Reconfiguring the Battery Innovation Landscape

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Abstract

Batteries are critical for energy transition strategies. This paper offers a comprehensive assessment of the trends and developments of battery innovation. Over 700,000 patents from the period of 2005-2019 are compiled and analyzed. Leading patent applicants and countries of origin are identified. Major patent applicants are mostly large East Asian companies, while Japan and South Korea are the leading countries followed by the US, Germany, and China. Different battery designs, the main battery components, and interactions with other clean technologies are examined. Based on the operative definitions for incremental/radical and product/process innovations, a battery innovation typology is set forth. Main findings are that patenting in batteries has risen robustly and lithium-ion is the most vibrant technology; the lead-acid set-up maintains consistent innovation activity, lithium-sulfur and flow batteries are the most notable emerging technologies; electrodes are the most salient battery component, followed by electrolytes, separators, and cell housing; the most significant interactions of batteries with clean energy technologies are between battery charging and photovoltaic energy as well as between battery charging and electric vehicles. Incremental innovation represents more than half of patents, while product innovation represents approximately 70% of total patents.

Keywords: secondary batteries; innovation; technological trajectory; patent data

Citation: Silva J., Távora G., Mendonça S. (2023) Reconfiguring the Battery Innovation Landscape. *Foresight and STI Governance*, 17(1), 34–50. DOI: 10.17323/2500-2597.2023.1.34.50

Introduction

The need to reduce CO_2 emissions and mitigate the climate crisis was recognized by the 195 countries that signed the Paris agreement in December 2015.[1] This challenge has motivated efforts toward a transformation in energy production and use. One avenue is shifting from a situation of nearly total dependence on fossil fuels to a scenario where low-carbon energy sources play an increasingly significant role in world energy production (Fagerberg et al., 2016). In recent years, the deployment of wind and solar photovoltaic (PV) energies has risen significantly, reaching 10% of the global electricity production in 2021 (IEA, 2021a). It is expected that investment in climate change mitigating technologies will continue to grow over the next decades (IEA, 2021a). The urgency to accelerate these investments has been highlighted by the Sixth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC, 2021). Additionally, the energy crises that emerged at the end of 2021 in the context of post-coronavirus lockdowns and geopolitical conflicts further stressed the need for an accelerated transition to energy infrastructures less dependent upon conventional systems. Hence, new ways to make energy supply-demand connections less subject to shocks and bottlenecks are at a premium.

The increasing use of intermittent and non-controllable power sources poses, nevertheless, a key conundrum in power grid management and, hence, a severe constraint in the ability to achieve a sustainable socio-technical reconfiguration (Sovacool et al., 2020). Wind and photovoltaic (PV) energy output is largely determined by environmental conditions, with production peaks not necessarily matching demand and usage behavior. Thus, energy storage is essential to adapt energy delivery to users' needs as it allows for harnessing surpluses and injecting them into the grid, when necessary, thus avoiding waste and reducing stress in the distribution infrastructure (Castillo, Gayme, 2014). Enabling power adjustments and signal quality control is a fundamental benefit of using energy storage. For instance, small electricity producers have the opportunity to accumulate energy surpluses and sell them when the sales price is higher, not only smoothing the volatility of the system, but also improving its economic efficiency (Diesendorf, Wiedmann, 2020). Moreover, it is known that frequently the potential financial profits are among the stronger motivations for installing small renewable energy systems (Hansen et al., 2022). Therefore, the development of working storage solutions is part of a broad set of much needed "systemic eco-innovations" (Jesus, Mendonça, 2018; Lehmann et al., 2022). The increased deployment of storage has the potential to increase the competitiveness of renewable electricity and enable a larger transition to a smarter, cleaner, entrepreneurial, more inclusive, and circular society.

Among the many energy storage alternatives, secondary rechargeable batteries (or simply batteries here) represent a robust approach. Due to their high energy density, modularity, and low response time, batteries are a very attractive solution for a wide range of energy storage applications (Van Noorden, 2014). Battery storage also enhances the stability and reliability of electricity grids while the bolstering the flexibility on the demand side to accommodate supply shocks and overall heightened uncertainty (IEA, 2022). Advances in battery technologies are thus expected to smooth the workings of power systems while opening new markets and technological opportunities (Shapiro, 2020). Battery evolutionary pathways do matter for energy decarbonization, since they are on par with government efforts to electrify domestic and mobility systems (Velázquez-Martínez et al., 2019). They are further critical for energy security, since they constitute buffers against breakdowns in the short run and provide increased adaptation options over the long run (Azzuni, Breyer, 2019; Jindal, Shrimali, 2022).

One of the main questions this paper aims to address is how progress is taking shape in battery technologies. In recent years, several studies have addressed innovation in energy technologies (Lee, Lee, 2013; Albino et al., 2014; Wong et al., 2014; Silva et al., 2015; Kittner et al., 2017). Other studies focused more narrowly on battery innovation, both analyzing different aspects of lithium-based technological trajectories (Wagner et al., 2013; Stephan et al., 2017), as well as alternative ones (Aaldering, Song, 2019). Similarly, the innovation activities taking place along the electric vehicle value-chain have been analyzed (Feng, Magee, 2020; Golembiewski et al., 2015), and the specific R&D trends of battery technology in electric vehicles were also addressed (Zhang et al., 2017). Additionally, the environmental challenges of the battery value chain and the circular business model in lithium-ion batteries has a been analyzed (Albertsen et al., 2021; Dehghani-Sanij et al., 2019; Levänen et al., 2018) while others have studied the impact of policy instruments on the innovation of environmentally friendly technologies (Bergek, Berggren, 2014). Recently, a joint report by the International Energy Agency (IEA) and the European Patent Office (EPO) analyzed the main patent trends in the field of electricity storage in the context of a project concerning pathways to a decarbonized economy (IEA, EPO, 2021). Patent data highlight global, regional, national, and even local topics of wide policy significance, and have been a recent focus as an underutilized evidence base for mapping and measuring promising technologies, leading companies, supporting institutions, and geographical hotspots (IEA, EPO, 2021).

We seek to contribute to this agenda by committing to two research approaches. First, in the context of systemic interdependencies, we adopt a neo-Schumpeterian perspective to motivate an evolutionary study of

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, accessed 16.01.2023.

electric batteries as "new combinations" that adapt to the evolving usage/production landscapes when facing modern-day challenges in stationary and mobile storage needs and requirements (Castellacci et al., 2005; Caraça et al., 2009). Second, our empirical strategy takes on more than 700,000 patent applications as an indicator of technological progress in order to profile the battery innovation patterns, namely in what concerns the rate and direction of technical change (see Lhuillery et al., 2017). What make batteries interesting is that they provide ready resilience and actionable opportunities, but also the accumulation of capabilities is heavily knowledge-intensive and slow to materialize in the marketplace (Mendonça et al., 2019).

Batteries in the Energy Transition

The role of storage in the evolving energy system

Energy storage is a puzzle with many pieces: some older, bigger, and stable; others less defined, shifting in importance or just starting to take shape. By far, the most important electricity storage technology in the world is pumped hydropower, presently accounting for more than 95% of the grid-connected power storage.[2] Despite being a mature technology with low response times and a very large capacity range, hydropower stations need particular geographical and climate conditions; these limitations constrain their use to certain regions and seasons while, at the same time, bringing about large pressures in terms of land usage and water management (Schulz et al., 2017). Several alternative energy storage solutions are available, ranging from mechanical approaches such as compressed air storage (CAES) to chemical and electrochemical solutions such as fuel cells or batteries.

Secondary rechargeable batteries harness electricity in the form of electrochemical energy, promoting the interchange between these forms of energy. The electricity stored in the battery can be used at a later moment, and possibly, in a different place. During battery charging, the electricity is transformed into electrochemical energy, a process that entails the interaction of the battery with the electricity production/supply technologies. When there is an electricity demand, the battery converts the electrochemical energy back to electricity, therefore, responding to the need while adding to the security of the energy system as a whole. The specific features of energy demand are profoundly dependent upon the type of application, and, in fact, batteries have a set of characteristics that allow them to adapt to very diverse applications.

As already mentioned, batteries are an interesting choice for very distinct applications. Presently, there are two emerging storage markets for which electrochemical batteries are the option of choice: power grids and electrical mobility. Although lithium-ion and lead acid batteries are presently very competitive, it is expected that in the coming years, emerging battery technologies will reach a relevant market share while enabling new battery applications (IEA, 2020a). The raw material extraction needed to fuel the expected growth of the electric mobility and grid storage markets, will put increased pressure on ecosystems and socioeconomic systems (IEA, 2021b). This issue is of particular concern if the current situation in which battery market growth mainly occurs at the expense of Li-ion technology remains entrenched. It is therefore important to expand the technologies and raw materials used in the manufacture of batteries and it is particularly relevant to identify the most promising emerging battery technologies (Metzger et al., 2023). Moreover, the energy and transport systems are at forefront of the digitalization revolution (Turovets et al., 2021), which poses new challenges for energy storage systems and battery technologies. Such challenges in "critical technology areas" call for innovation (Aaldering, Song, 2019; Golembiewski et al., 2015; IEA, 2020b; IEA, 2021b), especially in a post-pandemic/geopolitical conflicts/decoupling scenario where supply-chains are already under strain. Surely, one of the main limitations of battery storage scale-up (and further price decrease) is the availability of raw materials; the minerals (namely lithium and cobalt) required for their manufacturing are themselves non-renewable resources and environmentally expensive to extract, process, and manage (Metzger et al., 2023).

Battery innovation through a neo-Schumpeterian lens

This paper analyzes innovation dynamics in the different electric battery technologies. Battery, as any technology, is an artefact with a variety of practical applications in contemporary society (Dodgson, 2008). The knowledge base that enables it is derived from many disciplinary domains (some more science-based, like electrochemistry and materials science; some emergent from actual production and usage in actual settings, like mechanical engineering and design). The usefulness of batteries, however, is manifested in a particular context: that is, they are a medium that crucially interact with other technologies that channel power to them and are fed by the power they harness (Berndt, 2003, p. 3).

