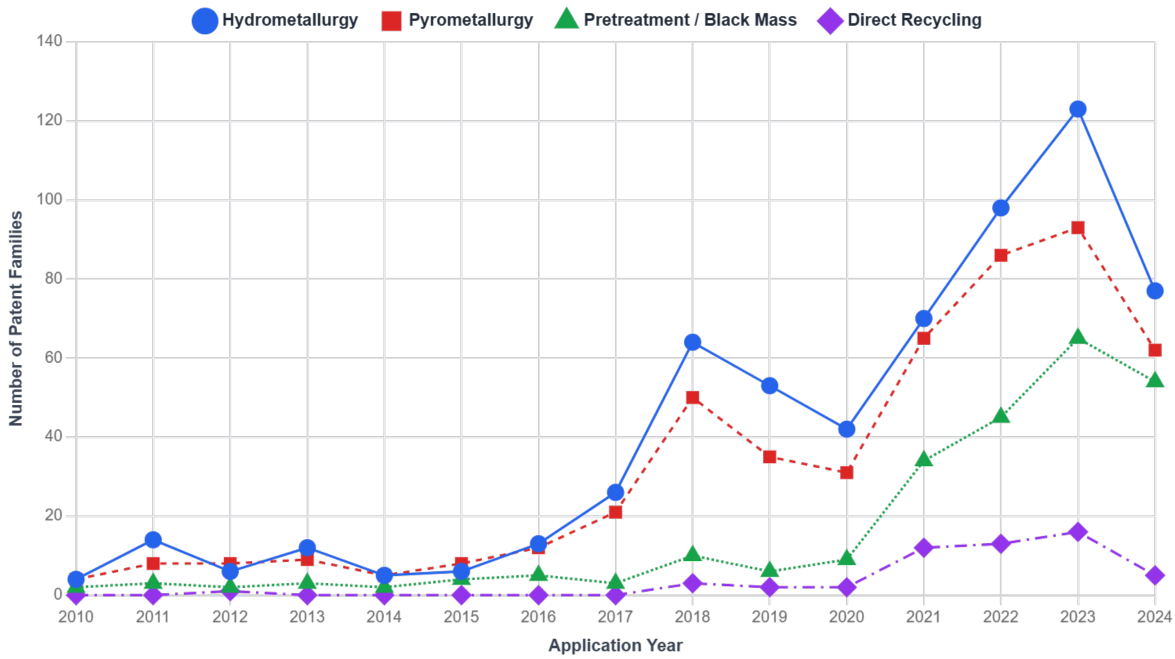

Figure 3.4: Evolution of patent applications across technological sub-clusters (2010-2024).

The observed dominance and sharp acceleration of hydrometallurgical patent applications after 2018 align closely with the technological and regulatory context outlined in Chapter 1. As global frameworks—most notably the EU Battery Regulation—mandate increasingly stringent recovery targets for critical raw materials such as lithium, cobalt, and nickel (European Parliament and Council of the European Union, 2023), innovators are prioritizing hydrometallurgy for its capability to yield higher elemental recovery rates and purity compared to conventional pyrometallurgy (Harper et al., 2019; Rezaei et al., 2025). Concurrently, the nascent but consistent emergence of direct recycling patents reflects the industry's long-term strategic shift toward closed-loop processes. By preserving the original cathode morphology, direct recycling addresses the imperative of reducing energy consumption and carbon footprint within the automotive battery supply chain (Wei et al., 2023; Hayagan et al., 2024), thereby directly aligning patenting activity with the circular economy objectives discussed in earlier chapters (Rezaei et al., 2025).

3.4 Patent Quality Proxy: Forward Citations

In addition to portfolio size, forward citations (i.e., citations received from later patents) provide a commonly used proxy for technological influence. However, citations are not a direct measure of commercial value, and interpretation requires caution: citations accumulate over time (older families are advantaged), citation practices differ across jurisdictions and examiners, and some citations may be added strategically rather than reflecting technical dependence.

Within the top assignee set, average forward-citation levels vary widely. Nanotek shows the highest average (about 9.1 citations per family), while Toyota (about 6.8) and Toshiba (about 5.4) also score high. Global Graphene Group (about 4.2) and Umicore (about 4.1) sit above the group average, whereas several portfolios are characterized by averages close to or below one citation per family. Because part of some portfolios is recent, low citation averages should not be equated with low value; they can also reflect a shorter time window for citations to accrue.

