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The geostrategic race for leadership in future electric vehicle battery technologies†

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Global leadership in electric vehicle battery technologies has become a critical geopolitical issue. This study analyzes a dataset of 32 572 patent families across six promising future battery technologies, along with policy documents, to assess the dynamics of geostrategic competition and regional positioning. While China leads in the number of patents across all six technologies, global leadership in patent quality varies, reflecting differences in regional policies and their effectiveness. Specifically, the findings reveal diverging competitive dynamics between high-energy lithium-based technologies (*e.g.*, lithium solid-state batteries) and low-cost non-lithium-based technologies (*e.g.*, sodium-ion batteries). This suggests a need to reassess competitiveness strategies, particularly in Western regions, which currently focus on developing domestic markets for established lithium-ion battery technologies and gaining more control over today's battery supply chains. In contrast, policies in China, Japan, and South Korea prioritize investment in the future battery patent landscape, where these regions already account for nearly 85% of global patents. This highlights a growing global innovation imbalance. Moreover, there is a risk that this innovation gap will continue to widen due to increasing disparities in technological capabilities, potentially jeopardizing geostrategic autonomy for some regions. Tailored policies and targeted investments in Europe and the United States are essential to achieve competitive positioning, enhance technological autonomy, and meet climate neutrality goals.

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Broader context

Achieving a sustainable and equitable energy future is a key challenge of the 21st century, with battery technologies serving as a cornerstone for decarbonizing transport, energy storage, and broader industrial systems. As global economies shift toward electrification, technological innovation in this domain has become a critical driver of both environmental progress and economic competitiveness. However, the distribution of innovation capabilities is increasingly uneven, influenced by geopolitical dynamics, resource availability, and regional policy frameworks. Addressing this imbalance is essential to fostering global cooperation, reducing supply chain vulnerabilities, and accelerating the pace of innovation needed to meet ambitious climate goals. Studies exploring the interplay between technological leadership, policy strategies, and innovation outcomes provide valuable insights into how regions can navigate these challenges and harness emerging opportunities. This study advances this research by systematically linking patent data with policy insights to provide a novel framework for understanding geostrategic competition in future battery innovation. By focusing on future technologies beyond conventional lithium-ion systems, it offers actionable perspectives to guide policymakers, industry stakeholders, and researchers in advancing energy transitions and mitigating global disparities. It also underscores the broader implications for achieving energy equity, economic resilience, and environmental sustainability on a global scale.

Introduction

Electric vehicles (EVs) are critical for decarbonizing the transport sector and mitigating climate change.[1–7] Global EV adoption is accelerating.[7,8] For example, global sales of battery electric vehicles (BEVs) increased by nearly 10% to approximately 11 million in 2024, though with stark regional differences—China's market is booming with over 7 million BEVs sold in 2024 (+12%), while Europe experienced a decline to 1.9 million (−6%).[9] These diverging market trends reflect varying national priorities and regulatory approaches to

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transport electrification, highlighting the complex interplay of technological, economic, and policy factors shaping the global EV landscape.

Lithium-ion batteries (LIBs) are currently the most common battery technology used in EVs.[10–15] Their superior gravimetric and volumetric energy densities, compared to traditional technologies like lead-acid or nickel–metal hydride batteries, enable lightweight, compact designs that maximize efficiency, range, and reliability.[13] However, LIBs still face several challenges, including the need for even higher energy density to further extend EV ranges, degradation over multiple charge–discharge cycles, safety risks from flammable liquid electrolytes, and supply chain vulnerabilities for critical raw materials such as lithium, cobalt, nickel, and graphite.[4,10–13,16–20] While the cost of EV LIB packs has declined substantially—by approximately 90% over the last 15 years,[21] with cost-effective chemistries such as LFP reaching \$60 per kW h at the cell level[22]—the rate of cost reduction has recently slowed. Raw material price volatility, particularly for lithium, remains a challenge as demand outpaces supply.[20] This is not due to a shortage of global lithium reserves—currently estimated at 115 million tons[23]—but rather to the high geographical concentration of production, long lead times for new mining projects, declining resource quality in some regions, and associated environmental and social concerns.[24] Moreover, China controls large parts of today's LIB supply chain, while the European Union (EU), the United States (US), and other regions aim to reduce their reliance on Chinese batteries and battery materials.[25,26]

The race is on to develop future battery technologies that enable longer ranges, lower costs, faster charging times, and greater safety.[11,13,27–31] Beyond technical improvements, achieving a dominant position in these technologies offers the opportunity to shape future battery supply chains and enhance countries' strategic autonomy.[32,33] As a result, several governments have introduced technology competitiveness strategies to build domestic capacity in future battery technologies (Supplementary Note S1, ESI†). For example, the United States—through its National Blueprint for Lithium Batteries[34] and the Inflation Reduction Act[35] —and the EU—through its Strategic Action Plan on Batteries[36] and the European Green Deal[37]—aim to develop their domestic battery markets and reduce dependence on foreign suppliers. Meanwhile, building on its success in LIBs, China aims to further strengthen domestic battery research and development (R&D) through its National Key R&D Programmes.[38]

To achieve their goals for future battery technologies, several governments are also providing substantial public funding to fuel innovation. For instance, South Korea plans to invest 150 billion won (US\$15.1 billion) in the development of future battery technologies by 2030.[39] Additionally, several alliances and networks have emerged to support battery R&D, such as Japan's collaborative innovation partnership LIBTEC, which currently includes 39 companies.[40] However, differences in competitiveness strategies and technological capabilities are putting regions on distinct trajectories and positioning them differently in the ongoing global technology race. Although the corporate sector can innovate without government incentives, companies often align with government innovation policies, as these provide critical frameworks and incentives for R&D investment. A case in point is the Inflation Reduction Act: in the first two years since its enactment, US corporate and consumer investment in clean technologies totaled \$493 billion—a 71% increase compared to the two years prior, according to the Clean Investment Monitor.[41]

In this article, we analyze patents and policy documents to provide insights into the geostrategic race for leadership in future battery technologies. Patents are widely recognized as indicators of R&D activity and technological competitiveness,[42,43] offering valuable insights into emerging technologies and innovation performance.[44–49] Their analysis can uncover latent patterns that inform policymaking and strategic R&D efforts.[50–52] However, patent practices vary across sectors and countries due to differences in examination procedures, enforcement of rights,[53] and the use of alternative protection mechanisms such as trade secrets or utility models.[54] While patents cover approximately 80% of the world's technical innovation data,[55] relying solely on patent counts has inherent limitations. To address this, we integrate both patent quantity and quality to provide a more nuanced and holistic assessment of global leadership in battery technologies.

Complementing the patent analysis with an examination of technology competitiveness strategies reveals government priorities and approaches to gaining an edge in specific technologies. This study is the first to combine patent and policy perspectives to explore geostrategic competition in future battery technologies (literature review in Supplementary Note S2, ESI†), offering a novel approach that connects technological innovation with governmental strategies for competitive advantage. By synthesizing these perspectives, we assess regional positions and trajectories, providing a comprehensive view of strategic positioning, innovation activities, technological trends, government support, and objectives in future battery technologies.

Methods and data

Identifying relevant future battery technologies

We conducted a qualitative analysis of academic literature and policy documents from the leading EV markets—Europe, China, and the United States—for approximately 95% of global EV sales in 2023.[3] This analysis was supported by expert consultations from both industry and academia (Supplementary Note S3 and Table S4, ESI†). Through this process, we identified six key future battery technologies (Supplementary Note S3 and Fig. S1, ESI†). These were then categorized into two groups: lithium-based high-energy technologies (next-generation LIBs (Next-Gen LIBs), lithium solid-state batteries (Li-SSBs), lithium–sulfur batteries (Li–S batteries), and lithium–air batteries (Li–air batteries)) and non-lithium-based low-cost technologies (sodium-ion batteries (SIBs) and new metal-ion batteries (NMIBs)).[56,57] While batteries can also be used in aviation and maritime applications, this study focuses exclusively on road transportation.[58]

For benchmarking purposes, we also included two state-of-the-art LIB technologies: lithium nickel manganese cobalt oxide (NMC)-based LIBs (high-energy) and lithium iron phosphate (LFP)-based LIBs (low-cost). Given the broad range of LIB chemistries, we focus on NMC and LFP cathodes, as they are the most commercially prevalent materials for high-energy and low-cost applications, respectively.[19] This selection enables meaningful cross-regional comparisons. Although other cathode chemistries exist (*e.g.*, lithium nickel cobalt aluminum oxide (NCA), lithium manganese oxide (LMO), lithium cobalt oxide (LCO)), our focused approach minimizes potential bias by enabling complete dataset generation for each selected chemistry and the application of consistent evaluation criteria across all regions. This strategy allows for more precise analysis of regional innovation patterns within equivalent technology segments. We focused on five regions: China (CN), Europe (including the EU and United Kingdom (UK)), Japan (JP), South Korea (KR), and the United States, which together account for 98% of total patenting activity in future battery technologies.