Today, batteries lie at the heart of complex engineering-intensive energy systems (Prencipe et al., 2005) that are themselves going through a rapid pro-sustainability structural change (Schot, Steinmueller, 2019). Batteries are touchstone devices that receive, store, and deliver energy. They exist in a cobweb of interdependencies, i.e., these devices are contingent upon dominant power sources and there are varieties of applications affecting them in the long-term (see Malhotra et

[2] https://sandia.gov/ess-ssl/gesdb/public/statistics.html, accessed 08.08.2022.

al., 2021). Likewise, the downstream context of battery applications matters as it exerts selective pressures that are interpreted by innovation agents so as to promote adaptation and evolutionary responses. In other words, available knowledge contributes to explain the momentum of technical change, while certain socioeconomic issues encourage or penalize the development of specific solutions. This combination of "supply-pushes" in power generation alternatives and "demand-pulls" in competing domains of application give rise to patterned dynamics often called technological trajectories (Dosi, 1982; Nelson et al., 2018). This evolutionary perspective on innovation recognizes that knowledge development is a problem-solving activity but also that not all pathways are traveled (Hung et al., 2022). That is, of all the possibilities that can be followed only a few end up being pursued, gain momentum, and become the basis for cumulative progress. Technical change is uneven in the problem space and, over time, technological solutions cluster and consolidate around specific choices (engineering/societal compromises).

Batteries have long been deployed in a variety of roles in networks of energy availability and use. Lately, electric generation and transmission players are increasingly interested in the use of batteries for large-scale energy storage in order to optimize grid operations (IEA, 2020a). Also, the increasing deployment of highly variable renewable options opens new opportunities to batteries in stationary applications (IEA, 2021a). Moreover, while for many decades batteries have been used as jump-start devices in conventional internal combustion engine vehicles, they have progressed to an even more central position in fully electrical approaches to mobility. It is expected that the use of battery-powered electric vehicles will register an eight-fold increase in the next decade (Dhakal, Min, 2020). Hence, batteries are increasingly present in electric transport, renewables-supported energy systems, smart grids, and new consumer electronic devices. These applications are gradually becoming woven together in new socio-technical systems (i.e., smart homes, sustainable mobility, smart cities, etc.), and the use environment shapes the technological trajectories that emerge over time (Malhotra et al., 2021). These forces push, shape, sustain, and constrain technical change. Hence, characterizing the key characteristics and functions that make batteries operative in this unfolding environment is a relevant empirical research agenda. This agenda contributes to further understanding the diverse institutional roles, industrial dynamics, and public policy opportunities in the contemporary economy.

Approach and Data

Patents as yardsticks

Patents are helpful for surveying innovative efforts and to explore the factors behind patterns of sectoral activity, geographic location, the evolution of the body of knowledge, and so on. (Bathelt et al., 2017; Nagaoka et al., 2010; Patel, Pavitt, 2005). Despite the vast literature on possible approaches and methodologies to measure innovation, a method to unambiguously evaluate innovation cannot be established (Dziallas, Blind, 2019; McKelvey, 2014). Measuring qualitatively different phenomena remains problematic (Smith, 2006) but continues to hold promise (Mendonça et al., 2021). The shortcomings of patents are well known and include non-patenting (including the preference for trade secrets as forms of appropriation), differing propensities to patent across technologies and firm sizes, etc.; but, in spite of these drawbacks, they remain useful for understanding the evolution of medium-high tech industrial artefacts (Mendonça et al., 2019). Therefore, using patents as an indicator is a matter of compromise, judgment, and the management of methodological trade-offs. Limitations of this indicator can be kept in check if the filings refer to more clearly delimited technologies if they are high in volume and coming from distributed places. When considering which batteries are concerned, it surfaces that not only are the numbers very robust (for most technological variants) and growing above general patenting activity (especially during the 2010s), but also that battery patents account for nearly 90% of all electrical energy storage (IEA, EPO, 2020).

Patents are a by-product of dynamic economic activity, providing the holder with a monopoly in the territory covered by the patent for a certain period. It also represents an exclusive ticket to technology markets, that is to say, it is an intangible asset that can be transacted commercially and also waged as a resource in litigation battles. Another point to bear in mind is that the economic significance of patents varies immensely; it is contingent upon a number of non-technology-related factors such as the country (different patenting policies and operational rules in each patent office regarding patentability thresholds) and industry (mainly due to the knowledge-based specificities and respective sectoral competitive regimes). In what this paper is concerned, patent applications are the chosen innovation indicator since they have substantive informational value regarding advances along the technological frontier and remain unique appropriability tools in medium-high and high-tech innovative industries, including when emerging technologies which are critical for sustainability are concerned (Leiponen, 2014; Mendonça et al., 2021).

Empirical evidence

The source for this study is the Global Patent Index (GPI), a source curated by the European Patent Office (EPO), allowing for the retrieval of thousands of entries per search while providing a format amenable to immediate statistical representation. Besides the quality and quantity of the data, the practical aspects of data handling are of great importance in empirical patent analysis.

In this study, we used the International Patent Classification (IPC) system. The IPC is composed of a coding scheme with a tree structure that becomes more specific as we descend in the hierarchy. The order of this hierarchy is section, class, subclass, group, and subgroup. A patent may cover several classification codes involving very different technological categories belonging to different industries, i.e., different sub-groups in distinct sections. Although it might be argued that this is a weakness of the patent indicator, it can translate into valuable information as it reveals patterns of multidimensionality of a given technology which, as the current analysis will leverage, can be highly beneficial for the purposes of analysis. In particular, a given patent that was allocated to different categories can be taken to be more combinatorial (in the classic Schumpeterian sense of innovation as a "new combination") relative to others.

The time elapsed between the patent application and its publication can range from one year to a year and a half. Thus, patents published in one particular year were submitted about two years before. From here on, we will consider the date of publication as the reference one but keeping these data features in mind. Likewise, it is considered that at the time of extraction, the database was already consolidated since the patents published between 2005 and 2019 were extracted during December 2020.

In this study, a choice was made to use as database patent applications regardless of the patent office where these were filled, instead of narrowing the database to a single patent office (Lee, Lee, 2013) or a limited group of patent offices (Kim, Lee, 2015). Our aim is not to measure the value of patents, for which other approaches would be preferable, such as the use of patent families (Martínez, 2011), but to identify the main developments and technological trajectories in terms of the exploration of the battery knowledge space without regard to the prospective economic value of the invention (Tahmooresnejad, Beaudry, 2019). Studies based on patent families are known to exclude many inventions (Criscuolo, 2006). In our case this could lead to losing less salient trends, such as the interactions between technologies or changes in innovation types. Furthermore, the fact that our study and the already mentioned IEA & EPO (2020) report both identify similar general trends in battery innovation is reassuring regarding the validity of our approach. Patterns are also corroborated by the results of Malhotra et al. (2021), who focuses on a narrower specification of batteries for a longer time using a different indicator construct. For a complementary study see (Metzger et al., 2023) with different patent evidence but corroborating results.

Technology identification

Electric batteries can be found in the IPC subclass H01M, which assembles patents related to the direct conversion of chemical energy into electricity. Three groups of the subclass H01M represent the different components of a battery system – electrodes, secondary cells, and non-active parts (Table 1).

To extract patent applications that refer to only one battery component, the database was searched for "NAP only" (for non-active parts), "Electr only" (for electrodes) and "SC only" (for secondary cells). The multi-component patent applications were collected using the following queries: "Non-active parts + Electrodes", "Non-active parts + Secondary cells", "Electrodes + Secondary cells", and "Non-active parts + Electrodes + Secondary cells". The ensemble named "Batteries all" was obtained by adding results from all these queries.

Table 1. **Patent Classification for Battery Components, IBC-based**

Groups	Contents
Non-active parts	
H01M 2 – constructional details, or manufacturing process, of the non-active parts	Technical matter regarding casing, wrapping, or covering the cell, connectors, sealing materials, separators, electrolyte containers, shock absorbers, etc.
Electrodes	
H01M 4 — electrodes	Advances related to electrode manufacturing, specific electrodes and electrodes materials, which are key battery components in terms of capacity, power and energy density (Mei et al., 2019).
Secondary cells	
H01M 10 – secondary cells; manufacture thereof	General manufacture details of the cell, electrolytes, accumulators, power tools, cooling mechanisms and so on.
Charging	
H02J 3/32	Subclass H02J contains patents for circuit arrangements or systems for supplying or distributing electric power and systems for electric energy storage. Group H02J3 includes circuit arrangements for AC mains and distribution networks, while the subgroup H02J3/32 refers to arrangements for balancing the network load using batteries for energy storage.
H02J 7	Group H02J7 contains the patents associated with circuit arrangements for charging or depolarising batteries, or for supplying load from batteries.
B60L 53	Subclass B60L contains applications related to the driving force of electrically propelled vehicles. Group B60L53 includes batteries' charging methods, specially adapted for electrical vehicles and charging stations.
H01M10/44	Applications of secondary cells charging or discharging methods.
Source: authors.	

The extraction method allowed all the patent applications to be separated according to the key-component topology, without data duplication.

During data collection, to avoid the inclusion of patents that are not related to secondary batteries, we made sure to exclude the subclasses of primary cells (H01M 6), fuel cells (H01M 8), hybrid cells (H01M 12), as well as of electrochemical current generators (H01M 14), and combinations of electrochemical generators (H01M 16). In this way, the collected evidence is exclusively devoted to the battery system construction set-up or to electrochemical storage in general. We used Boolean operators in the search protocol to exclude the aforementioned groups. Whenever possible, the queries were made based on the IPC classifications (classes, subclasses, groups, and subgroups). In the remaining cases, and for the sake of completeness, the queries were based on the presence of specific words in patent title/abstract. The reason for this choice was that IPC codes point directly to the technical field covered by the application, being more reliable than the appearance in the patent title/abstract of words like "battery" or "cell".