3.5 Integrated Portfolio Perspective: Quantity vs. Citation Impact

To combine the two dimensions (portfolio size and citation-based influence), Figure 3.5 positions the major assignees on a "quantity vs. impact" map. The horizontal axis reports the number of patent families, while the vertical axis reports average forward citations. The dashed reference lines correspond to the mean values across the plotted assignees (about 24 families and about 3 citations), providing a simple quadrant interpretation.

Figure 3.5: Portfolio positioning of major assignees (patent family count vs. average forward citations) in the automotive-related subset.

Nanotek Instruments appears in the high-volume/high-impact quadrant: it combines the largest portfolio (61 families) with the highest citation influence (about 9.1). Global Graphene Group also combines above-average volume with above-average citations. A second group (Toyota, Toshiba, and Umicore) falls in the high-impact/low-volume quadrant, suggesting more selective portfolios that are nevertheless widely referenced.

By contrast, Ascend Elements and Sumitomo are positioned in the high-volume/low-citation quadrant. This should not be read as evidence of low technical relevance: part of the effect may be explained by portfolio recency or by the fact that some inventions are less frequently cited even when they are strategically valuable. Finally, several assignees (e.g., UT Battelle, CATL, and Lyten) fall in the low-volume/low-citation quadrant, reflecting either smaller strategic positions or early-stage portfolios that have not yet accumulated citations.

3.6 Chapter Summary

In summary, the automotive-related subset (N = 1,013) exhibits a clear acceleration of patenting activity after 2016, culminating in a 2023 peak of 150 families within the 2010-2024 application-year window (N = 904). The jurisdictional distribution is dominated by the US and includes a substantial share of WO/PCT filings, indicating a strong international dimension in protection strategies. The assignee landscape is fragmented, with the top 12 organizations accounting for about 29% of families, and the combined quantity vs. citation perspective highlights different portfolio strategies across leading players. The exploratory sub-cluster comparison further suggests that established hydro- and pyrometallurgical routes still dominate the retrieved patent space, while pre-treatment/black-mass and direct-recycling portfolios remain more specialized niches. These empirical patterns are consistent with a field responding to both technological shifts (e.g., increasing emphasis on sorting and direct regeneration) and tightening regulatory and traceability requirements in key markets (Harper et al., 2019; Wei et al., 2023; Hayagan et al., 2024; European Parliament and Council of the European Union, 2023; European Commission, 2025; Rezaei et al., 2025).

Chapter 4

Conclusions

This thesis examined the evolution of innovation in lithium-ion battery recycling through a patent landscape approach focused on the automotive domain. By combining a reproducible Lens Structured Search with family-level analysis in Excel, the study built an automotive-related subset of 1,013 Simple Patent Families and used it to analyze temporal dynamics, protection geographies, leading assignees, and a citation-based proxy of portfolio influence. Taken together, the results do not describe a mature and fully stabilized technological field. They instead depict a rapidly intensifying area of innovation shaped by the expansion of electric mobility, the strategic importance of battery materials, and a regulatory environment that increasingly links recycling performance to traceability and verifiable recovery outcomes.

4.1 Main findings

The temporal pattern is the clearest signal. Within the 2010-2024 application-year window, patenting in the automotive-related subset accelerates after 2016 and again after 2020, reaching a peak of 150 families in 2023. This trajectory suggests that lithium-ion battery recycling is no longer treated as a peripheral waste-management issue at the margins of the EV transition. It is increasingly addressed as a strategic technological field linked to larger battery volumes, critical-material security, supply-chain resilience, and the economics of circularity. In this respect, the empirical pattern is consistent with the background developed in Chapter 1, which framed recycling as a structural component of the battery value chain rather than as a downstream afterthought (Harper et al., 2019; Wei et al., 2023; Rezaei et al., 2025).

At the technological level, the overlapping sub-clusters indicate that hydrometallurgy (765 families) and pyrometallurgy (622) still dominate the retrieved patent space, while pre-treatment / black mass (304) and direct recycling (72) remain narrower analytical lenses. This does not reduce the strategic importance of the smaller clusters. On the contrary, both the literature and the portfolio evidence suggest that safer disassembly, better sorting, and cleaner black-mass generation increasingly condition the performance of downstream recovery and regeneration routes. The field therefore appears to be widening from a metal-extraction focus toward a process-chain logic in which pretreatment quality, intermediate-stream purity, and final recovery are tightly linked (Harper et al., 2019; Wei et al., 2023; Hayagan et al., 2024; Rezaei et al., 2025).

