Supplementary Information:

The geostrategic race for leadership in future electric vehicle battery technologies

André Hemmelder[1], Frank Tietze[2], Simon Lux[1,3], Jens Leker[1,4], Lars Jahnke[1], and Stephan von Delft[1,5]*

[1] Institute of Business Administration at the Department of Chemistry and Pharmacy, University of Münster, Leonardo Campus 1, 48149 Münster, Germany.

[2] Innovation and Intellectual Property Management (IIPM) Laboratory, Centre for Technology Management (CTM), Institute for Manufacturing (IfM), Department of Engineering, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS, United Kingdom.

[3] Fraunhofer Research Institution for Battery Cell Production (FFB), Bergiusstr. 8, 48165 Münster, Germany.

[4] Helmholtz Institute Münster, IMD-4, Forschungszentrum Jülich GmbH, Corrensstr. 46, 48149 Münster, Germany.

[5] University of Glasgow, Adam Smith Business School, Glasgow G12 8QQ, United Kingdom.

[*] Corresponding author, E-Mail address: andre.hemmelder@uni-muenster.de

1. Supplementary Note 1. Analysing the battery policy reports.

Supplementary Note 1 presents the results of an analysis of 24 policy reports from leading EV battery markets (Supplementary Table S1), which were used to identify relevant future battery technologies to be included in the comparative analysis.

Supplementary Table S1: *Technology competitiveness strategies for future battery technologies a) of China, Europe, and the United States, and b) of Japan, and South Korea.*

a)	China	Europe	United States
Overall focus	Strengthen domestic resource exploration and recycling and optimise overseas supply; for a long time China massively relied on demand-side policies but is now shifting more and more toward a targeted battery strategy with increasing supply-side measures[1]	Strong focus on establishing a domestic lithium-ion battery supply chain (especially production in Europe)[2] and reducing material import dependencies, using recycling for state-of-the-art EV batteries at an early stage[3]; improving LIB cell design, materials, production technologies and recycling	A secure domestic battery materials and technology supply chain (reducing material dependency from others); *Short-term objective (2025):* Improving domestic LIB value chain and focus on Next-Gen LIB; *Long-term objective (2030):* Li-SSB and Li metal (Li-S, Li-air)[4]
High-energy	Both state-of-the-art NMC-based LIB[5] and future Li-SSB and Li-S batteries[6]	Both state-of-the-art NMC-based LIB and Next-Gen LIB, Li-SSB, Li-air, Li-S batteries[2,7,8]	Both state-of-the-art NMC-based LIB and Next-Gen LIB, Li-SSB, Li-air and Li-S batteries[4]
Low-cost	Both state-of-the-art LFP-based LIB[5] and non-lithium-based batteries, especially sodium-ion batteries	Future non-lithium-based batteries (NMIB and SIB) [2,8]	None
Technological strategy	Technology-diverse approach (focus on both low-cost and high-energy future batteries, given its advantage in state-of-the-art technologies)	Short-term focus on state-of-the-art batteries; mid-term focus on future high-energy batteries; long-term focus on future low-cost batteries	Less technology-diverse approach; focus on high-energy batteries
Mobility focus	New energy vehicles (BEV, HEV, PHEV, FCEV); achieve more than 50% NEV sales for total vehicle sales and more than 95% of NEV full electric by 2035[9]	Electrification of all new cars and vans	Zero-emission medium- and heavy-duty commercial vehicles
Driving force	Government-driven: Most influence by ministries, but increasing influence of intermediary organisations and key entrepreneurs on policy making	Driven by the European Commission, political and industrial associations (e.g., IPCEI Batteries, European Battery Alliance (EBA), Batteries European Partnership	Government-driven: Strong support of the Biden administration for future EV batteries: IRA offers substantial incentives to compete against China’s dominance

		Association (BEPA), Batteries Europe), as well as national governmental agencies	
Funding strategies	➢ All-solid-state lithium-metal battery technologies (US$6.7mn for battery projects)[9] ➢ All-climate battery technologies (US$8.3mn)[9] ➢ High-energy density lithium metal-based secondary batteries (approx. US$ 2.6mn for battery projects)[9] ➢ Low-cost LIB (LFP), Li-SSB, Li-S for energy storage and smart grid (approx. US$13.8mn for battery projects)[9] ➢ Funding focuses on progress in specific battery technologies, both high-energy and low-cost [advantage: domestic battery value chain is established]	➢ Two IPCEIs (€6.1bn (US$6.9bn) in total, paid by the member states) to support battery production[1] ➢ Horizon 2020/Europe calls, in cooperation with the BATT4EU partnerships (US$319.9mn EU contribution in 2021/2022 work program) for R&D activities[1] ➢ European Investment Bank support (more than US$1.1bn of financing in 2020, leveraging US$5.1bn in total)[1] ➢ Individual EU countries are using the Recovery Fund to invest in the battery sector and gigafactories.[1] ➢ Horizon Europe Programme and Co-Programme Partnership Batt4EU for domestic battery value chain (US$102.7bn)[10] ➢ Temporary Crisis Transition Framework (TCTF) to support key sectors for the transition to a net-zero economy (battery manufacturing, recycling, raw materials and others) (US$1.4bn)[10] ➢ Innovation Fund for clean energy (not specific) (US$40.9bn)[10] ➢ Funding focus on domestic supply chains (and recycling) (infrastructure/ecosystem focus, not on specific battery technological directions)	➢ High public investments in clean technologies (US$2bn) ➢ Bipartisan Infrastructure Act: Investments in a domestic battery supply chain (over US$6bn)[11] ➢ DOEs Loan Programs Office (LPO): loans to manufacturers of advanced technology vehicle battery cells (US$17bn)[11] ➢ DOE's Funding Programs: e.g., for battery materials processing and battery manufacturing and EV battery recycling and second life applications (US$3.1bn)[11] ➢ Inflation Reduction Act (IRA) (US$369bn)[11] ➢ Investing in America Agenda: for domestic supply chains (US$14bn)[11] ➢ Under the Bipartisan Infrastructure Law, the DOE will fund projects for domestic advanced battery manufacturing and recycling with US$2.91bn[12] ➢ Funding focus on domestic supply chains (and recycling) (infrastructure/ecosystem focus, not on specific battery technological directions)
Intellectual property strategic direction	Strengthening IP protection to implement the national IP strategy and encourage researchers to develop high-value IP rights in the field of new energy vehicles to enhance enforcement against infringement of IP rights[13]	Collaboration between BATT4EU and member states aims to facilitate the exploitation of the IP generated by the partnerships' R&I actions to boost national and regional initiatives[8];	R&D will be supported by strong IP protection and rapid movement of innovations from lab to market through public-private R&D partnerships like those established in the semiconductor industry.[4]