To analyze battery-charging technologies, we created a further search query with three groups that do not belong to the subclass H01M: H02J 3/32, H02J7 and B60L53 (see Table 1). The search query related to battery cooling[3] uses the expressions H01M10/60 or H01M10/443 or H01M10/486 or H01M50375 or H01M50/581 that include all the groups related to battery cooling or thermal management.

We made new queries to study the different battery technologies where the key battery component groups (H01M 2, H01M 4, H01M 10) were cross-checked with keywords from the patent front page, identifying the different batteries technologies. For instance, to identify lead-acid batteries patents, the keywords "lead-acid or "VRLA" (Valve Regulated Lead Acid) or "SLA" (Sealed Lead Acid) or "lead acc" (Lead accumulators) were introduced in the search queries. Since some of the emerging battery technologies analyzed do not have an IPC code, no specific battery-type IPC code was used in order to avoid a technology bias. We also made a specific search query for flow battery patents. Since flow batteries belong to the subgroup H01M 8/18, which is within the fuel cell hierarchy, we performed a survey including the H01M 8 group and adequate keywords (see Appendix A). In the last several years solid-state batteries have been gaining a lot of attention. These batteries use solid electrodes and solid electrolytes, which can be made of several different materials. In fact, this technology branch overlaps with a few of the technologies previously mentioned. The search query on solid state batteries was made by crossing the key battery component groups[4] with the keyword "solid state".

To inspect the interactions between patenting in batteries and photovoltaic/wind technologies, new search queries were implemented, inspecting the intersections between any IPC battery group and the groups related to PV/wind energies. To analyze the interactions of batteries with electric mobility, battery patents groups were cross-inspected with groups B60L 11 and B60L 50[5] associated with the power supply within electric vehicle systems. Finally, to examine the interactions of battery charging/supplying with other technologies, the charging/supplying load query was crossed with the wind/PV energy and the electric vehicle group codes. For this goal, some keywords were added to the search query. Moreover, the subgroup H02J 7/35, related to charging batteries with PV energy, was included in the charging battery-PV search. The details of the methodological protocols are further described in the Appendix A.

Innovation categorization

Possibly the most classic breakdown between types of innovation is the *product innovation* concept, i.e., the introduction of a new or significantly developed output in the economic system, and the *process innovation* concept, i.e., a novel or more sophisticated method of production or distribution (Fagerberg, 2004). Product innovations refer to outputs, whereas process innovations refer to the linkage between inputs and outputs. Recently Domnich (2022) made a survey of empirical studies on the impact on productivity with a specific emphasis on product and process innovation. In the case of batteries, an example of product innovation may be the refining of the battery design and an example of process innovation may be related to assemblage features.

Innovations can also be characterized by impact, being classified as incremental when representing smooth elaborations on prior set-ups of the technology or radical when a breakthrough causes a discontinuity with the established knowledge bases (Dodgson, 2008). Radical innovations combine more and unconnected knowledge domains, making them more encompassing and riskier than technologies that work in just one domain, thus providing a platform for new technological trajectories (Hesse, Fornahl, 2020). In the case of batteries, this may imply for example a new architecture of the cell. This paper adopts these criteria in order to distinguish between varieties of advancements in state-of-the-art battery technologies.

The extant literature does not provide unequivocal guidance on how to operationalize the product/process and radical/incremental concepts, and much lies

[3] Unlike the remaining, the searches related to cooling technologies and solid state batteries were made during 2022 using the 2022.01 version of IPC classification.

[4] In the 2022.01 version of IPC classification group H01M 50 replaced group H01M 2.

[5] B60L 11 was transferred to B60L 50 after the 2019.01 version of IPC classification.

in the hands of analysts facing the particular empirical materials and research goals (Dziallas, Blind, 2019; Katila, 2000). Based on the patent content and classifications (title, claims, descriptions, IPC categories, etc.), this study distinguishes between product and process innovations as well as radical and incremental innovations by considering a number of methodological options. Considering that there are several IPC subgroups related to the manufacture of battery components, a patent application containing at least one of these subgroups is considered a process innovation, and the applications not containing any of them are treated as product innovations. To characterize innovation impact, we posit that innovation is incremental if there is innovation in just one battery dimension (i.e., Electrodes, Non-active parts, and Secondary Cells) and radical if there are advances in at least two battery dimensions, proxying for the possible step-jumps stemming from connecting previously unrelated characteristics (Castaldi et al., 2015).

Our study goes through more than 700,000 patents applications for the period 2005–2019. The analysis of this database provides an insight into the most significant aspects of battery breakthroughs and innovation protagonists. The systematic interactions with renewable energies and mobility technologies are also analyzed. Based on the previously established definitions of incremental/radical and product/process innovation, the most important innovation types are weighed in. A number of distinct trends immediately emerge.

Results

Leading patent applicants

Figure 1(a) presents the leading 25 battery corporate applicants of the period 2005–2019. This list of heavy-duty applicants is almost entirely composed of large companies. Thirteen of these companies are Japanese, four are South Korean, three - Chinese, two - German, and two are from the US. The only non-corporate entity (a public research lab) that appears on this list is French, the Centre Energie Atomique (CEA).

The striking performance of Far Eastern players is in line with the results of IEA & EPO (2020). The notable role played by Japanese and South Korean corporations in patent applications may be justified, on the one hand, by the great importance of the higher-tech/export-oriented sectors in these countries in areas that are heavily dependent on batteries, such as consumer electronics and automobiles. On the other hand, it is widely recognized that the ambitious R&D policies, anchored on their own industries' priorities, developed by Japan and South Korea over the years with respect to "clean energy" technologies, including batteries since the 1990s, are strongly implicated in these technological achievements (IEA, 2008; Jeong, Mah, 2022). It is worth mentioning, by contrast, the example of Germany, that despite its ambitious energy transition strategy expressed in its successive energy research programs, in the absence of strong battery-related industrial interests, energy storage and rechargeable batteries were only established as research priorities in 2011[6].

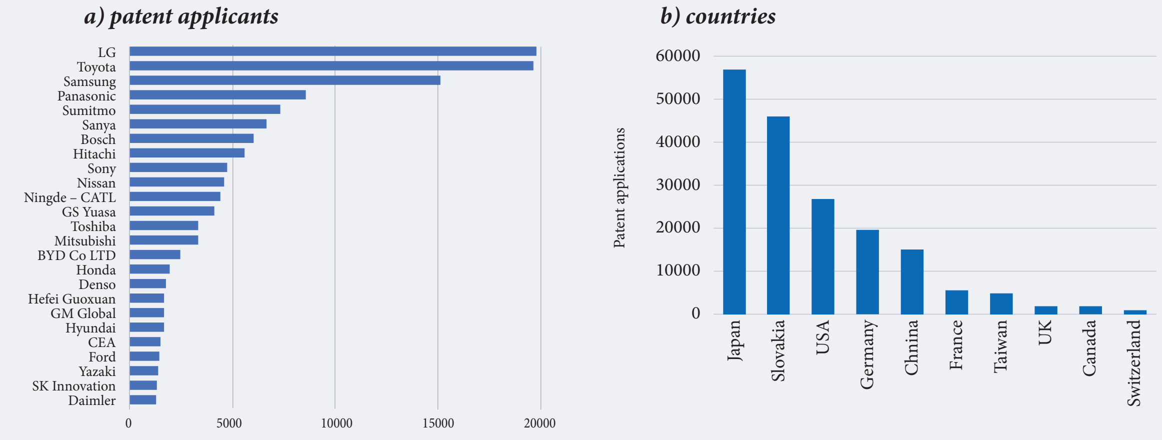
In Figure 1(b) it can be observed that the main innovation national players in batteries in the period 2005–2019 are Japan (JP) and South Korea (SK), followed by the United States (USA), Germany (GER), and China (CN). It is worth mentioning that when focusing on the patents published in the last five years, the rapid rise in patenting by large Chinese companies (IEA, EPO, 2020) is striking, a trend that if maintained will likely introduce significant changes in the leadership of battery innovation. Overall, the vibrant performance of the "Global East" appears largely attributable to deliberate national strategies for the development of clean energy technologies (Tan, 2010; Malhotra et al., 2021; May et al., 2018). The expansion rates of battery-related productive knowledge show that effective policy support is within reach as way to allow for greater global ambitions (IEA, 2022).

Main battery development pathways

Figure 2 displays the patenting trends across battery types (log-scale), and at least four empirical regularities can be outlined. First, Li-ion batteries are hegemonic throughout the field of batteries, sustaining an average annual growth rate of 17%, coming to represent more than three-quarters of all patents published in the period 2005–2019. The high inventive activity related to lithium-ion (Li-ion) technology can be attributed to its deployment in very different uses. Different applications have different performance criteria, but this technology has provided effective solutions (for mobility and stationary purposes) at declining relative prices (IEA, EPO, 2020, pp. 46–48). Second, there has also been resilient performance by the lead-acid (Pb-acid) type of batteries, a mature technology that maintains a steady innovation flow and a relevant role on the growing market of stationary storage applications (May et al., 2018). Third, some evidence of structural change can be identified: two battery approaches, redox-flow and lithium-sulfur (Li-S), took off around 2010 and have achieved growth rates of over 30% in the remainder of the period under analysis. Finally, a third kind of regularity can be noticed, the numbers for lithium-air (Li-air) and sodium-sulfur (Na-S) batteries are still marginal even if these two technologies have been pointed out as very promising, particularly Na-S having been suggested as valid option for grid storage applications (Hirsh et al., 2020). It must be highlighted that more than three quarters of battery-

[6] https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/6-energieforschungsprogramm-der-bundesregierung.html, accessed 16.01.2023.

Figure 1. **Top 25 Key Patent Applicants and Top 10 Countries with the Most Battery-Related Patent Applications (2005–2019)**



Source: authors.

related patents do not mention a specific technology and correspond to technological developments on specific battery components that can be inserted into batteries of very different technologies.