Data collection

We retrieved patent data from Clarivate's Derwent Innovations Index, using a combination of keywords and Cooperative Patent Classification codes (Supplementary Note S3 and Table S3, ESI†). This yielded 32 572 Derwent World Patent Index (DWPI) patent families related to the six future battery technologies and 17 587 patent families for the two state-of-the-art LIB technologies, as of March 20, 2025 (Supplementary Note 3 and Fig. S1, ESI†). For the state-of-the-art LIBs, we targeted patents specific to either LFP-based or NMC-based technologies, excluding patents referencing multiple cathode chemistries (Supplementary Note 3 and Table S3, ESI†). This ensured a clear distinction between LFP (low-cost EVs) and NMC (high-energy EVs).

Patent data were collected at the DWPI family level, which consolidates all international filings associated with the same technical invention.[44] This approach ensures that a single invention filed in multiple jurisdictions is counted only once, reducing duplication across regions. A patent family consists of patents filed in various patent offices that share a common priority application, including continuations or divisional filings.[59] While a patent granted in one jurisdiction does not automatically confer protection elsewhere, international treaties such as the Patent Cooperation Treaty (PCT) help streamline the filing process. Patent examiners typically consider prior art from other jurisdictions, reducing the likelihood of the same invention being granted multiple times. Prior to analysis, the dataset was pre-processed to remove duplicates, utility models, and design patents. Patent families were then assigned to one of the five regions based on the country code of the institution listed as the first patent assignee.

Assessing regional patent portfolio competitiveness

This study defines patent quantity as the *z*-score of the absolute number of patent families in each region r for a specific battery technology b, calculated across all five analyzed regions for that technology. A negative *z*-score indicates below-average performance, while a positive *z*-score indicates above-average performance within the context of the respective technology.

In addition to patent quantity, patent quality is a crucial metric for evaluating technological innovation. Patent quality is influenced by several factors, including innovativeness, technological relevance, patenting success, and technological breadth.[42,60–64]

Several composite Patent Quality Indices (PQIs) have been proposed in the literature, notably by Lanjouw and Schankerman (2004).[65] These PQIs typically combine metrics such as forward citations, patent family size, number of claims, and generality (Supplementary Note S4a, ESI†).[66] While these established indices have contributed substantially to patent quality assessment, they present specific limitations when applied to cross-country comparisons—the focus of this study—and thus require methodological adaptations:

(1) Existing PQIs often rely on a narrow set of dimensions[66] and omit key indicators such as the international reach of a patent portfolio. For instance, patent family size may reflect filings in the same country or across multiple countries, without indicating global reach—an essential consideration for country-level comparison.

(2) As emphasized by Higham *et al.* (2021),[67] metrics like backward citations and the number of claims are often shaped by applicants' legal strategies rather than the intrinsic quality of inventions.[68–70] Such legal and institutional differences are particularly relevant in country-level analyses, where they may reflect systematic distinctions between national innovation systems rather than true differences in patent quality.

(3) Forward citation counts are influenced by both the age of a patent (older patents have more time to accumulate citations) and by citation practices at different patent offices.[60] These variations can distort cross-regional comparisons if not properly normalized.

To address these issues, we adapted—rather than fundamentally redesigned—existing PQIs by integrating six established patent quality indicators.[42,59,60,63] This modified approach enables meaningful cross-national comparisons while accounting for systematic differences between patent systems. All indicators were *z*-standardized to ensure comparability regardless of scale or unit.

The final $PQI_{r,b}$ score for each region r and battery technology b is the mean of these *z*-standardized indicators, as shown in eqn (1), and was used to interpret patent quality:

$$PQI_{r,b} = \frac{1}{n}\sum_{i=1}^{n} X_{i,r,b}, \quad \text{with } n = 6 \text{ (number of quality indicators)} \tag{1}$$

where $X_{i,r,b}$ (with r = region, and b = battery technology) represents the *z*-standardized value of the following six quality indicators:

1. Technological relevance ($TR_{r,b}$): measures the global forward citation impact of a region's patent portfolio for a given technology, normalized by publication year and citation behavior of the filing patent office.

2. Technological scope ($TS_{r,b}$): reflects the diversity of a region's patent portfolio, based on the average number of 4-digit IPC subclasses per patent family.

3. Grant rate ($GR_{r,b}$): the share of granted patents within a region's portfolio for a given technology.

4. Innovation density ($ID_{r,b}$): number of patent families per patenting organization, indicating concentration of innovation activity.

5. Internationalization ($FPFR_{r,b}$): the average proportion of foreign patents within patent families, reflecting the international reach of patent protection.

6. Innovativeness ($I_{r,b}$): measured *via* eigenvector centrality in a forward citation network, indicating the influence of a region's patents.

A detailed explanation of the calculation methods for each indicator is provided in Supplementary Note S4b (ESI†).

Dynamic analysis of regional patent portfolio competitiveness

For the dynamic analysis of patent quantity and quality, we divided the dataset into two time periods: pre-2015 and post-2015. This division reflects a pivotal moment in the battery industry marked by a growing emphasis on sustainability and increased exploration of alternative battery materials.

We calculated patent quantity and quality for each period across all regions and battery technologies, using the same methodology described in the previous section and in Supplementary Note S4b (ESI†). This enabled a comparative analysis of regional developments over time for each battery technology.

In addition to examining relative trends, we assessed both the quantitative and qualitative growth of regional patent portfolios across the two periods, providing insights into how each region's innovation activities have evolved within each technology. Growth rates were calculated using the raw indicator values (*i.e.*, not the *z*-standardized values) according to eqn (2):

$$\text{Growth rate}_{r,b} = \left(\frac{\text{Indicator}_{r,b,\text{post-2015}}}{\text{Indicator}_{r,b,\text{pre-2015}}} - 1\right) \times 100 \qquad (2)$$

These growth rates were computed for the quantity indicator as well as for all six quality indicators for each region r and battery technology b.

To represent the overall qualitative growth for each region and technology, we used the median growth of the six quality indicators. The median provides greater robustness to outliers within the small set (here: six indicators) compared to the mean.

This approach offers a dual perspective on the dynamics of regional patent portfolios, capturing both inter-regional (cross-region) and intra-regional (within-region) developments in patent quantity and quality. As such, it provides a comprehensive view of evolving trends in technological leadership and the shifting landscape of global competitiveness.

Policy analysis

To complement the patent data analysis, we conducted a qualitative review of policy documents related to future EV battery technologies from 2015 to 2023, covering the key regions analyzed—China, Europe, Japan, South Korea, and the United States. The objective was to identify strategic priorities and policy directions in each region concerning battery innovation. We analyzed several key aspects of these policy documents (Table 1) to identify trends and strategic alignments for each region.

Results

Quantitative analysis of future battery technologies

Fig. 1 and 2 present the results of the patent analysis. Fig. 1a and b focus on six future battery technologies, reflecting this study's emphasis on understanding the global race for leadership in technologies that are not yet widely applied in EVs but hold high potential for future use. Fig. 1c and all subsequent figures (Fig. 2–4) broaden the scope to include both future and state-of-the-art battery technologies. Including state-of-the-art technologies is essential, as they represent the current competitive landscape and provide context for understanding regional strategies and geostrategic priorities in the transition from current to next-generation technologies. Furthermore, distinguishing between high-energy and low-cost applications is important for analyzing how regions are positioning themselves to lead in both performance and cost-effectiveness.

The findings show a substantial increase in the annual number of future battery patent applications since 2010, with approximately a tenfold growth between 2010 and 2022 (Fig. 1a). This growth coincides with the rapid expansion of the EV market since the early 2010s.[3,56,71] The data suggest a two-phase evolution: until the early 2010s, patenting activity primarily focused on future battery technologies for high-energy applications (shown in green in Fig. 1), such as Li-SSBs, Li–S batteries, and Next-Gen LIBs, which together still accounted for over 55% of annual patent applications in 2022

Table 1 Framework for analyzing policy documents

Key aspects	Description
Overall focus	Broad objectives for advancing EV battery technologies.
High-energy *vs.* low-cost focus	Priorities for developing high-energy or cost-effective future battery technologies.
Technology strategy	Approaches to innovation and R&D in battery technologies.
Mobility goals	Alignment of battery strategies with broader mobility objectives, such as EV adoption.
Driving forces	Economic, environmental, and geopolitical factors.
Funding strategies	Regional funding mechanisms and investment plans.
Intellectual property strategic direction	Trends in patenting and technology protection.
Geographic orientation	Geopolitical positioning and global supply chain considerations.