Geographic orientation	Established domestic battery value chain and optimise overseas supply[9]	Domestic battery value chain[10]	Domestic battery value chain[4]

b)	**Japan**	**South Korea**
Overall focus	Strong focus on the supply side and strategically planned the R&D strategies with roadmaps and milestones[14], importance of securing the manufacturing base[15], technological evolution of all-solid-state lithium-ion batteries[15]	Strong focus on establishing and diversifying the domestic supply chain and expanding domestic production[16]; The K-Battery development strategy shows a clear R&D focus on commercialising three types of advanced batteries: Li-SSB, Li-S and lithium-metal batteries by 2027, 2025 and 2028 respectively[17]
High-energy	Strong focus on all-solid-state lithium-ion batteries[15]	Research priorities on all-solid-state, Li-S, and lithium-metal (incl. lithium metal-air) batteries[1,16,17]
Low-cost	Less focus on low-cost batteries; alternative batteries including zinc anode/fluoride batteries[1]	Less focus on low-cost batteries[1]
Technological strategy	➢ Accelerating technological development to lead the world in the commercialisation of future batteries, including all-solid-state batteries (full-scale commercialisation around 2030), and steadily capture the future battery market. ➢ Strengthen investment through public-private/industry-academia partnerships[15]	3 core goals[17]: I. Promoting large-scale R&D programs in the form of public-private partnerships. II. Establishing a cooperation-based ecosystem for a sustainable supply chain. III. Promoting public and private demands for rechargeable battery[17].
Mobility focus	➢ Environmental improvements for the promotion of EVs[15] ➢ For passenger vehicles, electrified vehicles will account for 100% of new vehicle sales by 2035.[18] ➢ As for commercial vehicles, aiming for electrified vehicles to account for 20-30% of new light vehicle sales by 2030 and electrified vehicles and decarbonized fuel vehicles to account for 100% by 2040.[18] ➢ For heavy vehicles, aiming for an advanced introduction of 5,000 vehicles in the 2020s and setting a target for 2040 electrified vehicle penetration by 2030.[18]	Objectives: − Accumulated sales of 2.83 million eco-friendly cars (51% new cars) by 2025 projecting 7.85 million by 2030 − Reduce 8% of GHG (compared to 2017) by 2025 projecting 24% by 2030[19] − 100% emission-free vehicles until 2050[16]

Driving force	Japan aims to not leave it solely to the private sector, but the government will also support large-scale investment[15]; strategic formation of global alliances and global standards[15]	Battery policy and programs are set by the central government[1]. However, industry is strongly involved in the decision-making process and investment measures.[1,16]
Funding strategies	➢ NEDO is implementing the Green Innovation Fund (US$13.9bn)[14,20], with US$830mn focused on high-performance batteries, battery materials, and recycling technology[1,21] ➢ The Green Innovation Fund shall induce private companies to invest approx. estimated US$30.7 trillion[18] ➢ Not solely the private sector, but governmental support through large-scale investment to strengthen the manufacturing infrastructure for liquid LIBs, including securing upstream resources, and establishing a domestic manufacturing infrastructure.[15] ➢ NEDO R&D projects: approx.: US$ 34-41mn per year) for the development of material evaluation technology for SSBs and the development of alternative batteries.[1] ➢ Green Growth Strategy[18] ➢ METI's support for battery production, introduction of clean vehicles and stationary batteries (total US$1.1bn in FY 2021-2022), and securing raw materials through JOGMEC, etc.[1] ➢ A new Transition Bond is planned under the Basic Plan for GX, which envisages public-private investment of 48.3 bn yen (US$336,4mn).[1,22]	➢ Not only supporting the promotion of its EV-industry but also providing direct support for its battery manufacturers, e.g. by giving large tax credits[1] ➢ As a unique feature of the national strategy, three large private companies are going to invest a large amount (about US$ 32.8bn) together with the government[1] ➢ Korean New Deal – the pillar Green New Deal – upgraded in 2021 (Green New Deal 2.0): Total for Korean New Deal: US$159.7bn (US$53.3bn for the pillar Green New Deal)[16] ➢ Incentive Programmes of Export-Import Bank of Korea and Korea Development Bank: US$1.1bn)[16]
Intellectual property strategic direction	Targeting standardisation and intellectual property[14]	Good positioning at IP for Li-air and Li-S battery technologies[1]
Geographic orientation	Establish a domestic battery manufacturing infrastructure for liquid LIBs and strategic development of overseas operations to ensure a global presence[15]	Establish and diversify the domestic supply chain and expand domestic production[16]

2. Supplementary Note 2. Review of the state-of-the-art and differentiating the study from existing literature.

Supplementary Note 2 presents the results of the literature review. Supplementary Table S2 provides an overview of the identified relevant patent analyses of different battery technologies at the technology level for strategic decision-making.

