The metrics of battery leadership: Patenting patterns since 2000

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ABSTRACT

This study provides a technometric analysis of patent activity on electric secondary battery technologies from 2000 to 2019. Its goal is to enrich and buttress the existing literature on the topic by providing a deeper insight into how inventive dynamics in this field have been evolving, which technologies and concepts are emerging, declining, or becoming established, both in absolute and in relative terms, and how geographic locations can be characterized in terms of their position in the technology space. Mapping and measuring battery progress is relevant as this technology is a capping stone at the intersection of the current energy and digital transitions. Worldwide battery patent counts are assembled and broken down alongside time, territory, and technological dimensions. We take international patent families as an indicator and are able to extract 92,700 patent applications from the PATSTAT database, which is the empirical source for this study. We find that global battery patenting activity has been trending upwards in 2000-2019, that the majority of battery patents originates from Asia, and that several Asian and European countries exhibit high battery patent intensities in the given timeframe. Comparing the two decades of 2000-2009 and 2010-2019, a considerable increase in yearly battery patenting activity is observed. We find that four battery types (redox flow, solid-state, sodium-ion, and lithium-sulfur) display marked progress in recent years, that countries can be clustered in a meaningful way using their patenting performance across these four emerging battery types and the already established lead-acid technology, and that several other battery-related technologies such as energy storage systems, battery management systems, wireless power transmission, electric vehicle charging, and unmanned aerial vehicles (i.e. drones) are growing in relevance.

Keywords: electric batteries, patents, data mining, technometrics

1 Introduction

The importance of batteries has been growing and with two major fields of deployment being electric mobility applications and the storage of energy generated by fluctuating, non-dispatchable, renewable sources, their interlocking role at the intersection of the energy-digital transition is expected to grow further in the coming decades. A report about the recent developments in electricity storage technologies published by the International Energy Agency (IEA) in association with the European Patent Office (EPO), asserts that under the Sustainable Development Scenario (SDS) defined by the IEA, "the level of deployment and the range of applicability of batteries [...] expands dramatically" (IEA 2020[1], p. 28). In particular, battery technologies will move beyond consumer appliances and into industrial-size types of equipment: "Charging batteries in electric vehicles will become the largest single source of electricity demand, accounting for around 5% of global demand by 2050" (IEA 2020[1], p. 29). Furthermore, "the use of batteries in stationary energy storage applications is [already] growing exponentially" (IEA 2020[1], p. 32). Given this dynamic, it is worthwhile to identify and monitor the rate and direction of battery innovation.

For this study, we built a new dataset containing 92,700 international electric secondary battery patent applications (consolidated in terms of *international patent families*, or IPFs) from the years 2000 to 2019. The raw data was extracted from PATSTAT Online (edition: Autumn 2021), the web interface of the PATSTAT database[2] maintained by the European Patent Office containing a vast collection of data extracted from worldwide patent documents, usable for purposes of statistical analysis.

We find that the global battery patenting activity has been trending upwards in 2000-2019, that the majority of battery patents originates from Asia, and that several Asian and European countries exhibit high battery patent intensities in the given timeframe. Comparing the two decades of 2000-2009 and 2010-2019, a considerable increase in yearly battery patenting activity is observed. We find that that four battery technologies (redox flow, solid-state, sodium-ion, and lithium-sulfur batteries) have displayed increased patenting activity in the recent decade, that countries can be clustered in a meaningful way using their patenting distribution over these four emerging battery types and the already established lead-acid technology, and that several battery-related technologies and applications such as energy storage systems, battery management systems, wireless power transmission, electric vehicle charging, and unmanned aerial vehicles (i.e. drones) are growing in relevance both in absolute terms and relative to general battery patenting activity. These results complete and buttress a number of stylized facts on battery innovation that have been surfacing of late and attracting policy attention.[1]

This paper is organized as follows: Section 2 presents the key foundations and concepts that are relevant for this study. In section 3 results are presented, which are discussed in section 4. Section 5 concludes. Descriptions of the data selection process and the methods deployed for this analysis are provided in the Supplementary Information.