The pursuit of battery energy density and safety has boosted the interest in approaches based on solid electrolytes (Kim et al., 2015). Although solid state batteries are not a technology branch per se, but a specific construction form that intercepts several technologies, it is worth mentioning the rapid growth rate of patents in the last several years (since 2011 over 30% year-on-year). In 2019 the number patents associated with solid state batteries was already higher than for all non-lithium-ion battery technologies, a sign that this solution is becoming more important and emerging as a possible future trajectory.

Overall dynamics and key component technologies

The dynamics of battery patent applications over time is presented in Figure 3. The aggregate applications, i.e., "Batteries all" (read in the secondary axis), rise throughout, increasing five-fold through the entire period. This pattern is in line with the conclusions of a recent report by (IEA, EPO, 2020, p. 44) stating that the technical developments in batteries have signaled "a burst of innovation in this area" as trends have been faster than in general patenting. Moreover, there seems to be a chronology during this period: an early stage of growth (up to the early 2010s), then a moment of stagnation (until the mid-2010s), and a recovery until the end of the decade.

By breaking down battery dimensions and components, i.e., by highlighting particular elements of a battery set-up, we come to see that the "Secondary cells only" displays the most vibrant growth, followed but the "Non-active parts only", "Electrodes+SC", and "Non-active parts+SC". This fact comes across as a clear sign of strong investment in these specific dimensions of battery technology. The technology segment labeled "Electr only" did not recover from its relative stagnation and clearly diverged from the other single component technology groupings.

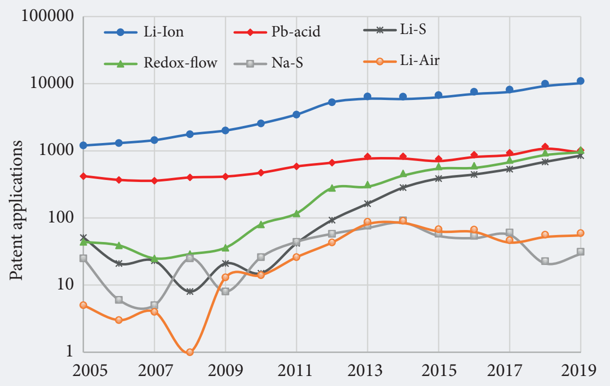
Among the multi-component patent applications, the packages "Elect+SC" and "NAP+SC" stand out from the rest, maintaining consistent growth over the analyzed period. In recent years these "packages" (i.e. specific configurations of battery components) even surpassed the "Electr only" and reached the level of "NAC only", suggesting a growing trend to submit patents covering more than one technological dimension. Conversely, "NAP+Elect" and "NAP+Elect+SC" packages had a very low number of patent applications in the period 2004–2019, showing that is not common to submit patents that address simultaneously non-active parts and electrodes (either with secondary cells or not).

Table 2 presents the number of patents with reference to the main battery components. Electrodes are by far the most innovative component of battery technology and is an indication that improving the battery performance is the most important driving force for innovation. Other significant components are Electrolytes, Cell Housing, and Separators. While patenting in Electrodes and Electrolytes is associated with the quest to increase battery capacity, particularly its energy density, the growing number of patents in cell housing and separators can be attributed to the need to adapt batteries to a growing number of different applications, that range from small consumer electronic devices (cell phones, tablets, etc.) to several different electronic mobility solutions (ex: cars, bikes, scooters, or unmanned aerial vehicles) (Golembiewski et al., 2015; IEA, EPO, 2020).

Battery charging and cooling

Figure 4 presents the upward trend of patents associated with battery charging/supplying load technologies (H02J3/32 and H02J7). It can be observed that

Figure 2. **Patent Applications for the Main Battery Varieties in the Period 2005–2019 (log-scale)**



Source: authors.

since 2009, the number of applications has been rising steeply, sporting an average annual growth rate of 19%. The substantial increase in solutions related to charging/supplying load technologies can be attributed to the required adaptation of these interface capabilities in the context of new applications. In particular, it is acknowledged that the need to deal with the emerging problems associated with the rising use of batteries is strongly related to the pressure to develop fast-charging technologies for electric mobility (Tomaszewska et al., 2019) and to adapt the battery charging/discharging to intermittent energy sources (Zhao et al., 2018).

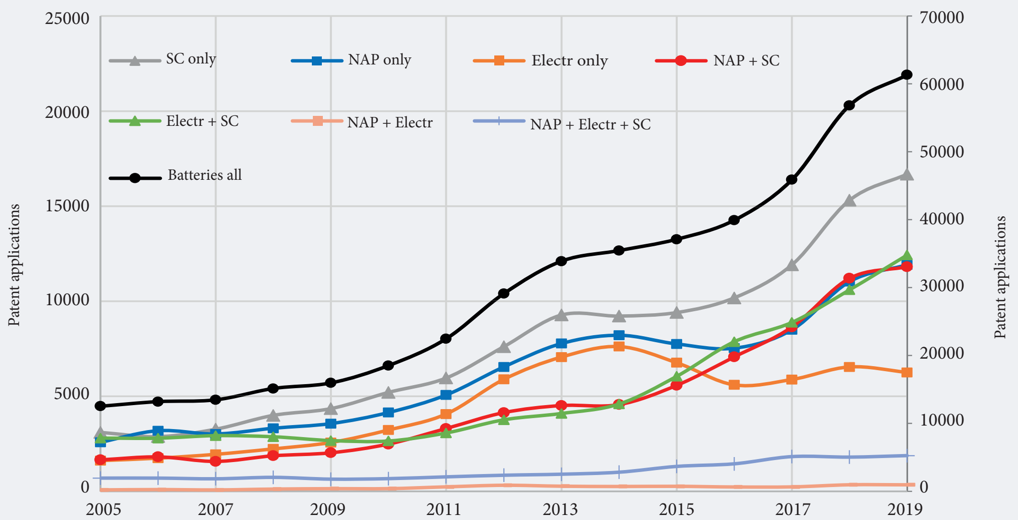
Due to its increasing energy density and the growing use of fast charging technologies, heat management in batteries has become a pressing issue, particularly in electric vehicle applications (Lu et al., 2020). Consequently, the number of patents with references to battery cooling technologies has increased steeply registering an average growth rate of 35% per year in the period 2005–2019, reaching over 8,000 patents in 2019, which is higher than for all non-electrode components.

Interactions with other clean technologies

One of the objectives of this study is to explore the existence of synergies of batteries with other "clean" technologies, namely renewable energies and electric vehicle technologies. The joint patenting between batteries/charging and wind energy is found to be unremarkable. In fact, is unlikely that this outlook will change in the near future since hydroelectric and CAES systems are more cost-effective choices to store wind energy than batteries (Barnhart et al., 2013; Ding et al., 2012). But, on the other hand, relevant interactions are found between battery technologies and other upstream (i.e., solar PV) and downstream developments (i.e., electrical vehicles), especially when charging is considered.

Figure 5 shows that the number of patents covering battery charging and PV technologies has been increasing consistently over the past decade, accounting for more than 20% of patenting in battery charging in recent years, a sign that the specific needs of associating batteries with PV systems have become a "focusing device" for battery innovation. It can also be observed that the evolution of the overlap between patenting in battery charging and the EV applications is likewise remarkable: by 2019 joint patenting accounted for more than a quarter of the total number of patents in battery loading.

Figure 3. **Patenting in Battery Technology Combinations (2005–2019)**

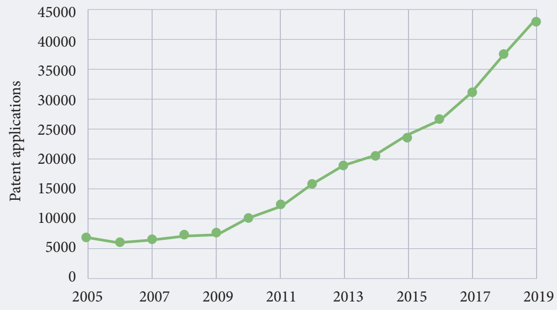


Note: The series «Batteries all» reads in the yy axis on the right.
Source: authors.

Table 2. **Number of Patents with Reference to the Main Battery Components in the Period (2005–2019)**

Component	Number of patents
Electrodes	1.7×10^5
Electrolytes	4.8×10^4
Cell housing	5.2×10^4
Separators	3.3×10^4
Source: authors.	

Figure 4. **Patenting Activity in Charging/ Supplying Loads from Batteries**



Source: authors.

General battery innovation patterns

A final analysis of innovation trajectories in this study is implemented by deploying the concepts of incremental/radical innovation and product/process innovation. Figure 6 shows the dynamics of different types of innovation over time. Besides the steady growth in patenting for all types of innovation (with the exception of incremental innovation in the 2014–2016 period), Figure 6 points out that incremental innovation is more common, as expected, but that evidence of an increase in the share of "radicalness" can be observed in later years. Moreover, the sharp rise in the number of incremental innovation patents and a subsequent decrease between 2014–2016 correlates well with the trend of "Electrodes only" patenting (Figure 3), suggesting that the temporary increase in incremental innovation patents was mainly driven by the boost in electrode innovation that reached its peak in 2014, after which a burst of patenting in multiple technology battery packages promoted an uptake of radical innovation. Most battery patents apparently cover products (artefacts or systems) and not so much processes (manufacturing assemblages and methods). It must be mentioned that, although all the innovation types witnessed a very significant increase in the total number of patent applications in the period 2005–2019, the shares of incremental/radical and product/process innovations remained mostly stable.

In Table 3 the relative shares of different types of innovation are presented. During the period 2005–2019, 62% of the battery patenting represents incremental innovation and 38% radical innovation, while 74% of the patents published correspond to product innovation and the remaining 26% represent process innovation. Thus, product innovation patents tend to be incremental, while process innovation patents are somewhat more radical.