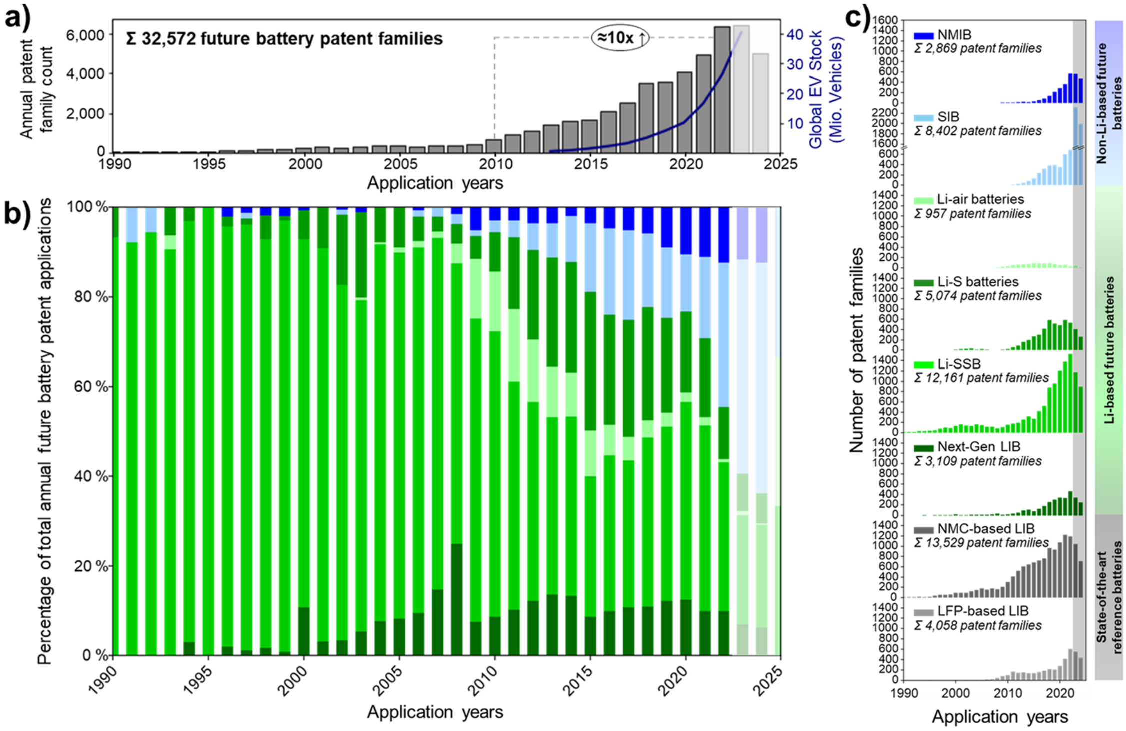

Fig. 1 Trajectory and composition of patent family counts for global future battery technologies. (a) Annual number of patent family applications for six future battery technologies (excluding state-of-the-art reference batteries) from 1990 to 2025. The navy line graph illustrates the global EV stock (million vehicles) from 2013 to 2023 (data source: ref. 3). (b) Relative composition of the global annual number of patent applications from 1990 to 2025. The annual patent family share for each battery technology is shown as a percentage of total patent applications for the respective year. (c) provides the legend for the color coding in (b). (c) Annual number of patent applications per technology from 1990 to 2025. In all figures, data for 2023–2025 are shaded to indicate incomplete publication, due to the typical 18-month lag between patent filing and publication (data as of March 2025).

(Fig. 1b). These technologies are known for their higher energy densities and longer lifespans.[72] However, since the early 2010s, the share of annual patent applications for non-lithium-based future battery technologies aimed at low-cost applications—namely SIBs and NMIBs—has grown, reaching nearly 45% by 2022 (shown in blue in Fig. 1b). This shift is likely driven by rising lithium prices,[3] supply chain issues,[73] new policies (*e.g.*, the Paris Agreement 2015, "Made in China 2025" Technology Roadmap 2015), and research initiatives (*e.g.*, ARPA-E, Horizon Europe),[74] as well as the widespread availability of materials for SIB and NMIB technologies.[72]

Despite the increasing share of low-cost, non-lithium-based future batteries (blue), and the declining share of lithium-based future battery technologies (green), Li-SSBs still accounted for 33% of patent families in 2022, followed by SIBs (32%) and NMIBs (12%) (Fig. 1b). The sustained interest in Li-SSBs can be attributed to their potentially superior performance characteristics, including higher safety and energy density.[13,72]

Among the six future battery technologies, patenting activity for SIBs, NMIBs, Li-SSBs, and Next-Gen LIBs shows a positive trend (Fig. 1c). NMC-LIBs (Σ 13 529) and Li-SSBs (Σ 12 161) accounted for the highest number of patent families globally, whereas Li–air battery technologies (Σ 957) had the fewest. While annual patent filings for Li–S batteries increased steadily after 2000, growth has stagnated since 2018 (Fig. 1c) or declined in some regions (Fig. 2). This stagnation is likely due to technological challenges, such as lithium polysulfide dissolution leading to capacity fade.[13,75,76] Similarly, patenting activity for Li–air batteries rose after 2008 but declined after 2016 (Fig. 1c), reflecting issues such as poor stability, limited cycle life, lower system-level energy densities, and long commercialization timeline.[13,76,77]

State-of-the-art reference batteries have shown an upward trend in recent years, particularly for NMC-based LIB technologies used in high-energy applications. The number of annual patent applications for NMC-based LIBs increased sharply in the early 2010s, while patent filings for low-cost LFP-based LIB technologies have only seen substantial growth in recent years (Fig. 1c).

The results of the regional analyses (Fig. 2) show that China dominates the patent landscape in terms of quantity, accounting for approximately 59% of global patents in future battery technologies. In addition, China leads in both state-of-the-art LFP- and NMC-based LIB technologies, with a particularly strong position in LFP-based LIBs.

Although China entered the race for future battery technologies relatively late—around 2013—our results indicate that it quickly became the largest patent holder globally across all six future EV battery technologies (while continuing to lead in state-of-the-art LIBs). This rapid growth was supported by a diversified technology strategy targeting both high-energy and low-cost innovations, encompassing both lithium-based and non-lithium-based technologies (Supplementary Note S1, ESI†), alongside substantial patenting subsidies.[78,79] Since 2016, China has significantly increased its patenting activities in non-lithium-based technologies (SIBs and NMIBs) (Fig. 2), reflecting the growing commercialization of SIB-powered EVs and the establishment of nearly 30 SIB manufacturing plants—either operational, planned, or announced—with a combined capacity exceeding 100 GW h.[73]

	Global	China	Japan	South Korea	United States	Europe
Future Batteries	32,572	19,290 (59%)	4,001 (12%)	4,184 (13%)	1,257 (9%)	1,032 (3%)
State-of-the-art Batteries	17,587	9,019 (51%)	3,112 (18%)	2,785 (16%)	1,243 (7%)	537 (3%)