2 Foundations and concepts

2.1 Electric secondary batteries

Electric secondary batteries are able to receive energy in the form of electricity, store it, and at a later time—and with a certain loss due to the energy conversion processes taking place—release it again, feeding electricity back to the grid or powering a given application. Secondary batteries are rechargeable, unlike primary batteries that can only discharge once and then need to be discarded. In the context of the ongoing energy transition away from dispatchable sources such as coal-fired power plants and towards alternatives such as wind and solar, whose input is not controllable and hardly synchronous with the population's and the industry's needs, batteries and other means of energy storage constitute a regulating bridge that conjoins the temporal gap between supply and demand while balancing the system as a whole. Furthermore, accelerated electrification in the transporting sector, especially in individual mobility, creates a focusing device calling out for more batteries with smaller sizes, higher capacities, and longer lifespans (critical technologies have systemic and non-linear impacts[3]).

When speaking of batteries, one has to differentiate between the terms “battery”, “module”, and “cell”. Whilst an entire battery pack potentially consists of multiple modules that are "wired in series and/or (less often) parallel", a module itself consists of multiple cells that "are connected in series or parallel" (Vezzini et al. 2014[4], p. 345). For simplicity's sake, electric secondary batteries, meaning battery packs in their entirety, will henceforth be referred to as *batteries*. The following section articulates the notion of innovation and provides a short overview of the advantages and limitations of using patents as an indicator for measuring it.

2.2 Industrial innovation and the uses of patents as an indicator

Innovation is the process through which ideas and knowledge are converted into useful applications. This means that innovation is a multi-phased process, open to feedback at every stage, molded in an ongoing fashion by a variety of players and institutional settings.[5,6] As innovation started to be regarded as an empirical phenomenon of significant importance, its measurement and analysis became an increasingly topical agenda. Quantification of an intrinsically qualitative matter is always a partial approach but it is highly desirable in order to understand technological change over time and across space; plus, it is useful for assisting managerial strategy and public policy.[7]

An indicator that is used to capture the abstract concept of innovation is patent data. Typically, patents are created by the interested parties (inventors, owners, intellectual property lawyers, patent offices, etc.) when an invention already has a viable conceptual proposal but is not yet tested or fully deployed in practice. Despite of only being partial evidence of innovation, patents are still irreplaceable as sources for further study.[8] When making the case for patents as a proxy for measuring innovation, Griliches classically explains that patents "are available; they are by definition related to inventiveness, and they are based on what appears to be an objective and only slowly changing standard" (Griliches 1990[9], p. 1661).

Patents are documents that describe intellectual property. Therefore, they contain information such as geographic locations associated with inventors, descriptions, and classifications of the respective inventions, and timestamps like their application and publication dates. This allows for the aggregation of patent counts alongside geographic, temporal, and technological dimensions and makes them a suitable material for a variety of analytical purposes, such as competitiveness studies and environmental research.[10] The following sub-section briefly reviews the scant literature that draws on battery patents.

2.3 Literature on battery patents analysis

Aaldering et al.[11] provide an analysis of battery patent data highlighting developments in post-lithium-ion battery technologies, Malhotra et al.[12] propose a citation network analysis combining knowledge extracted from patent data with results from interviews conducted with lithium-ion battery experts, and Stephan et al.[13] examine lithium-ion battery patents from a sectoral diversity perspective and emphasize how sectoral distance of prior knowledge affect certain features of subsequent knowledge.

The current study extends the existing literature on this matter. Specifically, it aims to confirm and extend the findings presented in the report by the IEA and the EPO.[1] It can be understood as a continuation of their basic methodological approach, enriched by some reasonable additions, which allow for a more granular perspective on some aspects of this topic.

The report by IEA and EPO presents information extracted from patents related to batteries and electricity storage. Our current study is more narrow (focuses on battery technology only) but has a longer time span. The research gaps that we identified and that the current study aims to fill are how patent counts are distributed across continents, how scaling them by the sizes of the respective labor forces affects the outcome of the analysis, what their distribution across another technological classification scheme looks like, how countries can be characterized based on their position in a resulting technology space, and what information can be extracted from patent titles and abstracts.

The authors of the report by IEA and EPO use the concept of international patent families (IPF) for aggregating and counting patent applications. They claim that an IPF "is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally" (IEA 2020[1], p. 4). The following section explains the differences between patent applications, patent families, and international patent families and highlights some advantages and limitations of the latter concept.

