Battery circularity

Innovation trends for a future source of critical materials

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Europäisches Patentamt
European Patent Office
Office européen des brevets

International Energy Agency

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List of abbreviations

AI	Artificial intelligence
CAGR	Compound annual growth rate
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CNRS	Centre national de la recherche scientifique
DLE	Direct lithium extraction
IPF	International patent families
EPC	European Patent Convention
EPO	European Patent Office
EV	Electric vehicles
HPAL	High-pressure acid leaching
ESG	Environmental, social, and governance
IAA	Industrial Accelerator Act
IEA	International Energy Agency
IP	Intellectual property
LIB	Lithium-ion battery
LFP	Lithium iron phosphate
NCA	Lithium nickel cobalt aluminium oxide
NEV	New energy vehicle
NMC	Lithium nickel manganese cobalt oxide
PCT	Patent Cooperation Treaty
PVDF	Polyvinylidene fluoride
R&D	Research and development
RTA	Revealed technology advantage
SDG	Sustainable Development Goals
SOH	State of health
TRL	Technology readiness level
WTO	World Trade Organization
UNCTAD	UN Trade and Development
UNEP	United Nations Environment Programme

List of countries and world regions

AU	Australia
BE	Belgium
BR	Brazil
CA	Canada
CN	People's Republic of China (P.R. China)
DRC	Democratic Republic of Congo
EU	European Union
Europe	Europe as referred to in this report generally means the 39 member states of the European Patent Convention (EPC)
DE	Germany
FR	France
IT	Italy
JP	Japan
KR	Republic of Korea
US	United States of America

About the European Patent Office

The European Patent Office was established in 1977. As the executive arm of the European Patent Organisation, it is responsible for examining European patent applications and granting European patents, which can be validated in up to 46 countries in Europe and beyond.

As the patent office for Europe, the EPO is committed to supporting innovation, competitiveness and economic growth across Europe by delivering high-quality products and services and playing a leading role in international co-operation on patent matters. The EPO is also one of the world's main providers of patent information. As such, it is uniquely placed to observe the early emergence of technologies and to follow their development over time. The analyses presented in this study are a result of this monitoring.

In October 2023, the EPO launched the Observatory on Patents and Technology, which serves as a digital hub for transparent and informed debate on innovation.

About the International Energy Agency

The International Energy Agency provides authoritative data, analysis and recommendations across all fuels and all technologies, and helps governments develop policies for a secure and sustainable future for all.

The IEA was created in 1974 and examines the full spectrum of issues, including energy security, clean energy transitions and energy efficiency. Its founding agreement helps ensure a quick and effective response to energy supply disruptions through emergency response measures and other mechanisms. Though analysis, it is also a global leader in understanding pathways to meeting key policy goals, including addressing climate change, reducing air pollution and achieving universal energy access. Its work on energy technology innovation spans the collection of national data on public energy R&D budgets, regular technology trend analysis and policy guidance for governments.

The IEA family of countries accounts for over 75% of global energy consumption, and includes 35 member countries, five accession countries and 13 association countries – Brazil, P.R. China, India, Indonesia, Morocco, Singapore, South Africa and Thailand.

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Executive summary

The deployment of lithium-ion batteries and other modern battery types is growing at a rapid pace. From around 180 GWh in 2020, the market size expanded more than five-fold to 1 100 GWh by 2024, and is projected to reach more than 3 500 GWh by 2030. The growth of this sector, which is driven by technological innovation, is a disruptive force in the energy system. More than one in four cars sold globally in 2025 was an electric vehicle that decreases oil demand and increases electricity demand. Large-scale battery energy storage facilities are enabling electricity grids to operate more flexibly, integrate larger shares of variable renewable electricity and bolster resilience against disruptions.

However, the emergence of a large-scale battery industry at the heart of the energy sector brings challenges. Around 1.2 million electric vehicle batteries could reach the end of their lifetime in 2030, and 14 million by 2040. This is a waste management concern that will need to be addressed. In addition, today's supply chains for battery minerals and components are highly concentrated, weakening supply resilience and economic competitiveness in some regions, while raising environmental questions about mining sustainability in others.

Battery circularity is being pursued as a technology option that can help tackle these issues. It includes recycling, reuse of batteries in vehicles and repurposing of batteries for new applications. If a significant share of critical materials can be recovered – something that has already been technically demonstrated in existing facilities – it will increase supply diversity and resilience while lowering pressure on primary mineral extraction and reducing associated environmental impacts.

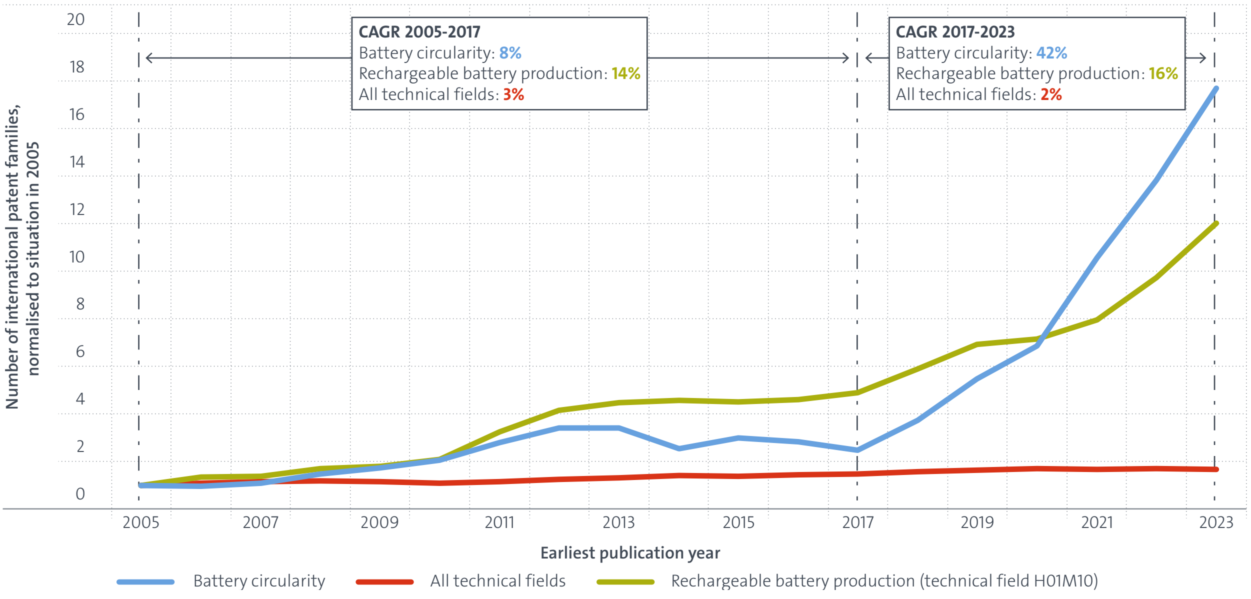
This report provides a new evidence base to support decision-making in both the public and private sectors. It draws on the latest information on battery circularity innovation trends which were not previously available. Based on the EPO's unique and comprehensive worldwide patent databases and the IEA's expert insights into the key issues for battery technologies, the report sheds light on the main locations of patenting, the leading patentors in the world and the technology categories receiving the most innovation attention. The technology categories covered include those for the collection and sorting of used batteries, mechanical processing, and treatments to recover valuable metals such as lithium, nickel, cobalt and copper from end-of-life batteries. As a potentially important secondary supply of those critical materials, battery circularity will compete with primary supplies, which is an area of technology that is also dynamic. One section of the report therefore investigates the innovation landscape for converting primary mined ore to battery-critical metals, enabling comparisons between the two fields.

Five key findings emerge from the details of this analysis.

KF1. Battery circularity innovation has been growing faster than other battery technology fields

Key figure 1.

Patenting activity in battery circularity, rechargeable battery production, and all technical fields combined (period: 2005-2023)



Source: EPO

Patenting is a leading indicator of technological change, and energy technology patenting is today led by battery innovation. The share of energy patenting represented by energy storage reached 40% in 2023, and data indicate that it is heading towards 50%. To our knowledge, no other energy technology has ever commanded such a dominant share. Patenting related to battery circularity is growing even faster than battery patenting in general, and far faster than the average across all technologies.

This is a new phenomenon. The pace of battery circularity patenting accelerated in 2017 and quickly overtook that for technologies related to new battery materials and manufacturing processes. Since 2017, international patent families (IPFs) related to battery circularity recorded a compound annual growth rate of 42%, compared with 16% for battery-metal refining technologies and 2% for all technical fields.[1,2] In 2017, global sales of electric cars broke the one million mark, and it became widely accepted that electric vehicle (EV) sales would continue to grow, becoming a major share of the global car fleet. For the first time, electric cars were responsible for around half of the absolute growth in total new vehicle sales in 2017. In parallel, between 2013 and 2018, governments in Europe and China introduced legislation to make companies responsible for electric vehicle batteries at the ends of their service lives, providing additional incentive to innovate the means of recycling and get patented approaches enshrined in evolving industrial standards. Embracing this pressure to recycle, China's largest battery manufacturer acquired a battery recycling company in 2015, helping it to become an innovation leader in this field.

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[1] Each IPF covers a single invention and includes patent applications filed and published at multiple patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. Unless otherwise stated, the patent trend data presented in this report refer to numbers of IPFs.

[2] The compound annual growth rate is a mean annualised growth rate over a specific time period. It mitigates the impact of the volatility of values, which may render other arithmetic means less meaningful.

KF2. Asian companies lead innovation across the whole value chain of battery recycling

Patent analysis shows that Asia – and China in particular – has emerged as the leading region for innovation in battery circularity technologies. While Europe and North America continue to generate important, globally relevant inventions, in 2023 Asian applicants accounted for 63% of IPFs in the field.

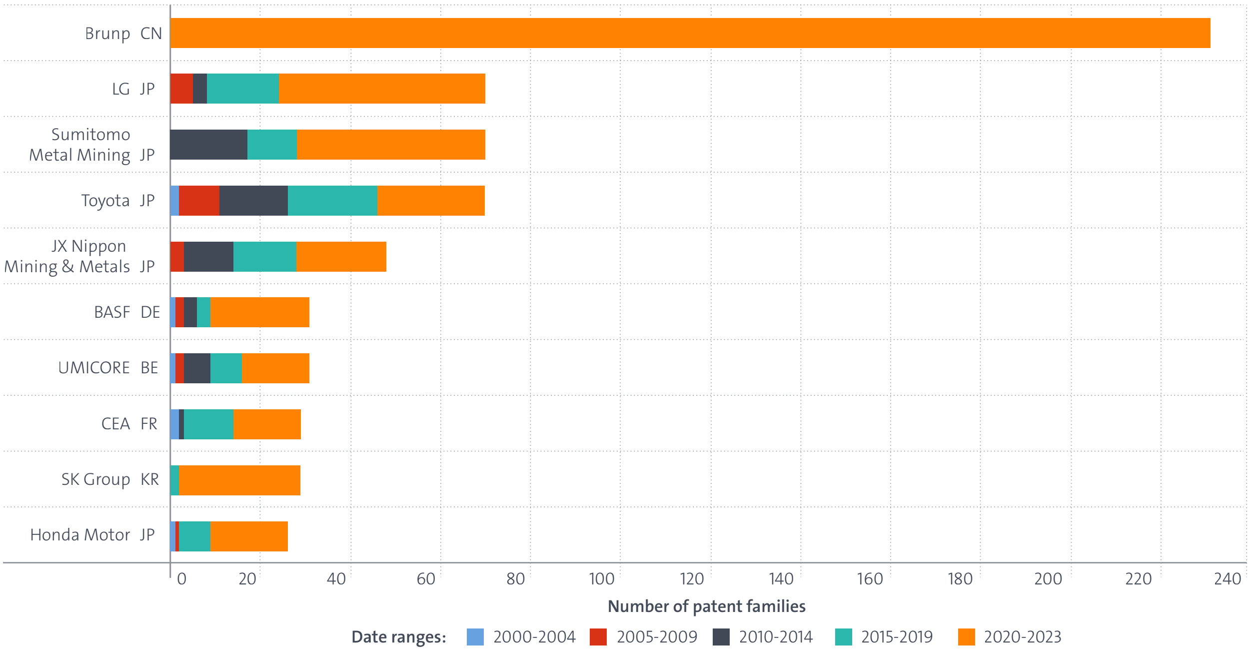
Until 2019, Japanese and Korean companies – including Toyota, LG, and Sumitomo Metal Mining – applied for more patents in the field than any other applicant. However, they have since been overtaken by Brunp – the recycling subsidiary of CATL, the largest battery manufacturer globally – which filed more than double the number of IPFs in 2020-2023 as Toyota, the second largest overall filer in the last two decades. Brunp, which was founded in 2005 in China and acquired by CATL (also Chinese) in 2015, has already installed recycling capacity equivalent to around 5% of the global total, supported by its access to battery manufacturing scraps from CATL factories, which are currently the largest source of recycling feedstock.

The companies that patent the most in this field are mostly patenting technologies related to the collection of used batteries and the recovery of metals through chemical transformation. Automotive companies in particular show a relative specialisation in the initial step of battery collection, whereas mining companies have a strong focus on chemical transformation. Brunp and LG (a company based in the Republic of Korea) are exceptions, with their activities spanning all segments of the recycling value chain.

Key figure 2.

Breakdown of inventive activity of the ten most active applicants in battery circularity according to date ranges and technology profile, for international patent families

Date ranges



Technology profile

	Collecting	Sorting and separating				Conditioning				Transformation	Enabling technologies	
	Pre-processing	Chemical	Mechanical	Physical	Pre-processing testing	Current collector	Graphite electrode	Relithiation and crystal repair	Repackaging for stationary applications	Chemical	Circularity-friendly design	Environment, health and safety
Brunp CN	55	4	76	11	2	24	19	1	1	166	2	2
LG JP	25	6	6	6	1	21		32	3	24	2	4
Sumitomo Metal Mining JP	7	1	7	1			1	3		66		
Toyota JP	40	2	10	1		4	1	9	13	16	2	
JX Nippon Mining & Metals JP	12	1	10	1		5				43	1	
BASF DE	5	3	5	4			3	4		28		
UMICORE BE	1			1						30		1
CEA FR	14	4	7	5		3		2		16		
SK Group KR	6		6	1		4		15		20		
Honda Motor JP	23		1	1				1		4		

Source: EPO

KF3. China has become the dominant player in battery circularity and refining of critical metals for batteries

Battery circularity represents a strategy to diversify future battery mineral supplies, thereby enhancing resilience in a supply chain that today is heavily concentrated in a small number of countries. Recovery of metals from batteries at the ends of their lifespans will compete with mined metals, which today are largely refined in P.R. China. This single country dominates the supply of 19 out of 20 refined critical minerals for the energy sector. Since 2020, China's share of IPFs in the field of battery metal refining has equalled that of the United States, reflecting its rapid expansion in an industry that has traditionally been dominated by large mining interests. When looking at all patent applications, including those only made in one national jurisdiction, the rise of Chinese patenting in this field is even more striking: from a share of about 10% in the early 2000s, Chinese national patents have averaged around 70% of all national and international patents globally in the five years to 2023.

As a means of diversifying away from a single major supplier of battery minerals, battery circularity innovation might be expected to be more geographically varied. However, the opposite is true. China's share of IPFs in battery circularity rose from 5% in 2013 to 29% in 2023. Much of this growth can be attributed to the surge of patenting by a single company – Brunp – which pursues a particularly international patenting strategy compared to other Chinese recyclers. Alongside this, in the five years to 2023, about 70% of the totality of IPFs and national applications worldwide were for Chinese national patents.

While care must be taken not to overinterpret the impact of national patents, which tend to be lower quality than IPFs and which have grown dramatically in P.R. China in the past 15 years in all technology fields, they are a useful indicator of dynamism in an area where most of today's industrial activity is within the Chinese market and not yet internationalised.

Overall, the field exhibits less geographic diversity than battery metal refining, which has significant contributions from companies headquartered in Australia, Canada and the United States, all of which are less present in battery circularity patenting. Europe's share of IPFs for battery circularity has declined from 22% in 2013 to 21% in 2023.

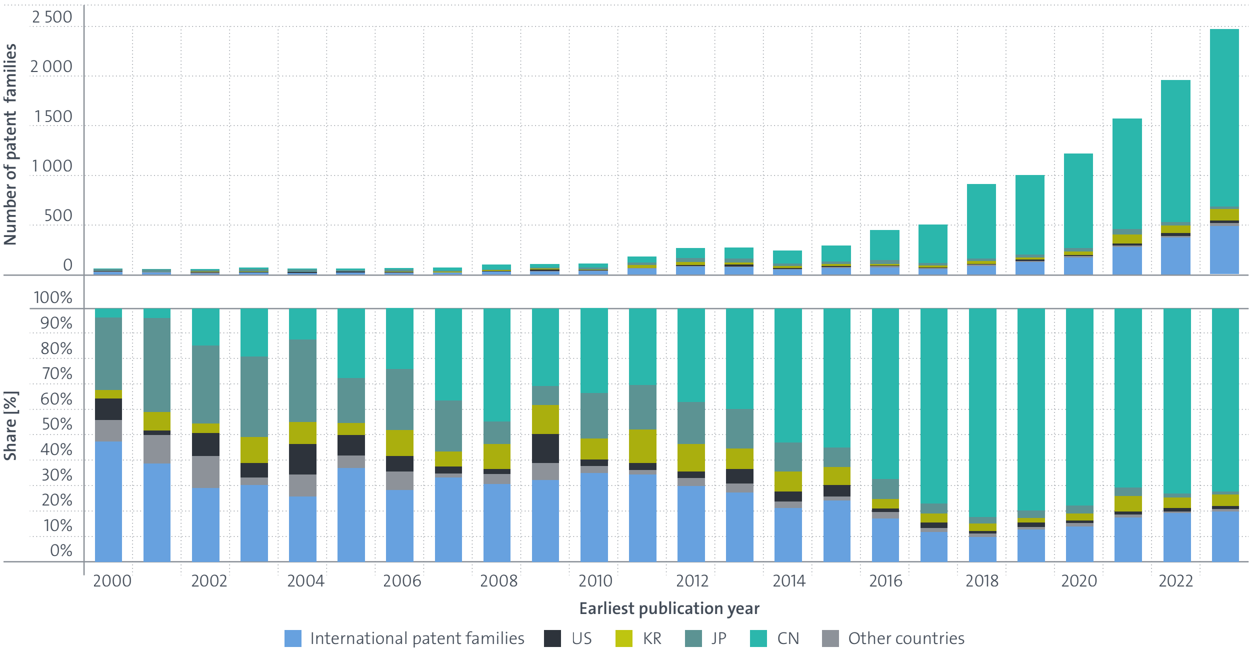
Key figure 3.

International and national patent families in battery circularity (top) and in refining critical metals for batteries (bottom)

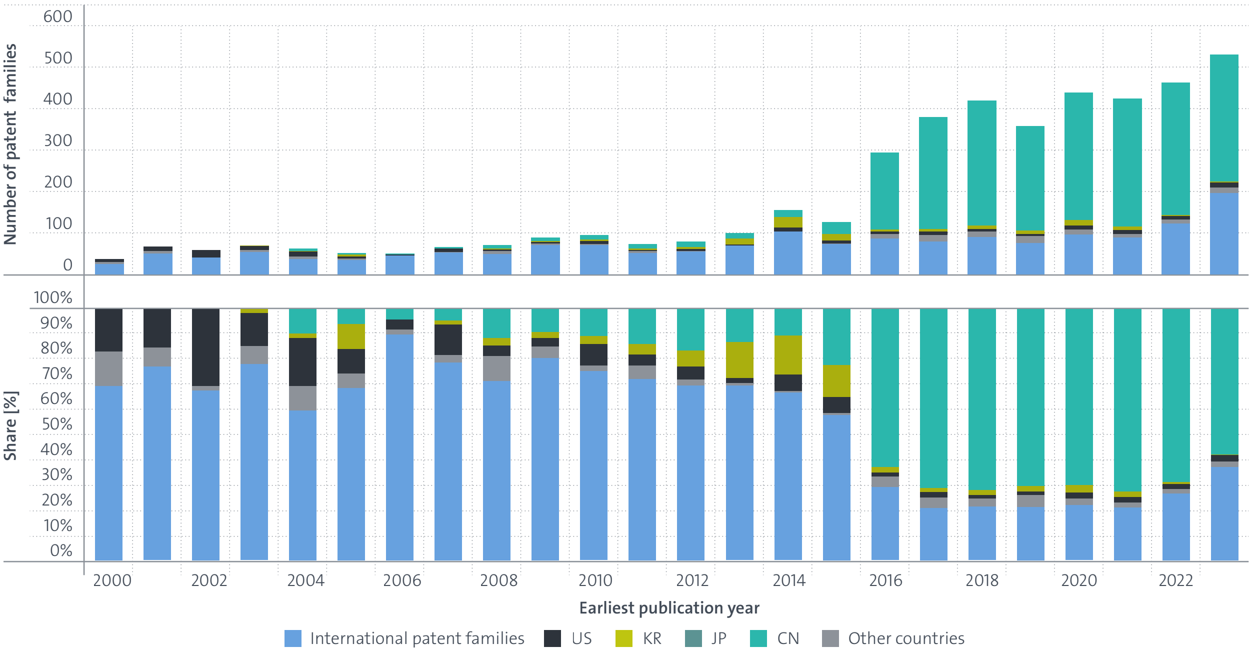
In both sub-charts, the upper plot shows the number of patent families. A distinction is made between international patent families with an international focus on the one hand (blue), mainly building on international patent applications and European patent applications, and national patent families on the other hand (other colours distinguishing between relevant territories). International patent families are related to inventions for which patent applications have been filed for at least two different countries whereas national patent families relate to inventions for which patent applications have only been filed in one country.

The lower plot presents the same data but normalised to 100% for each year. With that, the segments within the bar represent the share of IPFs or a territory of the total number of patent families for that year.

Battery circularity



Refining of critical metals for batteries



Source: EPO

KF4. Chinese applicants are increasingly looking to international patent protection

The field of battery circularity technology innovation has followed three phases since 2000:

- a period of limited but geographically diverse patenting up to 2005, with a high contribution from Japanese inventors
- a rapid increase in global inventive activity in the period 2005-2018, driven by applications for Chinese national patent applications
- a shift since 2018 towards more international patent families, reflecting a trend among Chinese patentors to seek protection outside China

Since 2018, the share of IPFs among all global patenting has almost doubled from a low point of 10% to around 20% in 2023. Just as the low point was driven by an expansion of Chinese national patents, the turnaround has been led by more Chinese inventions being patented in multiple regions rather than with Chinese national patents alone. However, the share of IPFs in the global total remains well below the level before 2015.

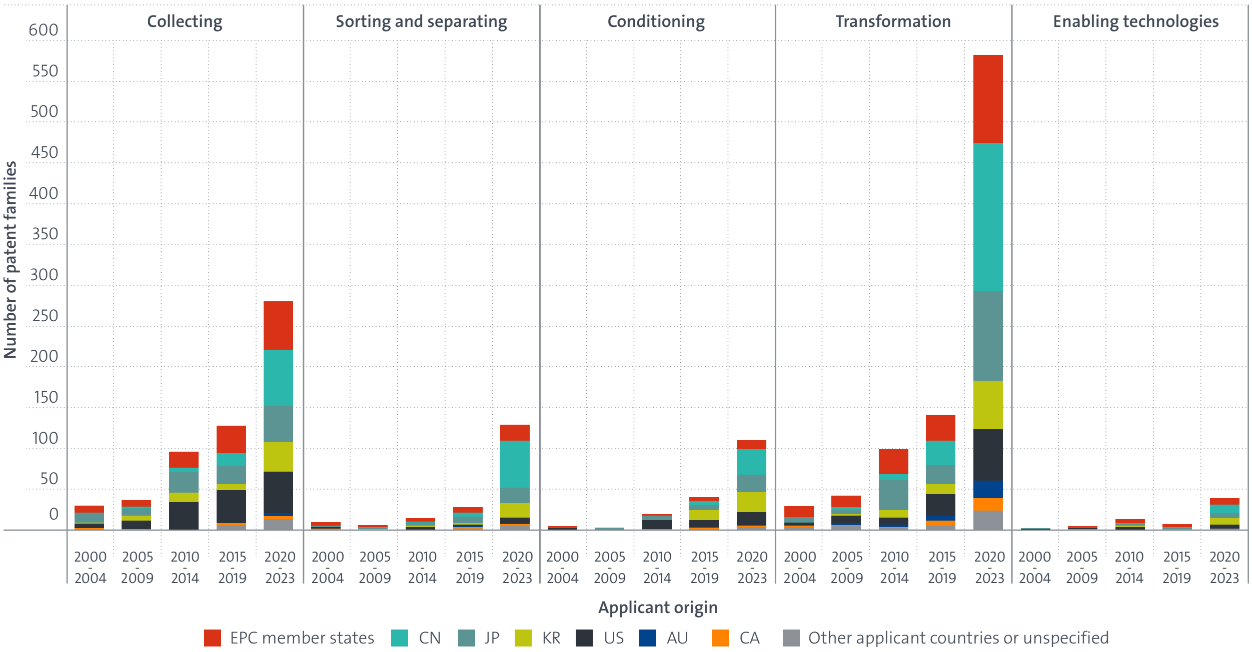
The logical interpretation of this trend is the development of a more international market for battery circularity, especially recycling, as regulatory requirements take shape in more countries and technology competition intensifies. This implies that Chinese applicants are eyeing opportunities elsewhere in the world. While international competition has the potential to spur more innovation and reduce costs, it also presents higher risks for technology owners that are not well integrated into existing battery manufacturing value chains.

Several policy challenges face governments that wish to support the scale-up of battery circularity and their domestic innovators. Firstly, circularity must be developed alongside other pillars of a critical raw materials strategy. In addition, attention must be paid to the looming gap between the number of innovators seeking to scale up this decade and the availability of end-of-life batteries, as well as overcapacity that already exists in P.R. China. Patient capital, government funding and managed access to waste materials are likely to be needed to ensure that a variety of promising approaches can be tested, refined and adapted to future changes in the main battery chemistries used in electric vehicles. Continued innovation will be important to further reduce the costs of battery recycling, ensure that it is adapted to the latest battery chemistries, and address the energy intensity and environmental impacts of the processing steps.

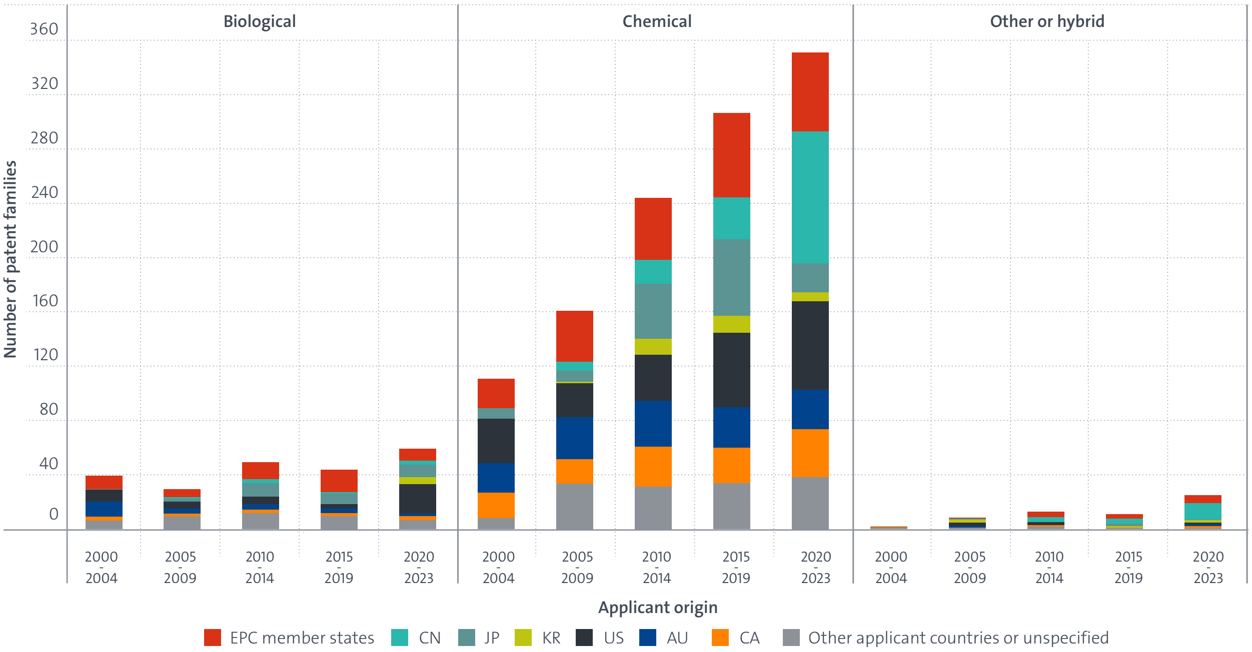
Key figure 4.

Applicant origin in battery circularity (top) and in refining of critical metals for batteries (bottom), with respect to international patent families

Battery circularity



Refining of critical metals for batteries: Treat raw materials



Source: EPO

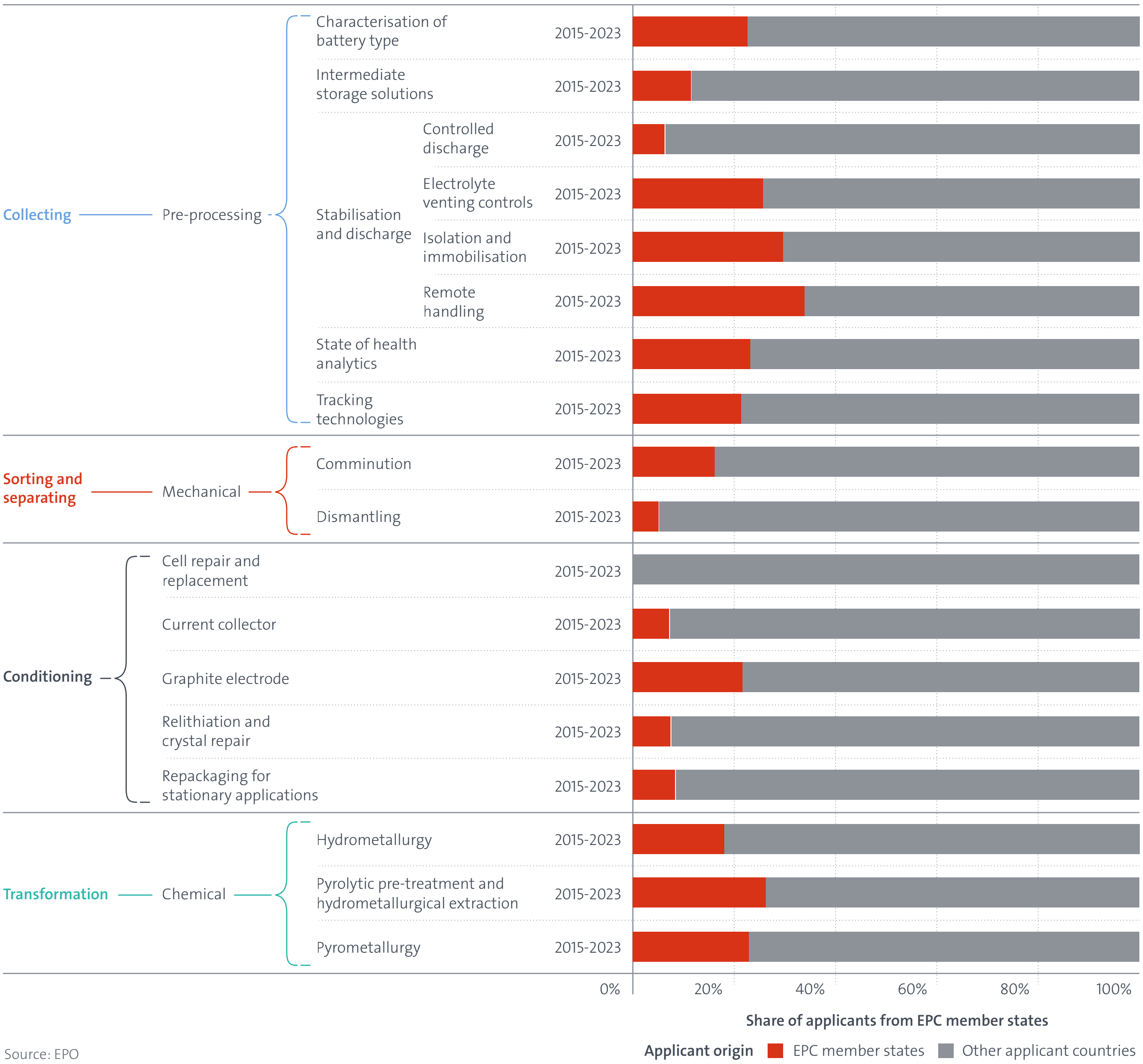
KF5. European innovation is concentrated on collection and pre-processing of batteries

European entities have persistently accounted for roughly 20% of all international patent families in battery circularity in the reporting period. European applicants are particularly active in collection and chemical transformation, with a focus on areas such as remote handling technologies (European applicants account for 34% of IPFs in this field), as well as isolation and immobilisation (30%) and hydrometallurgical extraction following pyrolytic pre-treatment (26%).