Innovation type by technology

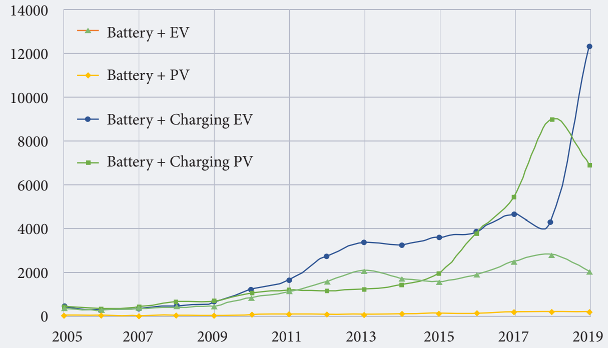
To further the analysis, the distribution of patents by the different innovation types was put into perspective by focusing on the four technologies with the highest innovation activity: Li-ion, Pb-acid, Li-S, and Flow batteries. In Figure 7 the variation in the period 2004–2019 of incremental and radical innovations for these four technologies is presented.

For Li-ion batteries, incremental and radical innovations were split almost evenly within the total number of patents. But different trends can be observed over time: after a strong increase of incremental innovation until 2014 (which correlates well with the growth of electrodes only and non-active parts only, see Figure 3), when it reached two-thirds of all the patents, it fell and was overtaken by radical innovation. It is worth noting the burst of radical innovation in mature Li-ion technologies, which is most likely associated with the need to adapt the technology to new applications. Two-thirds of Pb-acid patents represent incremental innovation, while the remainder corresponds to radical innovation. Such a share distribution, which remained stable over time, is quite expected for a mature technological technology like Pb-acid. For the emergent Li-S, two-thirds of patents represent radical innovations. The explosion of radical innovation patents occurred after 2014 when this type of innovation took the lead for Li-S technology. Finally, for the emergent flow-batteries, incremental innovation represents three-quarters of all the patents, and both innovation types maintain steady growth rates. The particular nature of flow-batteries (which is very different from the remaining battery technologies), and the fact that its applications are very focused on grid storage, might contribute to a concentration of the innovation effort in the improvement of battery performance, and not so much in non-active parts, such as separators, cell housing, etc., which can justify the trend to mainly patent incremental innovations.

It must be recalled that, as already mentioned, three-quarters of all patents make no mention of a specific battery technology, most of these patents represent innovation in a particular battery component, contributing to the overall "incremental innovation" of battery technologies, which represents 62% of all the patents.

In Figure 8, the variation of product and process innovation for the four main battery technologies is presented. One can observe that for the four technologies analyzed most of the patents correspond to product innovation (a trend corroborated by Malhotra et al., 2021).

Figure 5. **Evolution of the Joint Patenting of Battery Technologies with Electric Vehicle (EV)and Photovoltaic Energy (PV)**



Source: authors.

Table 3. **Share of Battery Patents in the Period 2005–2019 by Innovation Type (%)**

Innovation type	Degree of novelty		Total Prod/Proc
	Incremental	Radical	
Product	51	23	74
Process	11	15	26
Total Inc/Rad	62	38	100

Source: authors.

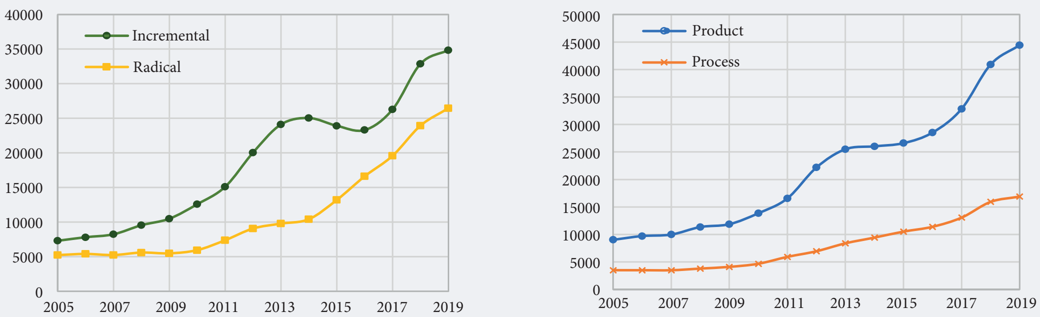
For the Li-ion technology, one third of patents represent process innovations. Both product and process innovations increase the number of patents over time and the relative shares are kept more or less stable. One third of the Pb-acid related patents represent process innovations, and although product and process innovations increase patenting over time, from to 2005 to 2019, the share of process innovations increased from 28% to 42%. One third of the Li-S technology patents represents process innovations, but product innovations have significantly increased its share in recent years reaching 75% in 2019. Finally, more than 90% of the patents on flow-battery technologies represent product innovations. In fact, while product innovations have experienced a significant growth in the analyzed period, patenting in process innovations is still modest. It is noteworthy that while for Li-ion and Pb-acid technologies, the share of process innovations tends to increase over time, the opposite trend is observed for Li-S and flow-battery technologies – such patterns are consistent with the maturity level of these technologies.

Overall, battery innovations are developing strongly. Large East Asian consumer electronics and automobile companies dominate the list of main patent applicants. Electrodes are found to be the most dynamic of battery components. Besides the more mature technologies like lithium-ion and lead-acid, the battery technologies that arise as the most promising in terms of innovation are lithium-sulfur and flow batteries. Synergies of battery technologies with upstream (i.e., energy production) and downstream technologies (i.e., energy use) occur mainly through battery charging/discharging. Incremental product innovations have been the dominant technological trajectory, but radical product innovations account steadily for nearly a quarter of the patents published in the period 2005–2019. All-in-all, by drawing on ample and detailed patent evidence on the rate and direction of technical change across the battery innovation ecosystem, this study presents findings that are of use to both private and public sectors, including market-oriented investors and independent regulators.

Conclusions

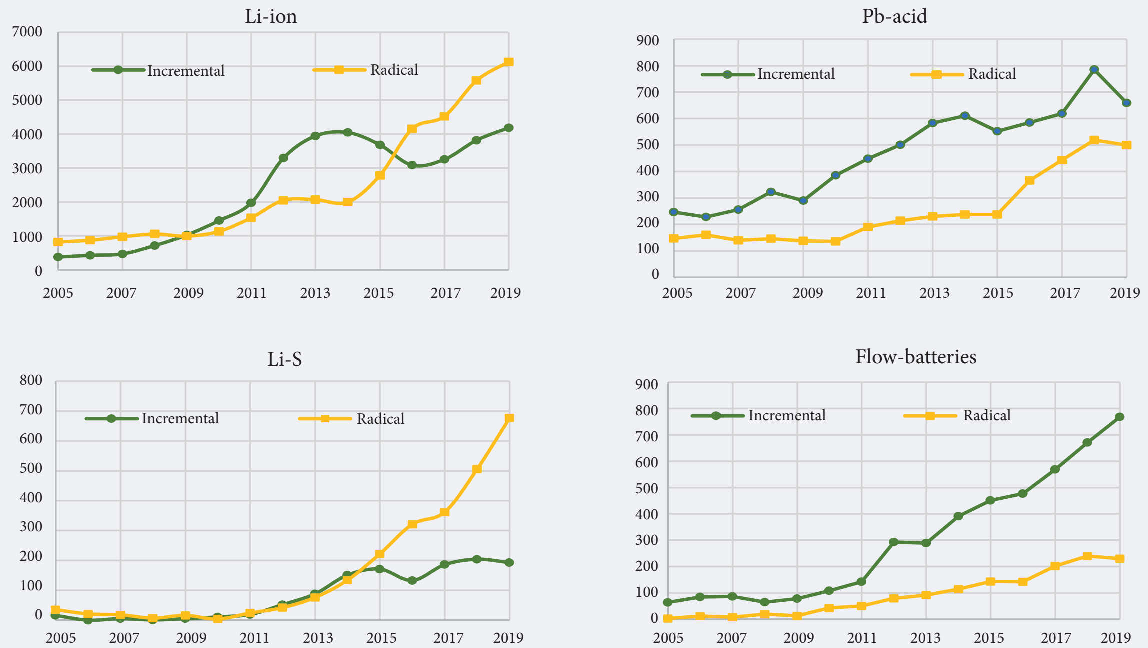
Over the last several decades, the concern with the role of new technology in pre-empting and mitigating climate change has emerged at top of the policy agenda across many national and international constituencies, largely driven by the synergies between the digital and sustainability challenges. The assumption of this paper is that electricity harnessing, storage, and dispatching has a pivotal role to play in the socio-technical transition toward a cleaner and more connected mode of innovation, production, distribution, and consumption. The theoretical baseline of this paper is founded on the

Figure 6. **Evolution Overtime of Innovation by Type**



Source: authors.

Figure 7. **Dynamics of Incremental and Radical Innovation for the Four Main Batteries Technologies**



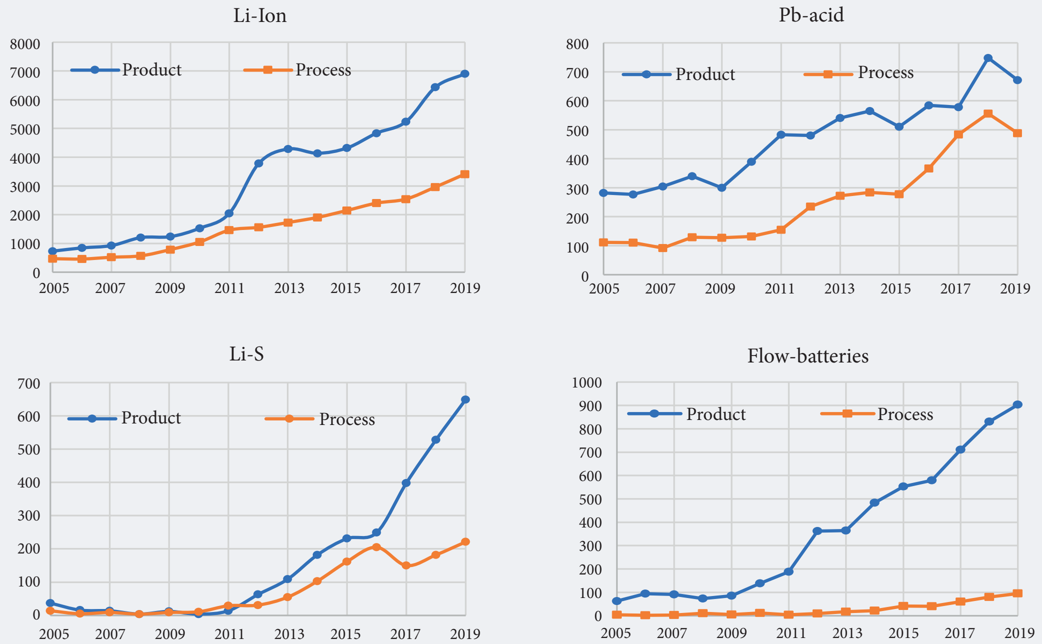
Source: authors.

understanding that innovation is an uneven, uncertain, and evolutionary phenomenon. By focusing on batteries and adopting a long-term perspective in what has become a rapidly moving field, we stress how functionalities and applications interact over time in what become technological trajectories. The large patent database assembled yields a set of results that correspond to a general picture in which battery breakthroughs have been gaining momentum at an irregular tempo, but consistently across a range of specific technology variants. These results may also provide some guiding principles for the development and investment in batteries and complementary low carbon energy technologies.