Supplementary Table S2: *Review of the current state of research in the field using patent analysis to investigate the technological race for leadership in future battery technologies for future electromobility.*

Publications	Analysis objective		Geographical scope							Battery technologies								Data base	
	Geostrat. Leadersh.	other	Global	Europe	China	US	Japan	South Korea	other	SoA LIB	Next-Gen LIB	Li-SSB	Li-air	Li-S	SIB	NMIB	other	Patents	other
Karkar et al. (2024)		●	🌐									🔋						📄	
Kim et al. (2024)		●	🌐									🔋						📄	
Liu et al. (2024)		●	🌐									🔋						📄	●
Yuan and Yuan (2024)		●	🌐									🔋						📄	
Block and Song (2023)		●	🌐									🔋						📄	
Koten (2023)		●	🌐							🔋			🔋				●	📄	
Metzger et al. (2023)		●	🌐							🔋		🔋		🔋	🔋		●	📄	
Silva et al. (2023)		●		🇩🇪	🇨🇳	🇺🇸	🇯🇵	🇰🇷	●	🔋			🔋	🔋			●	📄	
Altenburg et al. (2022)	♟			🇩🇪	🇨🇳	🇺🇸	🇯🇵	🇰🇷		🔋							●	📄	●
Block and Song (2022)		●	🌐							🔋		🔋						📄	
Moreno-Brieva and Merino-Moreno (2021)	♟			🇩🇪	🇨🇳	🇺🇸	🇯🇵	🇰🇷		🔋								📄	
Mejia and Kajikawa (2020)		●	🌐									🔋		🔋				📄	●
Aaldering and Song (2019)		●		🇪🇺	🇨🇳	🇺🇸	🇯🇵	🇰🇷	●				🔋	🔋	🔋			📄	
Naumanen et al. (2019)	♟			🇪🇺	🇨🇳	🇺🇸	🇯🇵			🔋							●	📄	●
Gibson et al. (2017)		●	🌐							🔋			🔋				●	📄	●
Krätzig and Sick (2017)		●	🌐							🔋		🔋	🔋	🔋	🔋			📄	
Lee et al. (2017)	♟			🇬🇧🇩🇪🇫🇷		🇺🇸	🇯🇵	🇰🇷	●	🔋							●	📄	●
Zhang et al. (2017)		●			🇨🇳					🔋			🔋				●	📄	
Sutopo et al. (2013)	♟			🇪🇺	🇨🇳	🇺🇸	🇯🇵	🇰🇷	●	🔋							●	📄	●
This study	♟			🇬🇧🇪🇺	🇨🇳	🇺🇸	🇯🇵	🇰🇷	●	🔋	🔋	🔋	🔋	🔋	🔋	🔋		📄	

Several prior studies used patent analyses to examine future battery technologies, but no comprehensive analysis of global technology leadership exist to date. Prior studies are briefly summarized below:

Karkar et al. (2024)[23] reviewed the potential of Li-SSB technology, focusing on patents held by leading companies such as Toyota, Samsung, and LG, which together account for over 3,400 patents and two-thirds of global production in the field. Their qualitative analysis includes patents held by a further 15 companies, aiming to provide insights into different strategies in Li-SSB technology. **Kim et al. (2024)**[24] forecasted the commercialization of Li-SSB technology and identified the dominant solid electrolyte type. Their analysis of Li-SSB patents from 2000 to 2020 indicates a shift to the growth phase, with oxide-based electrolytes leading, followed by sulphide- and polymer-based options. **Liu et al. (2024)**[25] developed an integrated approach to map technology evolution paths from scientific publications and patents, addressing the limitations of existing methods. Through an empirical study of Li-SSB technology, they validated the effectiveness of the method in predicting evolutionary trends and identifying innovation opportunities for companies. **Yuan and Yuan (2024)**[26] used natural language processing to analyze patents, revealing increasing innovation activity in Li-SSB development. Advances focus on electrolyte technology to improve conductivity and stability, while opportunities include cost reduction and lifetime extension. Their analysis provides insights into advances and opportunities in Li-SSBs. **Block and Song (2023)**[27] presented a novel analytical framework that uses patent claims from Li-SSB patents to extract material information. They employed network analysis to construct material networks and quantify assignees' chemical portfolios, providing insights into the battery patent landscape and supporting material discovery strategies. **Koten (2023)**[28] examined technology forecasting with a focus on EV batteries. Using methods such as patent analysis and pearl-curve forecasting, the study aims to provide insights into future battery technologies. It compared different forecasting methods and analyzed different types of batteries in the automotive industry. This guided resource allocation and investment decisions. **Metzger et al. (2023)**[29] analyzed over 90,000 secondary battery innovations using international patent families. This research highlighted the role of these innovations in the transition to a closed-loop circular economy. They observed a global acceleration of innovation, mainly from Asia, and identified emerging technology pathways such as Li-SSBs, Li-S batteries, redox-flow batteries, and SIBs. Their method provides insights into the circular characteristics of batteries. **Silva et al. (2023)**[30] provided an assessment of battery innovation trends and developments by analyzing over 700,000 patents from 2005-2019, identifying leading patent applicants and countries, examining different battery designs (including LIB, Li-air and Li-S batteries) and components, and proposing a battery innovation typology based on incremental/radical and product/process innovation. **Block and Song (2022)**[31] introduced a patent-based analytical framework to uncover the latent knowledge structure of technological domains, focusing on Li-SSB technology, comparing it with LIB technology and identifying key factors driving innovation and collaboration, particularly in the context of EVs, with the aim of facilitating coordinated R&D efforts and sustainable technology development. **Mejia and Kajikawa (2020)**[32] analyzed 48,045 articles and 56,501 patents on energy storage to identify emerging topics in academia and industry. They found a focus on optimizing Li-S batteries in academia and electrical digital computing for multi-power systems in industry. The study highlights the important role of industry in advancing new energy storage technologies and suggests opportunities for collaboration. **Aaldering and Song (2019)**[33] investigated the technological development trajectory of post-LIB technologies. The study included Li-air batteries, Li-S batteries, and SIBs. Patent data analysis was used to identify research trends, predict the future relevance of knowledge areas, and highlight the dynamics of technology convergence. The study provided insights for R&D planning that enable strategic adjustments in the pursuit of clean energy and green chemistry development. **Gibson et al. (2017)**[34] used technology forecasting with data envelopment analysis to predict future battery performance characteristics and compared them with US Department of Energy (DOE) range targets to assess their sufficiency for EVs. They found that incremental improvements in current battery technologies are insufficient to meet DOE performance targets for a longer range. These findings highlight the need to develop new battery technologies. **Krätzig and Sick (2017)**[35] developed a patent-based method to identify strategic reactions of companies towards technological change. This method focused on cell manufacturing companies in the LIB and post-LIB technologies and aimed to provide early insights for technology managers to assess investment options effectively. **Zhang et al. (2017)**[36] analyzed trends, patent types, multidisciplinary systems, and R&D cooperation in EV battery technology based on patent application data. They identified LIBs as the main future trend and highlighting the importance of multidisciplinary integration and R&D cooperation with government policy support to drive breakthroughs in this field.

Moreover, a small number of prior studies used patent analyses to examine the race for technology leadership in the field of state-of-the-art LIBs. These are summarized here:

Altenburg et al. (2022)[37] analyzed the technological capabilities and international competitiveness of the Chinese EV industry by combining patent data and qualitative analyses of subsector trends. The study revealed China's leapfrogging advancements in electric buses and LIBs, as well as its rapid progress in passenger vehicles. The findings underline the role of ambitious green transformation policies in driving catch-up and competitiveness. **Moreno-Brieva and Merino-Moreno (2021)**[38] assessed the positioning of leading countries in LIB technology generation. The study examined the existing geostrategic support between them using novel and established indexes. It revealed China's focus on technological regimes. In contrast, the United States, Germany, South Korea, and Japan prioritize scientific regimes. This results in direct technological competition between China and South Korea. Germany and Japan provide support in this competitive landscape. **Naumanen et al. (2019)**[39] analyzed publications and patents to investigate the development of heavy-duty electric battery vehicles in China, the EU, Japan and the United States. Using Latent Dirichlet Allocation, they identified emerging technology areas from more than 25,000 references since 2010. Their study focuses on battery technologies and shows that China leads in raw material reserves and production, followed by the United States, while Japan's contribution is limited due to its narrow natural resource base. **Lee et al. (2017)**[40] identified indicators for analyzing the competitiveness of energy technologies in major countries. They used an index based on patents and scientific publications. The researchers conducted an empirical analysis of nine measurement variables for photovoltaics, fuel cells, and secondary batteries in eight major countries. **Sutopo et al. (2013)**[41] analyzed the trade-offs between different battery technologies for EVs by mapping their performance characteristics. They placed particular focus on energy and power density requirements. They also evaluated global market shares, patents and publications related to batteries to assess the competitiveness of countries. Additionally,they discussed potential future energy storage technologies to improve battery performance.

In summary, we conclude that, to the best of our knowledge, prior research has not yet examined the technological race for leadership in future battery technologies for future electric vehicles using patent analysis across regions. To address this gap, our study provides findings from a three-stage cross-regional comparative analysis focusing on patenting quantity, patenting quality and patenting trajectories for technologies identified through literature analysis, policy reports and expert consultations.

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3. Supplementary Note 3. Figures and Tables.

	High-energy	Low-cost
Lithium-based future batteries	Next-Gen LIB 3,109 patent families Li-SSB 12,161 patent families Li-S batteries 5,074 patent families Li air batteries 957 patent families	
Non-lithium-based future batteries		Sodium-ion batteries 8,402 patent families New metal-ion batteries 2,869 patent families
State-of-the-art LIBs	NMC-based LIB 13,529 patent families	LFP-based LIB 4,058 patent families

Σ = 50,159 patent families (32,572 future battery + 17,587 state-of-the-art LIB patent families)

Duplication check: No duplicates in the different data sets; i.e. in total 50,159 different patent families!