This focus reflects Europe's potential to manage growing volumes of used batteries. Europe is home to several major companies that are active in this area, such as BASF (a chemical giant) and Umicore (a battery recycler) ex aequo in 6th place globally, as well as research organisations such as CEA in 8th place, and startups. The range of focus areas and patenting entities indicates that Europe's strengths are not narrowly targeted towards one approach only, but could potentially be a basis for an industrial ecosystem of complementary domestic players.

Key figure 5a.

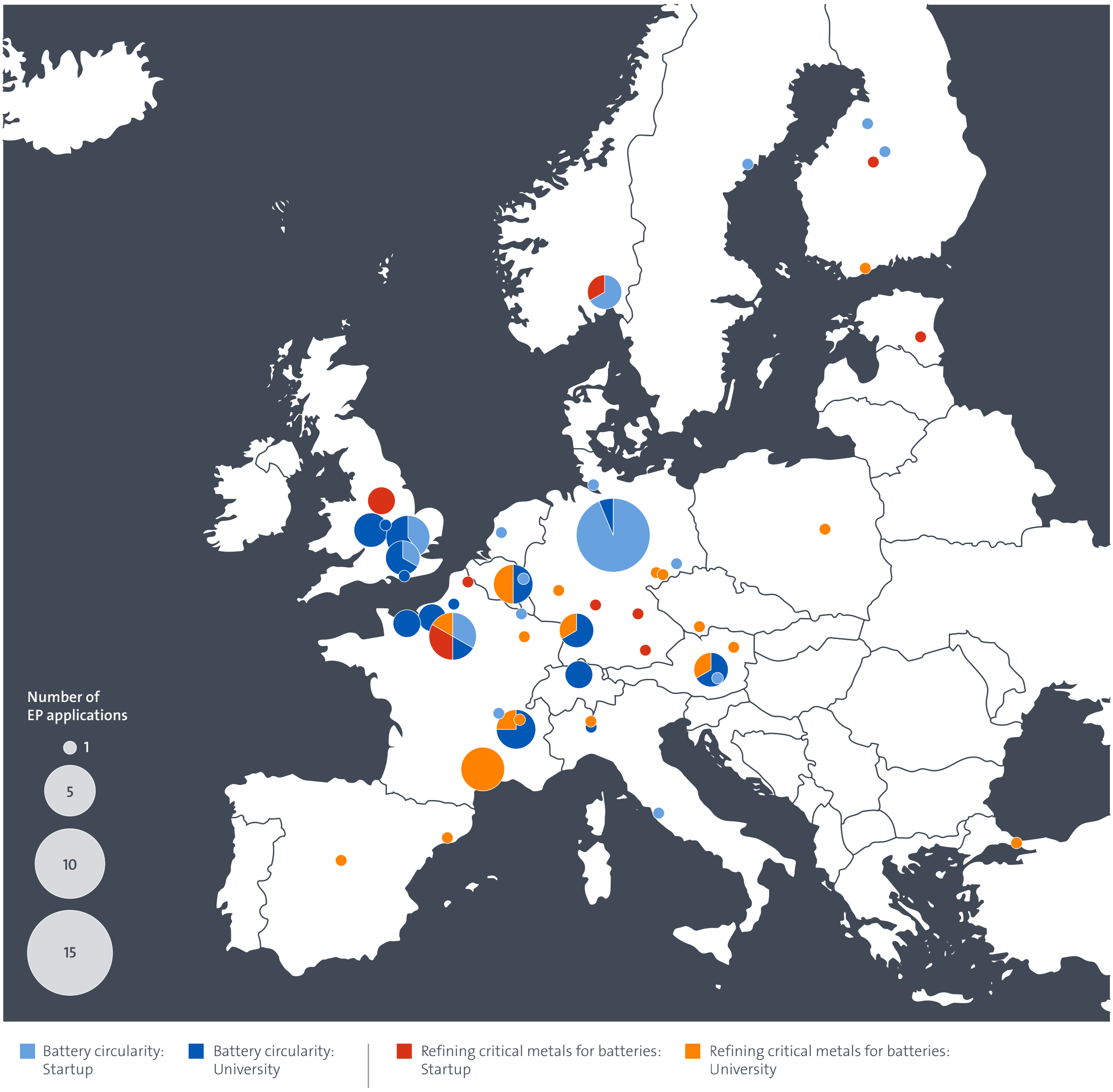
Share of applicants from EPC member states among selected technologies in battery circularity with at least 10 international patent families in the period 2015-2023



Source: EPO

Key figure 5b.

Geographical origin of European patent applications filed by startups and by universities related to battery circularity and refining of critical metals for batteries



Source: EPO

Glossary

Compound annual growth rate (CAGR)	Mean annualised growth rate over a specific time period
DOCDB	The EPO's master documentation database with worldwide coverage. It contains bibliographic data, abstracts, citations and DOCDB simple patent family information.
DOCDB simple family	A set of patent documents relating to patent applications claiming priority over the same earlier applications. The technical content covered by the patent applications in a DOCDB simple patent family is considered to be identical.
European patent	The European patent system makes it possible to obtain European patents valid in up to 39 contracting states to the European Patent Convention (EPC) on the basis of a single application. A European patent has the same legal effects as a national patent in each country for which it is granted. As of 2023, it is also possible to request unitary effect for a granted European patent.
European Patent Convention (EPC)	International treaty signed by the member states of the European Patent Organisation. The EPC establishes a single application procedure for obtaining patent protection in Europe.
European Patent Office (EPO)	Executive arm of the European Patent Organisation. European patents are granted by the European Patent Office in a centralised, cost-effective and time-saving procedure conducted in one of the official languages of the EPO (English, French or German). Every European patent application undergoes substantive examination before a European patent is granted to make sure that inventions for which patent protection is sought meet all of the legal requirements set out in the European Patent Convention.
Espacenet	Free online patent searching service developed by the EPO. It includes information on over 160 million patent documents from more than 100 patent offices on all continents. Espacenet is available at epo.org/espacenet.
First filing	First patent application filed for a new invention, typically with a national or regional patent office
International patent application	Patent application filed under the Patent Cooperation Treaty (PCT). An international patent application may result in patent protection in more than 150 countries.
International Patent Classification (IPC)	The International Patent Classification system is a hierarchical patent classification system used by the EPO and more than 100 patent offices worldwide. It breaks technologies down into eight sections with several hierarchical sub-levels. The IPC system has approximately 75 000 subdivisions and is updated on an annual basis.
International patent family (IPF)	A set of applications for the same invention that includes a published international patent application, a published patent application at a regional patent office, or published patent applications at two or more national patent offices.
Invention	A practical solution to a (technical) problem. The invention may be a new product, process or apparatus or any new use thereof. To be patentable under the European patent system, an invention must be technical, novel, involve an inventive step (i.e. it must not be obvious to those having ordinary skill in the technical area of the invention), and be considered as susceptible of industrial application.
National patent family	A set of applications for the same invention that consists of published patent applications at a single national patent office.
Patent	Legal title giving the patent owner(s) the right, for a limited period of time (usually 20 years as of the date of filing the patent application), to exclude others from using the protected invention in a commercial context without permission in those countries for which the patent has been granted. The protected invention is defined by the claims of the patent.
Patent application	Request for patent protection for an invention filed with the EPO or other patent office.

Patent classification system	The set of patent classification symbols assigned to categorise the technical subject-matter of a patent or utility model. There are various patent classification systems used today by national, regional and international patent offices.
Patent family	A set of patent documents covering the same or similar technical content, depending on the patent family definition.
PATSTAT	PATSTAT is a group of databases that contain bibliographical, procedural and other context information on millions of patents and utility models from numerous industrialised and developing countries. It is built from the EPO's databases of worldwide patent data.
Patent Cooperation Treaty (PCT)	An international treaty providing for a unified procedure for filing patent applications to protect inventions in its contracting states. Under the PCT, a single international application can be filed for patent protection in up to more than 150 countries. The PCT provides for a centralised procedure for filing the patent application whereby the substantive examination and the grant of the patent lies with the competent national or regional patent office(s).
Priority	Inventions can be protected by patents and utility models in more than one country. For a period of 12 months from the date of filing an application for a patent in a member state of the Paris Convention, the applicant or their successor can claim a right of priority from that application for any subsequently filed patent application that concerns the same invention. If the requirements are fulfilled, the date of the earlier application counts as the date of filing of the later application for the purposes of examining novelty and inventive step.

1. Introduction

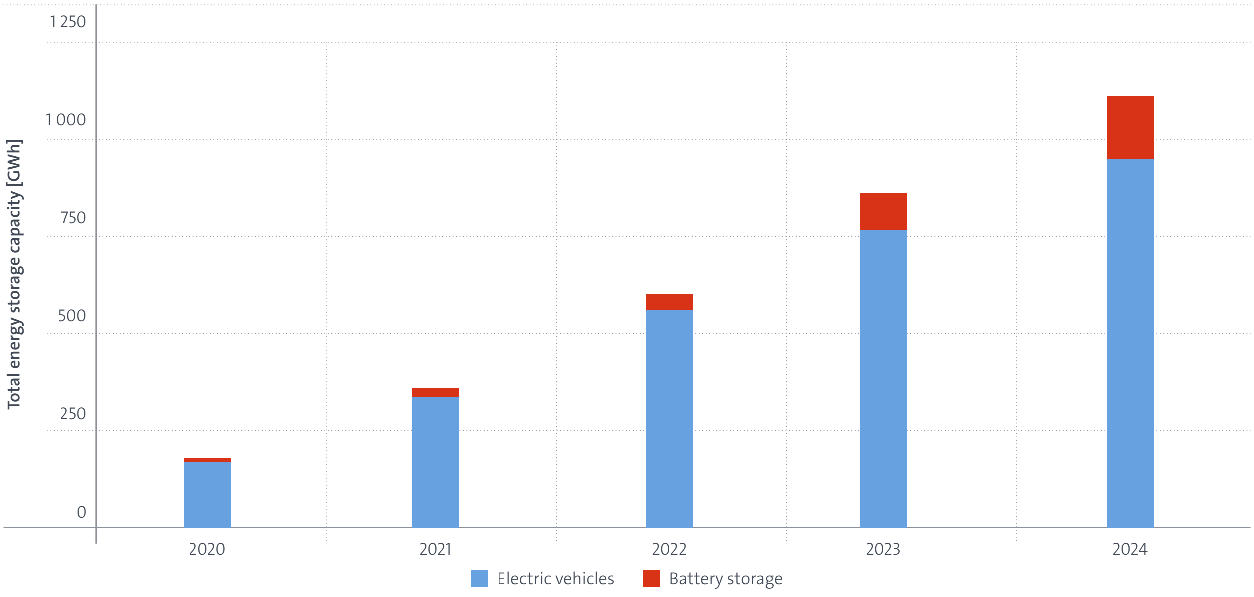
1.1 Background: Growth in EV batteries and the emerging end-of-life wave

Electrification is accelerating across mobility and power systems, and electric vehicles (EVs) are the dominant driver of lithium-ion battery (LIB) demand. The International Energy Agency (IEA) reports that nearly 1 000 GWh of EV battery capacity was deployed in 2024 (see Figure 1), and under current policy settings this figure is projected to jump more than three-fold by 2030 compared with this 2024 levels [International Energy Agency, 2025a].

Battery lifetimes are finite. As EVs age, the number of end-of-life batteries is expected to rise sharply, especially from 2035 onwards (see Figure 2). This implies that systems for collection, logistics and treatment of end-of-life batteries should be scaled accordingly in advance. Reputable projections illustrate the scale of the coming end-of-life wave. The International Council on Clean Transportation estimates that, globally, some 1.2 million batteries from light- and heavy-duty battery electric vehicles and plug-in hybrid electric vehicles will reach their end-of-life in 2030, rising to 14 million in 2040 and 50 million in 2050 [Tankou et al., 2023]. The IEA calculates that in the Announced Pledges Scenario (APS) – which assumes all government climate pledges will be met on schedule – primary supply requirements will be around 40% lower for copper and cobalt, and around 25% lower for lithium and nickel in 2050 thanks to recycling, compared with the case without recycling [International Energy Agency, 2025b].

Figure 1.

Global electric vehicle battery and battery storage systems deployment, 2020-2024



Source: International Energy Agency, 2025a

Main components and materials of lithium-ion batteries

Lithium-ion batteries consist of several highly specialised components that enable the storage and release of electrical energy through electrochemical reactions. The most important elements of a battery cell are the **cathode, anode, electrolyte and separator**, each of which contains specific materials that determine the battery‘s performance, cost and supply-chain requirements.

Cathode (positive electrode)

The cathode is typically the most valuable and material-intensive component of a lithium-ion battery. It contains lithium combined with other metals in complex compounds that store and release lithium ions during charging and discharging. Common cathode chemistries include lithium **nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP)**. The materials used in cathodes often include **lithium, nickel, cobalt, manganese and iron,** depending on the specific chemistry. Cathode materials are particularly important because they largely determine the battery‘s energy density, cost and reliance on critical minerals.

Anode (negative electrode)

The anode stores lithium ions when the battery is charged and releases them during discharge. In most commercial lithium-ion batteries, the anode is made primarily of **graphite,** although silicon-graphite composites and other advanced materials are increasingly being explored to improve energy density. During operation, lithium ions move from the cathode through the electrolyte and are stored within the layered structure of the anode material.

Electrolyte

The electrolyte is the medium that allows lithium ions to move between the cathode and the anode. In conventional lithium-ion batteries, it is typically a **liquid organic solvent containing a dissolved lithium salt**. This electrolyte conducts lithium ions but does not conduct electrons, which forces electrons to move through the external circuit, thereby generating electrical power.

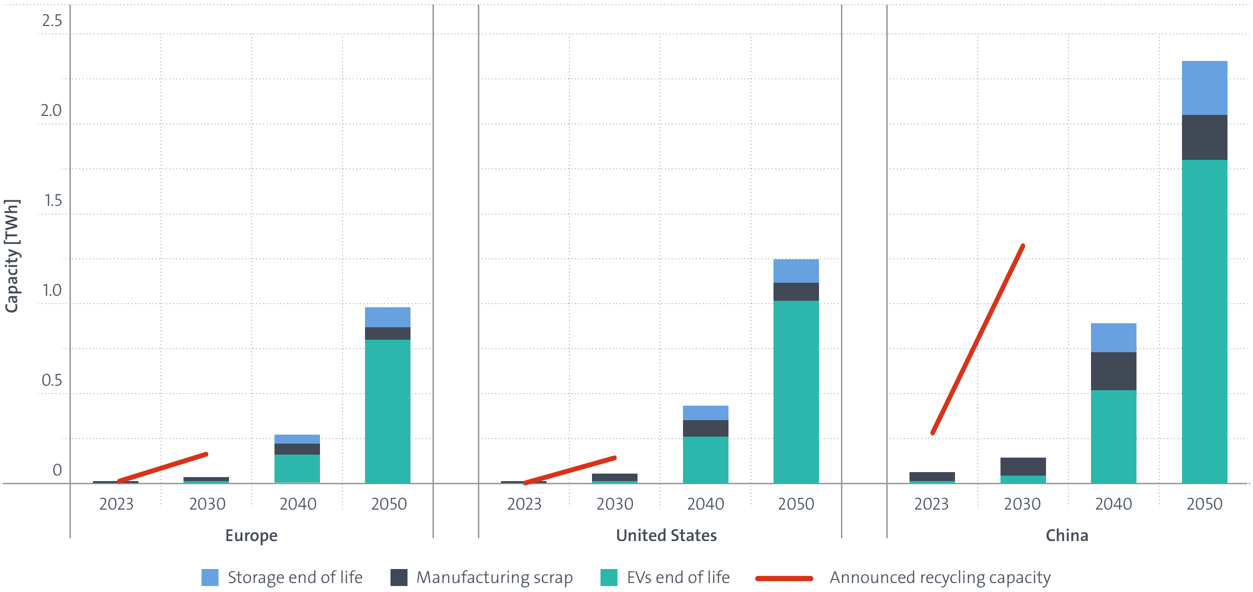
Separator

The separator is a thin, porous membrane placed between the cathode and anode. It prevents direct contact between the electrodes, which would cause a short circuit, while still allowing lithium ions to pass through the electrolyte between the two electrodes. This component plays an important role in battery safety and performance.

In addition to these core components, lithium-ion batteries also contain **current collectors, binders and conductive additives** as well as protective casings and thermal management systems at the cell and pack level. While these elements are essential for battery operation, the **cathode and anode active materials account for a significant share of the battery‘s material value,** particularly due to the presence of critical minerals such as **lithium, nickel, cobalt and graphite**.

Figure 2.

Maximum available battery recycling feedstock and recycling capacity by region in the IEA Announced Pledges Scenario, 2023-2050



Source: International Energy Agency, 2025a

These projections are uncertain, and depend on assumptions about vehicle lifetimes, battery durability [Geslin et al., 2025], second-life EV markets and collection rates. Nonetheless, they consistently indicate that end-of-life battery management will become dominated by vehicle batteries over the 2030s and 2040s [International Energy Agency, 2024a; Tankou et al., 2023]. While recycling of battery materials is already practiced today, production scrap accounts for nearly all of the recycling feedstock, i.e. offcuts and rejected material from battery manufacturing facilities that have not yet been integrated into useable batteries. Economies of scale and innovation will both be important to lower the costs and increase efficiency of battery recycling – both of which are necessary to achieve a more circular battery ecosystem.

Innovations across the recycling value chain can significantly improve the recovery of critical minerals while reducing environmental impacts. Traditional pyrometallurgical methods are highly energy-intensive, and although hydrometallurgical processes typically require less energy, they require reagents (acids) and wastewater treatment [Baum et al., 2022]. At the same time, the growing complexity and diversity of modern products often limit the effectiveness of existing recycling technologies, resulting in low recovery rates and material losses. Emerging solutions – from advanced collection and sorting to novel chemical and physical separation processes – are enhancing efficiency, selectivity and environmental performance. Supported by automation, artificial intelligence and improved tracking and quality control systems, these innovations are reshaping recycling by increasing recovery potential, reducing risks and improving the reliability and traceability of secondary raw materials [International Energy Agency, 2024a]. Patents are good indicators of R&D output, i.e. technical innovation at both company and country level [OECD, 2009], and therefore can be used to track advancements in the field.

Whereas some earlier research papers relating to patents and battery circularity exist, these are either quite general [Metzger et al., 2023] or relate to a very specific sub-context (such as recycling positive electrode materials from lithium-ion batteries) [Tong et al., 2025]. This more comprehensive overview of this topic is therefore of value to researchers, industry and policy makers.

1.2 Environmental and safety risks of disposal

Spent lithium-ion batteries can pose significant environmental and safety risks if landfilled or otherwise mismanaged. Risks arise from residual energy, reactive electrolyte salts and fluorinated materials which can contribute to fires, toxic emissions and contamination of land and water systems.

Fire and toxic gas risks are a central concern. Experimental work measuring emissions from lithium-ion battery fires shows that such fires can generate toxic fluoride gas emissions, including hydrogen fluoride, which can pose a critical hazard in confined or poorly ventilated spaces [Larsson et al., 2017]. In landfill settings, where batteries may be crushed, short-circuited or exposed to heat, these hazards can be amplified by delayed detection and limited suppression options.

Chemical contamination risks are increasingly documented. A recent study reported that a subclass of per- and polyfluoroalkyl substances used in some lithium-ion battery electrolytes – bis-perfluoroalkyl sulphonimides – was detected in landfill leachate samples, and the authors assessed these compounds as persistent and associated with aquatic toxicity endpoints in laboratory organisms [Guelfo et al., 2024]. This evidence indicates that disposal pathways can create routes for long-lived fluorinated contaminants to enter the environment, strengthening the case for strict diversion of LIBs from general waste streams.

In addition to fluorinated compounds, landfill leachate can mobilise dissolved metals, and physical degradation of cells can increase the likelihood of electrolyte release. While the extent of release depends on landfill design and local conditions, the evidence on fluorinated electrolyte components and the measured toxicity of fire emissions underscores that landfill disposal is not a benign endpoint for lithium-ion batteries, particularly as volumes increase [Guelfo et al., 2024; Larsson et al., 2017].

Contrary to the environmental risks of battery disposal, on average, recycling of energy transition minerals such as nickel, cobalt and lithium can cause 80% less greenhouse gas emissions than primary materials produced from mining [International Energy Agency, 2025c], providing a further incentive for recycling.

1.3 Geopolitical landscape of critical battery materials

The battery value chain is highly geographically concentrated, exacerbating the risk to supply chains exposed to supply disruptions and price volatility.

In its Global Critical Minerals Outlook 2025 report, the IEA shows that geographical concentration in both mining and refining has increased for several key battery minerals since 2020 (see Figure 3). For nickel, the share of the top three producers rose from around 60% in 2020 to almost 80% in 2024, driven largely by Indonesia's rapid expansion in mining and processing. Indonesia's share alone increased from roughly one-quarter to more than 40% over this period. In 2024, around two-thirds of global cobalt production was mined in the Democratic Republic of the Congo (DRC), while P.R. China accounts for almost 80% of refining. Lithium refining is similarly concentrated, with China accounting for about 70% of global refined lithium production in 2024, followed by Chile with around one-fifth of the market. Lithium mining is led by Australia, which supplied more than one-third of global output in 2024.

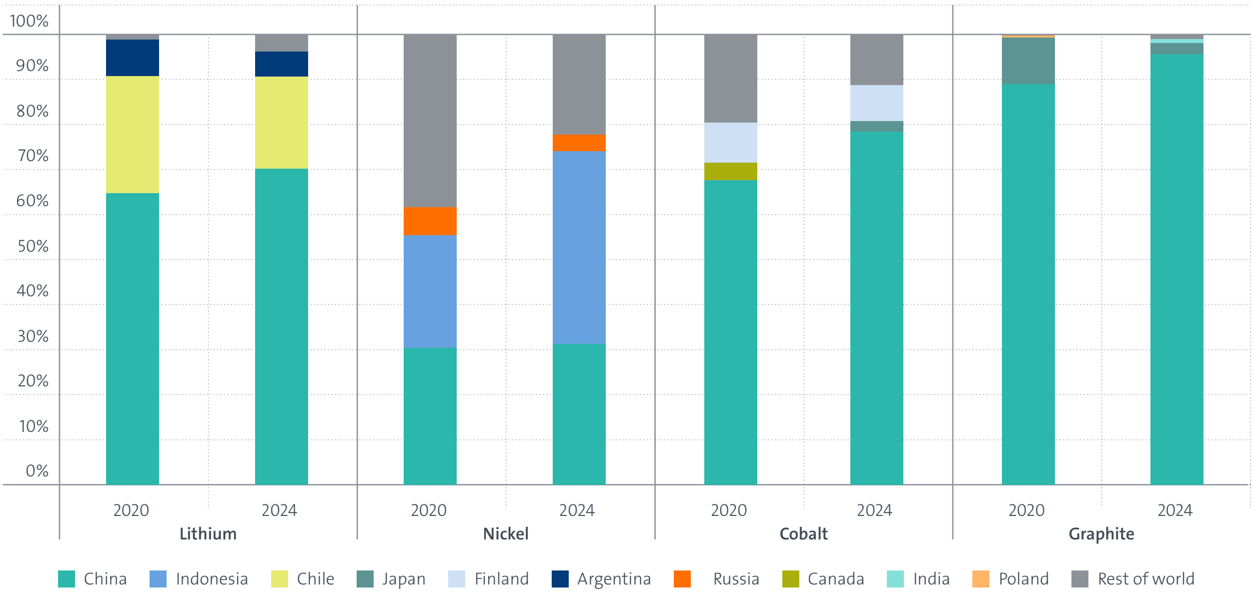
The IEA's market review of critical minerals reports that the average market share of the top three refining nations of key energy minerals rose from around 82% in 2020 to 86% in 2024, as some 90% of supply growth came from the top single supplier alone: Indonesia for nickel and P.R. China for cobalt, graphite and rare earths [International Energy Agency, 2025b]. China's stronghold extends beyond refining: two-thirds of global battery recycling capacity growth since 2020 has been in China [International Energy Agency, 2025c; Executive summary].

These trends are relevant for battery circularity, as recycling, over time, will become a strategic complement to mining and refining. Recovering metals from end-of-life batteries can reduce demand for primary extraction, and can diversify supply by creating domestic or regional secondary material streams, provided that recycling outputs meet battery-grade specifications and are integrated into precursor and cathode supply chains [Harper et al., 2019].

The volume and share of the secondary supply of the most critical raw materials for batteries (lithium, nickel, cobalt and graphite) in the IEA Announced Pledges Scenario are shown in Figure 4. In particular for lithium, nickel and cobalt, significant (>20%) shares of the total metal demand could be met by secondary supply by 2040.

Figure 3.

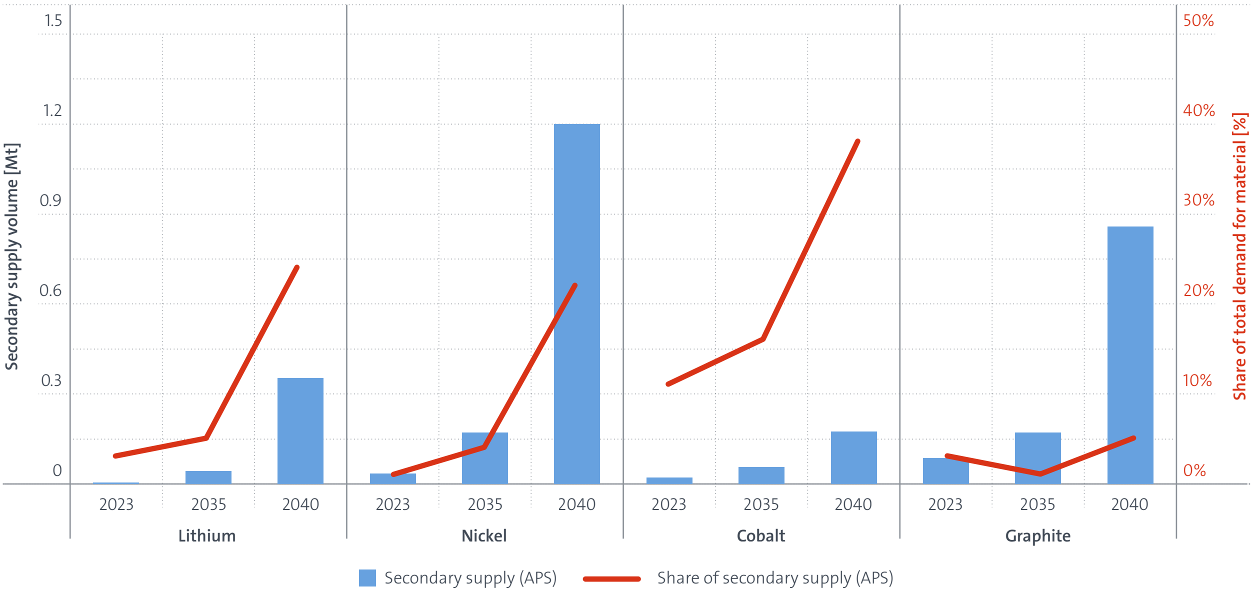
Share of refined material production by country, 2020 and 2024



Source: International Energy Agency, 2025c

Figure 4.

Secondary supply volumes and share of total demand for key energy minerals in the IEA Announced Pledges Scenario



Source: International Energy Agency, 2025c

1.4 Policy context

1.4.1 Global policy approaches relevant to battery circularity

Globally, battery circularity policy has tended to develop along three technical governance themes: (1) safety rules for transport and handling of used or waste batteries, (2) extended producer responsibility (EPR) and collection obligations, and (3) supply-chain rules that incentivise traceability and responsible sourcing.

In the **United States,** there is no single federal statute that specifically mandates the recycling of electric vehicle (EV) batteries. Instead, end-of-life lithium-ion batteries are regulated primarily under existing environmental law, most notably the Resource Conservation and Recovery Act, under which they are often classified as hazardous waste and subject to federal hazardous waste management requirements. The United States Environmental Protection Agency permits certain batteries to be managed under the Universal Waste regulations at 40 C.F.R. Part 273 to facilitate collection and recycling, although the application of these provisions to lithium-ion batteries has relied largely on guidance and state authorisation, with further regulatory updates under consideration [United States Environmental Protection Agency, 2026].

At the state level, regulatory activity related to battery recycling is more advanced and heterogeneous, reflecting the absence of a comprehensive federal mandate. California has enacted the Responsible Battery Recycling Act of 2022, which establishes a producer-funded stewardship system for most batteries, including lithium-ion batteries, and requires approved stewardship organisations to implement collection, recycling and reporting programs under the oversight of CalRecycle [CalRecycle, 2024]. California has also convened advisory processes to address EV and large-format battery management challenges as part of broader implementation efforts. Other U.S. states have adopted or proposed battery-specific extended producer responsibility laws, disposal bans and retailer take-back requirements, particularly for rechargeable batteries, resulting in a patchwork of state-level obligations that vary significantly in scope, enforcement mechanisms and covered battery types [National Conference of State Legislatures, 2023]. Collectively, these state initiatives play a central role in expanding battery recycling infrastructure in the United States, while also creating regulatory complexity for manufacturers and recyclers operating across multiple jurisdictions.

The **Chinese** government has formalised the legal framework for recycling new energy vehicle (NEV) batteries, placing the primary responsibility for recovering waste power cells on automakers. Under this regulation, taking effect on 1 April 2026, NEV manufacturers are required to establish recycling service outlets commensurate with their sales volumes in the regions where they operate. Automakers are also prohibited from refusing to accept waste batteries transferred by vehicle maintenance service providers and vehicle recycling companies. The regulation also mandates the creation of a national information traceability platform and a digital ID management system for NEV batteries, aimed at strengthening oversight of power battery flows throughout their life-cycle.

Across jurisdictions, a recurring practical challenge is that circularity objectives depend on high collection rates, safe transport and sufficiently detailed information on battery composition and history to enable appropriate repurposing or recycling. This motivates the EU's approach to digital product information, described below.

1.4.2 EU policy relevant to battery circularity

1.4.2.1 European Green Deal and circularity framing

The European Green Deal set the strategic direction for a climate-neutral and resource-efficient economy, and explicitly signalled forthcoming legislation to ensure a safe, circular and sustainable battery value chain [European Commission, 2019]. Building on this, the EU's Circular Economy Action Plan articulated a product-policy approach centred on durability, reuse, repair and high-quality recycling, including priority attention to resource-intensive value chains [European Commission, 2020].

Within this framing, batteries are treated not only as climate-enabling products but also as resource-intensive systems that require lifecycle governance. This has led to a regulatory approach that links performance and safety requirements with supply-chain transparency and circularity obligations.

1.4.2.2 EU Battery Regulation

Regulation (EU) 2023/1542 on batteries and waste batteries entered into force in August 2023 and replaced the previous Batteries Directive. It establishes lifecycle requirements covering sustainability, safety, labelling, collection, treatment and information provision, with multiple obligations phased in through implementing acts and deadlines specified in the Regulation (European Parliament & Council, 2023).

Minimum recycled content requirements are a prominent circularity instrument. Article 8 sets mandatory minimum shares of recycled cobalt, lead, lithium and nickel in active materials for certain battery categories, calculated per model and manufacturing plant. The minimum shares apply from 18 August 2031, at 16% cobalt, 85% lead, 6% lithium and 6% nickel, and increase as of 18 August 2036 for cobalt, lithium and nickel, to 26% cobalt, 12% lithium and 15% nickel [European Parliament & Council of the European Union, 2023].