From a protection-strategy perspective, the United States is the dominant jurisdiction in the dataset, while the strong WO/PCT presence confirms that many applicants preserve optionality across multiple national markets. European filings are smaller in absolute terms, yet their strategic importance is reinforced by the EU Batteries Regulation and the 2025 delegated act on recycling-efficiency and material-recovery calculation. These developments increase the value of process claims that are not only technically effective, but also measurable, auditable, and traceable within a compliance-oriented battery value chain. The regulatory clarification that black mass is an intermediate fraction rather than a final recovered output is especially significant in this respect, because it shifts attention toward process chains able to deliver cleaner intermediates and verified final recovery outcomes (European Parliament and Council of the European Union, 2023; European Commission, 2025).

At the organizational level, the landscape is moderately fragmented rather than concentrated in a handful of dominant players: the top 12 assignees account for about 29% of the patent families in the dataset. This fragmentation is consistent with the multi-step nature of battery recycling, where competitive positions can be built in pretreatment, purification, material regeneration, and production-loop integration. The assignee evidence also shows that volume and influence do not fully coincide. Nanotek Instruments and Global Graphene Group combine scale with above-average citation performance, whereas more selective portfolios such as Toyota, Toshiba, and Umicore achieve stronger citation impact despite smaller size. Leadership in this field, therefore, cannot be reduced to simple patent counts alone.

4.2 Implications for the evolution of the field

Taken together, these patterns suggest that battery recycling in the automotive domain is evolving from an end-of-life treatment problem into a strategic industrial capability. The relevant question is no longer only whether valuable materials can be recovered from spent batteries, but whether they can be brought back into the battery value chain with sufficient purity, yield, cost discipline, and documentation, a need increasingly formalized by lifecycle traceability tools such as the mandated digital Battery Passport (European Parliament and Council of the European Union, 2023). Patenting in this area should therefore be read not only as a sign of technical experimentation, but also as an attempt to secure positions in a part of electromobility that is becoming simultaneously industrial, regulatory, and supply-chain critical.

This broader shift helps explain why inventive activity is distributed across several layers of the process chain. Established hydro- and pyrometallurgical routes remain central because they offer industrial robustness and still dominate the current patent space. At the same time, the growing relevance of dismantling, black-mass treatment, sorting, binder removal, regeneration, and recycled-material upgrading suggests that future competitive advantage may depend on how effectively these steps are combined. In other words, the field appears to be moving toward more integrated recycling architectures rather than toward a simple replacement of one dominant route by another.

The current position of direct recycling can be interpreted in the same way. Within the retrieved patent space, direct-recycling patents remain limited in number, but they are strategically important because they attempt to preserve more of the embedded value in battery materials. Their future growth, however, is likely to depend not only on relithiation or regeneration chemistry, but also on chemistry sorting, cleaner feedstocks, safer disassembly, and reliable traceability. Direct recycling therefore appears less as a stand-alone alternative than as an option whose industrial viability depends on improvements upstream as much as downstream (Wei et al., 2023; Hayagan et al., 2024; Rezaei et al., 2025).

More broadly, the patent landscape suggests that battery recycling is becoming a field where engineering, materials strategy, and regulation increasingly converge. This convergence is especially visible in Europe, where policy now creates explicit performance thresholds and documentation rules, but it is not limited to Europe. The weight of international filing strategies indicates that organizations perceive the issue as global. For automotive firms, cell manufacturers, materials suppliers, and specialized recyclers alike, this means that recycling capabilities are likely to matter not only for waste compliance, but also for raw-material security, partnership formation, and future positioning in closed-loop battery supply chains.

4.3 Limitations and directions for further research

These conclusions should be read together with the methodological limits of the study. The main limitation concerns scope precision. The dataset was intentionally constructed as an automotive-related subset of lithium-ion battery recycling patents, not as an exhaustive census of all patents strictly limited to passenger-car traction batteries. This choice followed directly from the retrieval problem identified during query design: many recycling patents do not explicitly state the end use of the battery in the most searchable fields, even when they are clearly relevant to EV batteries in practice. Accordingly, the findings are best interpreted as robust patterns within a strategically relevant automotive-oriented slice of the broader recycling patent space, rather than as a definitive map of every automotive traction-battery recycling invention.