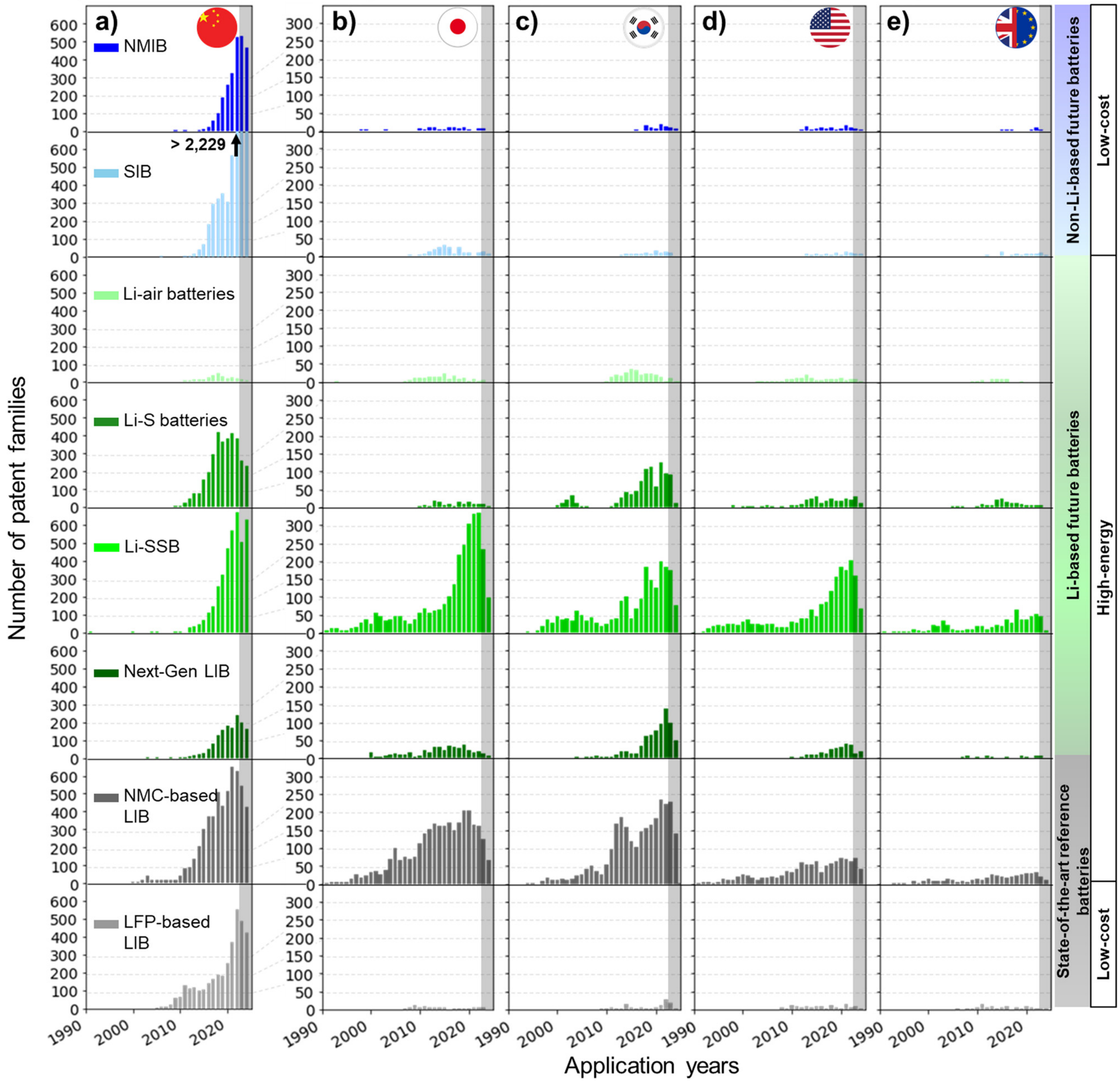

Fig. 2 Distribution of global patenting activity in future and state-of-the-art battery technologies across regions. The figure shows the number of patent families per technology over the application years for (a) China, (b) Japan, (c) South Korea, (d) the United States, and (e) Europe (EU + UK). The table above provides the total number of patents globally and by region, along with each region's share (in %) of the global patent landscape. In all figures, data for 2023–2025 are shaded to indicate incomplete publication, due to the typical 18-month lag between patent filing and publication (data as of March 2025).

While China holds the largest portfolio of NMC-based LIB patents, Japan and South Korea also maintain notable shares. However, Japan has experienced a marked decline in recent years.

Japan holds the third-largest patent portfolio in future battery technologies, slightly behind South Korea, with the two accounting for approximately 12% and 13% of the global patent landscape, respectively. Although Japan has long been a pioneer in future battery technologies,[80] its patenting activity has declined in recent years, with the notable exception of continued interest in Li-SSBs. On the policy front, Japan is focused on expanding LIB production capacity to protect its current market position while prioritizing investments in Li-SSBs and alternative technologies such as fuel cells[81] and fluoride shuttle batteries.[74] Japan also experienced a notable decline in the number of patents for SIBs, and both Japan and South Korea saw decreases in patent numbers for Li–air batteries.

Meanwhile, South Korea has shown an increase in patenting for Next-Gen LIBs. Trends for Li–S and Li-SSBs in South Korea were less consistent, showing some volatility, which contrasts with the country's policy emphasis on Li–S batteries and Li-SSBs.[74] South Korea also holds a substantial number of patents for high-energy NMC-based LIBs, particularly from the 2010s, but relatively few for low-cost LFP-based LIB technologies.

The United States and Europe account for 9% and 3%, respectively, of global patents across the six future battery technologies. US policy is primarily focused on lithium-based high-energy future battery technologies (shown in green in Fig. 2), especially Li-SSBs and Next-Gen LIBs (Supplementary Note S1, ESI†). This focus is reflected in the growing number of patent applications for these technologies in recent years (Fig. 2). The United States and Europe hold the smallest shares of NMC-based LIB patents and display only a marginal upward trend, which is considerably less pronounced than in China, Japan, and South Korea. Nevertheless, this slight increase aligns with their policy goals of strengthening domestic LIB value chains (Supplementary Note S1, ESI†). Europe's strategy includes a short-term focus on state-of-the-art LFP- and NMC-based LIB technologies, a mid-term emphasis on lithium-based future battery technologies, and a long-term goal of advancing non-lithium-based future battery technologies (Supplementary Note S1, ESI†). However, Europe accounts for only 3% of global future battery technology patents. Having initially concentrated on lithium-based technologies, Europe entered the less mature non-lithium-based NMIB field relatively late (around 2015), resulting in the smallest NMIB patent portfolio among the regions analyzed.

Comparative regional analysis of patent quantity and quality

Fig. 3 presents the relative patent quantity and quality for six future battery technologies and two state-of-the-art LIB technologies, covering both high-energy and low-cost categories. Relative patent quantity was measured using *z*-scores of absolute patent family numbers, while patent quality was assessed using a modified PQI, as detailed in the Methods section. The uncertainty of these quality measures is expressed through 90% confidence intervals, enabling robust comparison of patent quality across regions. It should be noted that the substantial variance in quality values—evidenced by the confidence intervals—precludes claims of statistical significance but allows for the observation of general trends across different technologies.

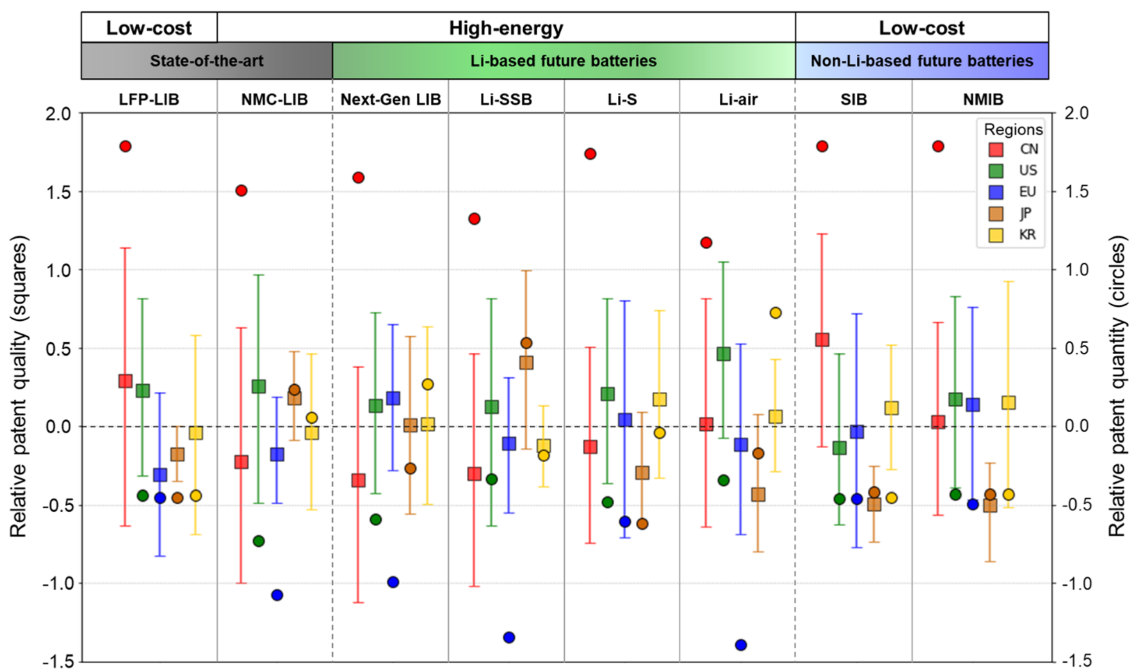

Fig. 3 Comparative analysis of relative patent quality and quantity across regions for six future and two state-of-the-art battery technologies. Squares represent relative patent quality with error bars indicating 90% confidence intervals. Circles indicate relative patent quantity. Data for each region are color-coded to facilitate cross-regional comparison.