Patent evidence for 2005–2019 shows that innovation in battery technologies is increasing strongly in a variety of technological aspects. The countries that most contribute to this increase are Japan, South Korea, USA, Germany, and China. Lithium-ion batteries are currently the main driving force of battery innovation, framing the most significant trends of the field. Lithium-sulfur and flow batteries assert themselves as the most promising emerging technologies, and their development should be attentively followed in the next several years. Lately, solid state batteries have been gaining a lot of attention and patent data for the period 2005–2019, indicating it to be a promising technological direction. Battery implementation challenges are highly sector-specific and define innovation pathways that are relevant for stakeholders engaged in decarbonizing strategies. The quest to increase battery capacity contributes to the electrodes being the most dynamic battery component. The need to increase energy density and reduce the battery charging time has boosted research on innovative battery cooling technologies. The specific features of energy production technologies, like PV, and energy usages like the electric car, have contributed to the rise of battery charging/supplying load to the most innovative technological component. In fact, the interactions of battery charging with these two technologies have become empirically noticeable. The overall evolution of the battery innovation typologies shows a steady growth of product, process, incremental, and radical innovation types, with stable shares of product/process and incremental/radical innovations. Incremental/product innovation tends to be the main mode of advancement overall during the past two decades.

The constructive engagement with science and technology processes that address major global societal challenges reflect the realm of possibilities for further progress. Following from this observation, it is clear that energy-relevant institutions (policy-setting entities, regulatory authorities, standard bodies, etc.) should bring an explicit dynamic view into their sectoral development agendas. Energy transformation is contingent upon continuous, sustained, and strategic commitments to innovation. Progress in storage technologies requires a diversity of sources of knowledge, experimentation avenues, and forceful investments. This unfolding set of learning paths reveals pointers that can guide public and private decision-makers, in what is a dynamic and shifting technological frontier. Reports by national and international agencies could

Figure 8. **Evolution Overtime of Product and Process Innovation**



Source: authors.

benefit, for instance, from systematically following research and innovation indicators. since being able to hold a long-view horizon is an urgent task in times of climate shocks and systematic scarcity.

One limitation of a patent-based study like ours is that patents detect more easily innovations put forward by large companies than by smaller ones. Also, by looking at individual patents, one cannot perceive unambiguously if these belong to an ensemble of patents that jointly protect a certain innovative package (meaning expert panels could be mobilized in future studies to add qualitative appraisals to science and technology indicators in order to provide more holistic assessments).

Finally, the analysis of the geographical distribution of patent applications suggests that countries that pushed through ambitious, consistent, and long-term R&D programs symbiotically coordinated with large industrial players on clean energy technologies, and particularly within the battery field, such as Japan, South Korea, and more recently China, have obtained an innovation edge that places them in a very favorable position in the energy transition process. These examples are a reminder that purposeful change is possible across the world.

The authors acknowledge the financial support of the Portuguese Fundação para a Ciência e Tecnologia (FCT). José Silva acknowledges FCT support through project UIDB / 50019 / 2020 – IDL. Sandro Mendonça gratefully acknowledges the support of FCT through the Business Research Unit (BRU-IUL) and the Research Unit on Complexity and Economics (UECE-REM). BRU-IUL benefited from grants UID/GES/00315/2013, UIDB/00315/2020; UIDB/05069/2020; PTDC/EGE-ECO/30690/2017 and is part of the project PTDC/EGE-ECO/30690/2017. Sandro Mendonça worked on this paper while he was Visiting Professor at the Department of Economics of the University of Insubria, Italy, and he thanks the institution for the research context, support and for the interactions with students and staff, namely Professors Andrea Vezzulli and Paolo Castelnuovo.

References

Aaldering L.J., Song C.H. (2019) Tracing the technological development trajectory in post-lithium-ion battery technologies: A patent-based approach. *Journal of Cleaner Production,* 241, 118343. http://doi.org/10.1016/j.jclepro.2019.118343

Albertsen L., Richter J.L., Peck P., Dalhammar C., Plepys A. (2021) Circular business models for electric vehicle lithium-ion batteries: An analysis of current practices of vehicle manufacturers and policies in the EU. *Resources, Conservation and Recycling*, 172, 105658. http://doi.org/10.1016/j.resconrec.2021.105658

Albino V., Ardito L., Dangelico R.M., Messeni-Petruzzelli A. (2014) Understanding the development trends of low-carbon energy technologies: A patent analysis. *Applied Energy,* 135, 836–854. https://doi.org/10.1016/j.apenergy.2014.08.012

Azzuni A., Breyer C. (2018) Energy security and energy storage technologies. *Energy Procedia,* 155, 237–258. https://doi.org/10.1016/j.egypro.2018.11.053

Barnhart C.J., Dale M., Brandt A.R., Benson S.M. (2013) The energetic implications of curtailing versus storing solar- and wind-generated electricity. *Energy & Environmental Science*, 6(10), 2804. http://doi.org/10.1039/c3ee41973h

Bathelt H., Cohendet P., Henn S., Simon L. (2017) *The Elgar Companion to Innovation and Knowledge Creation*, Cheltenham: Edward Elgar. http://doi.org/10.4337/9781782548522
Bergek A., Berggren C. (2014) The impact of environmental policy instruments on innovation: A review of energy and automotive industry studies. *Ecological Economics,* 106, 112–123. http://doi.org/10.1016/j.ecolecon.2014.07.016
Berndt D. (2003) Electrochemical Energy Storage. In: *Battery Technology Handbook* (ed. H.A. Kiehne) (2nd ed.), New York: CRS Publisher, pp. 1–99.
Caraça J., Lundvall B.-A., Mendonça S. (2009) The changing role of science in the innovation process: From Queen to Cinderella?. *Technological Forecasting and Social Change*, 76(6), 861–867. https://doi.org/10.1016/j.techfore.2008.08.003
Castaldi C., Frenken K., Los B. (2015) Related Variety, Unrelated Variety and Technological Breakthroughs: An analysis of US State-Level Patenting. *Regional Studies,* 49(5), 767–781. http://doi.org/10.1080/00343404.2014.940305
Castellacci F., Grodal S., Mendonca S., Wibe M. (2005) Advances and challenges in innovation studies. *Journal of Economic Issues*, 39(1), 91–121. http://doi.org/10.1080/00213624.2005.11506782
Castillo A., Gayme D.F. (2014) Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management,* 87, 885–894. http://doi.org/10.1016/j.enconman.2014.07.063
Chen K., Hou J., Song M., Wang S., Wu W., Zhang Y. (2021) Design of battery thermal management system based on phase change material and heat pipe. *Applied Thermal Engineering,* 188, 116665. http://doi.org/10.1016/j.applthermaleng.2021.116665
Criscuolo P. (2006) The "home advantage" effect and patent families. A comparison of OECD triadic patents, the USPTO and the EPO. *Scientometrics,* 66, 23–41. http://doi.org/10.1007/s11192-006-0003-6
Dehghani-Sanij A.R., Tharumalingam E., Dusseault M.B., Fraser R. (2019) Study of energy storage systems and environmental challenges of batteries. *Renewable and Sustainable Energy Reviews,* 104, 192–208. http://doi.org/10.1016/j.rser.2019.01.023
Dhakal T., Min K.S. (2021) Macro Study of Global Electric Vehicle Expansion. *Foresight and STI Governance*, 15(1), 67–73. https://doi.org/10.17323/2500-2597.2021.1.67.73
Diesendorf M., Wiedmann T. (2020) Implications of Trends in Energy Return on Energy Invested (EROI) for Transitioning to Renewable Electricity. *Ecological Economics,* 176, 106726. http://doi.org/10.1016/j.ecolecon.2020.106726
Ding H., Hu Z., Song Y. (2012) Stochastic optimization of the daily operation of wind farm and pumped-hydro-storage plant. *Renewable Energy,* 48, 571–578. http://doi.org/10.1016/j.renene.2012.06.008
Dodgson M., Gann D.M., Salter A. (2008) *The management of technological innovation: Strategy and practice* (2nd ed.), Oxford: Oxford University Press.
Domnich E. (2022) The impact of product and process innovations on Productivity: A review of empirical studies. *Foresight and STI Governance*, 16(3), 68–82. https://doi.org/10.17323/2500-2597.2022.3.68.82
Dosi G. (1982) Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy,* 11(3), 147–162. https://doi.org/10.1016/0048-7333(82)90016-6
Dziallas M., Blind K. (2019) Innovation indicators throughout the innovation process: An extensive literature analysis. *Technovation,* 80–81, 3–29. http://doi.org/10.1016/j.technovation.2018.05.005
Fagerberg J. (2004) Innovation: A guide to the literature. In: *The Oxford Handbook of Innovation* (eds. J. Fagerberg, D.C. Mowery), Oxford: Oxford University Press, pp. 1–16.
Fagerberg J., Laestadius S., Martin B.R. (2016) The Triple Challenge for Europe: The Economy, Climate Change, and Governance. *Challenge,* 59(3), 178–204. http://doi.org/10.1080/05775132.2016.1171668
Feng S., Magee C.L. (2020) Technological development of key domains in electric vehicles: Improvement rates, technology trajectories and key assignees. *Applied Energy,* 260, 114264. http://doi.org/10.1016/j.apenergy.2019.114264
Golembiewski B., Vom Stein N., Sick N., Wiemhöfer H.D. (2015) Identifying trends in battery technologies with regard to electric mobility: Evidence from patenting activities along and across the battery value chain. *Journal of Cleaner Production,* 87, 800–810. http://doi.org/10.1016/j.jclepro.2014.10.034
Hansen A.R., Jacobsen M.H., Gram-Hanssen K. (2022) Characterizing the Danish energy prosumer: Who buys solar PV systems and why do they buy them? *Ecological Economics,* 193, 107333. http://doi.org/10.1016/j.ecolecon.2021.107333
Hesse K., Fornahl D. (2020) Essential ingredients for radical innovations? The role of (un-) related variety and external linkages in Germany. *Papers in Regional Science,* 99(5), 1165–1183. http://doi.org/10.1111/pirs.12527
Hirsh H.S., Li Y., Tan D.H.S., Zhang M., Zhao E., Meng Y.S. (2020) Sodium-Ion Batteries Paving the Way for Grid Energy Storage. *Advanced Energy Materials,* 10(32), 2001274. http://doi.org/10.1002/aenm.202001274
Hung S.C., Lai J.Y., Liu J. S. (2022) Mapping technological trajectories as the main paths of knowledge flow: Evidence from printers. *Industrial and Corporate Change*, 31(3), 863–889. https://doi.org/10.1093/icc/dtab072
IEA, EPO (2020) *Innovation in Batteries and Electricity Storage,* Paris: IEA, EPO. https://www.iea.org/reports/innovation-in-batteries-and-electricity-storage, accessed 15.01.2023.
IEA, EPO (2021) *Patents and the Energy Transition,* Paris: IEA, EPO. https://www.iea.org/reports/patents-and-the-energy-transition, accessed 15.01.2023.
IEA (2008) *Energy Policies of IEA Countries: Japan 2008 Review. Review Literature and Arts of the Americas,* Paris: IEA. https://www.iea.org/reports/energy-policies-of-iea-countries-japan-2008, accessed 15.01.2023.
IEA (2020a) *Energy Storage*, Paris: IEA. https://www.iea.org/reports/energy-storage, accessed 15.01.2023.
IEA (2020b) *Energy Technology Perspectives 2020,* Paris: IEA. https://www.iea.org/reports/energy-technology-perspectives-2020IEA, accessed 15.01.2023.
IEA (2021a) *Global Energy Review 2021,* Paris: IEA. https://www.iea.org/reports/global-energy-review-2021, accessed 15.01.2023.
IEA (2021b) *The Role of Critical Minerals in Clean Energy Transitions – Analysis,* Paris: IEA. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, accessed 15.01.2023.
IEA (2022) *World Energy Review 2022,* Paris: IEA. https://iea.blob.core.windows.net/assets/9d0a2db4-965a-4e80-83da-562f038ff514/WorldEnergyOutlook2022.pdf, accessed 15.01.2023.