Supplementary Figure S1: Overview of patent datasets for the eight sample battery technologies. *The batteries are categorized according to their strategic role in electromobility, including low-cost and high-energy batteries, as well as future lithium-based batteries, non-lithium-based batteries and state-of-the-art reference lithium-ion batteries. The number of patent families in each dataset is indicated.*

Supplementary Table S3: Patent search queries for the entire battery patent dataset (n=50,159). *The table shows the patent search strategies for the state-of-the-art reference technologies NMC-based LIB (n=13,529) and LFP-based LIB (n=4,058) as well as for the future batteries Next-Gen LIB (n=3,109), Li-SSB (n=12,161), Li-S batteries (n=5,074), Li-air batteries (n=957), SIBs (n=8,402), and NMIBs (n=2,869); where n = number of DWPI patent families for each battery technology and N = sum of DWPI patent families across all battery technologies.*

Patent Search Query for state-of-the-art NMC-based LIB Patents:

CTB=((lithium OR (lithium ADJ1 ion)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*)))
AND CPC=(H01M00100525 OR H01M004405 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300* OR H01M0004131 OR H01M00041391)
NOT CPC=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)
NOT CTB=((lithium ADJ1 metal) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2))
NOT CTB=((((lithium OR Li) ADJ3 iron ADJ3 phosphate) OR LFP OR LiFePO4 OR (lithium ADJ3 ferrophosphate)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*) OR cathode* OR electrode*))
AND (**CPC**=(H01M0004131 OR H01M00041391) **OR CTB**=(NMC* OR NCM* OR (((nickel NEAR3 manganese NEAR3 cobalt) OR (Ni NEAR3 Mn NEAR3 Co)) ADJ3 (oxid* OR batter* OR cell* OR accumulator* OR (stor* ADJ1 device*) OR cathod* OR (active ADJ1 material*) OR material*))))
NOT CPC=(H01M0004386 OR H01M00041395)

NOT CTB=((next ADJ3 generation) OR NMC8* OR NMC9* OR NCM9* OR NCM8* OR ((silicon OR Si OR silicium) ADJ3 (electrode* OR anode* OR material* OR composite*)) OR (high ADJ1 nickel) OR ((next ADJ1 (gen OR generation)) ADJ1 (LIB OR ((li OR lithium) ADJ1 ion ADJ1 batter*))))

<u>Patent Search Query for state-of-the-art LFP-based LIB Patents:</u>

CTB=(((lithium OR (lithium ADJ1 ion)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*))))
AND CPC=(H01M00100525 OR H01M004405 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300*)
NOT CPC=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)
NOT CTB=(((lithium ADJ1 metal) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2)))
AND CTB=(((((lithium OR Li) ADJ3 iron ADJ1 phosphate) OR LFP OR LiFePO4 OR (lithium ADJ3 ferrophosphate)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*))) OR ((lithium OR Li) ADJ3 iron* ADJ3 phosphat* ADJ3 (cathode* OR electrode*)))
NOT CTB=(((next ADJ3 generation) OR NMC* OR NCM* OR NCA* OR ((silicon OR Si OR silicium) ADJ3 (electrode OR anode OR material OR composite)) OR (high ADJ1 nickel) OR (((next ADJ1 (gen OR generation))) ADJ1 (LIB OR ((li OR lithium) ADJ1 ion ADJ1 (battery OR batteries))))))
NOT CPC=(H01M0004386 OR H01M00041395 OR H01M0004131 OR H01M00041391)

<u>Patent Search Query for Next-Gen LIB Patents:</u>

CTB=((lithium OR (lithium ADJ1 ion)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*)))
AND CPC=(H01M00100525 OR H01M004405 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300* OR H01M0004131 OR H01M00041391)
NOT CPC=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)
NOT CTB=((lithium ADJ1 metal) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2))
NOT CTB=((((lithium OR Li) ADJ3 iron ADJ3 phosphate) OR LFP OR LiFePO4 OR (lithium ADJ3 ferrophosphate)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*) OR cathode* OR electrode*))
AND (**CPC**=(H01M0004131 OR H01M00041391) OR CTB=(NMC* OR NCM* OR (((nickel NEAR3 manganese NEAR3 cobalt) OR (Ni NEAR3 Mn NEAR3 Co)) ADJ3 (oxid* OR batter* OR cell* OR accumulator* OR (stor* ADJ1 device*) OR cathod* OR (active ADJ1 material*) OR material*))))
AND (CTB=((next ADJ3 generation) OR NMC8* OR NMC9* OR NCM9* OR NCM8* OR ((silicon OR Si OR silicium) ADJ3 (electrode* OR anode* OR material* OR composite*)) OR (high ADJ1 nickel) OR ((next ADJ1 (gen OR generation)) ADJ1 (LIB OR ((li OR lithium) ADJ1 ion ADJ1 batter*)))) **OR CPC**=(H01M0004386 OR H01M00041395))

NOT CTB=(NMC6* OR NCM6* OR NMC5* OR NCM5* OR NMC4* OR NCM4* OR NMC3* OR NCM3* OR NMC2* OR NCM2* OR NMC1* OR NCM1*)

Patent Search Query for Lithium-Solid-State Battery Patents:

CPC=(H01M0010052 OR H01M00100525 OR H01M004382 OR H01M004405 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300*)
AND CTB=(((lithium OR (lithium ADJ1 ion) OR (lithium ADJ1 metal)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*))))
NOT CTB=((lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2))
AND CPC=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)

Patent Search Query for Lithium-Sulfur Battery Patents:

CPC=(H01M0010052 OR H01M0004382 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300*)
AND CTB=(((lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*)))
NOT CTB=((lithium ADJ1 ion) OR (li ADJ1 ion) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2))

Patent Search Query for Lithium-Air Battery Patents:

CPC=(H01M0010052 OR H01M0004382 OR Y02E006010 OR Y02T001070 OR H01M000413 OR H01M2200* OR H01M2220* OR H01M2300*)
AND CTB=(((lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*)))
NOT CTB=((lithium ADJ1 ion) OR (li ADJ1 ion) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2))

Patent Search Query for Sodium-Ion Battery Patents:

CPC=(H01M0010* OR H01M004* OR H01M0050* OR H01M2200* OR H01M2220* OR H01M2300* OR Y02T001070* OR Y02E006010*) **AND CTB**=(((sodium ADJ1 ion) OR (Na ADJ1 ion) OR (sodium ADJ3 intercalation) OR (sodium ADJ3 insertion)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 device*))) **NOT CTB**=((lithium ADJ1 ion) OR (li ADJ1 ion) OR (sodium ADJ1 sul*ur) OR (Na ADJ1 sul*ur) OR (sodium ADJ1 air) OR (sodium ADJ1 oxygen) OR (Na ADJ1 air) OR (Na ADJ1 oxygen) OR (Na ADJ1 O2) OR (sodium ADJ1 O2) OR (solid* ADJ1 batter*) OR (solid ADJ1 state*) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2)); **NOT CPC**=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)
<u>Patent Search Query for New Metal-Ion Battery Patents:</u> **CPC**=(H01M0010* OR H01M004* OR H01M0050* OR H01M2200* OR H01M2220* OR H01M002300* OR Y02T001070* OR Y02E006010*) **AND CTB**=((((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 ion) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 ion) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 intercalation) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ3 insertion)) ADJ3 (batter* OR accumulator* OR cell* OR (stor* ADJ1 devic*))) **NOT CTB**=(((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 sul*ur) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 sul*ur) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 air) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 air) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 oxygen) OR ((K OR Ca OR Mg OR Fe OR Al OR Zn) ADJ1 O2) OR ((potassium OR calcium OR magnesium OR iron OR aluminium OR zinc) ADJ1 O2) OR (solid* ADJ1 batter*) OR (solid ADJ1 state*) OR (lithium ADJ1 ion) OR (Li ADJ1 ion) OR (lithium ADJ1 air) OR (lithium ADJ1 oxygen) OR (li ADJ1 air) OR (li ADJ1 oxygen) OR (li ADJ1 O2) OR (lithium ADJ1 O2) OR (lithium ADJ1 sul*ur) OR (li ADJ1 sul*ur) OR (sodium ADJ1 ion) OR (Na ADJ1 ion) OR (sodium ADJ1 air) OR (sodium ADJ1 oxygen) OR (Na ADJ1 air) OR (Na ADJ1 oxygen) OR (Na ADJ1 O2) OR (sodium ADJ1 O2) OR (sodium ADJ1 sul*ur) OR (Na ADJ1 sul*ur)) **NOT CPC**=(H01M00100562 OR H01M00100565 OR H01M23000065 OR H01M23000068 OR H01M23000071 OR H01M23000074 OR H01M23000077 OR H01M2300008 OR H01M23000082 OR H01M23000085)

Supplementary Table S4: Overview of expert consultation conducted between July and September 2023 to identify the most promising future battery technologies.

Position	Organization	Categorization
Management team member	Fraunhofer Research Institution for Battery Cell Production FFB	Science
Research associate	Fraunhofer Research Institution for Battery Cell Production FFB	Science
Research associate	Fraunhofer Research Institution for Battery Cell Production FFB	Science
Research associate	Münster Electrochemical Energy Technology (MEET) Battery Research Center at the University of Münster	Science
Senior consultant	Porsche Consulting	Industry
Manager	Porsche Consulting	Industry
PhD student	University of Münster	Science

4. Supplementary Note 4. Literature on various PQIs and calculation of our six patent quality indicators.

a) In the literature, several composite indices were proposed to measure patent quality. These are known as Patent Quality Indices (PQIs): The three different PQIs described below, based on the work of Lanjouw and Shankerman (2004)[42], each comprise four to six individual patent value metrics combined into a composite index. These metrics include, for instance, the number of forward citations, family size, number of claims, and the generality index[43]. Three alternative definitions are provided as follows: PQI 4 includes forward citations, family size, claims, and generality; PQI 4b replaces the number of claims with corrected claims; PQI 6 adds backward citations and the grant lag index[43].

b) This section outlines the detailed calculations and methods used to determine the six quality indicators for patent portfolios across different regions and battery technologies. These indicators were used to provide a more comprehensive assessment of patent quality, as described in the Method section, addressing the limitations of existing patent quality indicators (PQIs).

Technological Relevance (TR_i) was calculated for each patent family *i* filed in a specific publication year *t* by a particular patent office *o* within the battery technology *b* according to Ernst and Omland (2011)[44] as the global forward citations of a patent family *i* (C_i) divided by the average global forward citations of all patents in the same battery technology *b* and publication year *t* ($C_{t,b}$), adjusted by the average global forward citations per patent family from the filing patent office *o* in the same publication year *t* ($C_{t,o}$). The technological relevance of a region's patent portfolio in a battery technology ($TR_{r,b}$) is determined by averaging the TR_i of all *n* patent families in the portfolio assigned to the region *r* in battery technology *b* (see Equation 1).

$$TR_{r,b} = \frac{\sum_{i=1}^{n}\left(\frac{C_i}{C_{t,b}}\cdot\frac{1}{C_{t,o}}\right)}{n} \tag{1}$$

This metric continues to be used as a patent quality indicator in various studies, including recent work by Borges Ladeira et al. (2025)[45] and Kochtekov and Almaganbetov (2021)[46].