The results show that China clearly leads in patent quantity for both state-of-the-art LIB and future battery technologies across high-energy and low-cost categories. This dominance in patent quantity can be attributed, at least in part, to its public

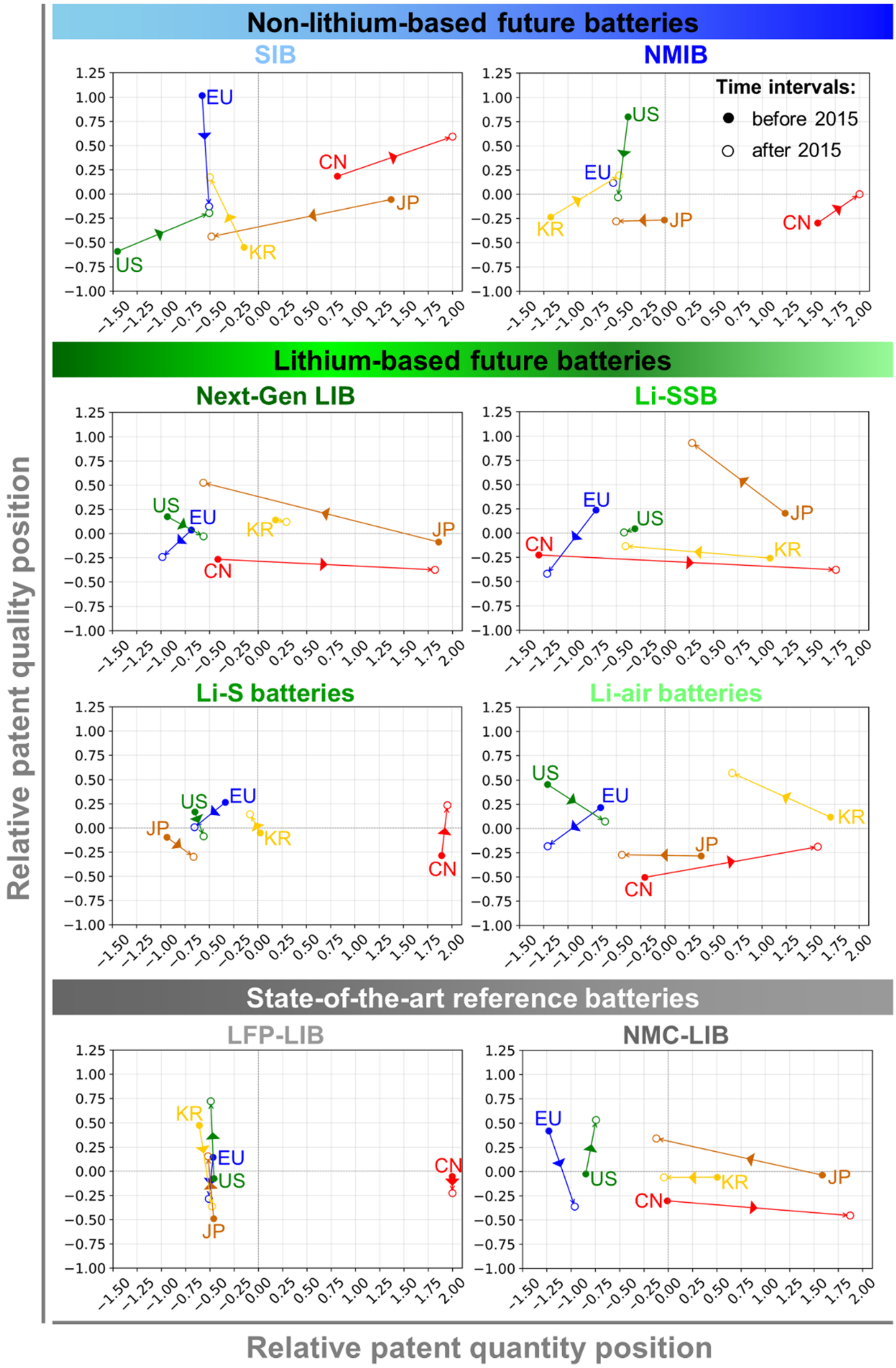

Fig. 4 Inter-regional developments in patent quantity and quality across six future and two state-of-the-art battery technologies. Regional trajectories in relative patent quantity and quality are shown for two state-of-the-art LIB and six future battery technologies, with pre-2015 represented by colored solid dots and post-2015 by colored hollow circles. Arrows, color-coded by region, indicate changes in relative positions for patent quantity and quality. Confidence interval values for patent quality are provided in Supplementary Note S4c, Table S5, ESI.†

R&D programs and patenting subsidies since the 2010s,[78] the strong research and production capabilities of Chinese battery manufacturers, and high domestic demand for EVs.[73,78] China accounts for around 90% of total patents for low-cost battery technologies, including state-of-the-art LFP and future SIB and NMIB technologies. Notably, it also demonstrates above-average patent quality for SIB technologies, aligning with its global dominance in SIB production.[73] In contrast, while China's patent quality for other low-cost technologies, such as LFP and NMIB, is average, its quality in high-energy batteries tends to be slightly below average for state-of-the-art NMC-based LIB, Next-Gen LIB, and Li-SSB technologies.

Japan shows above-average patent quantities for NMC-LIBs and particularly for Li-SSBs, aligning with its strategic focus on high-energy technologies—especially Li-SSBs (Supplementary Note S1, ESI†). While its patent quality for Li-SSBs is above average, it is average for NMC-LIB and Next-Gen LIB technologies. Patent quality for Li–S and Li–air technologies tends to be below average. In low-cost future technologies, Japan clearly lags in both patent quality and quantity, consistent with its limited emphasis on SIB and NMIB technologies in its technology strategy (Supplementary Note S1, ESI†). It also shows similarly low patent quantities for LFP-LIB, SIB, and NMIB technologies compared to South Korea, Europe, and the United States—all of which trail far behind China.

South Korea presents the most balanced portfolio among the regions. Its patent quantities are generally average across all high-energy technologies, with a notable strength in Li–air batteries. In this technology, South Korea demonstrates its strongest quantitative performance relative to other regions, although China still maintains higher absolute numbers. This strength in Li–air batteries partially aligns with its policy focus on Li-SSB, Li–S, and Li–air technologies (Supplementary Note S1, ESI†). Patent quality is consistent and average across both high-energy and low-cost categories.

The United States, by contrast, appears to prioritize patent quality over quantity. While its patent quantities for the eight technologies are below average—though higher than Europe's—its patent quality remains average to slightly above average across the board. This may reflect its emphasis on impactful research, supported by strong patenting activity from universities and research institutions, substantial private R&D investments (from both multinational corporations and start-ups), and robust government support.[73,74] The United States shows slightly above-average patent quality for Li–air technologies and average quality across the other seven technologies.

Europe lags notably behind other regions in terms of patent quantity for high-energy technologies. However, for low-cost batteries, its patent quantity is comparable to other regions except China. In terms of quality, Europe's patent portfolio is average across all technologies, in both state-of-the-art and future batteries for high-energy and low-cost applications.

While Europe and the United States do not show clear leadership in any of the eight battery technologies, China and Japan each lead in at least one. South Korea, in contrast, maintains stable performance across multiple battery technologies, generally ranging from average to above average, though without leading in any particular area. All regions emphasize Li-SSB technologies in their competitiveness strategies (Supplementary Note S1, ESI†), indicating potentially intense competition for leadership in this domain. However, the regions differ in both the quantity and quality of their Li-SSB patent portfolios. The results also suggest that Europe and the United States focus more on patent quality, while China and Japan prioritize quantity. South Korea tends to maintain a comparatively balanced approach in terms of both quantity and quality. Together, these findings indicate distinct strategic approaches across regions.

Dynamics in the race for technological leadership

To illustrate regional positioning and technological capabilities in the context of geostrategic competition over time, we analyzed intra- and inter-regional patent trajectories before and after 2015. Intra-regional trajectories were examined to identify changes in patent quantity and quality by comparing each region's average metrics before and after 2015 (Table 2). Regions can actively shape and align their technological trajectories through targeted strategies and investments. In contrast, inter-regional trajectories were assessed by plotting the relative positions of regions against one another for both periods (pre- and post-2015) (Fig. 4), using z-standardized values for patent quantity (x-axis) and patent quality (y-axis). This approach captures not only a region's internal development but also its performance relative to other regions over time. Here, regional positioning depends not only on a region's own efforts but also on those of its competitors. Even substantial investments may not secure technological leadership if competitors advance more rapidly, highlighting the influence of external factors beyond a region's direct control. By combining intra- and inter-regional perspectives, we aim to identify geostrategic positioning, regional strategies, and technological capabilities, offering insights into global innovation dynamics and emerging trends in technology leadership.

The analysis of inter-regional trajectories (Fig. 4) reveals China's substantial increase in relative patent quantity. After 2015, China became the leader in patent quantity across all analyzed technologies. Before 2015, China led only in the quantity of low-cost LFP-based LIB patents, with a moderate position in quality. This likely reflects its 1990s EV strategy aimed at catching up with Japan and South Korea by using subsidies to accelerate domestic LFP-based LIB production and foster a strong domestic EV market.[74] However, following 2015, while China's quantity position in LFP-based LIBs remained stable, its quality position declined. With the gradual reduction of subsidies since 2017,[73,74] China began transitioning from low-cost LFP-based to high-energy NMC-based technologies,[82] increasing its number of NMC-LIB patent families by approximately 859% over time (Table 2). Despite this growth, China has remained the lowest-ranked region in terms of inter-regional patent quality for NMC technologies since 2015.

Additionally, China's relative patent quantity significantly improved for future high-energy Li-SSB technologies—a focus area for all regions (Supplementary Note S1, ESI†). Although China has built a strong quantitative position in Li-SSBs since 2015, the quality of its patents tends to be below average, with Japan emerging as the quality leader. Furthermore, China has strengthened its relative position in both quantity and quality for high-energy Li–S and Li–air batteries, as well as for low-cost NMIBs—and especially SIBs. Since 2015, it has become the technological leader in SIB and Li–S batteries while also establishing a strong position in NMIB technologies (Table 2 and Fig. 4).