IPCC (2021) *Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Geneva: IPCC, https://www.ipcc.ch/assessment-report/ar6/, accessed 15.01.2023.

Jeong E., Mah J.S. (2022) The Role of the Government in the Development of the Rechargeable Battery Industry in Korea. *Perspectives on Global Development and Technology*, 21(2), 1569–1500. https://doi.org/10.1163/15691497-12341625

Jesus A., Mendonça S. (2018) Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics,* 145, 75–89. http://doi.org/10.1016/j.ecolecon.2017.08.001

Jindal A., Shrimali G. (2022) At scale adoption of battery storage technology in Indian power industry: Enablers, frameworks and policies. *Technological Forecasting and Social Change,* 176, 121467. https://doi.org/10.1016/j.techfore.2021.121467

Katila R. (2000) Using patent data to measure innovation performance. *International Journal of Business Performance Management*, 2, 180–193. https://doi.org/10.1504/IJBPM.2000.000072

Kim J.G., Son B., Mukherjee S., Schuppert N., Bates A., Kwon O., Choi M.J., Chung H.Y., Park S. (2015) A review of lithium and non-lithium based solid state batteries. *Journal of Power Sources,* 282, 299–322. http://doi.org/10.1016/j.jpowsour.2015.02.054

Kim J., Lee S. (2015) Patent databases for innovation studies: A comparative analysis of USPTO, EPO, JPO and KIPO. *Technological Forecasting and Social Change*, 92, 332–345. http://doi.org/10.1016/j.techfore.2015.01.009

Kittner N., Lill F., Kammen D.M. (2017) Energy storage deployment and innovation for the clean energy transition. *Nature Energy,* 2(9), 17125. https://doi.org/10.1038/nenergy.2017.125

Lee K., Lee S. (2013) Patterns of technological innovation and evolution in the energy sector: A patent-based approach. *Energy Policy*, 59, 415–432. http://doi.org/10.1016/j.enpol.2013.03.054

Lehmann C., Cruz-Jesus F., Oliveira T., Damásio B. (2022) Leveraging the circular economy: Investment and innovation as drivers. *Journal of Cleaner Production*, 360, 132146. https://doi.org/10.1016/j.jclepro.2022.132146

Leiponen A. (2014) Intellectual Property Rights, Standards, and the Management of Innovation. In: *The Oxford Handbook of Innovation Management* (eds. M. Dodgson, D.M. Gann, N. Phillips), Oxford: Oxford University Press, pp. 559–578. http://doi.org/10.1093/oxfordhb/9780199694945.013.020

Levänen J., Lyytinen T., Gatica S. (2018) Modelling the Interplay Between Institutions and Circular Economy Business Models: A Case Study of Battery Recycling in Finland and Chile. *Ecological Economics*, 154, 373–382. http://doi.org/10.1016/j.ecolecon.2018.08.018

Lhuillery S., Raffo J., Hamdan-Livramento I. (2017) Measurement of innovation. In: *The Elgar Companion to Innovation and Knowledge Creation* (eds. H. Bathelt, P. Cohendet, S. Henn, L. Simon), Cheltenham: Edward Elgar. http://doi.org/10.4337/9781782548522.00013

Lu M., Zhang X., Ji J., Xu X., Zhang Y. (2020) Research progress on power battery cooling technology for electric vehicles. *Journal of Energy Storage*, 27, 101155. http://doi.org/10.1016/j.est.2019.101155

Malhotra A., Zhang H., Beuse M., Schmidt T. (2021) How do new use environments influence a technology's knowledge trajectory? A patent citation network analysis of lithium-ion battery technology. *Research Policy,* 50(9), 104318. https://doi.org/10.1016/j.respol.2021.104318

Martínez C. (2011) Patent families: When do different definitions really matter? *Scientometrics,* 86(1), 39–63. http://doi.org/10.1007/s11192-010-0251-3

May G.J., Davidson A., Monahov B. (2018) Lead batteries for utility energy storage: A review. *Journal of Energy Storage*, 15, 145–157. http://doi.org/10.1016/j.est.2017.11.008

McKelvey M. (2014) Science, Technology, and Business Innovation. In: *The Oxford Handbook of Innovation Management* (eds. M. Dodgson, D.M. Gann, N. Phillips), Oxford: Oxford University Press, pp. 69–82. http://doi.org/10.1093/oxfordhb/9780199694945.013.029

Mei W., Chen H., Sun J., Wang Q. (2019) The effect of electrode design parameters on battery performance and optimization of electrode thickness based on the electrochemical-thermal coupling model. *Sustainable Energy and Fuels*, 3(1), 148–165. http://doi.org/10.1039/c8se00503f

Mendonça S., Schmoch U., Neuhäusler P. (2019) Interplay of patents and trademarks as tools in economic competition. In: *Springer Handbook of Science and Technology Indicators* (eds. W. Glänzel, H.F. Moed, U. Schmoch, M. Thelwall), Berlin: Springer, pp. 1023–1035.

Mendonça S., Confraria H., Godinho M.M. (2021) *Appropriating the returns of patent statistics: Take-up and development in the wake of Zvi Griliches* (SWPS Paper 2021-07). http://doi.org/10.2139/ssrn.3971764

Metzger P., Mendonça S.J., Silva J. A., Damásio B. (2023) Battery Innovation and the Circular Economy: What are Patents Revealing? *Renewable Energy* (In Press). https://doi.org/10.1016/j.renene.2023.03.132

Nagaoka S., Motohashi K., Goto A. (2010) Patent statistics as an innovation indicator. In: *Handbook of the Economics of Innovation* (vol. 2) (eds. B.H. Hall, N. Rosenberg), Amsterdam: Elsevier, pp. 1083–1127. http://doi.org/10.1016/S0169-7218(10)02009-5

Nelson R.R., Dosi G., Helfat C.E., Pyka A., Saviotti P.P., Lee K., Dopfer K., Malerba F., Winter S.G. (2018) *Modern Evolutionary Economics: An Overview,* Cambridge: Cambridge University Press.

Patel P., Pavitt K. (2005) Patterns of Technological Activity: Their Measurement and Interpretation. In: *Handbook of the Economics of Innovation and Technical Change* (ed. P. Stoneman), Oxford: Blackwell, pp. 14–51.