2.4 International patent families

A patent application is a formal request made by one or several applicants at a patent office of their choice. This could be the European Patent Office (EPO), the United States Patent and Trademark Office (USPTO), or any other national or regional patent office. The applicants' goal is to obtain legal protection for an invention that they deem (1) directed to patentable subject matter, (2) novel, (3) inventive, and (4) capable of industrial application, which are the four conditions for patentability.[14] The term *patent family* refers to the whole set of patent applications covering the same invention.[15] By counting patent families instead of individual applications, double counting of inventions is avoided. Now, by restricting the scope to only patent families that contain applications filed in two or more countries, one obtains international patent families. The benefit of this restriction is that only patents of higher expected value are assessed, resulting in a more homogeneous dataset with better comparability between elements.

Three limitations regarding the concept of IPFs should be considered, as discussed in Schmoch and Gehrke[16]: First, the propensity to patent in foreign territories differs between countries of origin, meaning that for example an applicant from a European country might be more inclined to seek protection in another European country than an applicant from China might be inclined to seek protection in the US. This can be problematic because both situations would imply that the respective patent is filed in two countries, making their patent family an international patent family. Secondly, in specific technologies, the patent numbers for some countries, such as Japan, may be overestimated. Thirdly, there can be some turbulence in the evidence since IPFs with seemingly two members at the stage of applications can be reduced to one member, later on, something that may happen with Chinese inventors (regarding the Chinese case, we further refer to Frietsch and Kroll[17]). Schmoch and Gehrke[16] discuss several other concepts that exist parallel to IPFs, highlighting their advantages and limitations. For the reason of comparability to the IEA-EPO report, we keep international patent families as our frame, so all depicted counts refer to IPFs.

2.5 International Patent Classification (IPC)

The international patent classification system (IPC) provides a hierarchical classification scheme that is used for categorizing patents according to different technological areas. This study builds on patents that can roughly be characterized in the following way: (1) innovations related to casing, wrapping, or covering, i.e. non-active parts of batteries; (2) innovations in battery electrode manufacturing; (3) innovations related to the manufacturing process of secondary cells; and (4) innovations related to charging of batteries. Patents belonging to these four fields were identified using the IPC classification scheme, which is a constituent part of the data provided at the PATSTAT database.

3 Results

3.1 Basic stylized facts

This section presents the results obtained by counting battery IPFs both on global and national levels, disaggregating the patterns into different technologies, and analyzing how countries position themselves in the technology space. Furthermore, we report results of a text mining approach deployed on patent abstracts. This first sub-section contains some basic patterns highlighting the most essential battery patenting trends.

The global aggregate yearly volume of battery IPFs increased almost every year during the timeframe assessed in this study. Only for two pairs of adjacent years (from 2001 to 2002 and from 2014 to 2015), there were slight decreases. The whole time period's average yearly growth rate in battery IPFs is 14.30% (all percentages are rounded to two decimal places) so that between 2000 and 2019 the total IPF output increased more than 11-fold. This dynamic is displayed in Fig. 1.

Asian countries dominate the battery market: The Asian continent's mean annual battery IPF output is approximately four times higher than Europe's and North America's (factor 3.57 and 4.09, respectively). Furthermore, the number of IPFs from Asia has increased by 15.97% on average each year during the 2000-2019 period. The average increase values for Europe and North America are 13.46% and 10.78%, respectively (see Fig. 2; please note the log-scaled y-axis).