Recycling performance is also addressed through material recovery targets. The European Commission announced implementing rules in July 2025 that specify material recovery targets for treatment and recycling of 90% for cobalt, copper, lead and nickel and 50% for lithium by 31 December 2027, increasing to 95% for cobalt, copper, lead, and nickel and 80% for lithium by 31 December 2031 [European Commission, 2025a]. These targets create practical consequences for process selection, particularly the need for high-efficiency hydrometallurgical steps for lithium recovery, and for robust sampling and mass-balance systems to verify performance.

A further core instrument is the digital battery passport. Articles 77 and 78 require an electronic battery passport, accessed via a QR code, for EV batteries, light-means-of-transport batteries, and industrial batteries above 2 kWh. The passport is intended to make specific lifecycle data available to defined actors, with the data structure and access rights detailed in Annex XIII and subsequent implementing acts, and it applies to batteries placed on the EU market from 18 February 2027 [European Parliament & Council of the European Union, 2023]. The Battery Pass Consortium's guidance provides an operational interpretation of the data categories and attributes that the Regulation expects to be made available through the passport [Battery Pass Consortium, 2023].

From a practical standpoint, the battery passport addresses an information problem that limits recycling. Battery packs are complex and design-diverse, and without standardised, accessible information, downstream actors may not know a battery's chemistry, hazardous constituents, carbon footprint declaration status, recycled content declaration or its operational history relevant to safety and second-life suitability. A digital passport is intended to support safe handling and disassembly, enable more accurate sorting by chemistry and design, reduce cross-contamination in recycling and improve confidence in claims such as recycled content and responsible sourcing – because verification depends on traceable data rather than assumptions.

Due diligence obligations in the Regulation, which apply to certain economic operators, are designed to connect sustainability and human-rights concerns in upstream supply chains with downstream market access. Although perhaps not directly relating to circularity, these provisions reinforce the role of traceability and reporting as enabling infrastructure for recycling markets and for the verification of recycled-content compliance [European Parliament & Council of the European Union, 2023].

1.4.2.3 Critical Raw Materials Act

The Critical Raw Materials Act establishes benchmarks for EU domestic capacity and diversification across strategic raw materials value chains. The European Commission summarises benchmarks for 2030 that include at least 10% of the EU's annual consumption for extraction, at least 40% for processing, at least 25% for recycling and no more than 65% dependency on a single third country for the EU's annual consumption of each strategic raw material [European Commission, 2024].

These benchmarks are not battery-specific requirements, but they reinforce the strategic rationale for battery recycling. Higher recovery and reintegration of battery materials can contribute to the recycling benchmark, and can partially offset concentration in mining and refining described by the IEA, particularly when recycling output can be converted to battery-grade precursors in Europe.

1.4.2.4 RESourceEU Action Plan

The RESourceEU Action Plan aims to accelerate the European Union's strategy to secure critical raw materials (CRMs) and reduce strategic dependencies in key industrial value chains. Battery raw materials are identified as an immediate priority due to their importance for electric vehicles, energy storage and the broader clean energy transition [European Commission, 2025a]. Within this strategy, circularity – and in particular recycling and the recovery of materials already present in the economy – is presented as an important tool to strengthen supply resilience.

The Action Plan states that circularity will be "a central enabler" of the EU's efforts to reduce dependencies on imported raw materials, supported through recycling projects and regulatory incentives to recover materials [European Commission, 2025b]. This approach is particularly relevant for battery materials such as lithium, cobalt, nickel, manganese and graphite, which are essential for battery production and currently subject to significant supply risks. Increasing the recovery and reuse of these materials is therefore seen as an important addition to domestic extraction and international sourcing.

One of the most immediate measures affecting battery circularity concerns the management of recycling feedstock. The Action Plan notes that a substantial share of battery recycling intermediates, particularly "black mass", is currently exported from Europe for further processing abroad. To address this issue, the Commission has decided that waste lithium-ion batteries and black mass will be classified as hazardous waste from September 2026. As a result, exports of these materials to non-OECD countries (e.g. P.R. China) will be prohibited [European Commission, 2025b]. The Commission also states that it will ensure the effective implementation of this measure and may introduce additional restrictions if necessary. This is expected to increase the availability of recycling feedstock for processing within the EU.

The Action Plan also proposes financial support for projects along the CRM value chain. The Commission intends to mobilise around €3 billion in EU funding within the next twelve months to support CRM-related projects [European Commission, 2025b]. Among the relevant instruments is the proposed "Battery Booster", with an envelope of €1.8 billion, which will support projects linked to battery raw materials, including lithium, cobalt, nickel, manganese and graphite. These measures are intended to reduce investment risks and accelerate the development of industrial capacity in Europe, including recycling activities.

Regulatory initiatives are also expected to improve the recovery of battery materials. The Commission notes that implementing acts under the Batteries Regulation (covering e.g. battery passports) will help ensure that battery raw materials can be more easily recovered and recycled. In addition, broader legislation related to circular economy goals will aim to improve the collection and treatment of end-of-life products containing critical raw materials [European Commission, 2025b].

In terms of timeline, several key measures affecting battery circularity are expected to be implemented between 2026 and 2027. Export restrictions on battery waste streams will take effect in September 2026, while regulatory initiatives and funding programmes will be introduced in the same period. The Commission expects that supported projects could become operational before 2029, contributing to increased recycling capacity and a stronger battery value chain in Europe.

1.4.2.5 Industrial Accelerator Act

The proposed Industrial Accelerator Act (IAA) seeks to strengthen the competitiveness and resilience of European industry by accelerating investments in strategic sectors and supporting the deployment of low-carbon manufacturing technologies, which includes batteries and related components.

Although the IAA does not directly regulate battery recycling or circularity, several elements of the proposal may indirectly influence the development of battery value chains in Europe with more recycling and reuse [European Commission, 2026].

The proposal introduces measures to accelerate industrial investment by simplifying permitting procedures for manufacturing projects. Member states are required to establish single access points where project promoters can submit a single application covering all permits required for industrial manufacturing projects (Art. 4(1)). In addition, a single permit-granting procedure must be established and co-ordinated by a designated authority (Art. 5(1)–(2)). The competent authority must confirm within 45 days whether an application is complete (Art. 5(3)). These provisions are intended to reduce administrative bottlenecks and accelerate the deployment of manufacturing projects. In the battery sector, this may facilitate faster investment in battery cell manufacturing, materials processing and recycling facilities.

Also, the Act aims to create lead markets for European-made industrial products by leveraging the scale of the EU Single Market. The proposal seeks to boost demand for clean and "Made in EU" technologies in strategic sectors, including batteries and automotive components (explanatory memorandum, p. 5). Policy options considered in the impact assessment include introducing minimum "Made in EU" requirements in public procurement and support schemes. These measures are intended to strengthen domestic manufacturing ecosystems and reduce strategic dependencies on external suppliers. By encouraging local production and integrated supply chains, the Act may indirectly support the development of European recycling and secondary-materials industries that supply the battery sector.

The proposal also emphasises that the IAA complements existing EU legislation, including the Batteries Regulation, which sets the framework for environmental and circularity requirements for batteries placed on the EU market. In this context, the Batteries Regulation establishes sustainability standards, while the IAA focuses on industrial deployment and market creation for European manufacturing. The proposal further notes that the forthcoming Circular Economy Act will complement these measures by boosting recycling and improving access to secondary raw materials across industrial sectors.

In addition, the Act introduces provisions governing foreign direct investment in strategic sectors, which may influence the development of the European battery ecosystem. Under Article 17, the framework applies where a foreign investment exceeding €100 million takes place in a sector where more than 40% of global manufacturing capacity is held by the third country of which the investor is a national or undertaking (e.g. P. R. China for batteries and refining of major critical raw materials). Investments falling under this rule must be notified and approved before implementation.

Under Article 18, such investments may be approved only if they fulfil at least four out of six “value-added” conditions, including a mandatory employment requirement. These conditions include limits on foreign ownership (generally below 49%), co-operation with EU partners, licensing of relevant intellectual property to the EU entity, investment in research and development in the Union (at least 1% of annual revenue), employment of at least 50% union workers and efforts to source inputs from EU suppliers (around 30%). These provisions are intended to ensure that foreign investment contributes to the development of European industrial ecosystems and value chains.

In the battery sector, these measures are likely to encourage foreign manufacturers, in particular major battery producers from third countries, e.g. P.R. China, to establish production facilities in Europe or enter into joint ventures with European firms rather than relying primarily on exports to the EU market. By linking market access to local value creation, the framework promotes investment models that involve European partners, local research activities and integration into regional supply chains.

From a policy perspective, the proposed regime seeks to balance openness to foreign investment with safeguards designed to maximise industrial benefits for Europe. Foreign investors may benefit from continued access to the EU market and from faster permitting procedures for manufacturing projects. European companies may benefit from new partnership opportunities that combine foreign capital and technology with local industrial capabilities. For the EU as a whole, the framework aims to strengthen domestic battery manufacturing capacity, support technology transfer and contribute to more resilient European battery value chains.

1.4.3 Policy and innovation

Regulatory measures can have a major impact on innovation. Some historic examples include the Clean Air Act, driving innovation in catalytic converters for internal combustion engines [Gerard and Lave, 2005], and the Montreal Protocol, driving innovation in replacement of gases harmful to the ozone layer with less damaging alternatives [Dugoua, 2021].

Some possible impacts of these policies – and similar legislation in other countries such as P.R. China – on technology and innovation could be:

- the development of traceability technologies prompted by the battery passport,
- stronger focus on hydrometallurgy and other methods than on pyrometallurgy, driven by 80% lithium recovery target, as lithium is traditionally not easily recoverable with pyrometallurgical methods [Baum et al., 2022],
- also, the purity of the recycled materials, mandatorily present in batteries in the future, needs to be sufficient to allow their incorporation into new batteries.

Battery chemistry choices can help reduce critical mineral needs

Today‘s lithium-ion battery market is largely between lithium iron phosphate (LFP) and nickel-containing chemistries such as lithium nickel cobalt manganese oxide (NMC) [Lombardo et al., 2026a]. Both chemistries rely on critical minerals, but to different degrees. NMC batteries require nickel, cobalt and manganese in addition to lithium, while LFP batteries rely only on lithium. Both chemistries use graphite in their anodes.

Sodium-ion batteries are emerging as a new player in battery markets, offering opportunities to diversify battery chemistries and supply chains, and 2026 could prove to be a pivotal year for the technology‘s scaling efforts [Lombardo et al., 2026b].

Sodium-ion batteries are often highlighted as a way to reduce reliance on critical minerals and diversify battery supply chains. This claim is only partially accurate. While sodium-ion batteries do not require lithium and graphite, the chemistries closest to commercial deployment rely on other critical minerals, such as nickel and manganese, whose processing remains highly concentrated geographically [International Energy Agency, 2026; International Energy Agency, 2025c]. However, the mining of other minerals used in sodium-ion batteries is more geographically diversified than that of minerals used in lithium-ion batteries, offering a potential advantage in upstream supply chain resilience.

Highly optimised and low-cost lithium-ion batteries – particularly the latest LFP technologies – continue to offer advantages in energy density, supply chain maturity and cost. For sodium-ion batteries to compete on a more equal footing, either sustained high lithium prices or technological advances that significantly improve the energy density of sodium-ion batteries would be required. Project pipelines also indicate that lithium-ion technologies are set to remain dominant in the coming years, with the announced pipeline for sodium-ion batteries more than ten times smaller than that for lithium-ion batteries [International Energy Agency, 2026].

Despite these challenges, sodium-ion battery performance is already sufficient for specific applications, most notably in cold climates and in hybrid battery systems that pair lithium-ion and sodium-ion cells. In these applications, sodium-ion batteries can complement lithium-ion technologies to meet different customer needs, offering a source of battery and battery minerals diversification.

1.5 Scaling and innovation

Economies of scale and innovation are central to reducing costs and improving the efficiency of battery recycling, and are therefore critical enablers of a viable value chain with high levels of battery recycling. At present, many recycling processes face high unit costs due to fragmented waste streams, heterogeneous battery designs, limited automation and insufficient volumes of recyclable material to fully utilise capital-intensive infrastructure. The scale up of recycling capacity allows fixed costs associated with collection systems, safety infrastructure, processing plants and regulatory compliance to be spread over larger material throughputs, leading to lower per-unit costs and improved economic resilience. At the same time, standardisation and learning from experience will help optimise many aspects of operations. Innovation through R&D and learning-by-doing will still be required to address technical bottlenecks that scaling alone cannot solve, such as efficient lithium recovery, separation of complex black mass streams, management of fluorinated binders and electrolytes, and adaptation to evolving battery chemistries with lower cobalt content. These technology areas are featured in a dedicated section of the IEA report The State of Energy Innovation 2025 (International Energy Agency, 2025d).

The literature consistently highlights that advances in process integration, automation, materials separation and hydrometallurgical selectivity are needed to ensure that recycling can deliver battery-grade secondary materials at competitive cost and quality. Without sustained innovation alongside scale-up, recycling runs the risk of remaining dependent on favourable commodity prices or policy support rather than becoming a structurally competitive component of the battery value chain [Harper et al., 2019].

1.6 Technologies for battery circularity

1.6.1 Overview of the recycling chain

Recycling of lithium-ion batteries is most commonly implemented in industrial practice through a relatively simplified route in which end-of-life batteries are stabilised, mechanically shredded and then subjected directly to metallurgical processing to recover valuable metals. This approach reflects the need for robust, scalable systems that can safely handle diverse battery designs and chemistries with minimal manual intervention. However, shredding-plus-metallurgy is not ideal in terms of materials efficiency, selectivity and quality. More comprehensive recycling flowsheets include distinct stages such as controlled intake and stabilisation, targeted disassembly or mechanical pre-treatment, physical separation to concentrate electrode materials into black mass, and conditioning steps to remove binders and contaminants before metallurgical recovery. These additional steps improve liberation, reduce cross-contamination and enhance the effectiveness of downstream hydrometallurgical or pyrometallurgical processes, particularly for lithium recovery and for producing battery-grade outputs. Direct regeneration of electrode materials is also emerging as a complementary pathway for selected chemistries, but it similarly depends on well-controlled upstream processing. Hence, while industrial recycling often begins with shredding for pragmatic reasons, achieving high recovery rates, lower energy use and higher-value circular outputs requires a more granular and integrated sequence of processing steps [Sommerville et al., 2020; Baum et al., 2022]. This report aims to take a comprehensive look at these process steps.

1.6.2 Intake, storage and stabilisation

At intake, batteries may still retain charge and they may be damaged, creating hazards including thermal runaway. Stabilisation approaches include electrical discharge, solution discharge and in-process controls such as wet shredding or shredding under inert atmosphere. The literature emphasises that industrial practice often combines partial discharge with process controls rather than fully discharging every unit, due to design diversity and scalability constraints [Sommerville et al., 2020].

Technology spotlight

Battery circularity inventions

Battery circularity has attracted significant attention and witnessed substantial progress in recent years. This development was made possible by various factors, in particular political pathmaking, technical advances and the increasing economic efficiency in the processes involved.

The following pages cover technologies related to the main stages of the battery circularity value chain.

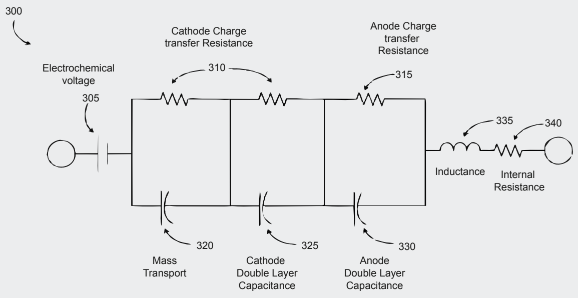
In addition, we present examples of patented inventions that illustrate specific technologies in battery circularity. Information on these inventions can be found, free of charge, via the EPO's Espacenet interface for patent information by clicking on the accompanying hyperlink.

Let's start with an invention that enables us to determine the state of health of a used battery.

EP4004570B1

Method and device for predicting state of health and remaining lifetime for used electric vehicle batteries

Understanding the health status and expected remaining lifetime of an electric vehicle (EV) battery is important before repurposing the battery for second-life applications. The patent presents a device for this purpose for connecting an unopened EV battery pack via an operable coupling to signal and power wiring. The device enables access to diagnostic information from the unopened EV battery. The device measures cell and/or module voltages and currents within the battery pack for several different depths of discharge. A self-learning algorithm implemented by the diagnostic device, which uses historical data and diagnostic information from the battery pack, determines the condition of the battery and provide recommended operational conditions for future use of the battery.



1.6.3 Disassembly and mechanical pre-treatment

While disassembly can improve stream purity, it is constrained at scale by labour intensity and design variability. Consequently, many systems rely on comminution, producing mixed fragments which then require separation. Comminution conditions, wet versus dry and air versus inert conditions influence both the safety and the degree of contamination introduced into the powder fractions [Sommerville et al., 2020].

1.6.4 Physical separation and formation of black mass

Black mass is the fine fraction enriched in cathode and anode active materials, typically containing cathode metal oxides, graphite, carbon black and binder residues, plus varying aluminium and copper fines. Mechanical separation uses techniques such as screening, magnetic separation, density separation, and, in some flowsheets, flotation or electrostatic separation. Separation efficiency is strongly affected by binder behaviour and by the extent of metal and polymer comminution into fines [Sommerville et al., 2020; Baum et al., 2022].

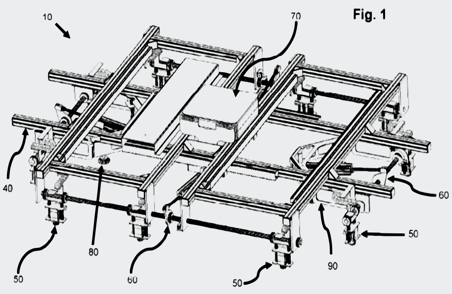
Example

Means for mechanical disassembly of EV battery elements.

EP4527567B1

Gripper for dismantling battery cover

Opening the battery cover of a battery of an electric vehicle can be time-consuming as well as hazardous, for example due to the risk of electrical shocks. This patent presents a system for automated dismantling of the housing cover of a battery unit, to be used by a robot. It has an interface for mounting the gripper, and a number of controllable push-off units that can separate the cover from the battery housing.



Example

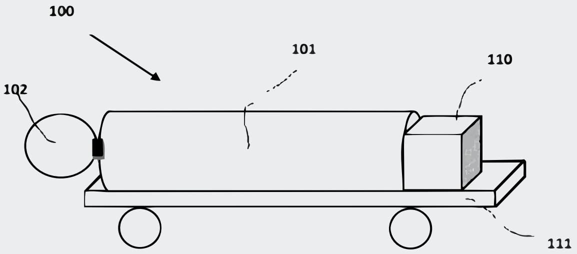
Controlled discharge of an EV battery, in particular batteries from accidented vehicles.

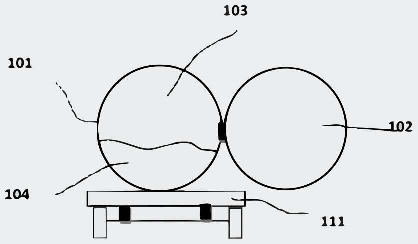
EP4233123B1

Mobile device for the treatment of defective accumulators and batteries, in particular for the treatment of defective accumulators used in land vehicles

The storage/disposal of electric vehicle batteries from vehicles that have been involved in an accident can be quite dangerous because these can spontaneously combust. They need to be able to be stabilised, preferably on-site. This patent exemplifies a solution by providing a truck with a tank into which the battery (or indeed the entire vehicle) can be placed, filled with water, and treated at temperatures of about 200°C under pressure.

Under these operating conditions, the separator between anode and cathode degrades, the battery shorts and loses its residual electrical charge, resulting in an exothermic reaction with a corresponding increase in temperature and pressure in the chamber (reactor). The active material (e.g., lithium) contained in the battery quickly hydrolyses and forms compounds which are no longer hazardous. The presence of H_2O, i.e. the moist environment, limits the temperature rise in the battery body, which could lead to decomposition of the plastic parts. The moist environment dampens temperature fluctuations and also binds the aggressive substances released from the battery. In this way, hazardous chemical reactions and the release of toxic gases can be prevented.





1.6.5 Black mass processing and conditioning

Black mass processing aims to remove or degrade binders such as polyvinylidene fluoride and to condition surfaces to enable downstream separation and leaching. While thermal treatment can decompose organics, it requires off-gas capture, particularly because fluorinated materials can generate hazardous gases. Solvent-based delamination and alkali treatments can detach powders and dissolve aluminium current collectors, but require solvent recovery and effluent treatment. Separation of graphite from cathode oxides is frequently attempted using flotation, with thermal or chemical conditioning used to restore selectivity when binder residues render both phases hydrophobic [Sommerville et al., 2020].

1.6.6 Metallurgical recovery routes

Hydrometallurgy typically uses acid leaching of black mass, followed by selective separation using solvent extraction, precipitation, ion exchange or electrowinning. Lithium is often recovered as carbonate or phosphate, while nickel, cobalt and manganese are recovered as salts suitable for precursor synthesis [Baum et al., 2022]. Independent reporting describes Fortum's Harjavalta facility as combining mechanical pre-treatment with hydrometallurgical refining of black mass at industrial scale [Chemical & Engineering News, 2023].

Pyrometallurgy uses high-temperature smelting to produce alloys rich in cobalt, nickel and copper, while lithium and aluminium largely report to slag phases. Pyrometallurgical routes are robust to feedstock variability but are energy-intensive and can require additional steps for lithium recovery [Baum et al., 2022]. A detailed third-party review discusses Umicore's Valéas™ process as a hybrid route combining pyrometallurgical treatment with subsequent refining, achieving high transition-metal recovery and secondary lithium recovery from streams such as flue dust and slag [Velázquez-Martínez et al., 2019].

1.6.7 Direct recycling and regeneration

Direct recycling aims to preserve the crystal structure of electrode materials. Techniques described in the literature include relithiation and thermal or chemical repair of spent cathode materials. These approaches can reduce energy use and reagent consumption but require well-sorted feedstocks and tight control of contamination, and they remain less mature than hydrometallurgical and pyrometallurgical routes in large-scale deployment [Baum et al., 2022]. Their application is simpler for almost pristine production scraps where electrodes can be easily removed, while it is significantly more challenging for end-of-life batteries.

Example

Pyrometallurgical process for the transformation of black mass

EP4347902B1

Energy-efficient pyrometallurgical process for treating Li-ion batteries

This patent presents a smelting process, for recovering of Ni and Co from batteries and other sources. The process comprises the steps of: a.) defining an oxidising level Ox and a battery-bearing metallurgical charge; b.) oxidising smelting of the metallurgical charge by injecting an O_2-bearing gas into the melt to reach the defined oxidising level Ox; and c.) reducing smelting of the obtained slag using a heat source and a reducing agent. The process is more energy-efficient than a single-step reducing smelting process and provides for a higher purity Ni-Co alloy using inexpensive slag conditioners such as limestone and silica.

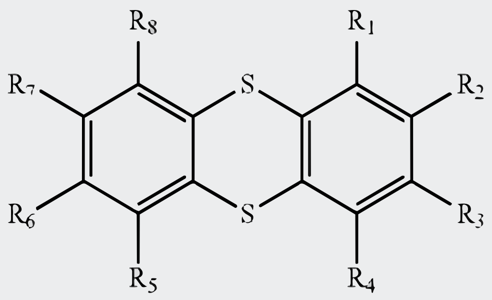
Example

Battery electrodes designed for more easy recycling

EP4333124B1

Novel organic electrodes and their use in electrochemical systems

In the patent, organic electrodes are disclosed which are free of metals and therefore much easier to recycle, but still provide good performance based on specific organic molecules as active material.



1.7 About this report

In this report, we focus on a selection of technologies that are driving development in the area of battery circularity or are promising candidates for future growth. Aimed at decision-makers in both the private and public sectors, the report is a unique source of information on these technologies and the technical problems they aim to solve.

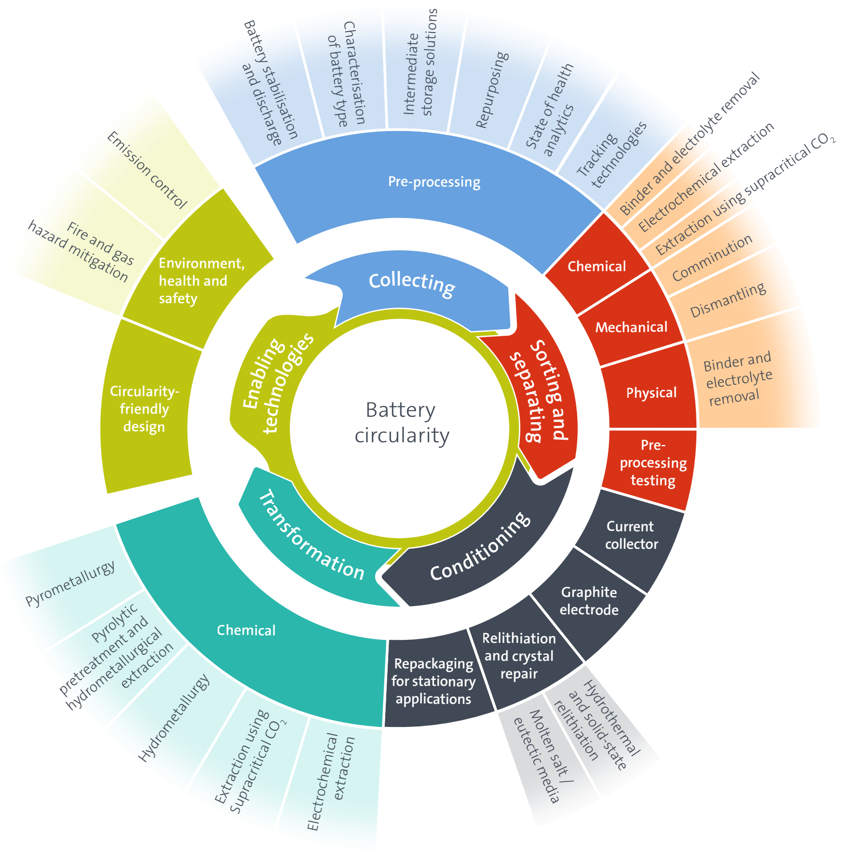
This report focuses on battery circularity, analysing developments in the various consecutive process steps in the value chain of battery recycling, covering traditional and more advanced processing steps, but also takes a side-step into the realm of refining of battery-critical minerals in order to give a complete picture of the feedstock cycle.

The report draws on the latest available patent information and the expertise of EPO examiners to provide a comprehensive analysis of the innovation trends driving technical progress related to battery circularity (see Figure 5). Patent information provides robust statistical evidence of technological progress. Unless otherwise stated, this insight report focuses on international patent families (IPFs).[3] IPFs are a standard indicator for inventions with international focus and confirmed potential. As patents are territorial rights, putting the picture for IPFs into the context of national patent families[4] can also be helpful to get a clearer view of local conditions, such as regulatory and legal constraints, and the role of specific countries as a location for research, manufacturing and other commercial activities in a given technical field.

Further explanations on methodology and sources of patent information are provided in the Annex.

Figure 5.

A cartography of battery circularity technologies used for this report



Source: EPO

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[3] International patent families are sets of applications for the same invention that consist of a published international patent application, a published patent application at a regional patent office, or published patent applications at two or more national patent offices.

[4] National patent families are sets of applications for the same invention that consist of published patent applications at a single national patent office.

The statistical results are complemented by in-depth qualitative perspectives from case studies and separate considerations on specific topics. Although global in scope, the report has a stronger focus on Europe (defined here as the 39 contracting states that are currently members of the EPO).

This report contributes to the UN Sustainable Development Goals, mainly to SDG 7 (Affordable and clean energy), SDG 9 (Industry, innovation, technology and infrastructure), SDG 11 (Sustainable cities and communities), SDG 12 (Responsible consumption and production) and SDG 13 (Climate action).

Australia–EU linkages in building battery value chains with more recycling and reuse

Australia is transitioning from a predominantly upstream supplier of critical minerals toward a strategic partner in circular, low-carbon battery value chains. At the same time, the European Union (EU) is embedding sustainability, circularity and traceability into conditions for battery market access. This creates a strong alignment between Australia's industrial upgrading agenda and Europe's regulatory-driven demand for circular battery systems.

1. Australia's value-chain position

Australia is a foundational supplier of battery inputs. It is the world's largest producer of lithium[5] and a major global producer of nickel, manganese, cobalt, copper and graphite used in battery cathodes and anodes. Historically, these materials have largely been exported as concentrates, capturing limited downstream value.

Current national strategies aim to shift Australia down the value chain into minerals refining, battery materials, recycling and other circularity technologies. The Critical Minerals Strategy (2023-2030), National Battery Strategy (2024) and Circular Economy Framework collectively emphasise processing capability, sustainability and value capture. Investments in research, skills and advanced manufacturing are strengthening Australia's capacity in battery recycling and materials recovery, positioning it as a potential provider of circulareconomy technologies and materials for European markets.

2. EU regulatory demand and the strategic fit with Australia

EU policy frameworks are reshaping global battery value chains by integrating lifecycle sustainability into market access. The EU Battery Regulation and the Critical Raw Materials Act contain traceability and sustainability provisions that support recycling and reuse.

For Australian firms, this translates into:

- more stable demand for responsibly sourced minerals and refined chemicals,
- commercial incentives to develop recycling and resourcerecovery technologies, and
- a clear rationale for protecting relevant intellectual property (IP) in European markets.

This strategic alignment has been formalised through co-operation instruments. In May 2024, Australia and the EU signed a Memorandum of Understanding on a Strategic Partnership on Sustainable Critical and Strategic Minerals, covering exploration, processing, refining, recycling and related standards. The partnership reflects a shared view that supplychain security and circulareconomy objectives are mutually reinforcing.

3. Emerging Australia–EU industrial linkages

Policy alignment is increasingly translating into concrete industrial, financial and IP linkages across battery value chains.

Financing and offtake arrangements are expanding, including deeper co-operation between the European Investment Bank and Australia to support criticalminerals and battery projects. European automotive and energy firms are securing Australian battery inputs through equity investments and longterm offtake agreements.

Australian firms are also embedding directly into European value chains. For example, Talga Group is developing an integrated graphite mine and anode refinery in Sweden, designated a Strategic Project under the EU Critical Raw Materials Act. In recycling, Primobius – a joint venture between Australia's Neometals and Germany's SMS Group – has deployed patented lithiumion battery recycling technology in Europe, including supplying IP for MercedesBenz's battery recycling plant in Germany.

[5] Geoscience Australia, Australia's Identified Mineral Resources (AIMR), preliminary tables, 2025.

Together, these examples illustrate complementary specialisation: Australia contributes critical minerals, midstream processing capability and circularity-focused IP, while Europe provides capital, scale and regulatory-driven demand.

4. Innovation, patents and EU linkages

EPO analysis shows that Australian applicants account for a small share of global patent filings in battery circularity and critical metal refinement technologies. These results are consistent with IP Australia research.[6] Australian-origin patent filings in these areas have a clear technical focus on the refinement and treatment of critical metals for batteries.

On average, Australian applicants account for ten international patent families per year in these areas of technology. In the refinement of critical metals for batteries, Australian applicants account for 8.9% of patent families published since 2000.

More recently, Australian applicants have become more engaged in battery circularity, with a marked increase in applications for materials recovery technologies. These technologies were the focus of less than a quarter of international patent families produced by Australian applicants between 2014 and 2021 in relation to battery circularity. The remaining three quarters focused on critical mineral refinement. After 2021, the picture has reversed: material recovery is the focus of more than half of patent families originating from Australia related to battery circularity in recent years.

Australian battery innovators frequently seek patent protection in Europe alongside other major jurisdictions with manufacturing ecosystems and regulatory demand. Australia's assignee profile is dominated by public research organisations and SMEs rather than large manufacturers, suggesting patents function primarily as:

- enablers of collaboration and licensing,
- signals to investors and strategic partners, and
- intellectual infrastructure linking upstream resources to downstream manufacturing and recycling.

This aligns with an innovation model centred on process IP, services and partnerships rather than vertically integrated cell production.

Summary

Australia is evolving from a rawmaterials exporter into a circular battery system partner for Europe. EU regulation, Australian industrial policy and emerging innovation capability are jointly shaping new valuechain linkages. The opportunity is a mutually reinforcing partnership: Australia contributes strengths in critical minerals, processing and circular innovation, while Europe pairs industrial scale and capital with strong innovation ecosystems and regulatory frameworks that drive sustainable demand.