Prencipe A., Davies A., Hobday M. (2005) *The Business of Systems Integration* (1st ed.), Oxford: Oxford University Press. http://doi.org/10.1093/0199263221.001.0001

Schot J., Steinmueller W.E. (2019) Transformative change: What role for science, technology and innovation policy?: An introduction to the 50th Anniversary of the Science Policy Research Unit (SPRU) Special Issue. *Research Policy*, 48(4), 843–848. http://doi.org/10.1016/j.respol.2018.12.005

Schulz C., Martin-Ortega J., Ioris A.A.R., Glenk K. (2017) Applying a "Value Landscapes Approach" to Conflicts in Water Governance: The Case of the Paraguay-Paraná Waterway. *Ecological Economics,* 138, 47–55. http://doi.org/10.1016/j.ecolecon.2017.03.033

Shapiro M.A. (2020) Next-generation battery research and development: Non-politicized science at the Joint Center for Energy Storage Research. *Energy Policy*, 145, 111771. https://doi.org/10.1016/j.enpol.2020.111771
Silva J.A., Oliveira S., Távora G., Mendonça S. (2015) The role of innovation in the future PV and storage markets. In: *Proceedings 31st European PVSEC*, pp. 3183–3186. https://doi.org/10.4229/EUPVSEC20152015-7DV.4.41
Smith K. (2006) Measuring Innovation. In: *The Oxford Handbook of Innovation.* (eds. J. Fagerberg, D.C. Mowery), Oxford: Oxford University Press, pp. 148–179. http://doi.org/10.1093/oxfordhb/9780199286805.003.0006
Sovacool B.K., Hess D.J., Amir S., Geels F.W., Hirsh R., Rodriguez-Medina L., Miller C., Palavicino C.A., Phadke R., Ryghaug M., Schot J., Silvast A., Stephens J., Stirling A., Turnheim B., Der Vleuten E., Lente H., Yearley S. (2020) Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Research and Social Science*, 70, 101617. http://doi.org/10.1016/j.erss.2020.101617
Stephan A., Schmidt T.S., Bening C.R., Hoffmann, V.H. (2017) The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy,* 46(4), 709–723. https://doi.org/10.1016/j.respol.2017.01.009
Tahmooresnejad L., Beaudry C. (2019) Capturing the economic value of triadic patents. *Scientometrics,* 118(1), 127–157. http://doi.org/10.1007/s11192-018-2959-4
Tomaszewska A., Chu Z., Feng X., O'Kane S., Liu X., Chen J., Ji C., Endler E., Li R., Liu L., Li Y., Zheng S., Vetterlein S., Gao M., Du J., Parkes M., Ouyang M., Marinescu M., Offer G., Wu B. (2019) Lithium-ion battery fast charging: A review. *eTransportation*, 1, 100011. https://doi.org/10.1016/j.etran.2019.100011
Turovets J., Proskuryakova L., Starodubtseva A., Bianco V. (2021) Green digitalization in the electric power industry. *Foresight and STI Governance,* 15(3), 35–51. https://doi.org/10.17323/2500-2597.2021.3.35.51
Van Noorden R. (2014) The rechargeable revolution: A better battery. *Nature,* 507(7490), 26–28. http://doi.org/10.1038/507026a
Velázquez-Martínez O., Valio J., Santasalo-Aarnio A., Reuter M., Serna-Guerrero R. (2019) A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective. *Batteries,* 5(4), 68. https://doi.org/10.3390/batteries5040068
Wagner R., Preschitschek N., Passerini S., Leker J., Winter M. (2013) Current research trends and prospects among the various materials and designs used in lithium-based batteries. *Journal of Applied Electrochemistry*, 43(5), 481–496. https://doi.org/10.1007/s10800-013-0533-6
Wong C.Y., Fatimah-Mohamad Z., Keng Z.X., Ariff-Azizan S. (2014) Examining the patterns of innovation in low carbon energy science and technology: Publications and patents of Asian emerging economies. *Energy Policy,* 73, 789–802. https://doi.org/10.1016/j.enpol.2014.05.010
Zhang Q., Li C., Wu Y. (2017) Analysis of Research and Development Trend of the Battery Technology in Electric Vehicle with the Perspective of Patent. *Energy Procedia,* 105, 4274–4280. http://doi.org/10.1016/j.egypro.2017.03.918
Zhao Y., Stein P., Bai Y., Al-Siraj M. (2018) A review on modeling of electro-chemo-mechanics in lithium-ion batteries. Journal of Power Sources, 413, 259-283. https://doi.org/10.1016/j.jpowsour.2018.12.011

Appendix A. **Methodological protocols of the study**

Battery components groups

Battery system component	Search query
Non-active parts	(((IPC = H01M2+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M4+ OR H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Electrodes	(((IPC = H01M4+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ OR H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Secondary cells	(((IPC = H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ OR H01M4+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts and electrodes	(((IPC = H01M2+ and H01M4+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M10+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts and secondary cells	(((IPC = H01M2+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M4+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Electrodes and secondary cells	(((IPC = H01M4+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M2+ or H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Non-active parts, electrodes and secondary cells	(((IPC = H01M2+ and H01M4+ and H01M10+) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Charging	(IPC = H02J7 or H02J3/32 or B60L53 or H01M10/44) AND (PUD [20050101, 20191231])
Cooling	(((IPC = (H01M00106* or H01M0010443* or H01M0010486 or H01M0050375 or H01M0050581)) and (PUD [20050101, 20191231])) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16))

Types of battery technologies

Battery type	Search query
Lead-acid	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (VRLA OR SLA OR lead +2w acid OR lead +2w acc+)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Lithium-air	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (Lithium +2w air OR Li +2w air OR lithium +2w oxygen OR LiO2 OR Li +2w O2)) AND NOT (IPC = H01M6 or H01M8 OR H01M12 OR H01M14 OR H01m16 OR H01M18))
Lithium-ion	(((IPC = H01M2+ OR H01M4+ OR H01M10+) and (PUD [20050101, 20191231])) AND (ABEN = (Li +2w ion OR LiFePO4 OR LiPo OR Li +2w Poly OR lithium +2w ion OR Lithium +2w cobalt OR Lithium +2w manganese OR Lithium +2w phosphate OR Lithium +2w iron +2w phosphate OR Lithium +2w titanate OR Lithium +2w Polymer)) AND NOT (IPC = H01M6+ OR H01M8+ OR H01M12+ OR H01M14+ OR H01M16+ OR H01M18+))
Lithium-sulfur	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (li +2w S OR lithium +2w sulphur OR lithium +2w sulfur)) AND NOT (IPC = H01M6 or H01M8 OR H01M12 OR H01M14 OR H01m16 OR H01M18))
Magnesium-ion	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (magnesium +1w ion OR Mg +1w ion)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Nickel-cadmium	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = nickel +2w cadmium OR Ni +2W cd OR Nicd) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Flow	(((IPC = H01M2 OR H01M4 OR H01M8 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (Flow +2w batter* OR Redox +2w flow +2w batter* OR RFB OR Vanadium +2w redox +2w batter* OR Vanadium +2w redox +2w flow OR VRB OR Zinc +2w bromine +2w flow OR Zinc +2w bromine +2w batter* OR ZNBR OR Iron +2w chromium +2w flow OR iron +2w chromium +2w batter*)) AND NOT (IPC = H01M6 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Sodium-sulfur	(((IPC = H01M2 OR H01M4 OR H01M10) and (PUD [20050101, 20191231])) AND (ABEN = (sodium +2w sulfur OR sodium +2w sulphur OR Na +0w S)) AND NOT (IPC = H01M6 OR H01M8 OR H01M12 OR H01M14 OR H01M16 OR H01M18))
Solid state batteries	((IPC = H01M2 or h01m4 or h01m10 or H01M50) and ((ABEN = solid +2w state)) AND (PUD [20050101, 20191231]))

Interactions with other technologies

Interaction	Search query
Batteries and PV	(IPC = (h01m10+) and (H02S+ or H01L 27/142 or H01L31/00 or H01L31/02 or H01L31/024 or H01L31/04 or H01G9/20 or H02S10/ or H01L31/042 or G05F1/67 or F21S9/03 or H01G9/20 or H01M14 or H01L31/0525 or B60K16/00 or B60L8)) and (PUD [20050101, 20191231]) AND not (IPC = H01M6 or H01M8)
Batteries and Wind	(IPC = (h01m10+) and (F03D+)) and (PUD [20050101, 20191231]) AND not (IPC = H01M6 or H01M8)
Batteries and Electric Vehicles	((IPC = H01M2 or h01m4 or h01m10) and ((IPC = B60L50 or B60L11) or (ABEN = electric +2w vehicle or ev or electric +2w mobility)) AND (PUD [20050101, 20191231]))
Charging Electric Vehicles Batteries	(((IPC = H02J7 or H02J3/32 or H01M10/44) and ((IPC = B60L11 or B60L50) or (ABEN = electric +2w vehicle or ev or electric +2w mobility))) or IPC = B60L53) AND (PUD [20050101, 20191231])
Charging Batteries with PV	(IPC = ((H02J7 or H02J3/32 or H01M10/44) and (H02S+ or H01L 27/142 or H01L31/00 or H01L31/02 or H01L31/024 or H01L31/04 or H01G9/20 or H02S10/ or H01L31/042 or G05F1/67 or F21S9/03 or H01G9/20 or H01M14 or H01L31/0525 or B60K16/00 or B60L8)) or H02J7/35) AND (PUD [20050101, 20191231])

Battery process innovation IPC sub-groups

IPC Code	Process Classifications
H01M 4 – Electrodes	H01M 4/04, H01M 4/08, H01M 4/10, H01M 4/12, H01M 4/139, H01M 4/1391, H01M 4/13915, H01M 4/1393, H01M 4/1395, H01M 4/1397, H01M 4/1399, H01M 4/16, H01M 4/18, H01M 4/20, H01M4 /21, H01M 4/22, H01M 4/23, H01M 4/26, H01M 4/28, H01M 4/29, H01M 4/30, H01M 4/82; H01M84; H01M 4/88
H01M 10 – Secondary elements	H01M 10/04, H01M 10/058, H01M 10/0583, H01M 10/0585, H01M 10/0587, H01M 10/12, H01M 10/14, H01M 10/16, H01M 10/28, H01M 10/38