In summary, China demonstrates strong interest in all analyzed battery technologies, particularly in future high-energy Li–S batteries and low-cost SIB and NMIB technologies.

Japan's trajectory shows a decline in its relative quantity position for seven out of eight battery technologies, with the exception of Li–S batteries (Fig. 4). It has ceded its previous leadership in patent quantity to China in high-energy Next-Gen LIB, Li-SSB, and the state-of-the-art NMC-LIB, as well as in low-cost SIB technologies. Nevertheless, Japan still maintains a strong overall position in these areas and appears to be emerging as the quality leader in both Next-Gen LIB and especially Li-SSB technologies—driven by its targeted policies and sustained funding (Supplementary Note S1, ESI†).

Furthermore, Japan shows declining patenting activity in low-cost future SIB and NMIB technologies, which aligns with its broader technology strategy (Supplementary Note S1, ESI†).

Based on our data, Japan appears to be shifting its focus toward future high-energy Li-SSB technologies while further reducing its emphasis on low-cost future batteries.

South Korea has experienced a decline in its inter-regional patent quantity positions across five out of eight technologies, with the exception of low-cost future NMIB and state-of-the-art LFP-LIB, as well as high-energy Next-Gen LIB technologies. While NMIB patent quantity has shown stronger growth, LFP-LIB and Next-Gen LIB technologies have experienced only a slight increase. However, inter-regional patent quality for LFP-LIBs appears to have declined, mirroring a similar trend observed in China. Both regions suggest a strategic shift from LFP-LIBs to NMC-LIBs, despite a relative decrease in inter-regional NMC-LIB patent quantity. This transition is reflected in South Korea's intra-regional growth in NMC-LIB patent quality (+46%) and quantity (+164%). Simultaneously, its intra-regional LFP-LIB patent quality has declined (−30%), although quantity has increased significantly (+227%) (Table 2).

South Korea appears to be emerging as the quality leader in Li–air batteries and is one of only three regions—alongside China (+186%) and the United States (+28%)—to show a positive intra-regional growth rate in patent quantity (+13%) for this technology. It is also, together with Japan (+6%) and the United States (+4%), among the few regions with a positive intra-regional growth rate in patent quality (+33%) for Li–air battery technologies.

Despite a decline in inter-regional patent quantity for five out of eight technologies, South Korea has demonstrated strong intra-regional growth in both quantity and quality—except for LFP-LIB quality (Table 2). Its positive trajectory from pre- to post-2015 is further supported by a stable or improving inter-regional quality position in seven out of eight battery technologies, with the exception of LFP-LIBs. As a result, South Korea has established average to slightly above-average positions in patent quantity and, more notably, in quality across future battery technologies. This is particularly evident in low-cost SIB and NMIB technologies, as well as high-energy Next-Gen LIB, Li–S, and especially Li–air battery technologies (Fig. 4).

Like China, South Korea appears to focus on all five high-energy technologies. Additionally, it has shown increasing interest in future low-cost technologies—SIBs and NMIBs—steadily

Table 2 Global growth and intra-regional developments in patent quantity and quality across six future and two state-of-the-art battery technologies, pre- and post-2015. (a) Intra-regional growth rates for patent quantity and quality (raw data, not z-standardized), presented per region and battery technology as "absolute growth rate quantity/absolute growth rate quality". EU shows NaN values for NMIB technology as Europe had no pre-2015 patents, preventing growth rate calculation from zero. (b) Global number of patent families per period by battery technology, with percentage changes

(a) Battery technologies	CN	US	EU	JP	KR
SIB	+9787%/+59%	+477%/+4%	+73%/−19%	+50%/+16%	+80%/+16%
NMIB	+6160%/−2%	+325%/−27%	NaN/NaN	+153%/+37%	+1020%/+82%
Next-Gen LIB	+2868%/−8%	+916%/+5%	−4%/−37%	+59%/+4%	+784%/+4%
Li-SSB	+3873%/+8%	+402%/−1%	+98%/+8%	+311%/+69%	+170%/+17%
Li–S batteries	+1008%/+42%	+251%/−10%	+14%/−18%	+156%/+7%	+545%/+32%
Li–air batteries	+186%/−6%	+28%/+4%	−77%/−37%	−25%/+6%	+13%/+33%
LFP-LIB	+404%/18%	+24%/+22%	−12%/−6%	−29%/+110%	+227%/−30%
NMC-LIB	+859%/+41%	+127%/+2%	+57%/−6%	+65%/+18%	+164%/+46%

	Number of patent families		
(b) Battery technologies	Pre-2015	Post-2015	Change
SIB	191	8211	+4199%
NMIB	92	2777	+2918%
Next-Gen LIB	463	2646	+471%
Li-SSB	2923	9237	+216%
Li–S batteries	710	4364	+515%
Li–air batteries	335	622	+86%
LFP-LIB	859	3199	+272%
NMC-LIB	4215	9314	+121%

strengthening its positions in both patent quantity and quality. However, this development may be overshadowed by China's notable growth in patent quantity in these technologies (Fig. 4).

Europe's inter-regional position in patent quantity and quality has declined across all four future high-energy battery technologies. Nevertheless, it maintains an average inter-regional quality position in Li–S and Li–air technologies (Fig. 4), along with positive intra-regional developments in Li-SSB technologies—reflected in a 98% increase in quantity and an 8% increase in quality (Table 2). Despite its inter-regional decline in high-energy technologies, Europe retains a moderate position in low-cost future SIB and NMIB technologies. Notably, it appears to hold the second-highest position globally in terms of patent quality for future low-cost NMIB technologies, despite only entering this field after 2015 (Fig. 4).

For state-of-the-art high-energy NMC technologies, Europe's patent quality appears to be on a downward trajectory, although its relative patent quantity has increased. This increase is reflected in a 57% rise in intra-regional patenting activity between the periods before and after 2015.

Overall, Europe appears to adopt a quality-focused, selective patenting strategy, with a particular emphasis on low-cost future battery technologies. It tends to rank second inter-regionally in NMIB quality and maintains average quality in SIB technologies. While Europe shows intra-regional growth in both patent quantity and quality for Li-SSB technologies, it lags behind in inter-regional comparisons. Its short-term focus on state-of-the-art LIBs, medium-term on Li-SSBs, and long-term on low-cost future batteries—as outlined in its policy strategies (Supplementary Note S1, ESI†)—is consistent with the patterns observed in patent data, particularly in low-cost future batteries and Li-SSB technologies.

Like Europe, the United States also shows interest in future low-cost battery technologies. However, while the United States has improved its relative patent quantity and quality for SIB technologies over time, its patent quality for NMIBs has declined, seemingly resulting in the loss of quality leadership in NMIBs to South Korea (Fig. 4).

In the domain of future high-energy battery technologies, the United States has also relinquished several of its previously strong positions. Before 2015, it ranked first in relative patent quality for Next-Gen LIBs and Li–air batteries, second for Li–S batteries, and third for Li-SSB technologies (Fig. 4). Post-2015, the United States experienced a downward trend in relative patent quality in three out of four lithium-based future battery technologies, falling to fourth for Li–S batteries and third for both Next-Gen LIBs and Li–air batteries (Fig. 4). However, in the case of Li-SSB technologies, the United States maintained an average relative z-standardized quality value (around 0), while Europe—previously ranked higher—experienced a decline in inter-regional patent quality, resulting in the United States rising from third to second place post-2015. Despite this relative improvement, the United States saw a slight absolute intra-regional decline (−1%) in patent quality for Li-SSB technologies (Table 2), even as it recorded substantial increases in intra-regional patent quantity for Next-Gen LIB (+916%), Li-SSB (+402%), and Li–S battery technologies (+251%), reflecting its policy focus on high-energy technologies (Supplementary Note S1, ESI†).

In contrast to the trend in future high-energy technologies, the United States appears to have positioned itself as the quality leader in state-of-the-art LIBs, both LFP and NMC. It seems to be surpassing South Korea in LFP batteries and Europe in NMC batteries. This aligns with longstanding policy efforts to build a domestic LIB supply chain—not only through recent legislative incentives such as the Inflation Reduction Act (Supplementary Note S1, ESI†), but also through earlier federal programs, particularly those under the Department of Energy's Vehicle Technologies Office Annual Merit Review (VTO AMR, since 2008),[83] including the Batteries for Advanced Transportation Technologies (BATT)[84] and Advanced Battery Research (ABR)[84] initiatives (both launched in 2008), as well as public-private partnerships such as FreedomCAR (2002)[85] and the United States Advanced Battery Consortium (USABC, founded in 1991).[86]

Conclusion

In the global race for leadership in future EV battery technologies, this study reveals an expanding battery technology landscape. Early patenting activity was primarily driven by Japan and South Korea (Fig. 2), with a focus on high-energy, lithium-based future battery technologies, which accounted for around 55% of global patent filings in 2022 (Fig. 1b). However, since the early 2010s, we have observed the growing prominence of low-cost, non-lithium-based future battery technologies, which made up nearly 45% of global patent filings for future battery technologies in 2022 (Fig. 1b). Among the technologies analyzed, patenting activity was primarily concentrated on Li-SSBs in the high-energy segment and SIBs in the low-cost segment (Fig. 1b and c), reflecting their promising applications and growth potential beyond 2030.