This Box is provided by IP Australia

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[6] IP Australia, Patent Analytics: Batteries (2019), pp. 8–9. Also: IP Australia, Patent Analytics Report on Battery Technologies (2021)

2. Battery circularity patenting trends

This section outlines the results of patent analyses regarding recent developments related to battery circularity.

The following subsections present important trends in battery circularity from 2000 to 2023, the latest year for which sufficiently comprehensive data were available for the analyses.

2.1 Overarching trends

To approach battery circularity as a whole, a composite dataset was created based on patent applications for the technologies covered in this insight report (see Section 1.7 and the Annex). Using this composite dataset, filing trends regarding these technologies were assessed first, and the findings then compared to the situation across all fields of technology (this section). Next, specific technologies in battery circularity were looked at (see Section 2.2) along with the most active applicants (see Section 2.4).

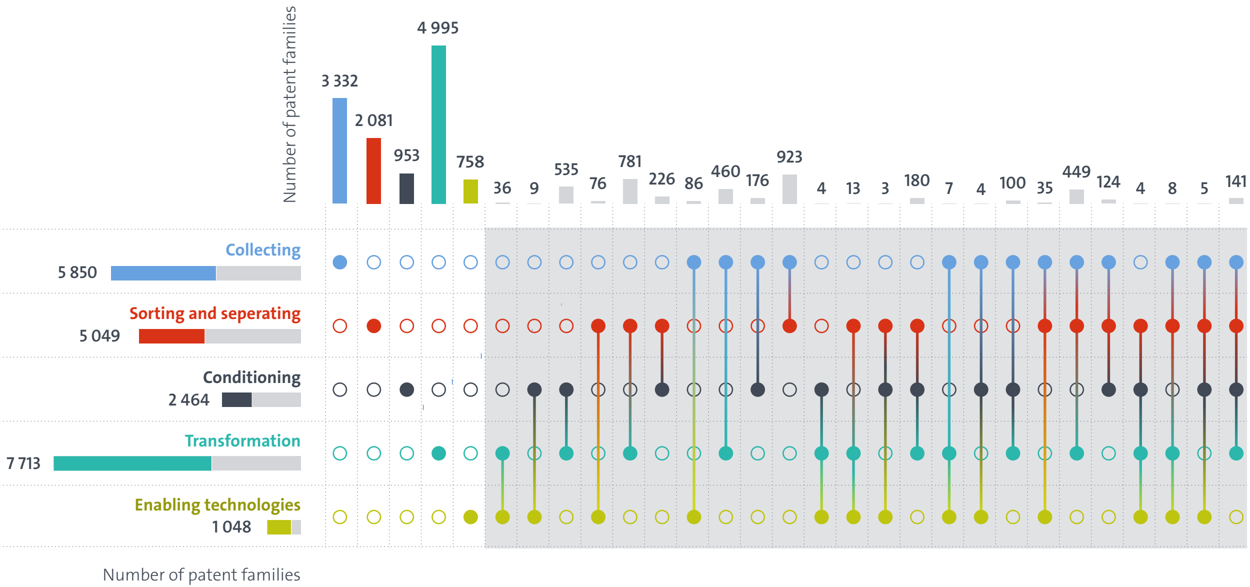
The suitability and quality of the composite dataset was confirmed by assessing samples for various search concepts. In addition, an analysis was conducted of the selectivity of the search concepts with regard to the main stages of the battery circularity value chain (collecting, sorting and separating, conditioning, and transformation) which were the main focus of this insight report.

Figure 6 shows the result of this assessment as a so-called UpSet plot to visualise the intersection of inventions in the field of battery circularity. It provides an overview of the extent to which inventions are related to the four main stages of the battery circularity value chain, apart from cross-sectional “enabling technologies”. The results suggest that the search concepts chosen to create the composite dataset address to a large extent one of the stages of the value chain only, and are sufficiently focused for breaking the area of battery circularity down into the four individual stages. Exceptions are the sorting and separating stage and conditioning stage, where less than 50% of inventions do not also address other stages.

Figure 6.

UpSet plot for search concepts related to the five stages of the battery circularity value chain per international patent families in the period 2000-2023

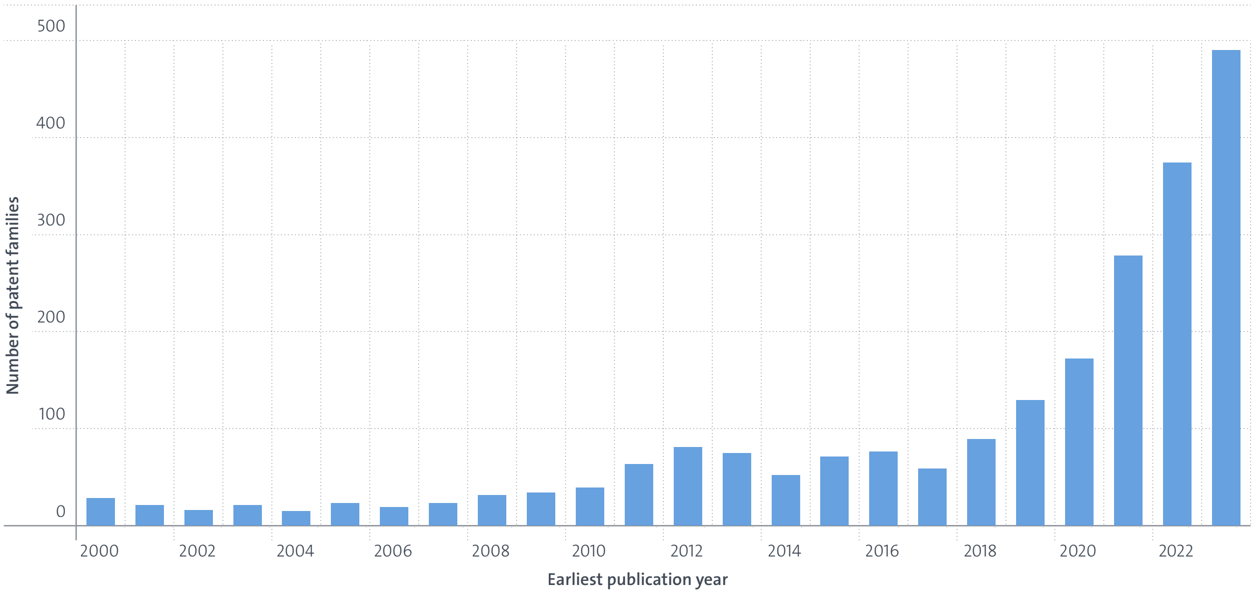
An invention in the field of battery circularity may address one or more of these stages of the battery circularity value chain. The dot matrix in the chart illustrates these possibilities. For example, the first column represents inventions that relate exclusively to collecting. The number of inventions corresponding to these possibilities are shown in the upper bar sub-chart. The left bar sub-chart provides an overview of the number of inventions. addressing the stages. For example, there are 3 332 inventions which cover only collecting technologies but none of the other stages of the value chain, and 5 850 inventions that address collecting technologies either exclusively or along with other stages of the value chain.



Source: EPO

Figure 7.

Number of international patent families in battery circularity, per earliest publication year



Source: EPO

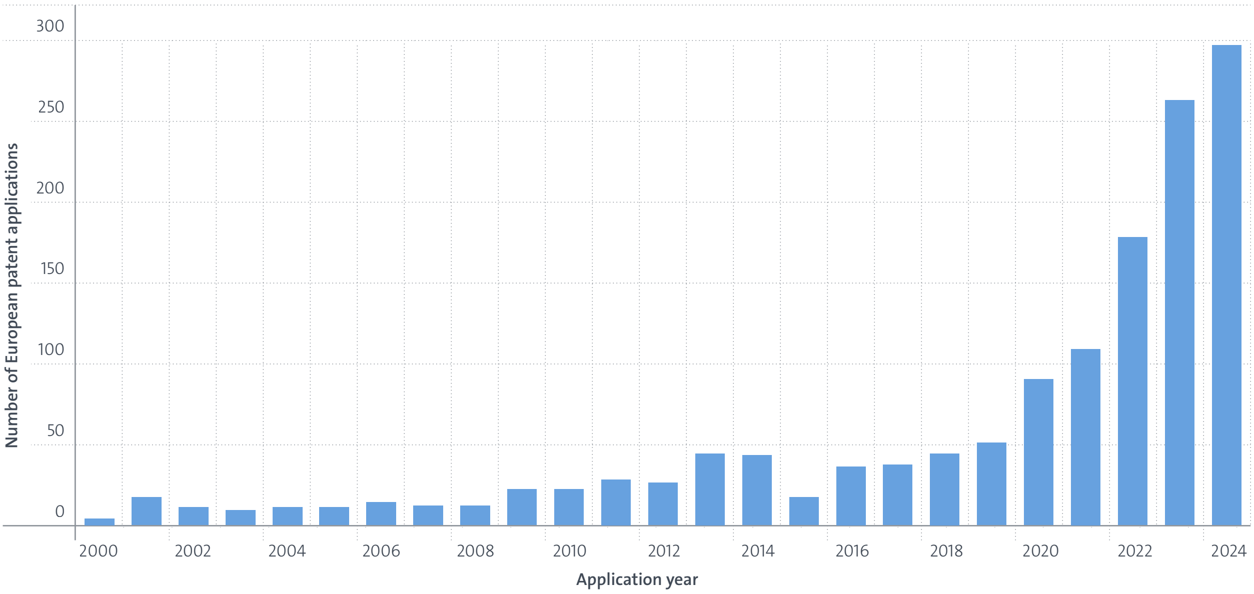
Figure 7 presents the overall patent filing trend in the area of battery circularity based on international patent families as a standard indicator for inventions with international focus and confirmed technological and economic potential. We identified more than 2 200 IPFs in the composite dataset for battery circularity in the period 2000-2023.

After a long period of moderate inventive activity in this field at the beginning of the reporting period, the number of IPFs started to increase considerably in the late 2000s before it plateaued somewhat until about 2014. After a modest decline until 2017, it turned into a period of very steep growth until the very recent past.

This development may indicate growing investment in battery recycling, reuse and associated technologies, and accelerating technological development and market relevance in this field.

Figure 8.

Number of European patent applications in battery circularity



Source: EPO

As explained above, only patent data up to 2023 were evaluated for this insight report. In order to obtain additional indications of the further development of invention figures in 2024, we evaluated the total number of European patent applications in the field of battery circularity. Figure 8 shows this development in the period 2010-2024. It goes along with the development of IPFs (see previous figure) in the reporting period, as patent families with European patent applications are, by definition, international patent families, and a large fraction of IPFs include European patent applications. Correspondingly, the further steep increase in the number of European patent applications in 2024 can be seen as a clear indication that the positive trend for IPFs has continued in 2024, as well.

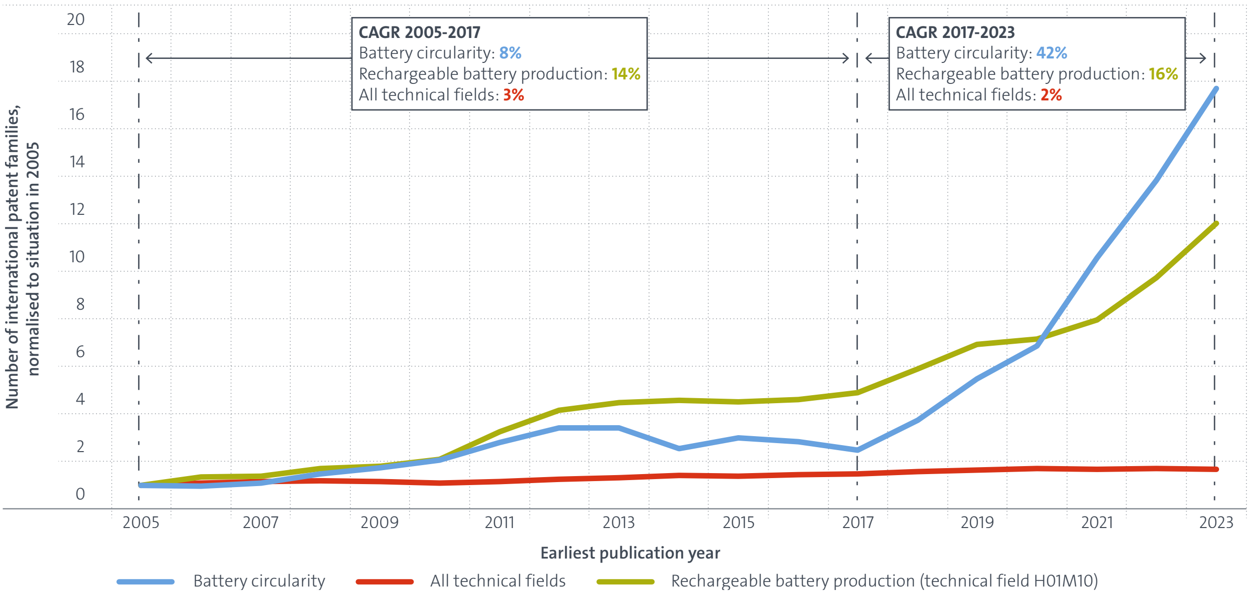
Inventive activity in battery circularity has accelerated markedly over the past two decades. Between 2005 and 2017, patenting activity in battery circularity technologies demonstrated a robust upward trajectory and grew significantly faster than the average across all technologies, although at a slower pace than innovations in battery technologies such as new materials or manufacturing processes (see Figure 9).

Inventive activity relating to battery circularity showed an inflection point for IPFs in 2017. Prior to this, the field has the appearance of a nascent technology, with IPFs mostly below 100 per year. As mentioned before, filings accelerated sharply as of 2017, with IPFs rising from the sub 100 base to nearly 500 by 2023. The total volume of inventions (including both national and international families) was more than 2 400 in 2023.

Between 2017 and 2023, international patent families showed a compound annual growth rate of 42% (see Figure 9). This growth rate surpassed that of technologies related to rechargeable batteries in general and their manufacture, and it stands far above the global baseline of around 2% over the same period – reflecting rapidly growing interest in this area. These observations suggest that battery circularity and its supporting technologies have evolved beyond a purely nascent phase towards a maturing innovation landscape.

Figure 9.

Compound annual growth rates in battery circularity, for international patent families



Source: EPO

As explained in Section 1.7, we additionally put the picture for IPFs into the context of national patent families to get a clearer view of local conditions and potential geographical hotspots, and of the business strategies of the applicants in the field.

In the composite dataset, national patent families were not evenly published by all patent authorities, but showed a strong tendency towards a small number of patent authorities representing specific application procedures. The share of these patent application routes can be taken as an indication of the business orientation of the patent applicants in the field. This share may also be an expression of the patent applicants' assessment of where their main competitors are located and/or where research and development in the field takes place.[7]

Figure 10 shows the number patent families in battery circularity per earliest publication year (top), and the share of IPFs and national patent families (bottom). A distinction is made between IPFs having an international focus on the one hand, mainly building on international patent applications and European patent applications, and national patent families on the other hand.

This distinction helped to indicate which countries play an important role as location of research and commercialisation in the field of battery circularity. It also highlights how the distribution between territories and between national and international protection has shifted over time, reflecting evolving innovation ecosystems and market priorities (see Figure 11).

The results suggest that Asia played an increasingly important role in the field until 2018, with Chinese national patent families leading by far in the past two decades, whereas the role of Japanese national patent families decreased substantially (see Figure 10). In the same period, the share of international patent families declined from about 50% to approximately 10% in 2018. A similar decline, but significantly less in scope, was observed for US national patent families. Other legislations only played a minor role. Since 2018, the share attributed to these Asian territories combined has decreased slightly, due mainly to a decline in the share of Chinese national patent families. Conversely, the share of international patent families has grown modestly again to about 20%.

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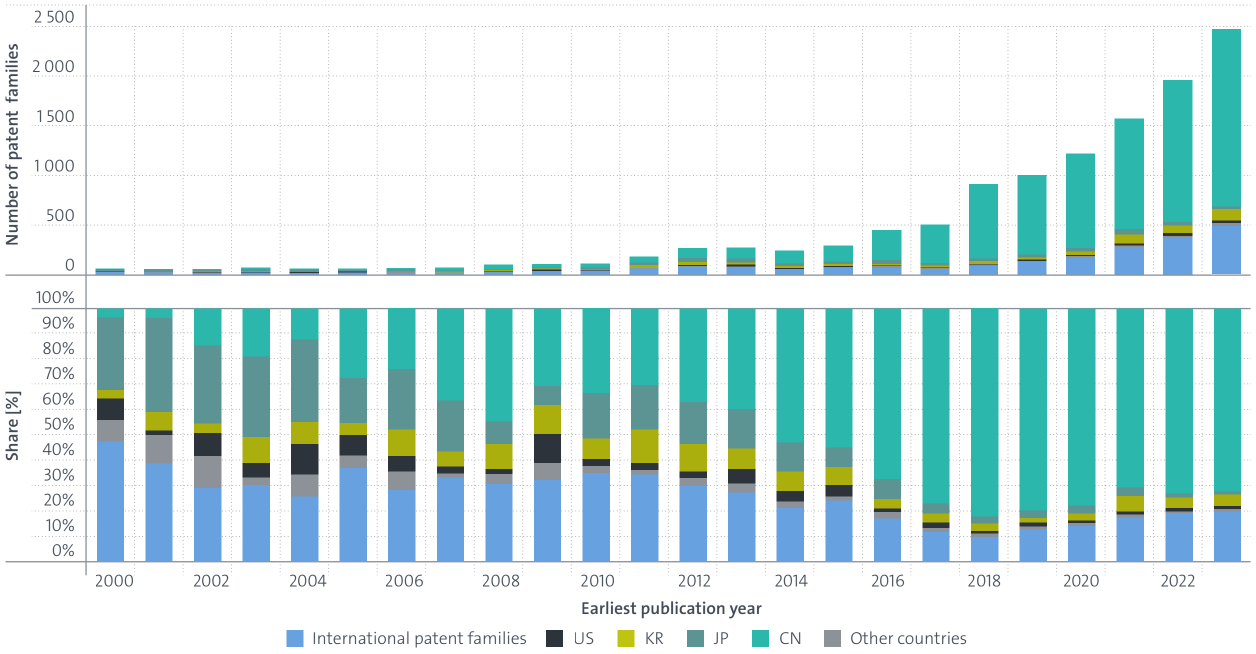
[7] The primary reason why patent applicants seek protection in specific countries is to secure the commercial use of their invention in target markets. They also frequently follow other strategic considerations, such as proximity to competitors' operations or key supply chain partners. Additionally, they often target countries with strong IP frameworks where they can enforce their IP rights.

Figure 10.

International and national patent families in battery circularity, per earliest publication year

The top sub-chart shows the number of patent families with a breakdown according to international patent families (blue) and the territories of the national patent families (other colours).

In the bottom sub-chart, the data are normalised to 100% of the patent families per earliest publication year. With that, the segments within the bar for each year represent the share of IPFs or a territory of the total number of patent families for that year.



Source: EPO

The modest decline observed in the share of Asian national patent families since 2017 may be related to a lower momentum in inventive activity by applicants from these countries or to a shift in their protection strategy towards international patent families.

To test these hypotheses, we assessed the share of IPFs with EP and PCT family members[8] by applicants from the said three Asian countries, EPC members states and the United States. The results show a growing contribution of applicants from the Asian countries to international patent families in battery circularity as of 2017 (see Figure 12).

Correspondingly, the reduction in national patent families for China, South Korea and Japan in favour of international patent families may be explained by a changing focus among applicants from these countries towards supranational protection (routes). To this end, we additionally took a closer look at the procedural aspects of international patent applications in the dataset. These applications are a common part of international patent families, and are usually based on so-called earlier national patent applications. Experience suggests that these earlier applications are predominantly filed by applicants from the country in question. This indicator of the origin of the applicants was particularly relevant in the present case, as the country of origin for national patent applications is often only very incompletely covered in patent statistical databases. Our results suggest that the observed gradual shift from Chinese national to international protection is due to increasing reorientation of applicants located in China.

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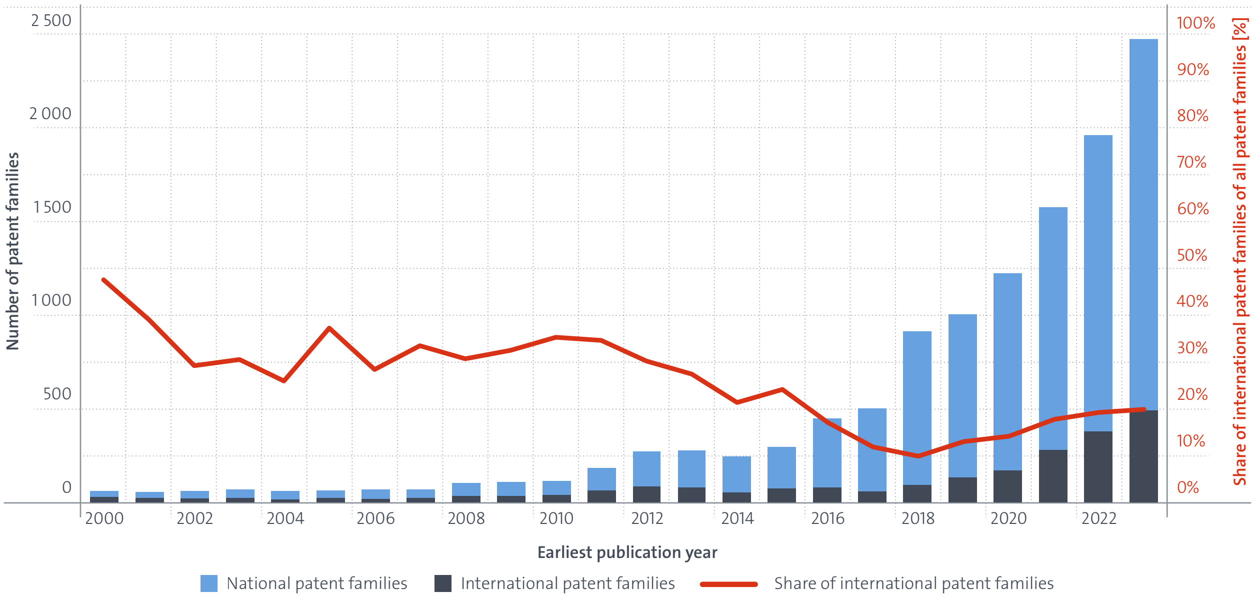
[8] The restriction to international patent families with EP and/or PCT patent family members was applied to ensure comprehensive coverage of applicant country information.

Figure 11.

Patent families in battery circularity per earliest publication year

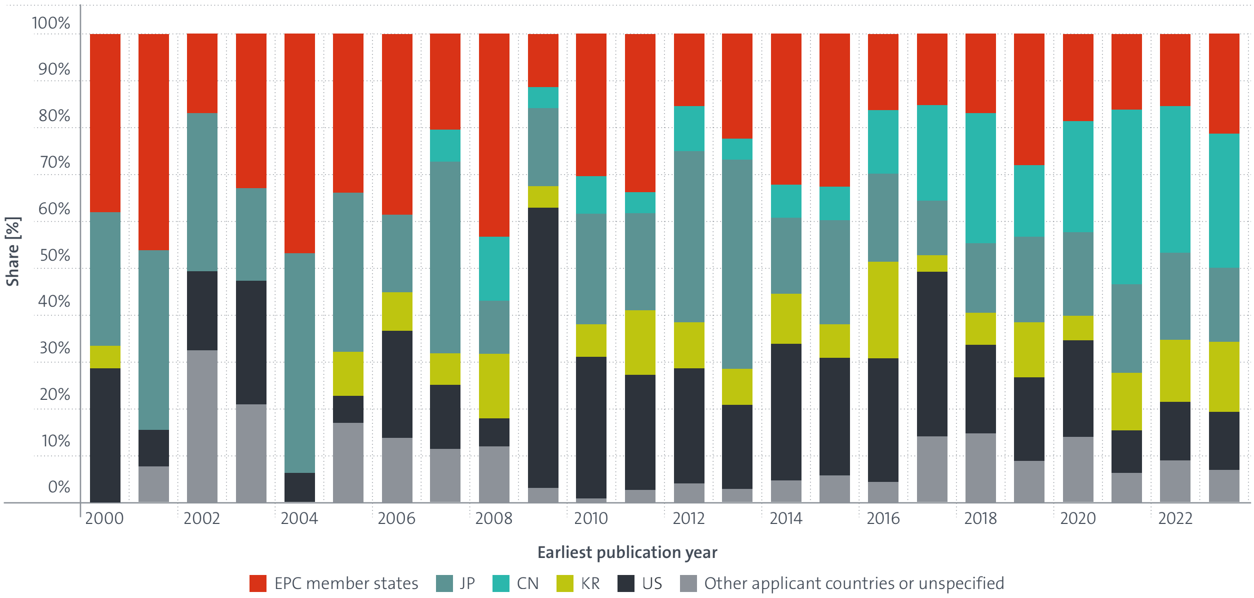
This chart combines relevant information from the two sub-charts in Figure 10 on the development of international (dark grey) and national patent families (blue). The share of IPFs of all patent families is shown in red (right scale).



Source: EPO

Figure 12.

Share in international patent families with EP and PCT application members in the field of battery circularity, per earliest publication year and selected applicant countries



Source: EPO

2.2 Breakdown according to the stages of the battery circularity value chain

A closer analysis of the technologies covered in this insight report provided further insights into the drivers of the overall growth in patenting observed in the field of battery circularity.

Table 1 shows the five most patented technologies in battery circularity at the beginning of each decade in the period 2000-2023. It reveals that technologies utilised in the collecting and (chemical) transformation stage of the battery circularity value chain have led the ranking in all decades of the reporting period. While technologies related to hydrometallurgy and to stabilisation and discharge had been consistently leading, the recent past has seen an upswing in comminution, which belongs within the sorting and separating stage. The top five technologies continuously account for 80 percent or more of all international patent families regarding battery circularity technologies, with a modest decrease suggesting a shift towards a broader technology base.

Most of the technologies we examined in the area of battery circularity show a significant increase in the number of inventions. Table 2 breaks the inventive activities down by date range. Among the technologies with at least five IPFs at the beginning of the reporting period, the following showed the highest growth rates[9] during this period: hydrometallurgy (more than fifteen-fold), comminution (more than fourteen-fold) and isolation and immobilisation (more than twelve-fold).

Table 1.

Technology hotspots in battery circularity at the beginning of each decade in the reporting period 2000-2023 (IPF-based, cumulative share of IPFs, based on concept level 4 of the cartography (see Table 4)

	2000-2004
Stabilisation and discharge	48
Hydrometallurgy	40
Pyrometallurgy	17
Comminution	16
Characterisation of battery type	10
Top 5	**93**
Share in IPFs	**92%**

	2010-2014
Stabilisation and discharge	127
Hydrometallurgy	114
Pyrometallurgy	42
Comminution	26
Pyrolytic pre-treatment and hydrometallurgical extraction	18
Top 5	**255**
Share in IPFs	**82%**

	2020-2023
Hydrometallurgy	661
Stabilisation and discharge	330
Comminution	251
Pyrometallurgy	208
Pyrolytic pre-treatment and hydrometallurgical extraction	83
Top 5	**1 086**
Share in IPFs	**83%**

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[9] Calculated as the number of IPFs in a specific date ranges compared to the corresponding value in the period 2000-2004

Table 2.

Development of specific technologies in battery circularity (international patent families, 2000-2023)

				Date range					
				2000-2004	**2005-2009**	**2010-2014**	**2015-2019**	**2020-2023**	**Total**
Collecting	Pre-processing	Battery stabilisation and discharge	Controlled discharge	1	5	21	21	95	143
			Electrolyte venting controls	20	11	31	45	90	197
			Isolation and immobilisation	7	20	43	70	96	236
			Remote handling	1	2	2	9	12	26
			Use of non-sparking tools		1			2	3
		Characterisation of battery type		10	6	13	23	56	108
		Intermediate storage solutions			2	4	6	16	28
		Repurposing		1	1	1	2	18	23
		State of health analytics			1	10	20	69	100
		Tracking technologies		7	5	16	17	66	111
Sorting and separating	Chemical	Binder and electrolyte removal		4	3	4	12	31	54
		Electrochemical extraction		2			4	8	14
		Extraction using supercritical CO_2		1	1	2	1	12	17
	Mechanical	Comminution		16	15	26	58	251	366
		Dismantling		1	2	8	8	42	61
	Physical	Binder and electrolyte removal		6	2	8	19	72	107
	Pre-processing testing			2				6	8
Conditioning	Cell repair and replacement			2	1	1	3	2	9
	Current collector			3	3	10	16	105	137
	Graphite electrode			2		5	9	83	99
	Relithiation and crystal repair			5	2	13	32	85	137
		Hydrothermal and solid state relithiation		1				2	3
		Molten salt/eutectic media				1	2	1	4
	Repackaging for stationary applications			1	5	22	16	32	76
Transformation	Chemical	Electrochemical extraction		7	12	17	38	76	150
		Extraction using supercritical CO_2		1	2	2	3	6	14
		Hydrometallurgy		40	45	114	163	661	1 023
		Pyrometallurgy		17	18	42	69	208	354
		Pyrometallurgy pre-treatment followed by hydrometallurgical extraction		6	5	18	42	83	154
Enabling technologies	Circularity-friendly design			1	4	11	10	37	63
	Environment, health and safety	Emission control		2	1	3	3	8	17
		Fire and gas hazard mitigation			2	4	3	16	25
			Grand total	**89**	**119**	**292**	**419**	**1 312**	**2 231**

2.3 Regional trends

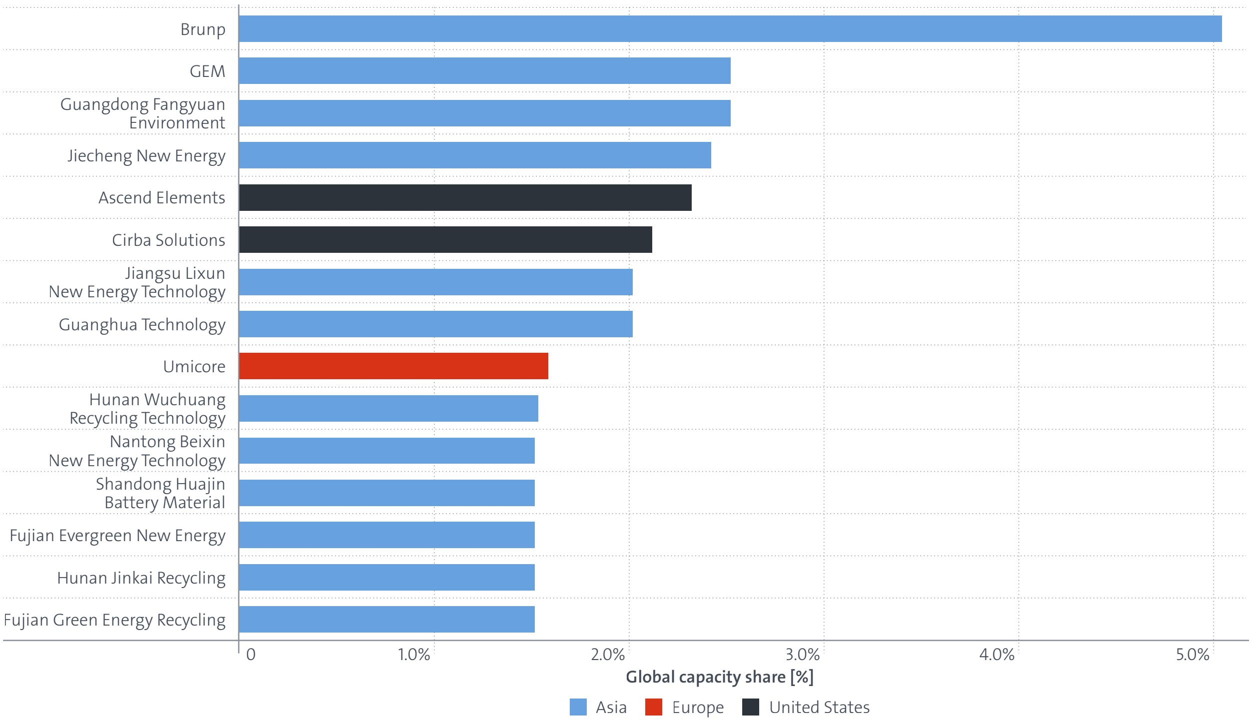
Asian applicants made the largest contribution to the technologies covered in this technology insight report. Europe and North America are the other two main regions from which new technologies originate.