Technological Scope ($TS_{r,b}$) (also referred to as *patent scope* or *technological breath*) depends on the diversity and number of patent classification codes (4-digit IPC codes) of patent applications within a portfolio[47]. To distinguish between technology areas, only 4-digit IPC codes at the sub-class level were considered, as defined by the DWPI, and the technological scope ($TS_{r,b}$) of a patent portfolio was calculated as the average number of IPC sub-classes per patent family *i* ($\sum IPC_i$) across all *n* patent families within the region *r* for a given battery technology *b* (see Equation 2).

$$TS_{r,b} = \frac{\sum_{i=1}^{n}\left(\sum IPC_i\right)}{n} \tag{2}$$

This metric was introduced by Lerner (1994)[47] and is still frequently used in patent studies as a valid indicator for determining patent value[43,48–50].

Grant Rate ($GR_{r,b}$) represents the proportion of granted patents relative to total filings. According to Ernst (2003)[51], it is the share of granted patents within a given patent portfolio. For each patent family *i*, the grant rate was determined by dividing the number of granted patents ($P_{r,b,i}^{granted}$) by the total number of patents ($P_{r,b,i}$). The region-specific grant rate for a particular battery technology ($GR_{r,b}$) was calculated as the mean of the grant rates across all *n* patent families in the region's portfolio (see Equation 3).

$$GR_{r,b} = \frac{\sum_{i=1}^{n}\left(\frac{P_{r,b,i}^{granted}}{P_{r,b,i}}\right)}{n} \tag{3}$$

The grant rate is widely accepted as a patent quality indicator in the literature[51]. Patent offices apply strict evaluation criteria, including novelty, inventive step, and industrial applicability. Patent applications merely represent intentions without legal protection. In contrast, granted patents have successfully passed rigorous examination and provide full legal protection. A higher grant rate therefore indicates a portfolio with innovations that better satisfy fundamental patentability requirements. This approach has been utilized in numerous studies, including Jung and Imm (2002)[52], Graham and Harhoff (2014)[53], and Schuster and Goodman (2025)[54].

Innovation Density ($ID_{r,b}$) (also referred to as *patent density* or *patent intensity*) reflects the efficiency of technological knowledge accumulation and builds on established innovation measurement frameworks by Ernst (2003)[51] and Hagedoorn and Cloodt (2003)[55], who emphasize the importance of assessing not only the volume of patents but also the concentration of innovative output per research entity. The metric measures the number of patent families per patenting organisation in a specific region *r* and battery technology *b* and was calculated by dividing patent families ($P_{r,b}$) by the number of different patent applicants ($A_{r,b}$)(see Equation 4).

$$ID_{r,b} = \frac{P_{r,b}}{A_{r,b}} \tag{4}$$

Moreover, empirical studies, such as Deng et al. (1999)[56], have shown that applicants with higher patenting activity tend to exhibit enhanced organizational performance.

Internationalization was measured using the Foreign Patent Family Ratio for regions *r* and battery technologies *b* ($FPFR_{r,b}$). This ratio was calculated by averaging the $FPFR_{r,b,i}$ values for all *n* patent families *i* in a given region *r* and battery technology *b*. Each $FPFR_{r,b,i}$ represents the proportion of foreign patents ($P_{r,b,i}^{foreign}$) to total patents within a single patent family ($P_{r,b,i}$). (see Equation 5).

$$FPFR_{r,b} = \frac{\sum_{i=1}^{n} \left(\frac{P_{r,b,i}^{foreign}}{P_{r,b,i}} \right)}{n} \quad (5)$$

Several scholars, including Lanjouw et al. (1996)[57], Lanjouw and Schankerman (2004)[42], and Reitzig (2004)[58], have shown that patent value is positively associated with the number of jurisdictions in which protection is sought. Since international filings involve substantial costs and strategic considerations, they are typically undertaken only for inventions with high expected commercial returns. The FPFR is therefore widely used as a proxy for patent quality.

Innovativeness ($I_{r,b}$) was calculated using Eigenvector centrality to assess a node's influence in a forward citation network analysis[59,60]. Patent families were treated as nodes, applicant country of origin as an attribute, and forward citations as edges. The Eigenvector centrality of a node $C_E(i)$ can be calculated using Equation (6).

$$C_E(i) = \frac{1}{\lambda} \sum_{j=1}^{n} A_{ij} x_j \quad (6)$$

Where A_{ij} representing the network's adjacency matrix, *n* the total number of nodes, x_j the relative centrality score of connected nodes, and λ the corresponding eigenvalue[59].

We conducted the analysis separately for each of the eight battery technologies. Innovativeness for each region *r* in a specific battery technology *b* was calculated as the average Eigenvector centrality of all *n* patent families *i* ($C_E(i)$)within that region and technology (see Equation 8).

$$I_{r,b} = \frac{\sum_{i=1}^{n} (C_E(i))}{n} \quad (7)$$

This metric quantifies a patent's connectedness to other influential patents in the network, with values ranging from 0 to 1[59]. Higher values indicate greater regional influence in innovation networks[59,60]. Eigenvector centrality has been widely applied in studies of innovation networks and knowledge flows, e.g., Greitemeier and Lux (2025)[61], Chai et al. (2020)[62], and Huang et al. (2018)[63].