A second limitation concerns what patent indicators can and cannot reveal. Jurisdiction counts capture protection strategies rather than the geographic origin of invention. Forward citations provide a useful proxy for technological influence, but they are time-sensitive and can be affected by examiner behavior, filing routes, and portfolio recency. Likewise, the apparent decline in the most recent year cannot be interpreted as a structural downturn because patent publication lag systematically affects the newest observations. Finally, assignee normalization required manual judgment, which improves interpretability but also introduces some unavoidable researcher discretion.

A third limitation is that patent evidence alone does not measure engineering superiority, industrial scale, or commercial adoption directly. Patent families reveal where organizations seek protected positions, but they do not show whether a given route is already the most cost-competitive, whether it performs best environmentally, or whether it has overcome the operational constraints of large-scale deployment. For this reason, the value of the patent landscape approach lies in showing where inventive and strategic attention is concentrated, not in replacing process-engineering evaluation or techno-economic assessment.

These limitations also point to useful directions for further research. One line of work would be to deepen the technological granularity of the analysis by separating recycling patents more explicitly by chemistry or target stream, for example distinguishing NMC/NCA-oriented recovery from LFP-related process innovation, or separating lithium recovery from graphite and cathode-regeneration strategies. A second line would be to examine the pre-treatment and direct-recycling niches in greater detail, since the present thesis suggests that these smaller sub-clusters may be disproportionately important for future process integration. A third line would be to extend the organizational perspective by combining portfolio counts with collaboration, citation, or legal-status analyses, and by linking patent evidence more systematically to industrial and policy milestones.

4.4 Final remarks

Overall, the thesis indicates that lithium-ion traction battery recycling is emerging as a strategic technological field at the intersection of circular-economy objectives, critical-material security, process engineering, and regulatory compliance. The patent evidence does not point to a single settled trajectory. Instead, it reveals a field still structured by established hydro- and pyrometallurgical routes, but increasingly shaped by better pretreatment, cleaner intermediate fractions, stronger traceability, and more selective or regenerative recovery strategies.

From this perspective, the main contribution of the thesis is not to identify a single 'best' recycling route, but to show how inventive activity is distributed across time, jurisdictions, and organizations within an automotive-related subset of the patent space. What emerges is a technological landscape in which future competitiveness in electric mobility may depend not only on how batteries are manufactured and deployed, but also on how effectively their materials can be recovered and recirculated within robust, auditable, and economically credible process chains. In this sense, battery recycling should be understood not as a peripheral downstream activity, but as an increasingly central part of the industrial architecture of electromobility.

Appendix A

Lens Structured Search queries and result counts

Table A.1 reports the exact Lens Structured Search strings used in this work and the corresponding number of Simple Patent Families returned. The sub-cluster queries (Steps 3.1–3.4) are exploratory and not mutually exclusive.

Table A.1: Detailed Lens Structured Search queries and result counts.

Step	Description	Query Logic / String	Families
1	Total Pool (Core Tech)	(title:("lithium-ion" OR "Li-ion" OR "lithium ion") OR abstract:("lithium-ion" OR "Li-ion" OR "lithium ion") OR claim:("lithium-ion" OR "Li-ion" OR "lithium ion")) **AND** (title:(recycl* OR recover* OR reclamation OR "black mass") OR abstract:(recycl* OR recover* OR reclamation OR "black mass") OR claim:(recycl* OR recover* OR reclamation OR "black mass"))	7,259
2	Final Dataset (Automotive)	[Step 1 Result] **AND** ("electric vehicle" OR automotive OR vehicle OR traction OR car OR "hybrid vehicle" OR BEV OR PHEV)	1,013
3.1	Sub-cluster: Hydrometallurgy	[Step 2 Result] **AND** (hydrometallurg* OR leach* OR "solvent extraction" OR precipitat* OR bioleach* OR "solvometallurg*")	765
3.2	Sub-cluster: Pyrometallurgy	[Step 2 Result] **AND** (pyrometallurg* OR smelt* OR furnace OR calcin* OR roast* OR slag OR "thermal treatment")	622
3.3	Sub-cluster: Pre-treatment / Black Mass	[Step 2 Result] **AND** ("black mass" OR dismantl* OR shredd* OR comminution OR "mechanical separation" OR "mechanical treatment")	304
3.4	Sub-cluster: Direct Recycling	[Step 2 Result] **AND** ("direct recycling" OR relithiat* OR "cathode regeneration" OR "cathode healing" OR "cathode repair" OR "direct regeneration")	72

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