Battery recycling capacity this decade, like all mid- and downstream stages of the battery supply chain, is dominated by China for both pre-treatment and material recovery. The largest recycler, Brunp, is expected to be responsible for about 5% of global recycling capacity in 2030. Analysis of announced projects indicate that both capacities are set to increase significantly, reaching around 10 million tonnes (Mt) of cell-equivalent capacity by 2030. Some diversification will occur with North America holding 10% of pre-processing and material recovery capacity by 2030, while Europe will hold around half of this, with 5% of each. Korea is also set to play a major role in material recovery capacity going forward, reaching almost 600 kt in 2030, amounting to a global share of around 5%. Nevertheless, China is poised to retain over 80% of global pre-treatment share and 75% of global material recovery capacity in 2030.

Looking at the top battery recycling companies' capacity announcements also shows some levels of diversification beginning in 2023 when all of the top 20 companies were Chinese. By 2030, US companies Ascend Elements and Cirba Solutions stand to become the fifth- and sixth-largest pre-treatment companies and the sixth- and seventh-largest companies for material recovery. Umicore is Europe's largest recycler, with a 2% market share for both the pre-treatment and metal recovery stages. Revolt, the battery recycling subsidiary of Northvolt, may still become a major player, with 2% of the material recovery market if – also in view of Northvolt's bankruptcy and subsequent take-over by Lyten – its capacity announcements are actually achieved. Nevertheless, both markets appear set to remain dominated by China, with CATL subsidiary Brunp – today's market leader – having the largest market share of both stages, with around 5% of the pre-treatment and recovery markets: double the share of the second-largest company.

Figure 13.

Top global battery pre-treatment recycling companies by capacity based on announced projects, 2030



Source: International Energy Agency, 2025b; Figure 2.10

This geographical concentration is also reflected in our patent analyses. The analyses, however, also show that non-Asian applicants play an important role in inventions with an international focus and high economic potential. Figure 14 presents a technological and geographical breakdown of international patent families related to battery circularity. Applicants from Asia (mainly China, South Korea and Japan), Europe and the United States accounted for the largest share of inventive activity in battery circularity. This figure provides an overview of the number of international patent families for the stages of the battery circularity value chain per earliest publication year, with a breakdown according to main applicant countries and regions (top). The bottom sub-plot presents the share of the applicant countries and regions per date range and stage of the battery circularity value chain.

While applicant countries other than the aforementioned nations played only a minor role in all periods and stages, the share of the main applicant countries changed considerably over the course of the reporting period. The contribution of applicants from the noted Asian countries grew considerably in all stages of the battery circularity value chain except collecting, with China-based applicants playing an increasingly prominent role. This increase in share was mostly at the expense of applicants from the United States and EPC member states. Applicants from EPC member states largely kept their role in the collecting and conditioning stages.

However, it should be noted that a decline in the relative share of inventive activity does not necessarily correspond to an absolute decline in inventive activity. For example, the number of inventions by European applicants in the field of transformation has risen sharply in recent years, and their relative share has fallen only because Asian applicants have shown even greater inventive activity in that same period.

In addition to the geographical distribution of applicants described above, we examined the origin of the inventors. For most countries, the share of all international patent families based on the applicant's country of residence is essentially identical to that based on the inventor's country of residence. This can be interpreted to mean that the inventive activity took place in the applicant's country, and not at remote subsidiaries or research centres.

Figure 14.

Applicant origin in battery circularity, for international patent families with EP and/or PCT patent family members

The analysis was restricted to international patent families with at least one EP and/or WO patent family member to provide comprehensive coverage of applicant country information in the data. Fractional counting was used with respect to applicant countries and sub-technologies.

Source: EPO

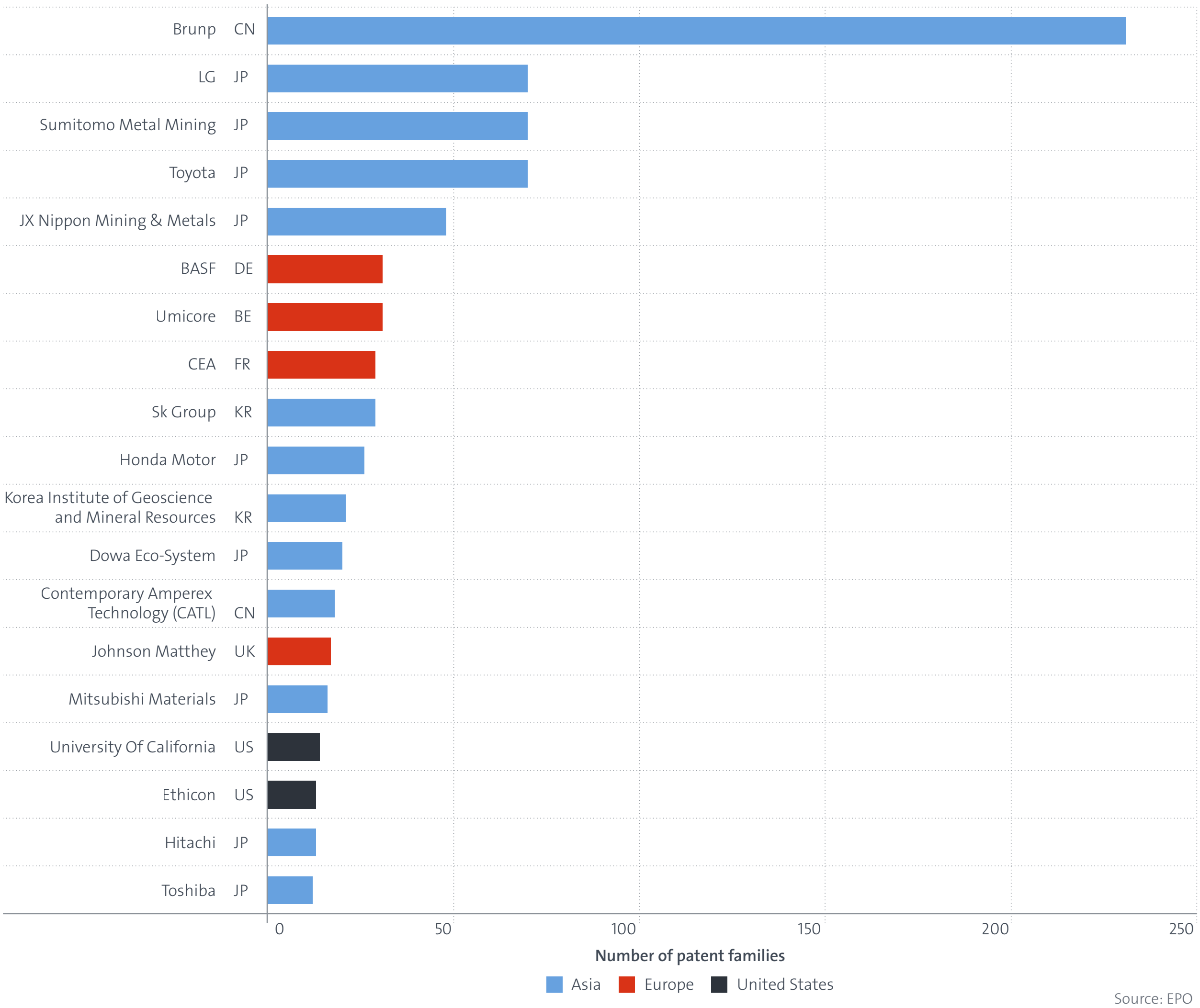
2.4 Most active applicants

Figure 15 presents the most active patent applicants in the field of battery circularity with respect to international patent families. The leading applicants, including major industrial players, show substantial differences in filing volume, with the top few applicants significantly outpacing the rest. Among the most active applicants, 69% are located in Asia, 21% in Europe and 11% in the United States. Most of these applicants are companies. The only three exceptions are the French public government-funded research organisation CEA (Commissariat à l'énergie atomique et aux énergies alternatives), the Korea Institute of Geoscience and Mineral Resources (KIGAM) and the University of California.

The majority of these applicants demonstrated inventive activity throughout the entire period, as shown in Figure 16. For each applicant, the horizontal bar representing the number of IPFs is subdivided into time-range segments showing when these inventions were first made publicly available. This highlights proprietary inventive and innovation patterns. The breakdown can help identify technological newcomers, rapidly growing innovators and established long-term contributors in battery circularity. For example, Toyota shows sustained filing activity across multiple decades, indicating long-term engagement whereas Brunp, as a subsidiary of Chinese battery manufacturer CATL, is a newer entrant with substantial R&D activities and already topping the list by a wide margin by having shown virtually all of its inventive activity to date in the last sub-period under review (2020-2023).

Figure 15.

Most active applicants in battery circularity, for international patent families

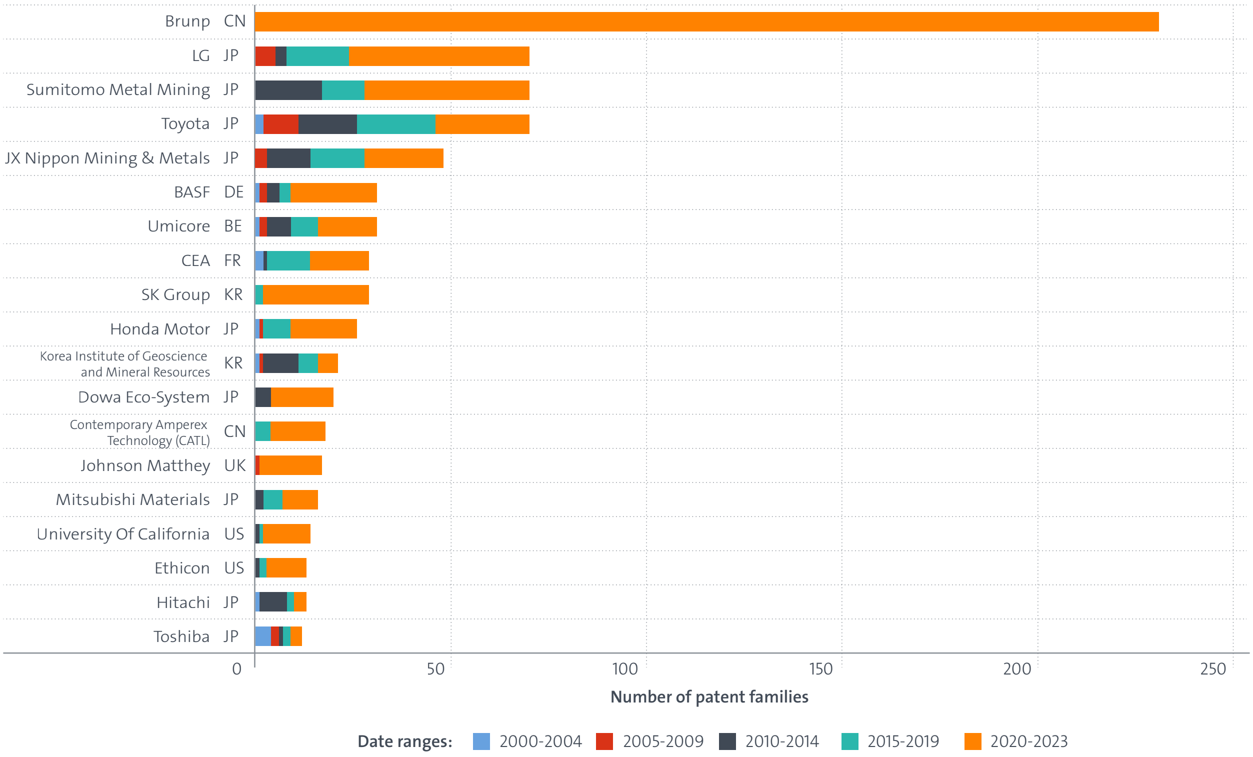


Source: EPO

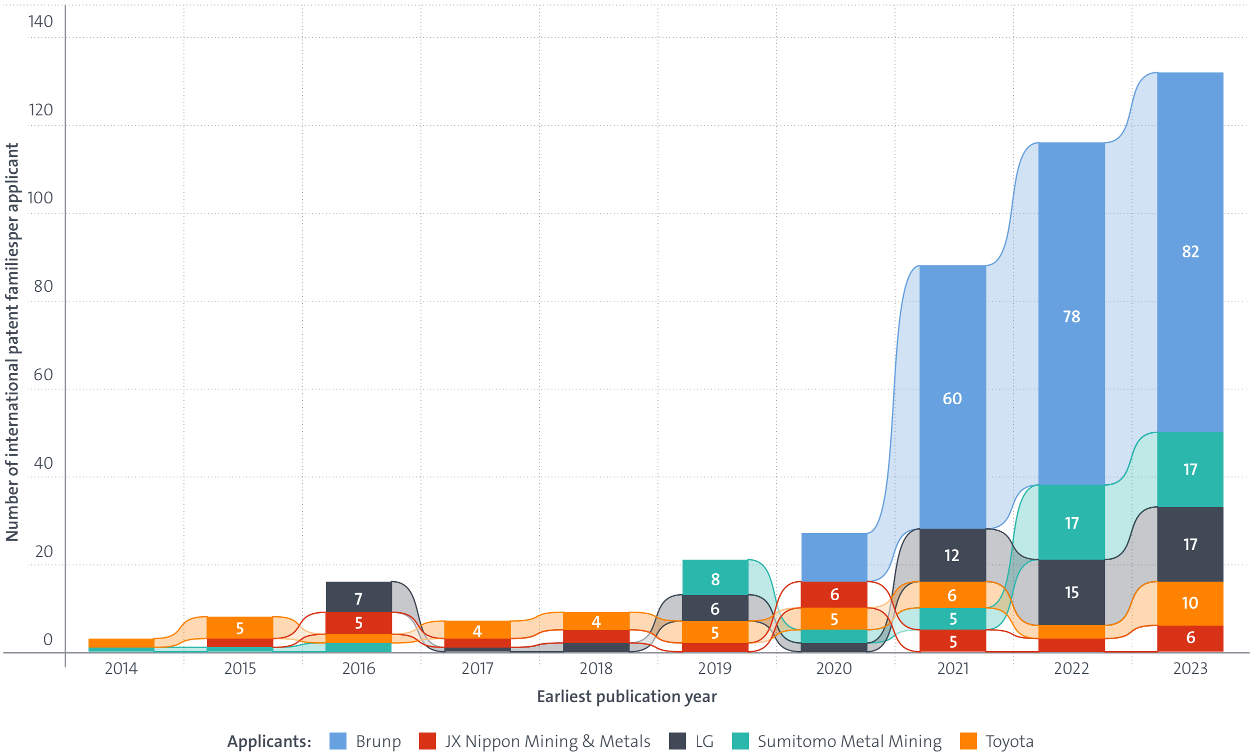
Figure 16.

Inventive activity of the most active applicants in battery circularity, per date range and international patent family

Date ranges



International patent families by applicant (top 5)



Source: EPO

Apart from their various different inventive activities in the reporting period, the most active applicants also show substantial differences regarding their technology profile. In Figure 17, we present a technology-profile matrix for the most active applicants in the field, based on their number of international patent families regarding the technologies covered in this insight report. In the technology-profile matrix, the rows list the most active applicants, while the columns represent the technologies at level 2 and level 3 of the cartography used for this insight report. The bubble sizes indicate how many IPFs each applicant has in each sub-technology.

The matrix reveals where each applicant is technologically specialised. Some companies have broad activity across multiple sub-areas, while others show strong focus on specific technical domains.

Figure 17.

Technology profile of the most active applicants in battery circularity, for international patent families

		Collecting	Sorting and separating				Conditioning					Trans-formation	Enabling technologies	
		Pre-processing	Chemical	Mechanical	Physical	Pre-processing testing	Cell repair and replacement	Current collector	Graphite electrode	Relithiation and crystal repair	Repackaging for stationary applications	Chemical	Circularity-friendly design	Environment, health and safety
Brunp	CN	55	4	76	11	2		24	19	1	1	166	2	2
LG	JP	25	6	6	6	1		21		32	3	24	2	4
Sumitomo Metal Mining	JP	7	1	7	1				1	3		66		
Toyota	JP	40	2	10	1			4	1	9	13	16	2	
JX Nippon Mining & Metals	JP	12	1	10	1			5				43	1	
BASF	DE	5	3	5	4				3	4		28		
Umicore	BE	1			1							30		1
CEA	FR	14	4	7	5			3		2		16		
SK Group	KR	6		6	1			4		15		20		
Honda Motor	JP	23		1	1					1		4		
Korea Institute of Geoscience and Mineral Resources	JP	5		4						1		20		
Dowa Eco-System	CN	1		15				10		1		16		
CATL	UK											17		
Johnson Matthey	KR	7		2				3	2	3		4	3	1
Mitsubishi Materials	JP	5	4	9	4			2	3	1		13		
University of California	US	5	1		2				3		1	9		
Ethicon	US	13												
Hitachi	JP	8		1								5		
Toshiba	JP	8		1			1	1		2	4	1		

Source: EPO

The variation in technology profiles shows that the most active applicants are generally not competing identically. Some cover all stages of the workflow or specialise in narrow but critical recycling steps, whereas others are emerging players with early activity in one or two areas. This diversity implies a multi-layered innovation landscape where companies may contribute differently across the value chain.

A small group of large industrial actors, most notably Brunp, show broad and dense activity across many technologies. This indicates a high degree of vertical integration spanning multiple steps of the battery circularity chain, and the capacity to innovate simultaneously in feedstock conversion, mechanical/chemical separation, conditioning, and enabling technologies.

As shown in the previous figure, many but not all of the most active applicants are broadly positioned across the various stages of the value chain. In addition, some of them have significantly different profiles in terms of their temporal coverage of the sub-areas. In particular, the most active Chinese applicants can be considered newcomers, whereas most other Asian and European applicants look back on decades of inventive activity regarding the battery circularity chain.

Against this backdrop, the breakdown according to the stages of the value chain provides further interesting results (see Figure 18). In the collecting stage in particular, the majority of the most active applicants have been engaged in inventive activity for a long time. This is especially true of Japanese and South Korean applicants. In contrast, the sorting and separating sub-sector and conditioning sub-sector are new territories for many of the active applicants.

Figure 18.

Breakdown of inventive activity of the most active applicants in battery circularity according to the stages of the value chain and date ranges, for international patent families

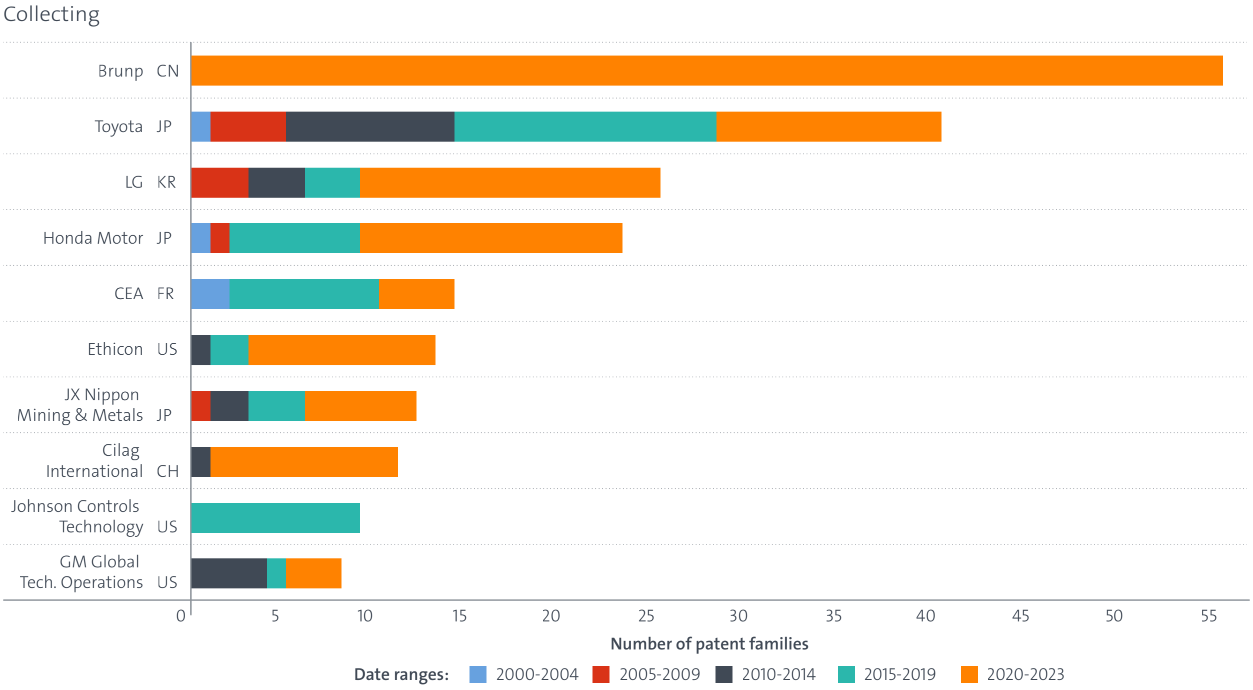
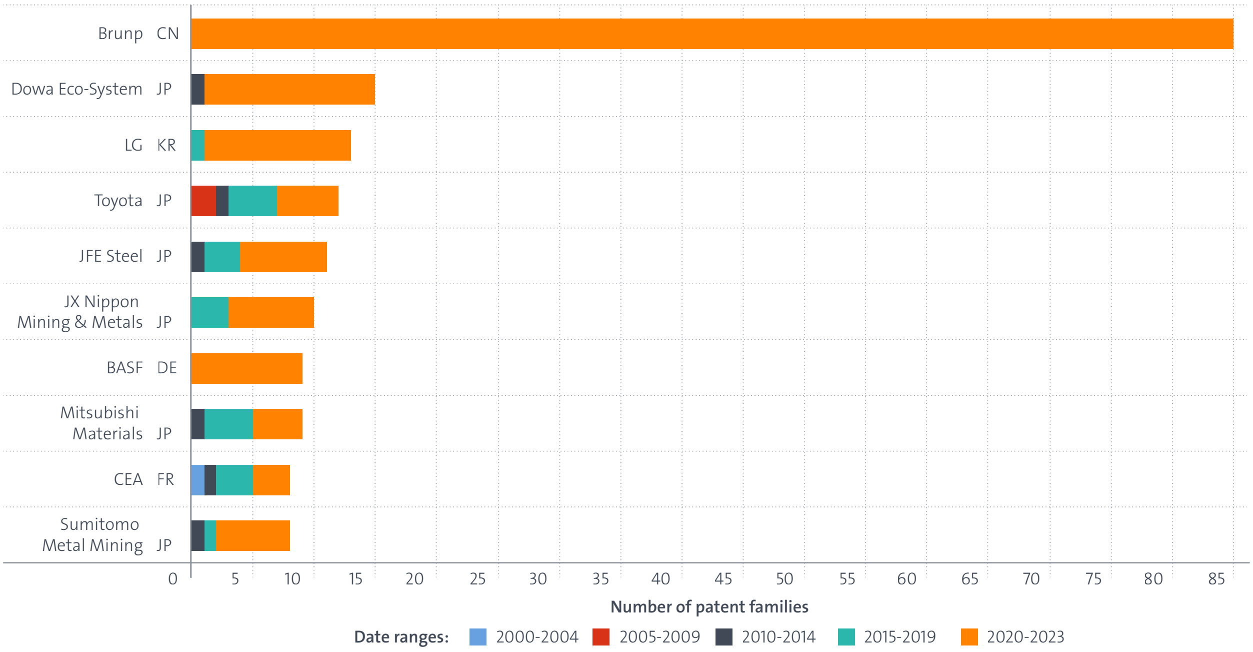


Figure 18. cont

Sorting and separating



Conditioning

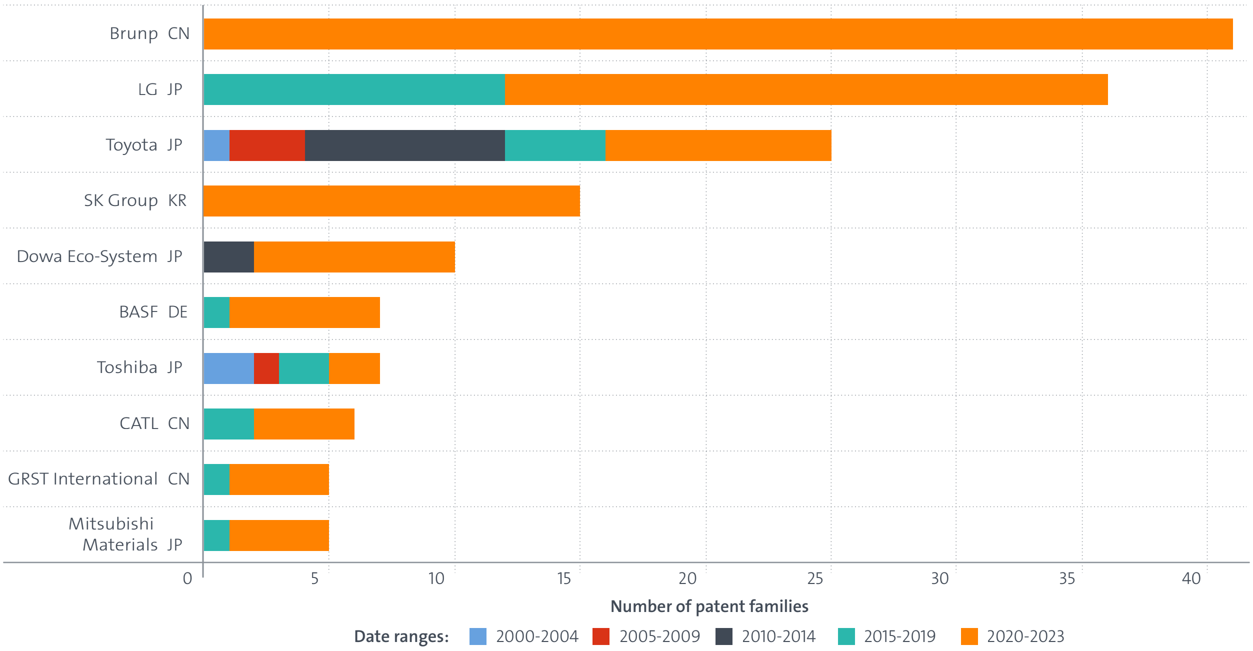
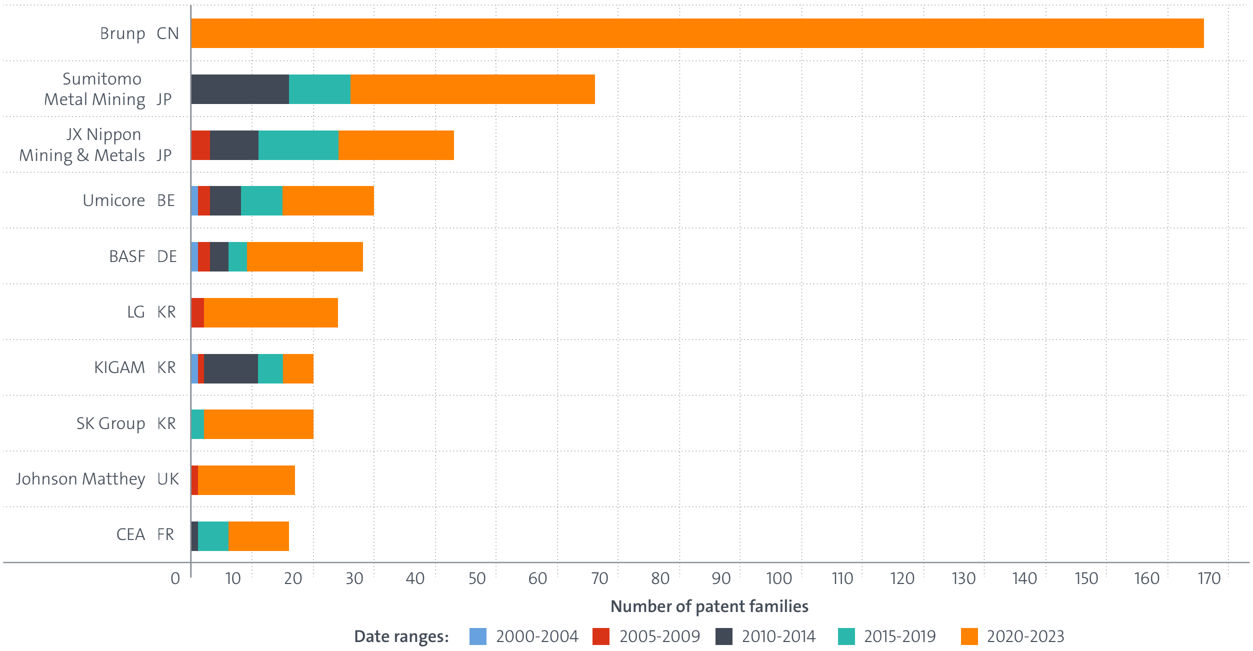


Figure 18. cont

Transformation



Source: EPO

European patent applicants make an important contribution to the development of this technical field, accounting for around 20 percent of international patent families in the area of battery circularity in the reporting period. Among the technologies for battery circularity, applicants from EPC member states demonstrate a high level of inventive activity in technologies related to remote handling (accounting for 34% of all international patent families in this field), as well as in isolation and immobilisation (30%) and in hydrometallurgical extraction following pyrolytic pre-treatment (26%) (see Figure 19).

A look at European applicants among the most active applicants confirms the observations for the most active applicants in general, and provides further interesting information. Figure 20 presents a ranking of the most active patent applicants from EPC member states in the field of battery circularity in terms of the number of international patent families.

Corporate European applicants tend to dominate, but (predominantly French) research organisations also appear in the ranking, demonstrating the role of research-driven innovation in the field, with CEA ranking third. The ranking shows a highly skewed distribution typical of emerging but rapidly scaling technology areas: A small number of leading

BASF as new European battery circularity powerhouse

To ensure completeness of the patent data, we report on trends up to and including 2023, but do not report on 2024 and later. Without this restriction, BASF would more than double its total number of IPFs (from 31 to more than 60) and thereby become the largest European filer of IPFs by a considerable margin and move up in the global ranking.