From a policy perspective, China, Japan, and South Korea are increasingly emphasizing future battery technologies. China demonstrates strong policy interest across all future battery technologies, particularly in high-energy Li–S and low-cost SIB and NMIB technologies. This is driven by a clear focus on patent quantity, likely explained by substantial subsidies, but it has not yet translated into leadership in patent quality. This may suggest that public funding alone is insufficient to drive improvements in both quality and quantity. Japan prioritizes high-energy Li-SSBs, consolidating its leadership in patent quality, while South Korea pursues a balanced strategy, showing strength in both high-energy technologies—particularly Li–air batteries—and low-cost technologies, especially NMIBs. South Korea also stands out for maintaining a balance between patent quality and quantity, being the only country to show rising intra-regional growth in both metrics across all eight battery technologies, except for LFP-LIB quality.

Moreover, analysis of policy documents indicates that Europe and the United States tend to prioritize short-term improvements to the LIB supply chain, in contrast to the futureoriented focus of Asian countries. While Europe exhibits intra-regional growth in both quantity and quality of high-energy Li-SSB patents, it lags in inter-regional comparisons. Europe appears to follow a selective, quality-focused strategy centered on low-cost future battery technologies such as NMIBs, where it emerged as the quality leader post-2015. In contrast, the United States leads in the quality of state-of-the-art LIBs, excelling in both low-cost LFP and high-energy NMC technologies—reflecting its strategic emphasis on strengthening the domestic battery supply chain.

Overall, Asian regions appear fully committed to advancing future battery technologies. China and South Korea are targeting both future low-cost and high-energy technologies, while Japan is concentrating on high-energy technologies, particularly Next-Gen LIBs and Li-SSBs. In contrast, Western regions prioritize low-cost future batteries and state-of-the-art LIBs across both high-energy and low-cost segments. These findings reveal a divergence in regional strategies and priorities, which could widen the capability gap in future battery technologies and potentially undermine geostrategic autonomy—particularly in the United States and Europe. This divergence may compromise their long-term competitiveness, highlighting the need for better alignment between innovation efforts and long-term policy goals.

This study offers the following key insights: competitive dynamics in future battery technologies are becoming increasingly polarized, with high-energy lithium-based batteries (dominated by Japan, China, and South Korea) and low-cost non-lithium-based technologies (dominated by China) evolving along separate trajectories. This split—where Li-SSBs are receiving considerable attention in patent and policy data for high-energy EV applications, and SIBs garner similar focus for low-cost EV applications—necessitates a reassessment of competitive strategies, particularly in Western regions.

Effective policy support, aligned with clear long-term objectives and informed by competitors' current and future positions, appears critical to securing leadership in future battery technologies. Countries such as China, Japan, and South Korea are aligning their innovation and policy efforts, while Europe and the United States risk falling behind by focusing primarily on short-term LIB supply chain improvements—potentially limiting their ability to remain competitive in the global race. A shift in European and US policy should not only prioritize increased investment in future battery technologies, but also, crucially, establish mechanisms to foster collaboration with leading companies in Asia. Facilitating knowledge sharing and the transfer of intellectual property—rather than imposing economic barriers such as tariffs—appears essential for closing the innovation gap.

Author contributions

A. H.: conceptualization, investigation, methodology, data curation, software, formal analysis, visualization, project administration, writing – original draft, writing – review & editing; F. T.: conceptualization, methodology, writing – original draft, writing – review & editing, supervision; S. L.: writing – review & editing, supervision; J. L.: writing – review & editing, supervision; L. J.: software, formal analysis, writing – review & editing; S. V. D.: writing – original draft, writing – review & editing.

Data availability

This study draws on multiple data sources. Patent data were obtained from Clarivate's Derwent Innovations Index, a commercially licensed database subject to access restrictions. Consequently, the raw patent records cannot be publicly shared. However, full details of the search strategy and query operators used to retrieve the data are provided in the ESI,† enabling replication for users with database access. The policy analysis is based on publicly available documents, all of which are cited and cataloged in the ESI.† Additional industry and market data, including electric vehicle sales figures, were sourced from publicly accessible reports published by Bloomberg and the International Energy Agency. Full references for all sources are included in the manuscript's bibliography.

Conflicts of interest

The authors declare no competing interests.

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References

1 G. Crabtree, *Science*, 2019, **366**, 422–424.
2 Z. A. Needell, J. McNerney, M. T. Chang and J. E. Trancik, *Nat. Energy*, 2016, 1.
3 IEA, *Global EV Outlook 2024. Moving towards increased affordability*, International Energy Agency, Paris, 2024.
4 D. Pulido-Sánchez, I. Capellán-Pérez, C. de Castro and F. Frechoso, *Energy Environ. Sci.*, 2022, **15**, 4872–4910.
5 N. Armaroli and V. Balzani, *Energy Environ. Sci.*, 2011, **4**, 3193.
6 J. B. Dunn, L. Gaines, J. C. Kelly, C. James and K. G. Gallagher, *Energy Environ. Sci.*, 2015, **8**, 158–168.
7 P. Du, T. Liu, T. Chen, M. Jiang, H. Zhu, Y. Shang, H. H. Goh, H. Zhao, C. Huang, F. Kong, T. A. Kurniawan, K. C. Goh, Y. Du and D. Zhang, *Energy Environ. Sci.*, 2025, DOI: 10.1039/D5EE00116A.
8 M. B. Anwar, M. Muratori, P. Jadun, E. Hale, B. Bush, P. Denholm, O. Ma and K. Podkaminer, *Energy Environ. Sci.*, 2022, **15**, 466–498.