To account for the uncertainty in the PQI composite index, we calculated 90% confidence intervals (CIs) using bootstrapping with 1000 iterations. These intervals represent a range within which we expect the true values to fall, based on the sample data. The 90% confidence level was chosen to balance precision and variability, providing a narrow yet statistically valid range for the estimates. Bootstrapping was performed by resampling the six z-standardised indicators with replacement, calculating the mean for each sample, and determining the 5th and 95th percentiles to derive the lower and upper bounds of the CIs. The random seed (42) was set to ensure reproducibility of the results. The bootstrapping process was implemented in Python using the *numpy* and *pandas* libraries, with *np.random.choice* for resampling and *np.percentile* to compute the percentiles for the CIs.

The CIs derived from this process are presented in Supplementary Table S5, which provides the range of values for the PQI composite index in the dynamic analysis. These intervals are essential for interpreting the results shown in Figure 4 of the main text, ensuring that the findings are not only robust but also statistically valid.

c) ***Supplementary Table S5: PQI values with corresponding upper and lower CI boundaries by region and battery technology for the pre- and post-2015 periods.*** *(a) SIB, (b) NMIB, (c) Next-Gen LIB, (d) Li-SSB, (e) Li-S Batteries, (f) Li-Air Batteries, (g) LFP-LIB, (h) NMC-LIB.*

a) SIBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	0.1832	-0.4806	0.7893	0.5928	-0.1455	1.3644
EU	1.0180	0.5338	1.5320	-0.1286	-1.0102	0.6542
JP	-0.0564	-0.6126	0.4455	-0.4402	-0.7338	-0.1768
KR	-0.5515	-1.1081	-0.0513	0.1730	-0.3878	0.6671

US	-0.5932	-1.1188	-0.0249	-0.1969	-0.9195	0.3603

b) NMIBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.2971	-0.9366	0.2569	0.0006	-0.7096	0.6595
EU	NaN	NaN	NaN	0.1177	-0.5321	0.6881
JP	-0.2667	-1.0394	0.3126	-0.2801	-0.6144	0.0237
KR	-0.2359	-0.7568	0.2988	0.1934	-0.5944	0.9451
US	0.7996	0.2471	1.3862	-0.0315	-0.8481	0.7067

c) Next-Gen LIBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.2658	-1.1656	0.6914	-0.3747	-1.1244	0.3265
EU	0.0369	-0.6559	0.6733	-0.2427	-0.9284	0.4251
JP	-0.0871	-0.5638	0.3253	0.5251	-0.2097	1.3595
KR	0.1407	-0.2723	0.5233	0.1209	-0.5966	0.6149
US	0.1753	-0.6265	0.8958	-0.0287	-0.5479	0.3896

d) Li-SSBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.2263	-1.1220	0.6247	-0.3797	-1.2572	0.4302
EU	0.2370	-0.3410	0.8278	-0.4210	-0.9209	0.0370
JP	0.2045	-0.2540	0.6630	0.9300	0.2711	1.6098
KR	-0.2590	-0.8805	0.2739	-0.1354	-0.3081	0.0621
US	0.0440	-0.7639	0.7772	0.0061	-0.5099	0.4657

e) Li-S batteries	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.2855	-1.0447	0.2607	0.2353	-0.6373	1.1008
EU	0.2657	-0.4790	0.9890	0.0078	-0.8204	0.8112
JP	-0.0965	-0.8597	0.4164	-0.2983	-0.8887	0.0375
KR	-0.0504	-0.8175	0.4345	0.1415	-0.4576	0.7114
US	0.1667	-0.4872	0.7727	-0.0864	-0.5070	0.3522

f) Li-air batteries	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.5047	-1.3551	0.2108	-0.1888	-0.9386	0.5173
EU	0.2171	-0.6270	1.0376	-0.1836	-0.9014	0.4645
JP	-0.2838	-0.8255	0.1430	-0.2718	-0.9775	0.1323
KR	0.1171	-0.2687	0.4372	0.5722	-0.0414	1.1247
US	0.4544	-0.1217	1.0772	0.0721	-0.6138	0.6942

g) LFP-LIBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.0527	-1.0097	0.8338	-0.2264	-0.9400	0.5043
EU	0.1446	-0.3724	0.6615	-0.2848	-0.9098	0.3994
JP	-0.4905	-0.9511	-0.2020	0.1542	-0.2597	0.5193
KR	0.4744	-0.3008	1.2539	-0.3633	-1.0551	0.2211
US	-0.0758	-0.4919	0.3242	0.7203	0.0193	1.4085

h) NMC-LIBs	<2015			≥2015		
Region	PQI	Lower CI	Upper CI	PQI	Lower CI	Upper CI
CN	-0.3023	-1.1617	0.5392	-0.4542	-1.1941	0.3674
EU	0.4202	-0.0840	0.9486	-0.3613	-0.8260	0.1033
JP	-0.0362	-0.5079	0.3985	0.3420	0.0270	0.6696
KR	-0.0577	-0.6423	0.4662	-0.0595	-0.7349	0.7010
US	-0.0239	-0.8657	0.7713	0.5330	-0.2471	1.3180

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