BASF currently focuses its battery recycling efforts at its Schwarzheide location in Germany, and has begun commercial operation of its black mass plant there. This facility has an annual processing capacity of up to 15 000 tonnes of end-of-life lithium-ion batteries and production scrap, which is roughly equivalent to 40 000 electric vehicle batteries per year. In addition to the new black mass production, BASF's Schwarzheide location also operates Europe's first fully automated cathode active materials production site and one of Europe's largest black mass storage facilities.[10]

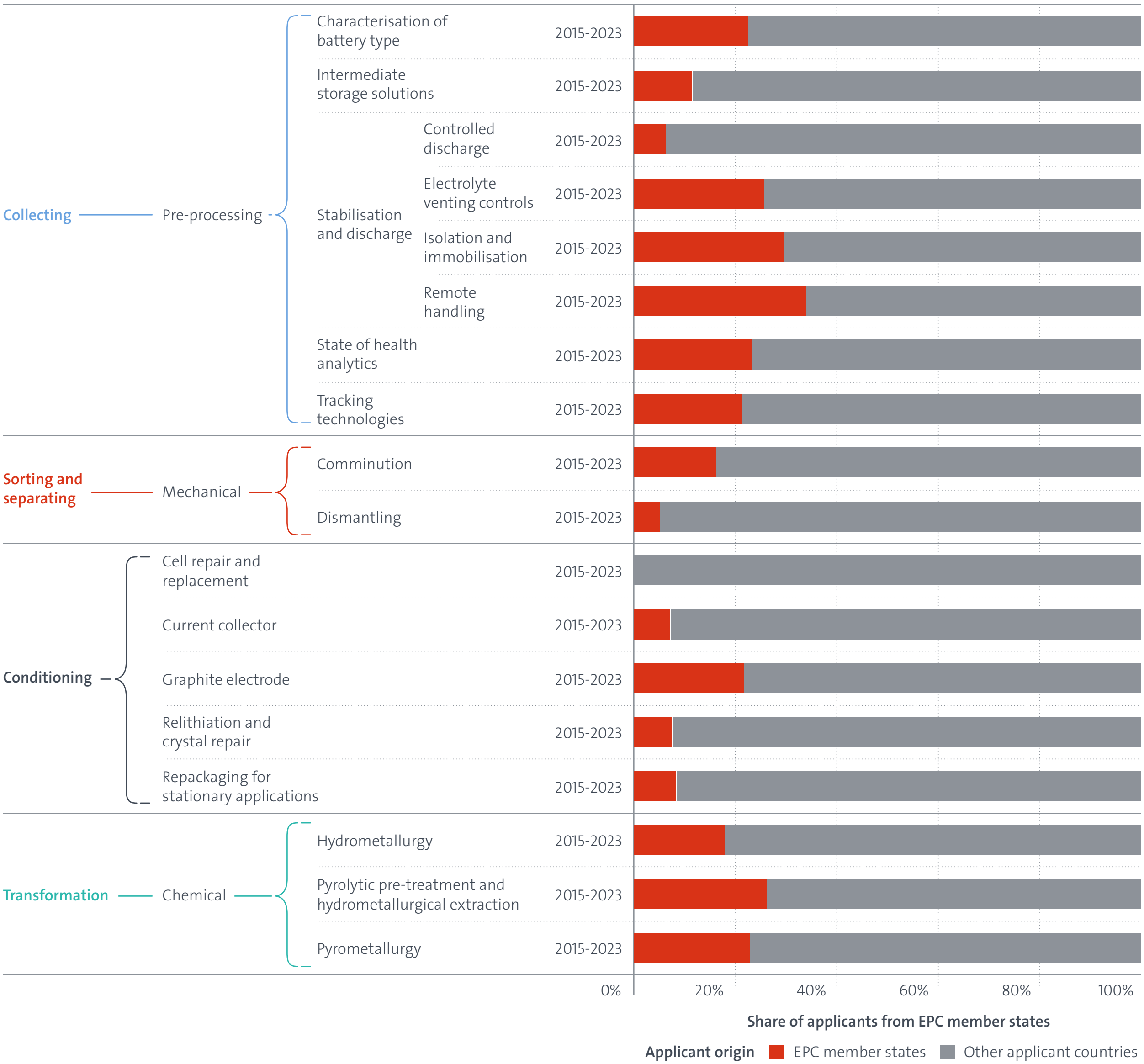
[10] https://www.basf.com/global/en/media/news-releases/2025/06/p-25-112

companies hold significantly more international patent families (IPFs) than the rest. A long tail of medium-sized and smaller applicants follows. This pattern suggests that first movers, often industrial players, have built patent portfolios early, whereas specialised players add niche innovations but do not compete at the same scale.

The results suggest that EPC-based industry is strongly engaged in scaling recycling infrastructure, not just basic research. This reflects the fact that battery circularity requires capital-intensive technologies – e.g. to build infrastructure for sorting, pre-processing, and metallurgical extraction – and inventions in these fields are often tied to large-scale industrial processes. At the same time, there is a range of applicants with smaller patent portfolios which often specialise in process engineering, chemical processes and materials. The presence of these rather specialised applicants indicates technological diversification within Europe, with SMEs contributing significantly to the development of the field.

Figure 19.

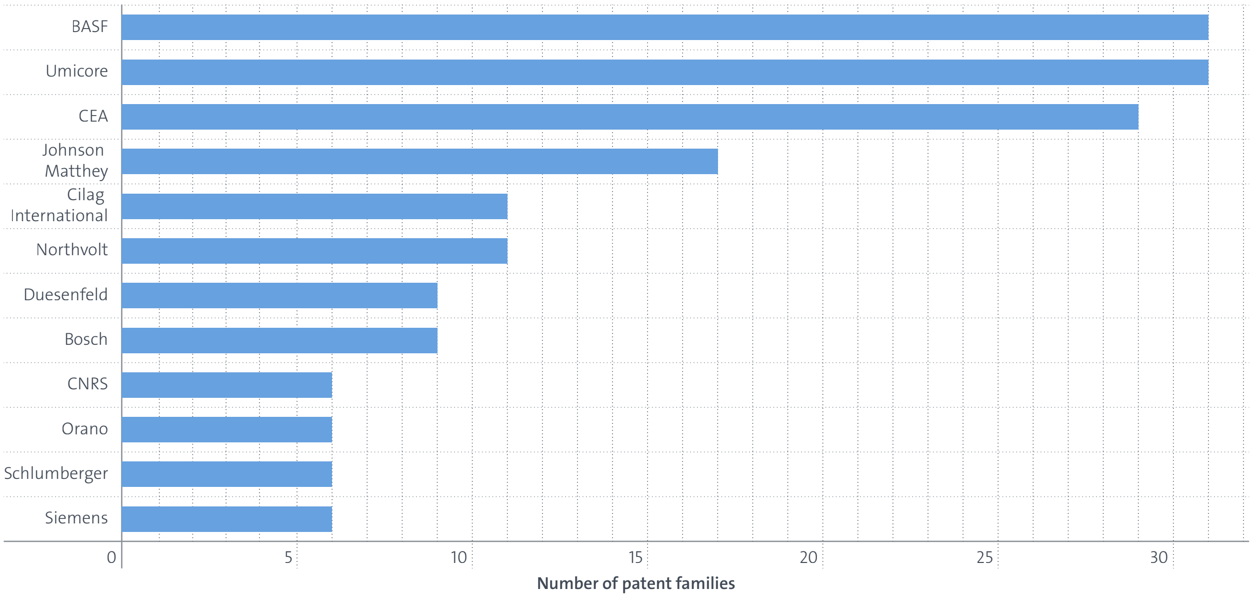
Share of applicants from EPC member states among selected technologies in battery circularity with at least 10 international patent families in the period 2015-2023



Source: EPO

Figure 20.

Most active applicants from EPC member states in battery circularity, based on international patent families



Source: EPO

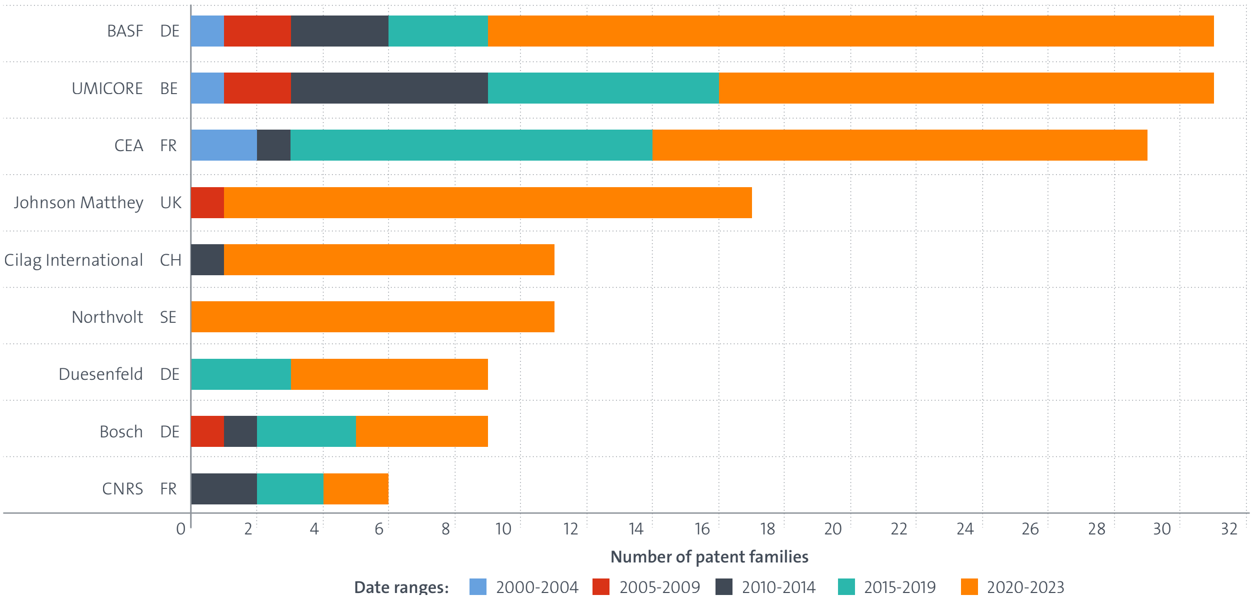
Similar in general to the situation for the most active applicants in the field (see further above), the breakdown of inventive activity among European applicants provides interesting insight into the development and priorities of these applicants. In Figure 21, the number of international patent families are presented for the most active European applicants, with a breakdown into colour-coded segments, where each segment represents a date range indicating when the inventions were first published. This presentation helps to see how their inventive activity has evolved over time, which in turn helps to identify historical pioneers, recent fast-growing players, and applicants with declining or plateauing activity.

This segmentation reveals that several active European applicants, such as Umicore and CEA, exhibit steady inventive activity across multiple decades, indicating mature research and development programs. Other active applicants, including Johnson Matthey and Duesenfeld, show strong growth in recent years, signalling emerging players or increased strategic focus on battery circularity.

The overview of active European applicants in the field of battery circularity was supplemented with an analysis of their technology profile. Figure 22 presents the technology-profile matrix of the top European patent applicants active in the field. Some applicants including BASF, CEA and Duesenfeld have broad, diversified portfolios, whereas others show specialisation in particular technologies.

Figure 21.

Breakdown of inventive activity of the most active applicants from EPC member states in battery circularity according to date ranges, for international patent families



Source: EPO

Figure 22.

Technology profile of the most active applicants from EPC member states in battery circularity, for international patent families

Source: EPO

2.5 Focus on European startups and universities

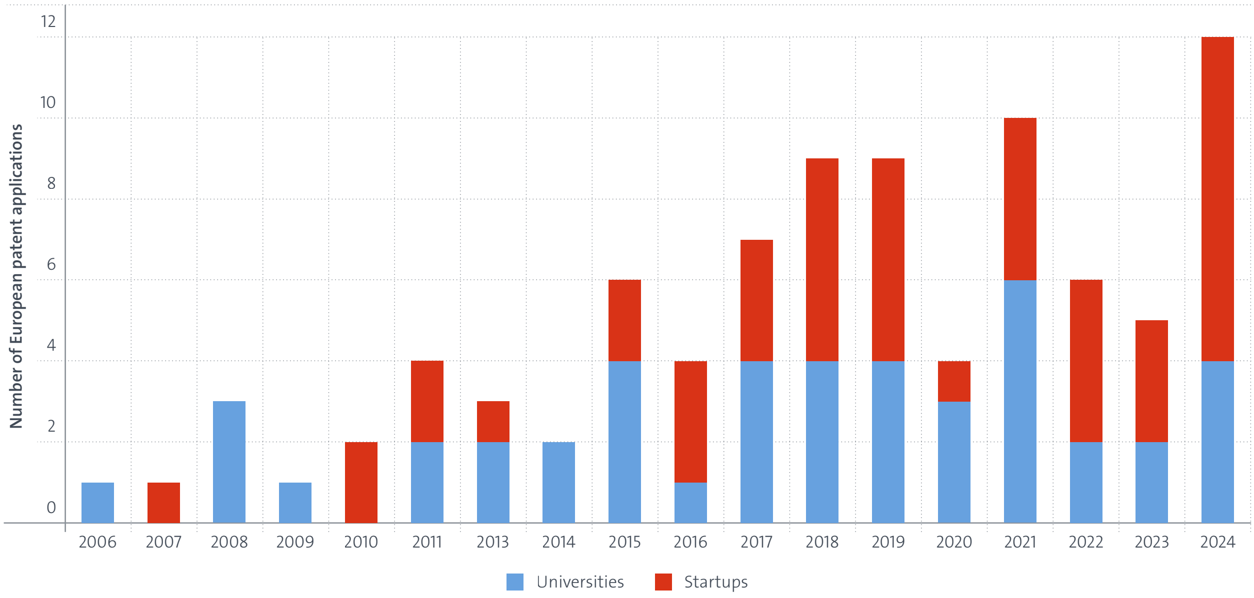
Data from the EPO's Deep Tech Finder tool provided further insight into the contribution of European startups and universities to progress in the field of battery circularity, and refining of critical metals for batteries. We identified more than 60 European startups and universities which have sought patent protection under the European patent system for inventions in this field since 2001. In total, 26 individual startups from 11 of the 39 EPC member states filed 49 European patent applications in this period. Moreover, 35 universities from 12 EPC member states filed 47 European patent applications.

Startups and universities focus on different technological sub-areas, and show different patenting activities. While the technologies being commercialised by many startups were first developed at universities, often with government funding, not all technologies originating at universities are equally spun off into startups. In Europe, startups in the battery circularity field are mainly seeking to commercialise techniques related to collecting, mechanical sorting and separating and chemical processes for the chemical transformation of battery components or black mass. European universities additionally focus on technologies related to collecting and chemical processes for the transformation of battery components, followed by chemically treating raw materials (see Table 3). These university-led areas may also generate startup activity if the market becomes conducive and the inventors are able to differentiate themselves from likely competitors.

Figure 23 presents an overview of how European startups and universities contribute to patenting activity in the fields of battery circularity and refining of critical metals for batteries, based on European patent applications. While the filing numbers of startups and universities are still rather low and the corresponding relative fluctuations are still high, we observed a clear upward trend.

Figure 23.

Patenting activities of European startups and universities in battery circularity and refining of critical metals for batteries, based on European patent applications



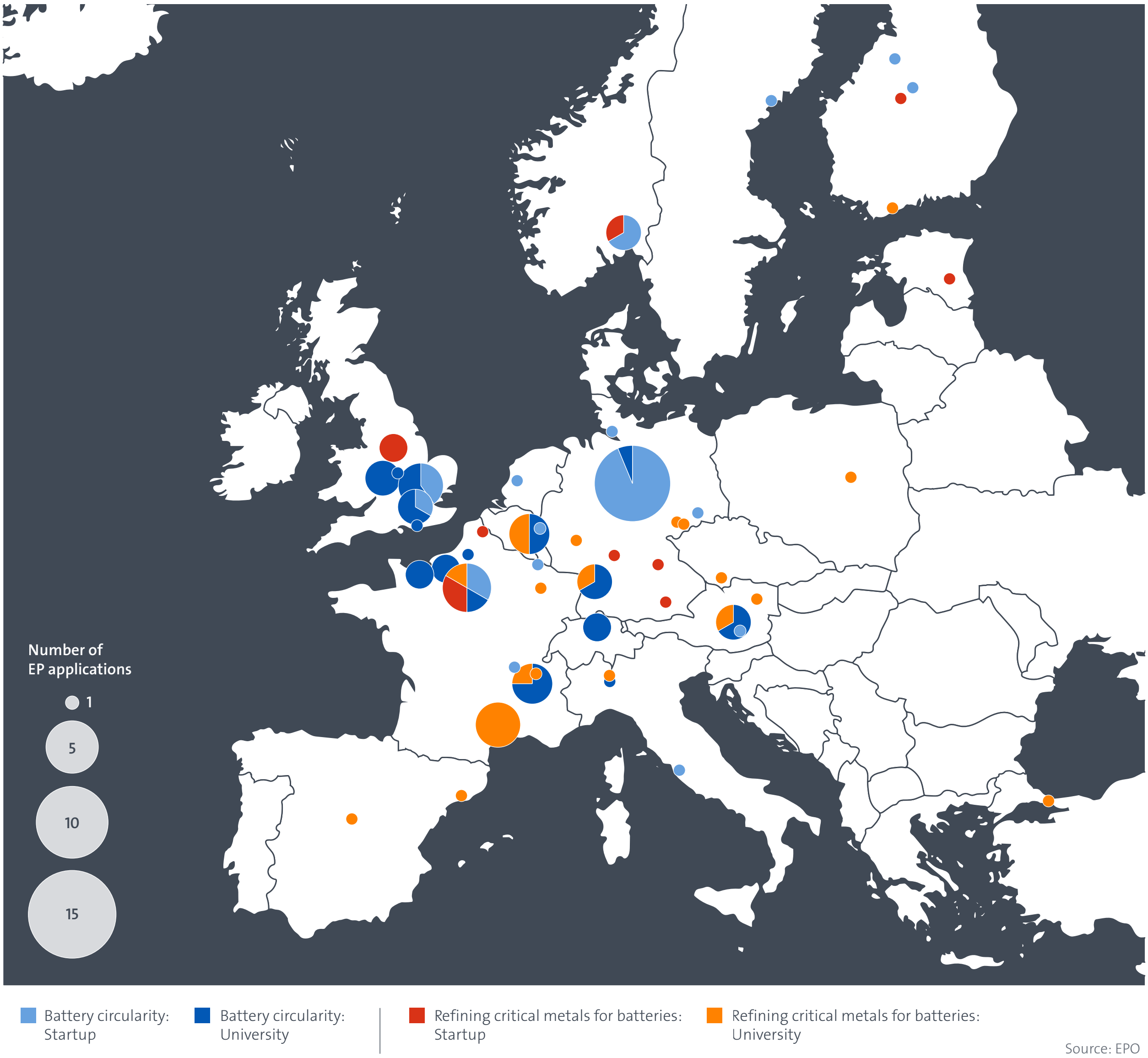
Source: EPO

As in many other technical areas, inventive activity by universities and startups is not evenly distributed across Europe. Figure 24 shows the geographical distribution of these entities which sought patent protection under the European patent system in the past decades. It provides map-based visualisations for battery circularity (blue tones) and refining of critical metals for batteries (orange tones). The bubbles indicate where the applicants are located, and their size corresponds to the number of European patent applications from these applicants.

Startups and universities are distributed across multiple European countries, with clusters in France, Germany, the United Kingdom and the Nordic countries. However, the geographical distribution of the applicants for battery circularity and for refining of critical metals for batteries do not coincide, suggesting that inventive activity in these fields is not concentrated in the same regions, as was observed in many other technical fields, too.

Figure 24.

Geographical origin of European patent applications filed by startups and by universities related to battery circularity and refining of critical metals for batteries



Source: EPO

Example

Cylib: How an innovative startup plans to revolutionise the recycling of lithium-ion batteries

In recent years, numerous dynamic startups have emerged throughout Europe, dedicated to the recycling of lithium-ion batteries. One noteworthy player is the young German company Cylib. Founded in 2022 as a spin-off from RWTH Aachen University, Cylib is now building one of Europe‘s largest recycling facilities for batteries from electric vehicles.

It all started when young researchers Paul Sabarny and Dr. Lilian Schwich at RWTH Aachen University questioned why established industrial processes recycled only a fraction of a battery‘s valuable materials. Typically, only the most expensive metals such as cobalt and nickel were recovered efficiently, while many other key components continued to be treated as waste. For example, graphite and lithium were largely not recycled for economic reasons, even though Europe is dependent on imports of these materials. Known processes were inefficient and not competitive compared to the use of primary raw materials.

Their breakthrough came with the realisation that most of the challenges associated with existing strategies for lithium recovery are linked to the fact that they target lithium at the end of the recycling process, after the more expensive metals have been retrieved. Therefore, their idea was to reverse the process by developing a pre-treatment that recovers lithium at an early stage of the recycling process rather than at its end.

As described in their patent DE102022121918B4 (EP4581180A1), this can be achieved by transforming lithium compounds in the material to be recycled during a pyrolytic process step in the presence of carbon dioxide. In this way, lithium carbonate is formed which can then be selectively washed out with water. This allows lithium to be recovered without the additional carbonation additives or acids often used in alternative processes. In a subsequent step, graphite can be recovered by flotation, which is also mainly water-based. Thus, two of the most difficult components to recycle can be recovered in an environmentally friendly manner before the actual hydrometallurgical processing begins.

According to Cylib, its recycling process attains over 90% recycling efficiency while reducing the carbon footprint by 80% compared to the extraction of primary raw materials. Following successful pilot-scale testing in Aachen, Cylib broke ground for an industrial-scale recycling plant at CHEMPARK Dormagen in September 2024.

Photo at left, from left to right: Dr. Gideon Schwich, Dr. Lilian Schwich and Paul Sabarny (from left to right) founded Cylib in 2022

Photo: Cylib/Jann Höfer

Financing for the project comes from a mix of private and public partners. Alongside investors such as Bosch Ventures and Porsche Ventures, Cylib has secured substantial funding from the EU and the state of North Rhine-Westphalia (ERDF/JTF programme: €26.1 million), as well as from the German federal government (STARK programme: €63.4 million).

Cylib can put these funds to good use, as it is already planning to set up another recycling line for batteries with lithium iron phosphate chemistry, complementing the first recycling line for batteries based on nickel manganese cobalt oxide chemistry. Cylib has filed further patent applications to also protect its intellectual property on the recycling of LFP-based batteries. Together, both lines will have a capacity of 60 000 tonnes annually – equivalent to 140 000 electric vehicle batteries.

Cylib currently employs 120 people who are working to make this a reality. If everything goes according to plan, operations at the Dormagen plant will commence as early as 2027 – marking a milestone in Europe‘s transition toward a circular battery economy.

Source: German Patent and Trade Mark Office (DPMA)

Table 3.

Patenting activity of startups and universities in the area of battery circularity and refining of critical metals for batteries, by technology, based on the number of EP patent applications

			Universities	**Startups**	**Number of European patent applications**
Battery circularity	Collecting	Pre-processing	6	16	22
	Sorting and separating	Chemical		2	2
		Mechanical	3	12	15
		Physical	4	9	13
	Conditioning	Current collector	4	4	8
		Graphite electrode	2	6	8
		Relithiation and crystal repair	1	1	2
	Transformation	Chemical	14	18	31
	Enabling technologies	Circularity-friendly design of batteries and processes	4	1	5
		EHS		1	1
Refining of critical metals for batteries	Treating raw materials	Biological	8	3	11
		Chemical	19	9	27
		Other or hybrid	1		1
		Total	**47**	**44**	**89**

Special focus:
Refining of critical metals for batteries

Background

Critical minerals such as lithium, cobalt, nickel, copper, graphite and rare earth elements have become foundational to modern economies. While electric vehicles, battery storage, wind turbines, solar photovoltaics and electrical grids are the dominant sources of new demand for many of these materials, critical minerals are also indispensable in industrial equipment, high-tech manufacturing, AI data centres and semiconductors, aerospace components, robotics and defence applications, highlighting their strategic value across the economy [International Energy Agency, 2025c].

Demand for critical minerals has risen sharply in recent years. In 2024, global lithium demand increased by around 30% year-on-year, while demand for nickel, cobalt, graphite and rare earth elements rose by around six to eight percent. Under the IEA's Stated Policies Scenario, demand for many key minerals such as lithium is projected to grow several-fold by 2040, with graphite and nickel roughly doubling and cobalt and rare earth elements rising by around 50–60%. Under the Net Zero Emissions by 2050 scenario, mineral demand for energy technologies almost triples by 2030 and quadruples by 2040, reaching close to 40 million tonnes (Mt) as electrification and battery deployment scale globally [International Energy Agency, 2025c]. Batteries remain among the most mineral-intensive technologies in the energy system, driving the bulk of incremental demand for lithium, nickel, cobalt and graphite across all scenarios.

The supply needed to meet this demand, particularly in refining and processing, remains highly geographically concentrated, creating structural vulnerabilities. The average market share of the top three producers of key energy minerals reached around 86% in 2024, up from roughly 82% in 2020. A single country dominates the refined production of 19 out of 20 strategic minerals analysed [International Energy Agency, 2025c]. Recent export controls on rare earths and battery-related materials have shown that these concentration risks are no longer theoretical, with new licensing requirements and restrictions disrupting global supply chains for components such as permanent magnets, affecting electric vehicles, wind turbines and defence applications [International Energy Agency, 2025d].

The risk profile differs by mineral. Lithium mining shows some potential for diversification to 2030 based on the project pipeline, whereas nickel, cobalt and rare earth supply chains remain highly concentrated. Copper faces heightened risks of future shortfalls, in the absence of timely investment, due to continued and strong demand growth and declining outputs from existing mines [International Energy Agency, 2025c].

A growing number of policy announcements demonstrate how critical minerals have been rising to become a key area of focus. Governments are responding with a range of policy measures to improve resilience and security. These include incentives for domestic mining and refining, strategic international partnerships and trade agreements, stockpiling, sustainability standards and explicit mandates, and support for recycling and circular-economy approaches. The IEA also underscores the importance of continued innovation breakthroughs in easing supply pressures, lowering environmental impacts, enabling diversification and boosting efficiency across mining, processing and recycling technologies [International Energy Agency, 2025c].

The recycling of critical minerals is a particularly important, yet still under-developed pillar of supply security. Collection and recycling efforts should focus on various sources of feedstock, including manufacturing scrap, end-of-life batteries, solar panels, wind turbines and consumer electronics as well as re-processing of waste streams at existing mines [International Energy Agency, 2024a]. While production scrap currently dominates secondary supply, end-of-life recycling is expected to grow rapidly as electric vehicle batteries and other products reach retirement after 2030. Scaling recycling will require clear targets, better collection systems, design-for-disassembly, advanced recovery technologies and supportive policy as well as investment frameworks. If successful, secondary supply from recycling can reduce primary supply requirements for key energy minerals by 25–40% by 2050 in a scenario that meets national energy and climate pledges [International Energy Agency, 2024a].

Critical minerals sit at the intersection of energy, industry and technology, and managing fast-rising demand, highly concentrated supply chains and sustainability constraints will depend on coherent policy action, continued innovation throughout the value chain and international co-operation. Through its data collection, scenario analysis, policy guidance and international co-operation platforms, the IEA plays a central role in helping governments and industry anticipate risks, diversify supply chains and strengthen the resilience and sustainability of global critical-mineral markets.

Technologies for refining of critical materials for batteries

Direct lithium extraction

Direct lithium extraction (DLE) is an innovative technology that can unlock vast unconventional resources by extracting lithium from both existing brines and geothermal and oilfield brines containing lithium concentrations typically considered too low for traditional evaporation methods to process economically.

DLE operates by pumping lithium-rich brine from reservoirs, selectively capturing lithium mainly via adsorption or ion exchange methods, and then purifying it into lithium chloride or using electrolysis and processing the chemical into battery-grade lithium carbonate or lithium hydroxide. After extraction, the brine is reinjected to sustain reservoir pressure. Extensive research and testing is being conducted on DLE technologies to unlock the potential of lithium brines, and other promising alternatives to adsorption and ion exchange include solvent extraction, membrane technologies, and electrochemical and chemical precipitation.

While DLE can offer a faster, more efficient and environmentally promising approach to lithium production compared with traditional processes, it faces scalability and environmental hurdles of its own on its way to widespread adoption, such as freshwater and higher energy consumption. The choice between the DLE methods depends on brine characteristics. Adsorption is effective for high-lithium-concentration brines, using fewer chemicals, offering greater scalability and having lower upfront costs. Meanwhile, ion exchange is optimal for lower lithium concentrations or complex brines with competing ions such as sodium and magnesium, but it requires careful management of potential chemical waste.

Reprocessing of tailings and mine waste

Mining waste includes all materials generated during the extraction and processing of ore into commercially viable products. It can come in many forms, such as waste rock produced while accessing the ore deposit, tailings generated when separating desired materials from the rest, and mine drainage water, which could be surface or groundwater draining from active or abandoned mines. Sometimes there are minerals left within this mine waste that had low economic value at the time of extraction and therefore were not considered economically viable to recover. It may have also been the case that the appropriate technology was not available at the time of original recovery. However, increasing demand for minerals in energy technologies have prompted a re-evaluation of the financial feasibility of recovering these minerals, positioning mine waste as a potential new source of supply.

Novel synthetic graphite production

Battery-grade synthetic graphite is made from high-temperature treatment of a blend of lower-purity carbon-based raw materials such as petroleum coke, coal tar pitch or oil. This creates a uniform carbon structure suited for high-performance, fast-charging, long-lasting lithium-ion battery anodes. It is purer than natural graphite in terms of carbon content and tends to behave more predictably, making it a competitive alternative to natural graphite. However, the production process is highly energy-intensive (up to four times more carbon-intensive than natural graphite anode production) and can be significantly more costly than processing of natural graphite. The graphitisation of coke products into synthetic graphite is the largest source of energy consumption, and the carbon emissions increase substantially if fossil-based electricity is used for this process. These issues require innovative technologies to produce synthetic graphite in a more environmentally friendly way.

Some solutions being studied include “lengthwise graphitisation” that uses the resistance of the carbon material itself to convert electric energy into heat energy which graphitises the material, and using induction furnaces to use the material’s inherent conduction properties to achieve the required temperatures in shorter times than regular ovens/furnaces. Other technologies with relatively lower technology readiness levels (TRLs) are “bio-graphite”, which uses amorphous carbon in biomass to produce battery-grade graphite, and methane pyrolysis, which uses solar-thermal energy or joule heating to achieve methane pyrolysis to produce hydrogen and synthetic graphite. The overall aim of all these novel technologies is to significantly reduce the emissions footprint of producing synthetic graphite, while also achieving gains in processing time and costs.

In-situ leaching

In-situ leaching, also known as in-situ recovery, is a mining method that extracts minerals from underground deposits by dissolving them, yet without digging large open pits or underground tunnels. In in-situ leaching operations, a solution is injected into the ore-bearing rock through wells, where it dissolves the target mineral. The mineral-rich liquid is then pumped back to the surface and processed to separate and concentrate the valuable material, which can later be refined. This approach is used for resources such as uranium, copper, lithium and rare earth elements.

This technology avoids the need for open-pit or underground mines, leading to energy savings, lower emissions and reduced water consumption. It also does not require waste stockpiling or tailings dams, thus resulting in lower capital needs and a smaller environmental footprint.

High-pressure acid leaching

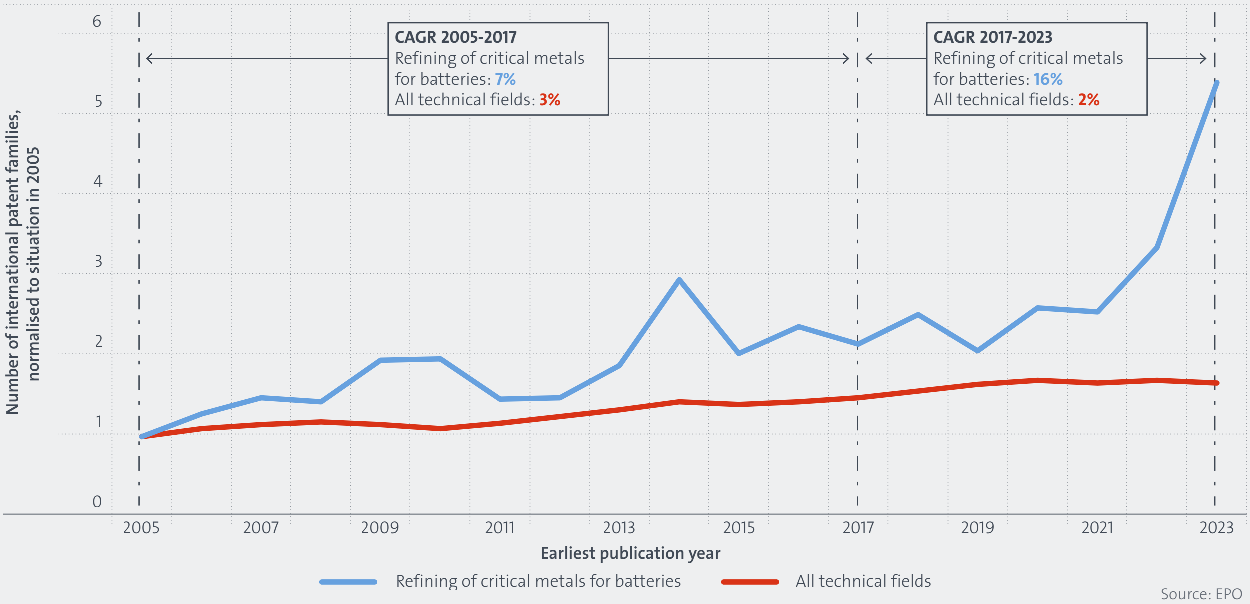
High-pressure acid leaching (HPAL) is a hydrometallurgical process in which mined and crushed ore is treated with concentrated acid in pressurised, high-temperature reactors (autoclaves) to dissolve target metals. The resulting metal-rich solution is then separated and concentrated, producing intermediates suitable for further refining. HPAL is primarily used for laterite ores containing nickel and cobalt, allowing extraction of metals that are otherwise difficult to recover using conventional methods – also enabling processes to achieve battery-grade products after further refining – but requires significant energy and careful handling of acidic, high-pressure conditions.