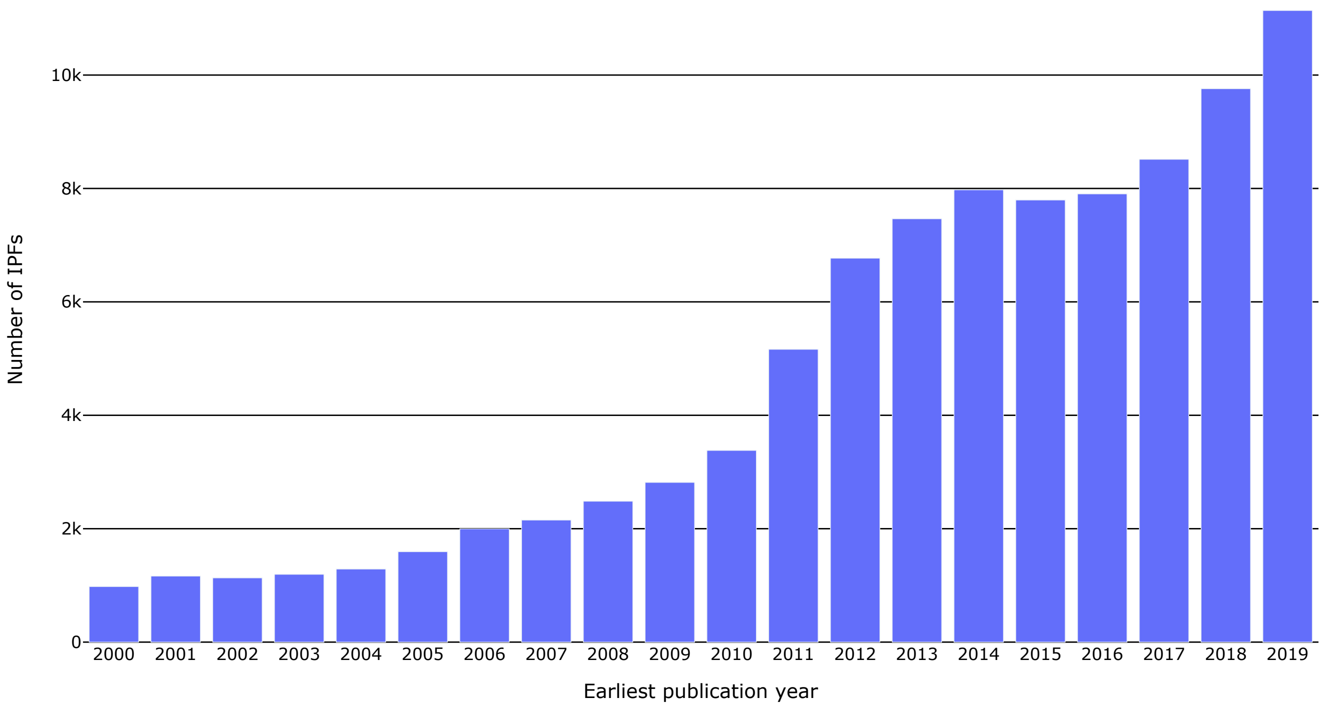

Figure 1. Total number of battery IPFs, 2000-2019. The global battery patenting activity displays a robust increase with a brief halt after a turning point between 2011 and 2012.