9 T. Wicke, *Electric vehicle sales in 2024: Chinese manufacturers on the rise, stagnation in Europe*, Fraunhofer Institut für System- und Innovationsforschung ISI, 2025.
10 Y. Song, L. Wang, L. Sheng, D. Ren, H. Liang, Y. Li, A. Wang, H. Zhang, H. Xu and X. He, *Energy Environ. Sci.*, 2023, **16**, 1943–1963.
11 *Nat. Energy*2022, **7**, 461, DOI: 10.1038/s41560-022-01073-y.
12 H. Liu, Z. Zhu, Q. Yan, S. Yu, X. He, Y. Chen, R. Zhang, L. Ma, T. Liu, M. Li, R. Lin, Y. Chen, Y. Li, X. Xing, Y. Choi, L. Gao, H. S.-Y. Cho, K. An, J. Feng, R. Kostecki, K. Amine, T. Wu, J. Lu, H. L. Xin, S. P. Ong and P. Liu, *Nature*, 2020, **585**, 63–67.
13 F. Duffner, N. Kronemeyer, J. Tübke, J. Leker, M. Winter and R. Schmuch, *Nat. Energy*, 2021, **6**, 123–134.
14 A. Wolf, F. Nagler, P. Daubinger, C. Neef, K. Mandel, A. Flegler and G. A. Giffin, *Energy Environ. Sci.*, 2024, **17**, 8529–8544.
15 L. Mauler, F. Duffner, W. G. Zeier and J. Leker, *Energy Environ. Sci.*, 2021, **14**, 4712–4739.
16 J. Wesselkämper, L. Dahrendorf, L. Mauler, S. Lux and S. von Delft, *Resour., Conserv. Recycl.*, 2024, **201**, 107218.
17 A. L. Cheng, E. R. H. Fuchs, V. J. Karplus and J. J. Michalek, *Nat. Commun.*, 2024, **15**, 2143.
18 T. S. Schmidt, M. Beuse, X. Zhang, B. Steffen, S. F. Schneider, A. Pena-Bello, C. Bauer and D. Parra, *Environ. Sci. Technol.*, 2019, **53**, 3379–3390.
19 S. S. Sharma and A. Manthiram, *Energy Environ. Sci.*, 2020, **13**, 4087–4097.
20 IEA, *Global Critical Minerals Outlook 2024*, IEA, 2024.
21 US Department of Energy, FOTW #1354, August 5, 2024: Electric Vehicle Battery Pack Costs for a Light-Duty Vehicle in 2023 Are 90% Lower than in 2008, according to DOE Estimates, available at: https://www.energy.gov/eere/vehicles/articles/fotw-1354-august-5-2024-electric-vehicle-battery-pack-costs-light-duty, accessed 1 April 2025.
22 S. Jayanthan, Where are EV battery prices headed in 2025 and beyond? available at: https://www.spglobal.com/automotive-insights/en/blogs/2025/01/where-are-ev-battery-prices-headed-in-2025-and-beyond, accessed 1 April 2025.
23 U.S. Geological Survey, Mineral Commodity Summaries 2025 – Lithium, available at: https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-lithium.pdf, accessed 1 April 2025.
24 IEA, *The Role of Critical Minerals in Clean Energy Transitions*, IEA, 2022.
25 T. Altenburg, N. Corrocher and F. Malerba, *Technol. Forecase. Soc.*, 2022, **183**, 121914.
26 F. Moreno-Brieva and C. Merino-Moreno, *Environ. Sci. Pollut. Res.*, 2021, **28**, 28367–28380.
27 J. Schnell, F. Tietz, C. Singer, A. Hofer, N. Billot and G. Reinhart, *Energy Environ. Sci.*, 2019, **12**, 1818–1833.
28 K. G. Gallagher, S. Goebel, T. Greszler, M. Mathias, W. Oelerich, D. Eroglu and V. Srinivasan, *Energy Environ. Sci.*, 2014, **7**, 1555.
29 P. Bonnick and J. Muldoon, *Energy Environ. Sci.*, 2020, **13**, 4808–4833.
30 Z.-J. Zheng, H. Ye and Z.-P. Guo, *Energy Environ. Sci.*, 2021, **14**, 1835–1853.
31 C. Wang, J. Liang, Y. Zhao, M. Zheng, X. Li and X. Sun, *Energy Environ. Sci.*, 2021, **14**, 2577–2619.
32 X. Sun, Z. Liu, F. Zhao and H. Hao, *Environ. Sci. Technol.*, 2021, **55**, 12180–12190.
33 A. Santecchia, R. Castro-Amoedo, T.-V. Nguyen, I. Kantor, P. Stadler and F. Maréchal, *Energy Environ. Sci.*, 2023, **16**, 5350–5370.
34 Federal Consortium for Advanced Batteries (FCAB), National Blueprint for Lithium Batteries. 2021–2030, 2021.
35 in 117th Congress, 2022.
36 European Commission, Annex 2: Strategic Action Plan on Batteries, European Commission, Brussels, 2018.
37 European Commission, A Green Deal Industrial Plan for the Net-Zero Age, Brussels, Belgium, 2023.
38 MoST, 2021 National Key R&D Program New Energy Vehicles, MoST, 2021.
39 H. Yang, South Korea announces $$15 bln investment in advanced battery technologies, available at: https://www.reuters.com/world/asia-pacific/south-korea-announces-15-bln-investment-advanced-battery-technologies-2023-04-20/, accessed 17 September 2024.
40 LIBTEC, available at: https://www.libtec.or.jp/, accessed 17 September 2024.
41 L. Bermel, R. Cummings, B. Deese, M. Delgado, L. English, Y. Garcia, H. Hess, T. Houser, A. Pasnau and H. Tavarez, *Clean Investment Monitor: Tallying the Two-Year Impact of the Inflation Reduction Act*, Rhodium Group LLC, MIT Center for Energy and Environmental Policy Research, 2024.
42 H. Ernst, *World Pat. Inf.*, 2003, **25**, 233–242.
43 N. S. Clarke, *World Pat. Inf.*, 2018, **54**, S4–S10.
44 B. Probst, S. Touboul, M. Glachant and A. Dechezleprêtre, *Nat. Energy*, 2021, **6**, 1077–1086.
45 J. L. Contreras, M. Eisen, A. Ganz, M. Lemley, J. Molloy, D. M. Peters and F. Tietze, *Nat. Biotechnol.*, 2020, **38**, 1146–1149.
46 A. Block and C. H. Song, *J. Energy Storage*, 2023, **71**, 108123.
47 M. Sharifzadeh, G. Triulzi and C. L. Magee, *Energy Environ. Sci.*, 2019, **12**, 2789–2805.
48 H. Pettersson, K. Nonomura, L. Kloo and A. Hagfeldt, *Energy Environ. Sci.*, 2012, **5**, 7376.
49 X. Gao, H. Wu, C. Su, C. Lu, Y. Dai, S. Zhao, X. Hu, F. Zhao, W. Zhang, I. P. Parkin, C. J. Carmalt and G. He, *Energy Environ. Sci.*, 2023, **16**, 1364–1383.
50 H. Park, K. Kim, S. Choi and J. Yoon, *Expert Syst. Appl.*, 2013, **40**, 2373–2390.
51 P. Borgstedt, B. Neyer and G. Schewe, *J. Cleaner Product.*, 2017, **167**, 75–87.
52 L. Aristodemou and F. Tietze, *World Patent Inform.*, 2018, **55**, 37–51.
53 X. Fu and Q. G. Yang, *Res. Policy*, 2009, **38**, 1203–1213.
54 W. Cohen, R. Nelson and J. Walsh, Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not), Cambridge, MA, 2000.
55 G. Asche, *World Pat. Inf.*, 2017, **48**, 16–28.
56 Z. P. Cano, D. Banham, S. Ye, A. Hintennach, J. Lu, M. Fowler and Z. Chen, *Nat. Energy*, 2018, **3**, 279–289.

57 P. Cicconi and P. Kumar, *J. Energy Storage*, 2023, **73**, 109197.
58 S. M. Katalenich and M. Z. Jacobson, *Energy*, 2022, **254**, 124355.
59 A. Block and C. H. Song, *J. Cleaner Product.*, 2022, **353**, 131689.
60 H. Ernst and N. Omland, *World Pat. Inf.*, 2011, **33**, 34–41.
61 M. Park, E. Leahey and R. J. Funk, *Nature*, 2023, **613**, 138–144.
62 G. Ahuja and C. Morris Lampert, *Strategic Manage. J.*, 2001, **22**, 521–543.
63 J. Lerner, *The RAND J. Econ.*, 1994, **25**, 319.
64 S. Shane, *Manage. Sci.*, 2001, **47**, 205–220.
65 J. O. Lanjouw and M. Schankerman, *Econ. J.*, 2004, **114**, 441–465.
66 Measuring Patent Quality. Indicators of Technological and Economic Value, OECD Science, Technology and Industry Working Papers, 2013.
67 K. Higham, G. de Rassenfosse and A. B. Jaffe, *Res. Policy*, 2021, **50**, 104215.
68 D. Harhoff, F. M. Scherer and K. Vopel, *Res. Policy*, 2003, **32**, 1343–1363.
69 T. Fischer and J. Leidinger, *Res. Policy*, 2014, **43**, 519–529.
70 J. M. Kuhn and N. C. Thompson, *Int. J. Econ. Business*, 2019, **26**, 5–38.
71 S. Hardman, K. Fleming, E. Kare and M. Ramadan, *MIT Sci. Policy Rev.*, 2021, 46–54.
72 Bloomberg NEF, Electric Vehicle Outlook 2023, 2023.
73 IEA, Global EV Outlook 2023. Catching up with climate ambitions, International Energy Agency, Paris, 2023.
74 C. Endo, T. Kaufmann, R. Schmuch and A. Thielmann, Benchmarking International Battery Policies. A cross analysis of international public battery strategies focusing on Germany, EU, USA, South Korea, Japan and China, Fraunhofer Institut für System- und Innovationsforschung ISI, Karlsruhe, 2024.
75 Z. Li, I. Sami, J. Yang, J. Li, R. V. Kumar and M. Chhowalla, *Nat. Energy*, 2023, **8**, 84–93.
76 L. J. Aaldering and C. H. Song, *J. Cleaner Product.*, 2019, **241**, 118343.
77 W.-J. Kwak, R. Sharma, D. Sharon, C. Xia, H. Kim, L. R. Johnson, P. G. Bruce, L. F. Nazar, Y.-K. Sun, A. A. Frimer, M. Noked, S. A. Freunberger and D. Aurbach, *Chem. Rev.*, 2020, **120**, 6626–6683.
78 X. Li, *Res. Policy*, 2012, **41**, 236–249.
79 M. Liu, Y. Wen, X. Wu, S. Zhang and Y. Wu, *Environ. Sci. Technol.*, 2024, **58**, 18213–18221.
80 K. Uosaki, M. Watanabe, K. Kanamura, S. Nakanishi, M. Tatsumisago, K. Takada and S. Ye, *J. Phys. Chem. C*, 2023, **127**, 22865–22867.
81 M. Naumanen, T. Uusitalo, E. Huttunen-Saarivirta and R. van der Have, *Resour., Conserv. Recycl.*, 2019, **151**, 104413.
82 ICCT, Race to electrify light-duty vehicles in China, the United States and Europe. A comparison of key EV market development indicators, 2021.
83 US Department of Energy, 2008 Annual Merit Review, available at: https://www.energy.gov/eere/vehicles/articles/2008-annual-merit-review-results-summary, accessed 10 April 2025.
84 US Department of Energy, Energy Storage Research and Development, available at: https://www.energy.gov/node/811464, accessed 10 April 2025.
85 US Department of Energy, FreedomCAR: Energy Security for America's Transportation, available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/freedomcar_agreement_2002.pdf?Status=Master, accessed 10 April 2025.
86 National Research Council (NRC), *Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership*, National Academies Press, Washington, DC, 1998.