Patenting trends

Refining of battery-critical materials showed impressive growth in the period 2000-2023 (see Figure 25 and Figure 26), although less dynamic than in battery recycling. Overall, chemical technologies to treat raw materials showed above-average growth, and dominated in absolute patent family numbers in that period among all technologies in that field. While the number of international patent families grew steadily, the number of national patent families multiplied in the past decade. Correspondingly, the share of IPFs of all patent families in the field decreased to about one-third in the recent past.

Figure 25.

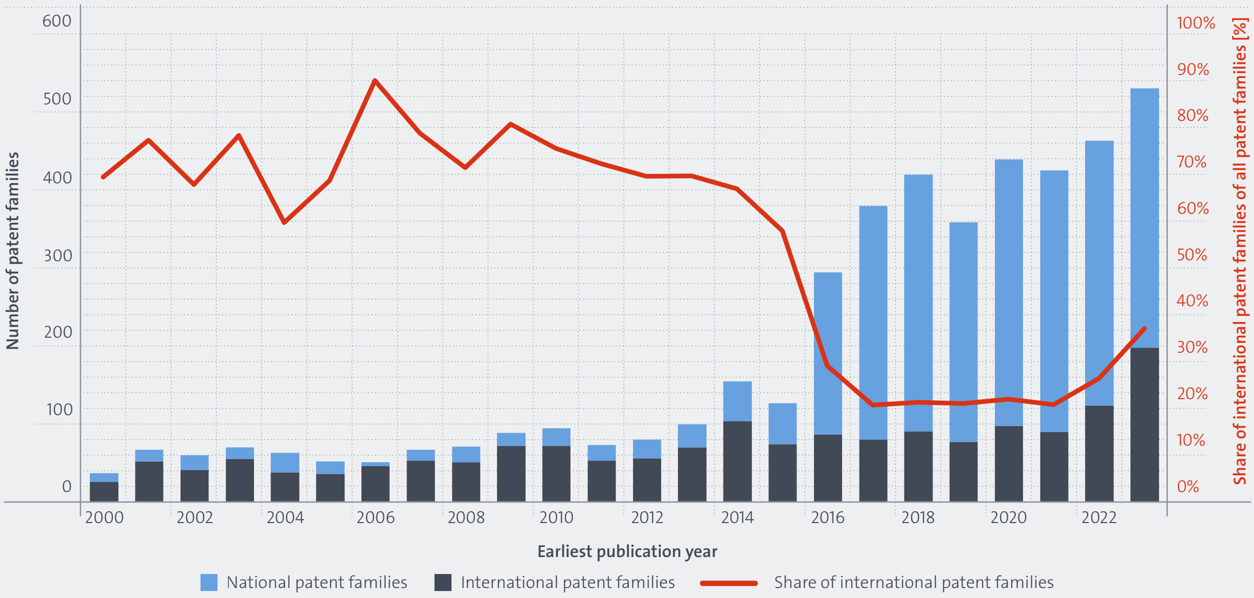
Compound annual growth rates in refining of critical metals for batteries, for international patent families



Source: EPO

Figure 26.

Patent families in refining of critical metals for batteries per earliest publication year



Source: EPO

In contrast to the acceleration in battery circularity, refining of critical metals for batteries exhibited more modest momentum during the study period (see Figure 26). While both fields started from a similarly modest pre-2010 base, the total inventive activity in metal refining only exceeded 500 inventions (both national and international patent families combined) per year in 2023, which only about 20% of the corresponding figure for battery circularity in that year. A particularly notable feature of the technological development is the collapse in the share of IPFs for metal refining, which plunged from more than 70% before 2014 to approximately 20%, whereas battery circularity technologies saw a rather continuous decrease in that period, before the more recent upturn. However, the overall share of IPFs among all metal refining patent families remains around double the corresponding level for battery circularity.

Similar to battery circularity, technologies for refining of critical metals for batteries saw a steep increase in inventive activity in the past decade. Remarkably, Chinese national patent families surged drastically in 2016 and then for the most part remained on a high level until 2023, accounting for roughly 90% of all national patent families (see Figure 27). This might have been driven by the extension of electric vehicle subsidies to individual consumers in China, which, however, were only available for sales of electric vehicles equipped with batteries from approved suppliers,[11] all of which were Chinese,[12] between 2015 and 2019. Correspondingly, the share of international patent families among all patent families in that sub-area dropped in 2016. Its share started to increase again as of 2022, perhaps reflecting a more global interest. The noted sudden increase in the number of Chinese national patent families is to a large extent due to patent filing originating from Chinese corporate and research applicants such as Central South University, Chinese Academy of Science and China Enfi Engineering.

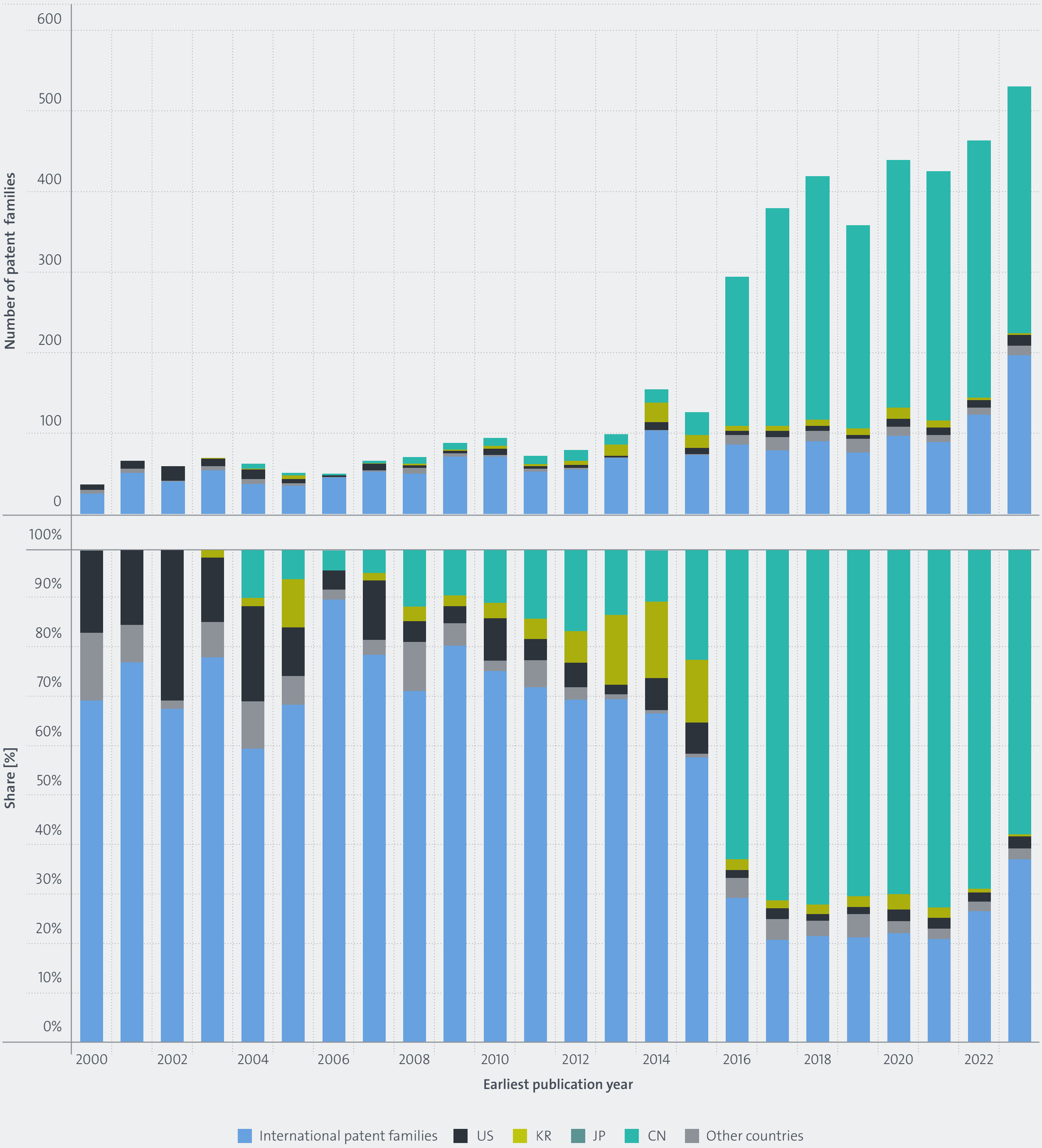
This trend is also evident in the data for the three chemical sub-technologies we covered for this report (see Figure 28). The strongest momentum is shown by technologies related to direct lithium extraction followed by technologies related to solvent extraction and ion exchange for metal separation and purification. In the reporting period, the share of international patent families of all patent families decreased but remained significant.

[11] See http://www.caam.org.cn/chn/1/cate_2/con_5152858.html

[12] See https://www.bbc.co.uk/future/article/20251110-how-china-won-the-worlds-battery-race

Figure 27.

Share of national patent families among all patent families in refining of critical metals for batteries



Source: EPO

Figure 28.

Number of patent families in refining of critical metals for batteries, with a breakdown according to sub-technologies and date ranges

Source: EPO

Biological technologies showed slower but continuous growth in the reporting period. Among the two biological sub-technologies we examined in this report, bioleaching showed significantly higher inventive activity throughout the entire period, while phytomining remained largely a niche technology.

Thirdly, we looked at processes for refining of critical metals for batteries which combine mechanical, chemical and, occasionally, biological elements. These are typically employed for treating more complex or lower-grade materials, such as mining tailings. Among these essentially hybrid technologies, we scrutinised technologies related to roasting and acid/alkaline leaching, and the extraction from tailings/waste. Both showed high momentum regarding inventive active in the report period, whereas only the latter sub-technology rose to some significance.

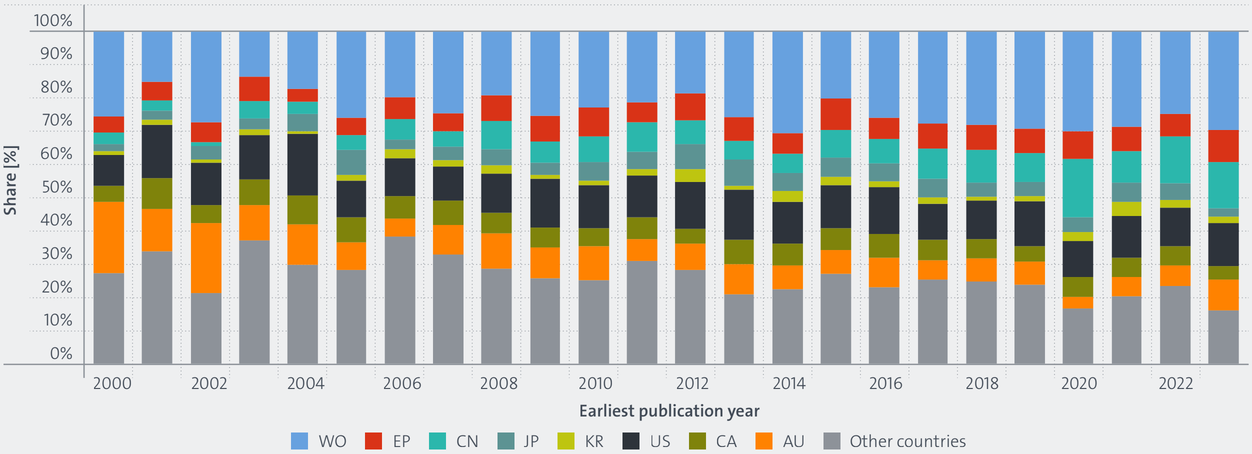
A look at the countries for which patent protection was sought in this sub-area reveals interesting differences compared to technologies related to battery circularity. In the latter field (Figure 29, middle), patent protection is sought primarily in the same countries and regions as in all technical fields overall (Figure 29, bottom). In refining of critical metals for batteries (Figure 29, top), however, Australia and Canada also made a significant contribution. Both countries play a strategic role in the extraction and treatment of raw materials, notably concerning minerals critical for the global energy transition.

Figure 29.

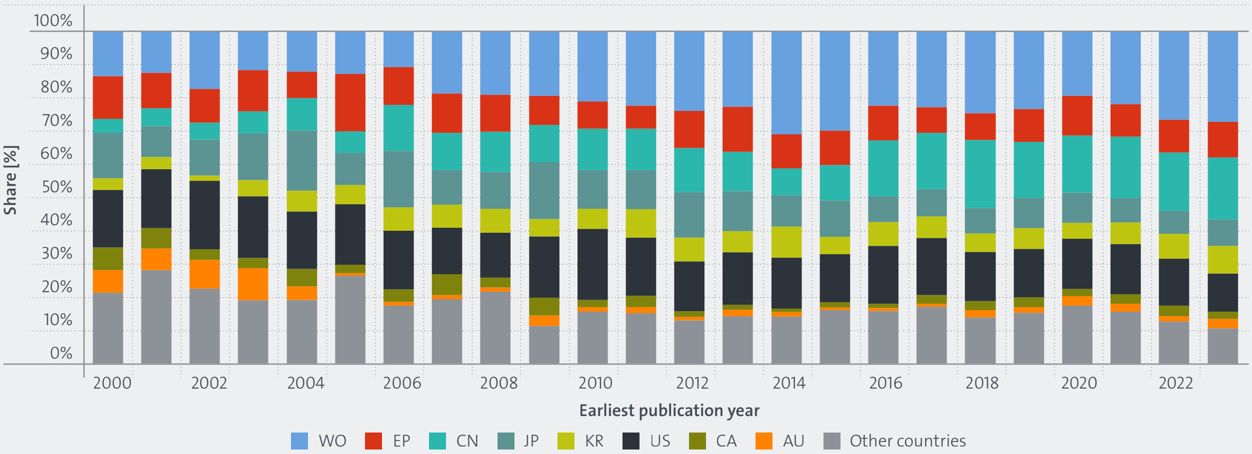
Patent application routes chosen for IPFs in refining of critical metals for batteries (top), battery circularity (middle) and for all technical fields combined (bottom), per earliest publication year.

The information is presented as per selected patent application routes.

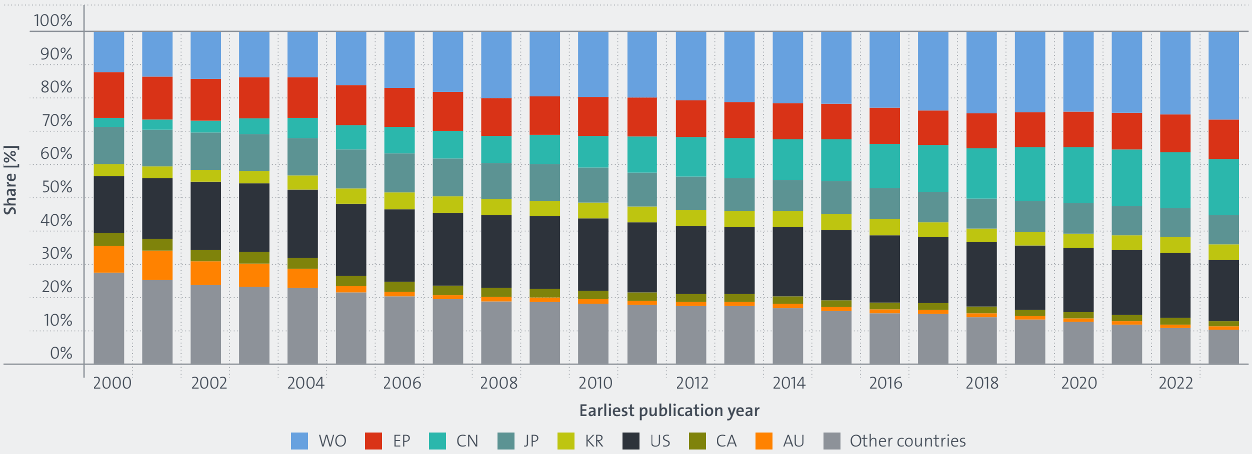
Refining of critical metals for batteries



Battery circularity:



All technical fields combined:

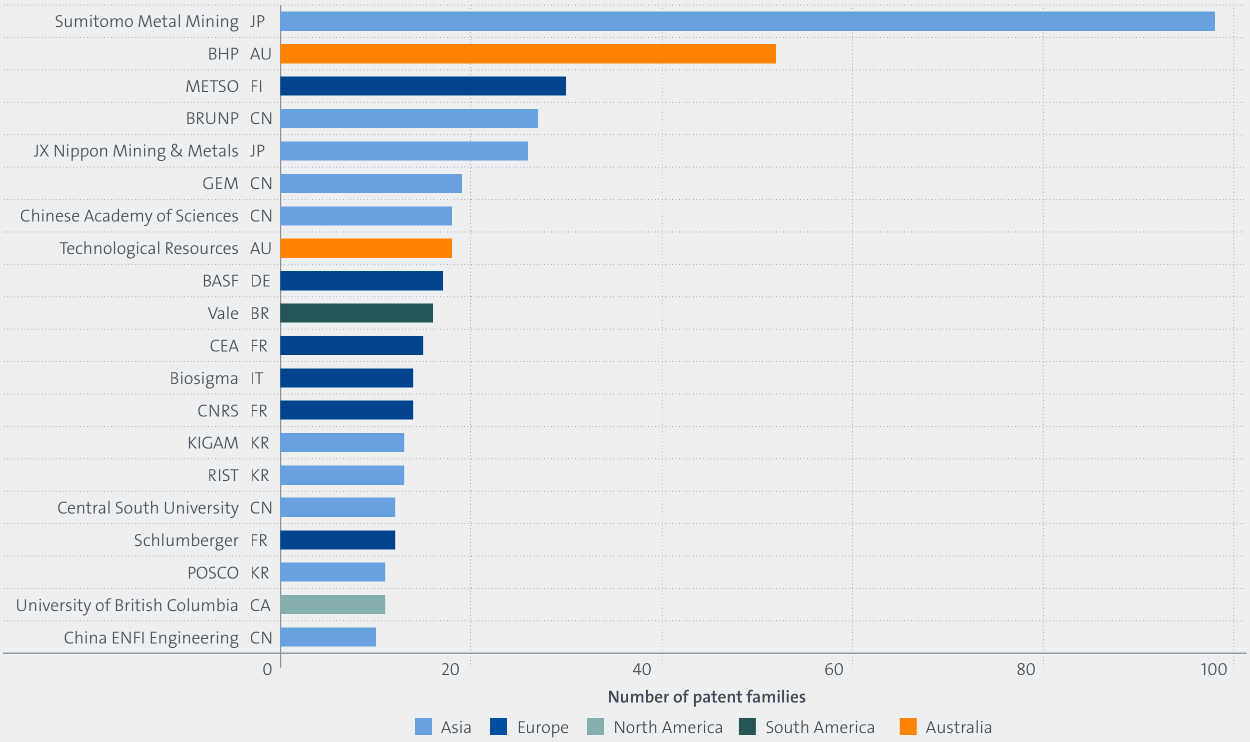


Source: EPO

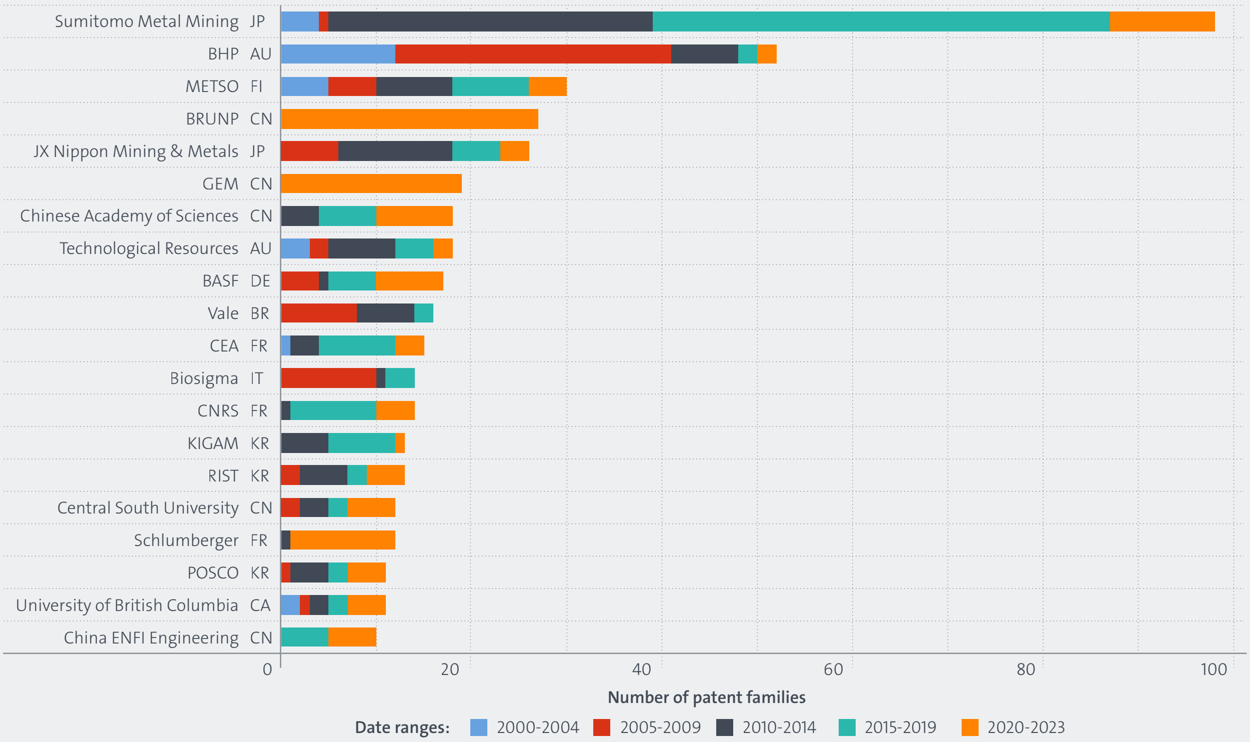
Figure 30.

Most active applicants in refining of critical metals for batteries, with respect to international patent families and per date ranges

Per region



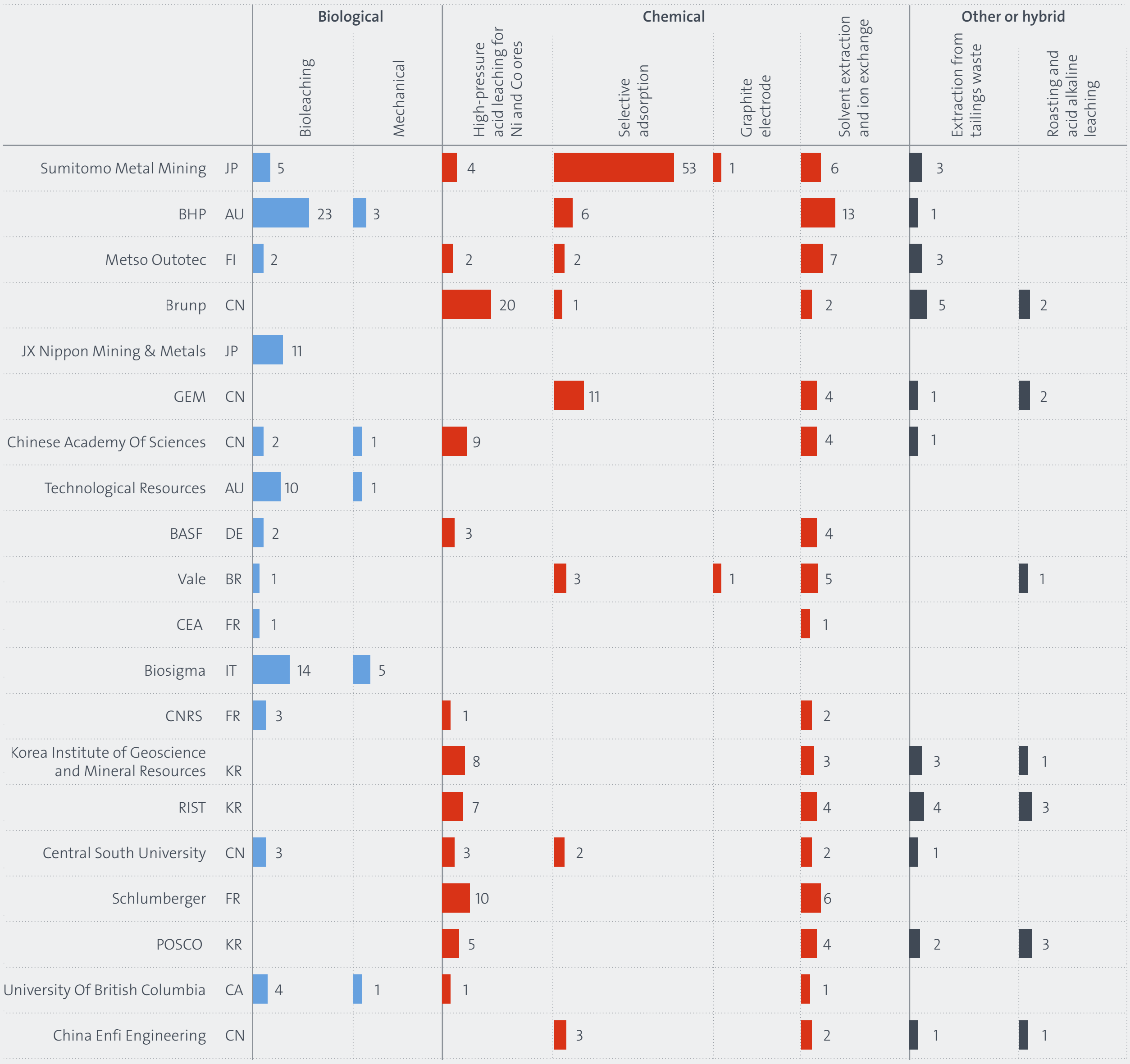
Date ranges



Source: EPO

Figure 31.

Technology profile of the most active applicants in refining critical metals for batteries, with respect to international patent families in the period 2000-2023



Source: EPO

Unlike in battery circularity where mainly patent applicants from Asia are among the most active applicants, the situation in refining of critical metals for batteries is much more diverse. Figure 30 shows the 20 most active applicants in this field (top), originating from Asia (10 applicants), Europe (6), Australia (2), and South America and North America (1 each).

While most of them look back on decades of inventive activity in the field, such as Sumitomo Metal Mining, BHP and Metso Outotec (see Figure 30 (bottom)), a significant fraction of the most active applicants entered the field recently. Prominent examples are China-based Brunp – the recycling branch of the battery manufacturer Contemporary Amperex Technology (CATL) – and GEM.

However, it is not only this historical profile that distinguishes the most active applicants, in some cases quite significantly. Their technology profiles can also show considerable differences. Figure 31 shows a technology profile of the most active applicants. This technology profile helps identify which technologies each applicant focuses on most. It also helps to spot differences in technological specialisation among leading applicants. This information allows us to see technology strategies at a glance, in particular whether a company is broadly positioned with respect to technologies in the field, such as Sumitomo Metal Mining and BHP, or a niche specialist.

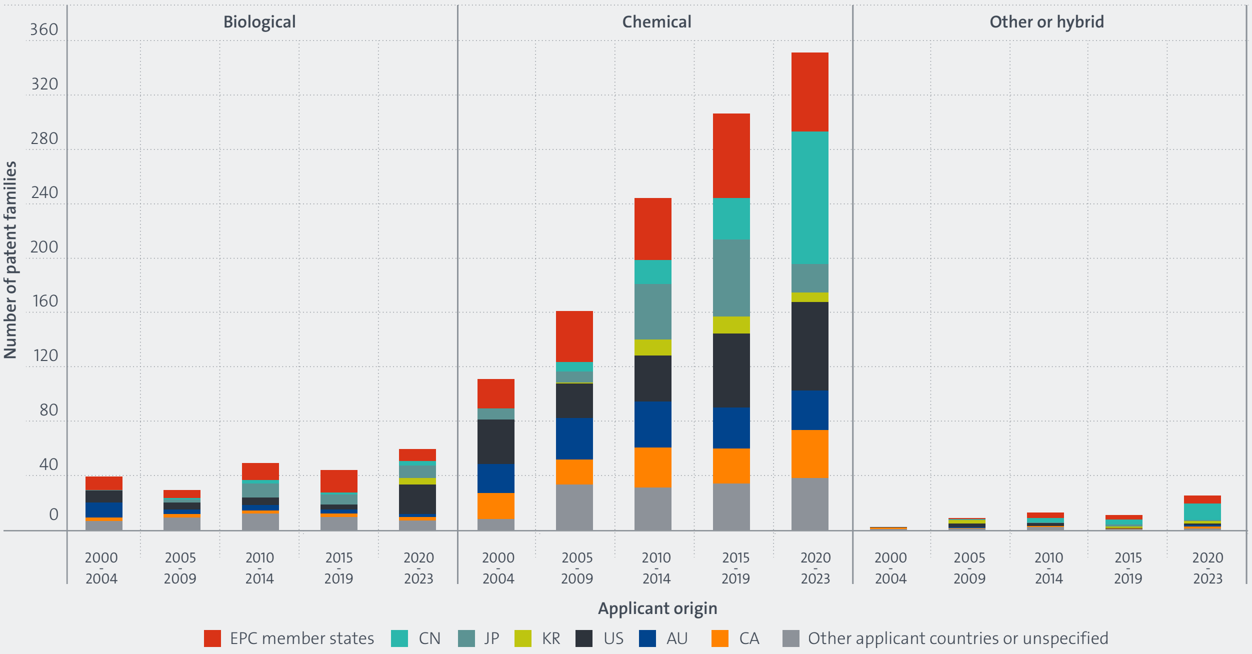
Similar to battery circularity, it is mostly applicants located in P.R. China that have driven inventive activity regarding technologies for refining of critical metals for batteries in the recent past. However, when looking at inventions with an international focus, the picture becomes more diverse.

Figure 32 shows the aplicant origin for these technologies, with a breakdown according to date ranges. While the role of applicants from Asia remains high with respect to international patent families, applicants from Europe, the United States, Canada and Australia make an important contribution, too.

Figure 32.

Applicant origin in refining of critical metals for batteries, with respect to international patent families

The analysis was restricted to international patent families with at least one EP and/or WO patent family member to provide comprehensive coverage of applicant country information within the data. Fractional counting was used with respect to applicant countries and sub-technologies.



Source: EPO

3. Conclusions and outlook

Demand for lithium-ion batteries is booming around the world, not only for electric vehicles, but also for stationary energy storage and a host of other applications, including defence. The number of batteries reaching the end of their first life is expected to rise sharply from the mid-2030s onwards, creating a waste management challenge. However, technologies related to battery circularity have the potential to harness these end-of-life batteries to reduce pressure on battery supply chains, which are currently highly concentrated geographically. As a growing secondary resource for critical raw materials such as lithium, cobalt, nickel, manganese and graphite, these technologies could also support the relocation of industrial capacity within the battery manufacturing value chain, thereby strengthening the link between where batteries are made and where they are used. In addition, if a substantial share of the critical materials contained in batteries can be returned to the production cycle, reliance on primary mining and its associated environmental impacts will be reduced.

Our data show that innovation in battery circularity technologies has accelerated rapidly over the past two decades. Between 2005 and 2017, patenting activity in battery recycling and related technologies grew substantially faster than the global average across all technological fields. Since 2017, this growth has accelerated even further. International patent families related to battery circularity increased at an annual rate of roughly 42% between 2017 and 2023, far above the overall global innovation baseline of around 2% over the same period, and also outpacing general international filings in secondary battery technologies. This surge reflects growing industrial and policy attention to closing material loops in battery value chains.

The innovation landscape is increasingly shaped by Asian companies. Our results indicate that Asia, and P.R. China in particular, has become the leading region in the development of battery circularity technologies. One reason that China is moving faster than other countries relates to the presence of most of the world’s battery manufacturing capacity in the country. Whereas the recycling markets in other regions face uncertainty about recycling feedstock availability, Chinese factories are already recycling large volumes of production scrap, which currently represents the main source of recycling feedstock. One prominent example is Brunp – the recycling subsidiary of CATL, the world’s largest battery manufacturer – which has emerged as one of the most active innovators in battery recycling technologies.

Historically, leadership in internationally patented recycling technologies was more diversified. Until around 2019, Japanese and Korean companies, including major automotive and battery manufacturers, played a leading role in patenting activity. This shift highlights how closely battery circularity innovation is linked to developments in battery manufacturing itself. Companies that dominate battery production often possess structural advantages in recycling, including technological expertise, supply chain integration and access to manufacturing residues.

These dynamics have important implications for the future structure of battery value chains. Countries that combine strong battery manufacturing capacity with recycling technologies may be well positioned to capture value from secondary materials and reduce reliance on imported raw materials. However, recycling alone will not eliminate the need for primary extraction in the coming decades, particularly while the stock of batteries reaching their end of life remains relatively limited. Circularity should therefore be seen as one element of a broader resource strategy that also includes diversified sourcing, responsible mining and improvements in material efficiency.

Focus on Europe: policy momentum and an evolving innovation ecosystem

Europe occupies a distinctive position: while Asian companies dominate the list of top patent applicants in battery circularity, European actors continue to contribute significantly to high-value international inventions, accounting for around one fifth of international patent families in the field. Europe also hosts a diverse innovation ecosystem that includes industrial companies such as Umicore and BASF, research organisations like CEA, universities and emerging startups.

Recent European policy initiatives increasingly seek to strengthen this ecosystem while linking battery circularity to broader goals of critical materials security and industrial competitiveness. In addition, initiatives such as the proposed 2026 Industrial Accelerator Act will support the development of integrated battery value chains that could include circularity-related technologies. At present, the European regulatory framework in this area, including sustainability and recycled-content criteria for battery supplies, is one of the most advanced worldwide.

Outlook

The role of battery circularity as a source of mineral supplies is likely to expand significantly. This will support efforts to mitigate environmental impacts and strengthen competitiveness. The regions that successfully attract investment and generate economic value will be those that manage the policy challenges and support innovation.

One key policy challenge is to ensure that circularity develops alongside other pillars of the critical raw materials strategy. Regulations can enhance market-based incentives to invest, but it is important that they reflect real-world expectations for battery supply and demand. The looming gap between the number of innovators seeking to scale up this decade and the availability of end-of-life batteries means that many of them face a wide “valley of death”. The overcapacity that already exists in China means that recycling plants would have an average utilisation rate of only 20% today, even if all the available material in China were collected and processed.

In advanced economies, the potential lack of sufficient off-takers for recycled minerals – such as companies producing cathode active materials – raises further challenges around effective supply chain diversification and investment in facilities that can use these recycled outputs, or partnerships with companies overseas that can, with Korea being an option in this regard. Patient capital and government funding are therefore likely to be needed to ensure that a variety of promising approaches can be tested and refined, including novel pricing schemes and business models. Competing battery circularity innovators will all need some access to the limited flows of waste material in the coming years. They may also need access to financial support to manage the volatility of mineral prices and the changing nature of battery chemistry: batteries containing iron and phosphorous have fewer valuable metals than those containing nickel, manganese and cobalt.

Continued innovation will be important to further reduce the costs of battery recycling, ensure that it is adapted to the latest battery chemistries, and address the energy intensity and environmental impacts of the processing steps. Innovation could help overcome disadvantages faced by regions with high energy prices and strong regulations for the management of waste in relation to processes such as hydrometallurgy.

4. Bibliography

List of scholarly sources (articles, sections)

Battery Pass Consortium, 2023] Battery Pass Consortium, 2023, “Battery Passport Content Guidance for the EU Battery Passport”
https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance.pdf

Baum et al., 2022] Z.J. Baum, R.E. Bird, X. Yu, and J. Ma,Ma, 2022, “Lithium-ion battery recycling: Overview of techniques and trends”, ACS Energy Letters, 7(2), 712–719
https://doi.org/10.1021/acsenergylett.1c02602

CalRecycle, 2024] CalRecycle, 2024, “SB 1215 Covered Battery-Embedded Products”
https://calrecycle.ca.gov/electronics/embeddedbatteries/

Chemical & Engineering News, 2023] Chemical & Engineering News, 2023: “Lithium-ion battery recycling goes large”
https://cen.acs.org/environment/recycling/Lithium-ion-battery-recycling-goes/101/i38

Demey and Golzio, 2020] Y.T. Demey and D. Golzio, 2020, “Search strategies at the European Patent Office”, World Patent Information, 63, 101989
https://doi.org/10.1016/j.wpi.2020.101989

Dugoua, 2021] E. Dugoua, 2021, “Induced innovation and international environmental agreements: Evidence from the ozone regime”, Centre for Climate Change Economics and Policy Working Paper 391/Grantham Research Institute on Climate Change and the Environment Working Paper 363
https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2021/06/working-paper-363-Dugoua.pdf

European Commission, 2019] European Commission, 2019, “The European Green Deal (COM(2019) 640 final)”
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52019DC0640

European Commission, 2020] European Commission, 2020: “A new Circular Economy Action Plan: For a cleaner and more competitive Europe (COM(2020) 98 final)”
https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Commission, 2024] European Commission, “Critical Raw Materials Act] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020”
http://data.europa.eu/eli/reg/2024/1252/oj

European Commission, 2025a] European Commission, 2025, “Commission Delegated Regulation (EU) 2025/606 of 21 March 2025 supplementing Regulation (EU) 2023/1542 of the European Parliament and of the Council by establishing the methodology for calculation and verification of rates for recycling efficiency and recovery of materials from waste batteries, and the format for the documentation”
http://data.europa.eu/eli/reg_del/2025/606/oj

European Commission, 2025b] European Commission, “RESourceEU Action Plan] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS RESourceEU Action Plan Accelerating our critical raw materials strategy to adapt to a new reality (COM(2025) 945 final)”
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52025DC0945

European Commission, 2026] European Commission, “COM(2026)100 – Proposal for a Regulation on establishing a framework of measures for accelerating industrial capacity and decarbonisation in strategic sectors (Industrial Accelerator Act)”
https://single-market-economy.ec.europa.eu/publications/industrial-accelerator-act_en

European Parliament & Council of the European Union, 2023] The European Parliament & The Council of the European Union, 2023, “Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC”
http://data.europa.eu/eli/reg/2023/1542/oj

Federal Register, 2024] Federal Register, 2024, “Clean Vehicle Credits Under Sections 25E and 30D; Transfer of Credits; Critical Minerals and Battery Components; Foreign Entities of Concern”
https://www.federalregister.gov/d/2024-09094

Gerard and Lave, 2005] D.Gerard, L.B. Lave, 2005, “Implementing technology-forcing policies: The 1970 Clean Air Act Amendments and the introduction of advanced automotive emissions controls in the United States” Technological Forecasting & Social Change 72, 761
https://doi.org/10.1016/j.techfore.2004.08.003

Geslin et al., 2025] A. Geslin, L. Xu, D. Ganapathi, K. Moy, W.C. Chueh, and S. Onori, 2025, “Dynamic cycling enhances battery lifetime”, Nature Energy 10, 172–180
https://doi.org/10.1038/s41560-024-01675-8

Guelfo, et al., 2024] J.L. Guelfo, P.L. Ferguson, J. Beck, et al., 2024, “Lithium-ion battery components are at the nexus of sustainable energy and PFAS release”, Nature Communications, 15, 5548
https://doi.org/10.1038/s41467-024-49753-5

Harper et al., 2019 G. Harper, R. Sommerville, E. Kendrick, et al., 2019, “Recycling lithium-ion batteries from electric vehicles”, Nature, 575, 75–86
https://doi.org/10.1038/s41586-019-1682-5

International Energy Agency, 2024a] International Energy Agency, 2024, “Recycling of Critical Minerals: Strategies to Scale Up Recycling and Urban Mining – World Energy”
https://www.iea.org/reports/recycling-of-critical-minerals

International Energy Agency, 2024b] International Energy Agency, 2024, “Global EV Outlook 2024: Outlook for battery and energy demand”
https://www.iea.org/reports/global-ev-outlook-2024/outlook-for-battery-and-energy-demand

International Energy Agency, 2024c] International Energy Agency, 2024, “Global Critical Minerals Outlook 2024: Market review”
https://www.iea.org/reports/global-critical-minerals-outlook-2024/market-review

International Energy Agency, 2025a] International Energy Agency, 2025, “Global EV Outlook 2025: Electric vehicle batteries”
https://www.iea.org/reports/global-ev-outlook-2025/electric-vehicle-batteries

International Energy Agency, 2025b] International Energy Agency, 2025, “Strategies to scale up recycling and urban mining”, A World Energy Outlook Special Report
https://www.iea.org/reports/recycling-of-critical-minerals

International Energy Agency, 2025c] International Energy Agency, 2025, “Global Critical Minerals Outlook 2025”
https://www.iea.org/reports/global-critical-minerals-outlook-2025

International Energy Agency, 2025d] International Energy Agency, 2025, “With new export controls on critical minerals, supply concentration risks become reality”
https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality

International Energy Agency, 2025e] International Energy Agency, 2025, “Interim Provisions on the Traceability Management of Power Battery Recycling in New Energy Vehicles”
https://www.iea.org/policies/24953-interim-provisions-on-the-traceability-management-of-power-battery-recycling-in-new-energy-vehicles

International Energy Agency, 2026] International Energy Agency, 2026, “Sodium-ion battery installed and announced manufacturing capacity by chemistry and region, 2025 and 2030”
https://www.iea.org/data-and-statistics/charts/sodium-ion-battery-installed-and-announced-manufacturing-capacity-by-chemistry-and-region-2025-and-2030

Larsson, et al., 2017] F. Larsson, P. Andersson, P. Blomqvist et al., 2017, “Toxic fluoride gas emissions from lithium-ion battery fires”, Scientific Reports, 7, 10018
https://doi.org/10.1038/s41598-017-09784-z

Lombardo et al., 2026a] T. Lombardo, L. Paoli, A. Fernandez Pales, T. Gül, 2026, “Global battery markets are growing strongly – and so are the supply risks”
https://www.iea.org/commentaries/global-battery-markets-are-growing-strongly-and-so-are-the-supply-risks

Lombardo et al., 2026b] T. Lombardo, L. Paoli, A. Fernandez Pales, T. Gül, 2026, “Sodium-ion battery momentum grows, but challenges remain”
https://www.iea.org/commentaries/sodium-ion-battery-momentum-grows-but-challenges-remain

Metzger et al., 2023] P. Metzger, S. Mendonça, S.A. Silva, B. Damásio, 2023, “Battery innovation and the Circular Economy: What are patents revealing?”, Renewable Energy, 209, 516–532
https://doi.org/10.1016/j.renene.2023.03.132

National Conference of State Legislatures, 2023] National Conference of State Legislatures, 2023, “Extended Producer Responsibility”
https://documents.ncsl.org/wwwncsl/Environment/Extended-Producer-Responsibility-f01.pdf

OECD, 2009], OECD, 2009, “OECD Patent Statistics Manual”, OECD Publishing, Chapter 2 https://doi.org/10.1787/9789264056442-en
Sommerville et al. 2020] R. Sommerville, J. Shaw-Steart, V. Goodship, et al., 2002, “A review of physical processes used in the safe recycling of lithium-ion batteries”, Sustainable Materials and Technologies, 25, e00197
https://doi.org/10.1016/j.susmat.2020.e00197

Tankou et al., 2023], A. Tankou, G. Bieker, and D. Hall, 2023, “Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches”
https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf

Tong, et al., 2025], Z. Tong and X. Zhu, 2025, “A Patent Landscape Analysis on the Recycling of Lithium-Ion Battery Positive Electrode Materials: Trends, Technologies, and the Future”, Batteries, 11, 110
https://doi.org/10.3390/batteries11030110

United States Environmental Protection Agency, 2026] United States Environmental Protection Agency, 2026, “Used Lithium-Ion Batteries”
https://www.epa.gov/recycle/used-lithium-ion-batteries

Velázquez-Martínez, et al., 2019] O. Velázquez-Martínez, J. Valio, A. Santasalo-Aarnio, et al., 2019, “A critical review of lithium-ion battery recycling processes from a circular economy perspective”, Batteries, 5, 68
https://doi.org/10.3390/batteries5040068

5. Annex/Methodology

5.1 Using patent information

In essence, patents are legal rights that give patent holders the right to exclude others from commercially exploiting the patented invention. They can be valid in the country or region for which they are granted. Patents can help attract investment, secure licensing agreements and provide market exclusivity.

Accordingly, patent systems promote innovation, technology diffusion and economic growth by allowing patent holders to secure investment in research and development, education and infrastructure, while requiring them to make their inventions available to the public. The publication of patent applications is a key feature of the patent system, and creates a rich repository of technical and other content known as patent information. Patent information enables other inventors, researchers, engineers, managers, investors and policymakers to build on existing inventions, to access knowledge often unavailable elsewhere and to analyse trends in innovation and market developments. As a result, patent information is at the heart of any patent system.

Patent information enables inventors to build on the published inventions of others and thus avoid the mistake of investing in developing a solution to a problem that has already been solved and potentially protected by others. Patent information contains a wealth of technical and other information, much of which cannot be found in any other source. As the leading provider of high-quality patent information worldwide, the EPO has collected, standardised and harmonised information on more than 160 million patent documents from over 100 countries in its databases, containing more than one billion records. These databases are growing by tens of millions of records every year.

Patent information from these databases is available through numerous free and commercial patent information services provided by patent offices and service providers around the world. The information can be used for a variety of analytical purposes, such as exploring technical trends and the filing strategies of applicants, or calculating indicators of innovation activity, commercialisation and knowledge transfer.

5.2 Methodology of this EPO technology insight report

This EPO technology insight report aims to provide useful insights into specific technologies related to battery circularity.

The report is based on publicly available patent information and provides an overview of the relevant technologies.

The methodology of this report is based on a three-step process.

Step 1: Create and tune a basic dataset

A basic dataset is created, usually by using various custom search concepts such as building on keywords and on patent classification symbols for specific technologies.

It is usually necessary to remove unrelated patent documents, either automatically or manually, in order to improve the quality of the basic dataset.

The creation of a meaningful basic dataset is critical to providing a reliable basis for sound patent analysis in step 2.

Step 2: Patent data analysis

In this second step, analyses are performed on the basic dataset by aggregating the data to patent families as a representative of inventions, generating descriptive statistics, testing hypotheses and identifying patterns in the data, etc.

Step 3: Further processing and visualisation

In this third step, the data are further analysed and processed, and the results visualised and summarised.

5.3 Patent retrieval

For this report, EPO experts developed specific search strategies to identify patent documents related to specific technologies for battery circularity and refining of critical metals for batteries. An overview of these technologies is shown in the next figure.

The search strategies combine relevant keywords and patent classification symbols (see the box below headed "Technologies for battery circularity and patent classification schemes"). The search strategies were optimised for the EPO's in-house search tools. The patent classification symbols and keywords used for this report efficiently capture documents with a focus on these technologies.

The volume of search results obtained using the search methodology will increase over time due to the dynamic nature of the technical field and the patent databases, as patent documents related to battery circularity are continuously added to these databases. Accordingly, we intend to update this report in the future, which would also give us an opportunity to review the latest patent trends related to battery circularity.

Table 4.

Cartography used for this technology insight report: Detailed overview of the search concepts

Concept level 1	Concept level 2	Concept level 3	Concept level 4	Concept level 5	Definition
Circularity					Circularity refers to the design and management of battery materials and products so that they remain in use for as long as possible, are recovered at the end of the lifecycle of the battery, and are reintegrated into new batteries or other products instead of being discarded.
	Collecting				Collecting is the step where used or damaged batteries are gathered from consumers, corporate users or battery producers. Good collection processes keep batteries safe during transport and make sure they arrive at facilities that can handle them properly.
		Pre-processing			Pre-processing includes all the handling steps between collection and the main recycling processes. It focuses on making batteries safe, testing them, and getting them into a form suitable for reuse, repair, or further treatment.
			Battery stabilisation and discharge		Stabilisation and discharge are mainly about discharging remaining energy and controlling gas or electrolyte release so that batteries can be opened or shredded without causing fires or leaks. Such action eliminates the immediate safety risks posed by used batteries.
				Controlled electrical discharge	Controlled discharge safely drains the remaining electrical energy from a used battery through dedicated circuits or resistors. It prevents dangerous short circuits which can cause overheating, fires and internal damage that complicates later recycling.
				Electrolyte venting controls	Electrolyte venting controls allow controlled discharge of gases and volatile liquids from used batteries in a managed process. The goal is to prevent sudden ruptures and capture flammable or toxic vapours so they do not build up in equipment or the workplace air.
				Isolation and immobilisation	Isolation and immobilisation keep used batteries separated from each other and from conductive objects that could cause short circuits. To this end, items such as non-conductive packaging, terminal covers and packing materials are used that prevent batteries from shifting in boxes or containers.

Concept level 1	Concept level 2	Concept level 3	Concept level 4	Concept level 5	Definition
				Remote handling	Remote handling uses robots or long-reach tools so workers do not have to stand next to potentially hazardous batteries. That way, activities such as cutting, opening or moving damaged devices can be performed while keeping personnel at a safe distance in case of shocks, fires or gas releases.
				Use of non-sparking tools	Non-sparking tools are made from materials that do not create sparks when they hit metal. Using them reduces the chance of igniting flammable electrolyte vapours or gases from damaged batteries.
			Characterisation of battery type		Characterisation is mainly about identifying the kind of battery. Important aspects are its chemistry, size, shape and internal design. This information guides safe handling, sorting and the choice of the most efficient recycling or reuse path.
			Intermediate storage solutions		Intermediate storage solutions are ways to keep batteries safely stored during collection and processing. This can include fire-resistant containers, separation by chemistry and condition, and sometimes cooled or monitored rooms to reduce fire risk.
			Repurposing		Repurposing gives used batteries a “second life” instead of directly recycling them. For example, old electric-vehicle packs can be reused in stationary energy storage applications where lower performance is still acceptable.
			State of health analytics		State-of-health analytics estimate how much useful life a used battery still has. These analytics combine measurements (like capacity and internal resistance measurement) and in some cases the usage history to decide whether a battery should be reused, repaired or fully recycled.
			Tracking technologies		Tracking technologies include barcodes, radio-frequency identification (RFID) tags and digital product passports. These enable a battery to be tracked from manufacture right through to recycling. This makes it easier to understand what is inside each battery, where it came from, and how it should be handled and processed.
	Sorting and separating				Sorting and separating focus on splitting mixed battery waste into cleaner streams. Better separation leads to higher-quality recovered materials and more efficient downstream chemical processing.
		Chemical			Chemical sorting uses solvents and reagents to selectively dissolve certain components. It can help remove binders and electrolytes and separate various active materials.
			Binder and electrolyte removal		These activities use chemicals to dissolve the polymer binder in the battery that glues active powders to metal foils. Chemicals also help to wash out the electrolyte. Once those are gone, powders and foils separate more easily, giving cleaner metal and active-material streams.
			Electrochemical extraction		Electrochemical extraction uses electricity to move specific ions, such as cobalt or nickel ions, in a liquid solution onto an electrode where these ions precipitate.
			Extraction using supercritical CO_2		Supercritical carbon dioxide can penetrate battery materials and extract organic solvents and some salts. It helps to remove electrolyte materials in a controlled way from the battery, and allows solvent to be recovered without burning it.
		Mechanical			Mechanical methods rely on physical forces like cutting, crushing and screening. They break batteries apart and separate fractions by size, shape, or density.

Concept level 1	Concept level 2	Concept level 3	Concept level 4	Concept level 5	Definition
			Comminution		Comminution is the general term for breaking batteries into smaller pieces by shredding, milling or crushing. It liberates metals, plastics and powders from each other, but also mixes them, so it must be followed by additional separation steps.
			Dismantling		Dismantling means taking battery packs and modules apart, often by undoing screws, welds, and connectors. It can produce cleaner streams – such as separate housings, busbars and cells – but tends to be slower and harder to automate.
		Physical			Physical methods in this context are non-chemical techniques that exploit basic physical properties like density, magnetism or response to heat. They help refine the output from shredders and other mechanical steps.
			Binder and electrolyte removal		This is about using heat, cold or vacuum in place of solvents to removed physical binders and electrolytes. For example, cooling to very low temperatures can make physical binder brittle so that it cracks off foil materials.
		Pre-processing testing			Pre-processing testing checks batteries or shredded material before full treatment. It may measure remaining voltage, temperature, gas build-up or basic composition in order to route devices and materials into the right processing line and catch unsafe items early.
	Conditioning				Conditioning is about processing steps that restore or upgrade battery components so they can be reused rather than fully broken down. It focuses on activities such as repairing cells, cleaning collectors and rejuvenating active materials.
		Current collector			Current collectors are thin copper and aluminium foils that carry electrical current inside the battery. Conditioning them is about removing coatings and contaminants from the current collectors so that the metals can be reused directly or sold as high-quality scrap.
		Graphite electrode			The idea behind this concept is to recover and upgrade the graphite material used in battery anodes. This involves removing binder and electrolyte residues from the graphite to ensure it is of a high enough purity to be reused in new batteries.
		Relithiation and crystal repair			Relithiation and crystal repair aim to “heal” used cathode materials instead of dissolving them. By restoring lost lithium and fixing damaged crystal structures, the as-treated material can largely regain its original properties.
			Hydrothermal and solid-state relithiation		Hydrothermal relithiation treats cathode powders in hot, pressurised water together with lithium-containing chemicals. This allows lithium ions to re-enter the material and helps repair structural damage that happened during battery use.
			Molten salt/ eutectic media		This technology is about placing used cathodes in a bath of molten salts that conduct ions at moderate temperatures. Lithium ions move through the molten salt into the cathode material, and the heat plus the salt environment help heal defects in the crystal lattice of the cathode material.
		Repackaging for stationary applications			Once tested and conditioned, cells can be reassembled into new packs for stationary applications such as home or grid storage. As these applications are less demanding than electric vehicles, cells with reduced capacity can remain useful for many years.

Concept level 1	Concept level 2	Concept level 3	Concept level 4	Concept level 5	Definition
	Transformation				This concept covers processes that convert used batteries into purified raw materials for new batteries or other applications. These processes usually produce metal salts, alloys or refined powders rather than whole batteries.
		Chemical			Chemical processes dissolve or thermally treat battery materials so that specific metals and compounds can be separated and purified. These processes are key to large-scale industrial recycling.
			Electrochemical extraction		Electrochemical extraction is a process that recovers metals from solutions by causing them to precipitate onto electrodes. This method can selectively extract valuable metals, reducing the need for further chemical separation.
			Extraction using super critical CO_2		Supercritical carbon dioxide can be used as an environmentally-friendly solvent to remove remaining organics and some salts before or during chemical refining processes. This reduces contamination of the hydrometallurgical process environment and enables certain solvents to be recovered.
			Hydrometallurgy		Hydrometallurgical processes use liquid chemicals – often acids with oxidants – to dissolve metals from shredded battery materials. Metals like lithium, cobalt, nickel and manganese are then separated and purified, typically by precipitation and solvent extraction.
			Pyrometallurgy pre-treatment followed by hydrometallurgical extraction		In this hybrid process, the battery material is first heated to break down the plastics and drive off the organics, resulting in a cleaner solid residue. This residue then undergoes closed-loop hydrometallurgical processes, which operate more efficiently when organics have already been removed.
			Pyrometallurgy		Pyrometallurgy is a process in which mixed battery waste is melted with fluxes at high temperatures to form metal alloys and slag. The process handles mixed feedstocks well and needs relatively simple pre-treatment. However, it requires extensive energy input, and some elements can go lost in the slag.
	Enabling technologies				Enabling technologies are devices, measures and design choices that make collection, separation and recycling safer and more efficient. These technologies include better product design, safety systems, and process controls.
		Circularity friendly design of batteries and processes			The idea behind this concept is to design batteries and processes with the reuse and recycling of materials in mind from the outset. This includes standardising device formats, avoiding hard-to-remove glues, clearly labelling chemistries and designing process layouts that facilitate disassembly.
		Environment Health and Safety			EHS stands for environment, health and safety. It encompasses all measures that protect workers, the public and the environment throughout the entire battery lifecycle and recycling process.
			Emission control		Many lithium-ion batteries contain fluorine in their electrolytes, which can form highly corrosive acids such as hydrofluoric acid when heated or in the event of a fire. Controlling these acids requires ventilation, scrubbing systems and resistant materials to safely capture or neutralise them.
			Fire and gas hazard mitigation		Fire and gas hazard mitigation involves the use of early detection, ventilation and suppression systems to address the issues of thermal runaway and gas release. The aim is to prevent a single faulty battery from causing a larger fire or explosion and to keep air quality safe.

Concept level 1	Concept level 2	Concept level 3	Concept level 4	Concept level 5	Definition
Refining critical metals for batteries					Related technologies are processes that do not contribute directly to materials collection, separating or recycling, but help reduce the environmental footprint of mining as the main source of battery materials. They also improve long-term resource availability.
	Treat raw materials				This concept is about extracting and refining metals like lithium, nickel, and cobalt from ores, brines, or mining waste. It includes biological, chemical, physical, and hybrid processes.
		Biological			Biological processes use living organisms to extract metals. These processes typically operate at low temperatures and can handle low-grade materials, balancing speed with lower energy consumption.
			Bioleaching		Bioleaching uses microorganisms, such as bacteria or fungi, that naturally produce acids to dissolve metals from rock or waste. Although it is slower than conventional chemical leaching, it can be cheaper and more environmentally friendly for certain deposits.
			Phytomining		Phytomining involves growing special plants on metal-rich soils or mine waste. These plants absorb metals into their tissues. After harvesting and burning the plants, the metals can be recovered from the resulting ash.
		Chemical			Chemical processes rely on acids, bases and organic solvents to dissolve and separate metals. These methods are widely used in the mining industry for producing battery-grade materials.
			Direct lithium extraction		Direct lithium extraction involves pulling lithium out of brines using selective materials such as specialised sorbents, resins or membranes. This process is faster and uses less water than traditional evaporation facilities, which is important in dry regions.
			High pressure acid leaching for Ni and Co ores		This concept is about treating nickel and cobalt ores with hot, pressurised acid to efficiently dissolve the metals. The resulting solution is then processed further to produce the high-purity compounds needed for battery cathodes.
			Solvent extraction and ion exchange for metal separation and purification		Solvent extraction and ion exchange are processes to separate specific metals from mixed solutions. They enable highly pure streams to be obtained from complex leach liquids.
		Other or hybrid			This concept encompasses processes that are not covered elsewhere in the technology map. These processes often combine mechanical, chemical and, occasionally, biological elements. They are typically employed for treating more complex or lower-grade materials, such as mining tailings.
			Extraction from tailings/waste		Tailings are the sand and slurry left over from mining operations. Extracting metals from these materials transforms waste into a valuable resource and reduces the long-term environmental risk associated with storing tailings.
			Roasting and acid/ alkaline leaching		Roasting involves heating ores or waste materials in air or controlled atmospheres to alter the chemical composition of the metals. After roasting, the metals are more accessible and can be dissolved by acid or alkaline leaching, after which they are recovered from the solution.

Box: Technologies for battery circularity and patent classification schemes

Patent offices assign patent classification symbols to categorise the technical subject-matter of a patent or utility model. Patent classification symbols are defined as part of what are known as “patent classification systems”. There are various patent classification systems used today by national, regional and international patent offices.

Two patent classification systems are of particular importance.

The **International Patent Classification (IPC)** system is a hierarchical patent classification system used by the EPO and more than 100 patent offices on every continent. It breaks technologies down into eight sections with several hierarchical sub-levels. The IPC system has approximately 75 000 subdivisions, and is updated on an annual basis. Further information about the IPC system is available on a dedicated website.

The **Cooperative Patent Classification (CPC)** system builds on the IPC system and provides a more granular and detailed classification structure. The CPC system has more than 250 000 sub-divisions and is updated four times a year. It is used by more than 30 patent offices worldwide, including the EPO. Further information about the CPC system is available on the CPC website.

IPC and CPC classification symbols can be used to quickly retrieve relevant patent documents using search interfaces such as the EPO’s free search interface Espacenet, available on the EPO website.

For the purposes of this study, sub-divisions in the IPC and the CPC systems were used and combined with other search terms to restrict the resulting dataset to patent documents closely related to battery circularity. The following table shows a selection of the IPC and CPC sub-divisions used:

Sub-division	Description
B09B101	Type of solid waste
B09B2101	Type of solid waste
B01D2257	Components to be removed
B07B2200	Type of materials being separated
C22B	Production and refining of metals
G06F	Electric digital data processing
G06N	Computing arrangements based on specific computational models
H01M4	Electrodes
H01M6	Primary cells; Manufacture thereof
H01M6/52	Reclaiming serviceable parts of waste cells or batteries
H01M10	Secondary cells; Manufacture thereof
H01M10/54	Secondary cells; Manufacture thereof: Reclaiming serviceable parts of waste accumulators
H01M50	Constructional details or processes of manufacture of the non-active parts of electrochemical cells other than fuel cells, e.g. hybrid cells
Y02P10	Technologies related to metal processing
Y02W30/84	Technologies for solid state waste management: Reuse, recycling or recovery technologies: Recycling of batteries or fuel cells

5.4 Data sources and tools used

The quality of patent data analysis largely depends on the completeness, correctness and timely availability of relevant patent information in the patent databases from which the basic dataset for the subsequent analysis is extracted.

It is not possible to guarantee the absolute completeness of the relevant patent information since not all data are available from all patent offices. However, there are several patent databases with very good or excellent coverage of patent information from the main patent offices. These patent databases are mostly based on EPO worldwide patent data as a central source of prior art patent information.

EPO worldwide patent data contain bibliographic and other information on more than 160 million patent documents from more than 100 patent authorities on every continent. These data are available via the EPO's patent information products and services, and other major free and commercial patent search interfaces.

Patent searches were carried out for this EPO technology insight report using EPO worldwide patent data from the EPO's internal data platforms and search interfaces such as ANSERA[13] in order to create the basic dataset for subsequent patent analyses.

The resulting basic dataset was combined with value-added data contained from the EPO's PATSTAT product line,[14] which provided the enriched basis for the patent data analysis step and was used for further processing and visualisation of the data.

5.5 National and international patent families

To protect a single invention in multiple markets, a number of national or regional patents are required because patents are strictly territorial. A large number of patents, therefore, does not necessarily mean a large number of inventions.

A more reliable measure is to count international patent families (IPFs), each of which represents a unique invention and includes patent applications filed and published in at least two countries.

Technically speaking, an IPF is a patent family that includes a published international patent application, a published patent application at a regional patent office, or published patent applications at two or more national patent offices. The regional patent offices are the African Intellectual Property Organization (OAPI), the African Regional Intellectual Property Organization (ARIPO), the Eurasian Patent Organization (EAPO), the European Patent Office (EPO) and the Patent Office of the Cooperation Council for the Arab States of the Gulf (GCCPO).

IPFs are a standard indicator for inventions with international focus and confirmed potential. They are a reliable and neutral proxy for inventive activity because they provide a degree of control for patent quality and value by only representing inventions deemed important enough by the applicant to seek protection internationally. A relatively small proportion of applications meet this threshold. The IPF concept enables a comparison of the innovative activities of countries and companies internationally, since it creates a sufficiently homogeneous population of patent families that can be directly compared with one another, thereby reducing the national biases that often arise when comparing patent applications across different national patent offices.

For these reasons, the focus of this insight report was set on international patent families.

However, as patents are territorial rights, putting the picture for IPFs into the context of national patent families[15] was also helpful to get a clearer view of local conditions, such as regulatory and legal constraints, and

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[13] See Demey and Golzio (2020), and Scheu et al. (2006).

[14] The Autumn 2025 edition of PATSTAT Global was used for this report.

[15] Meaning sets of applications for the same invention that consist of published patent applications at a single national patent office

the role of specific countries as a location for research, manufacturing and other commercial activities in a given technical field.

5.6 Notes on the limits of the study

This report provides a snapshot of specific technologies related to battery circularity taken in the light of patent data.[16] The methodology on which this report is based can be used freely, which means that everyone can adapt the chosen search and analysis approach to their needs, for example to follow trends and developments in other established or emerging technical fields.

This report makes use of publicly available EPO worldwide patent data as well as EPO in-house and publicly available search and analysis tools.

Like many patent analyses, this report is based on specific search strategies combining keywords and patent classification symbols.

For most patent analyses, it is impossible to simultaneously achieve 100% recall, i.e. to retrieve as many relevant documents as possible and 100% precision, which is to exclude as many non-relevant documents as possible. This study is no exception. The search queries chosen to create the basic dataset for the selected battery circularity technologies were designed to strike a balance between recall and precision in order to provide a meaningful overview of the field.

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[16] Date of extraction of the basic dataset from the EPO's internal data platform: March 2026. The basic dataset was combined with data from the EPO's PATSTAT product line (Autumn 2025 edition), which used backfile data extracted from the EPO's master documentation database (DOCDB) in July 2025.

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