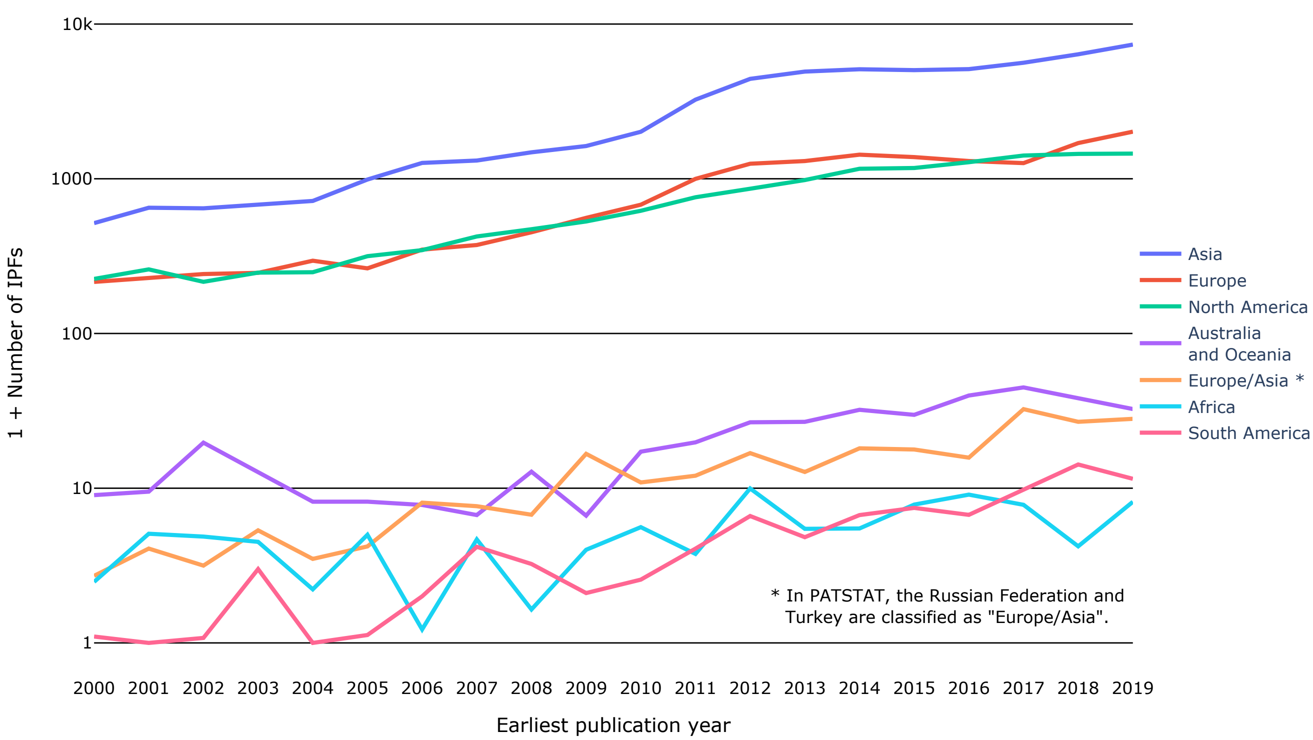

Figure 2. Battery IPFs by inventors' continents of origin, 2000-2019. The y-axis is log-scaled and all values are incremented by 1. It is clear that the number of battery IPFs from Asia (blue) is considerably higher than of any other continent.

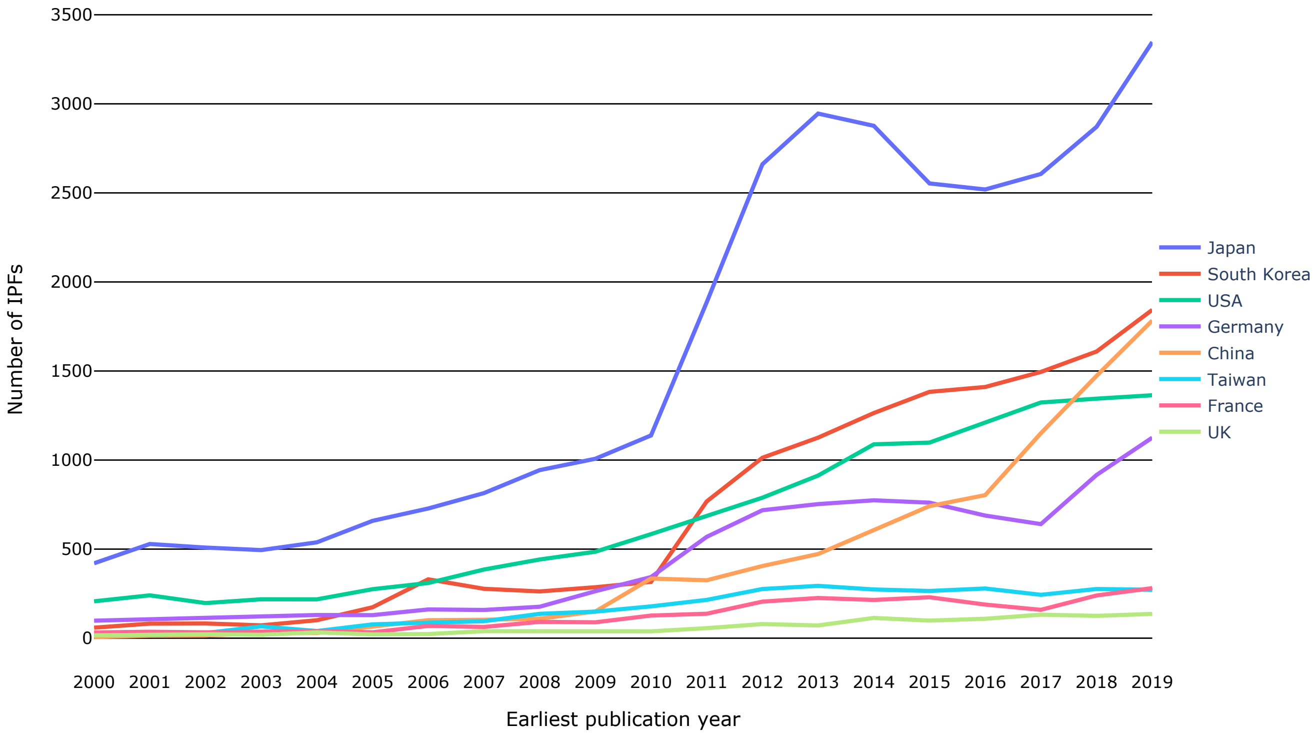

Figure 3. Battery IPFs by inventors' countries of origin, 2000-2019. The eight countries with the highest total battery IPF counts over the given timeframe are displayed. Japan (blue) has the highest battery IPF output in the given timeframe, whilst other countries' IPF counts (especially South Korea's (red) and China's (orange)) have been surging in the recent decade.

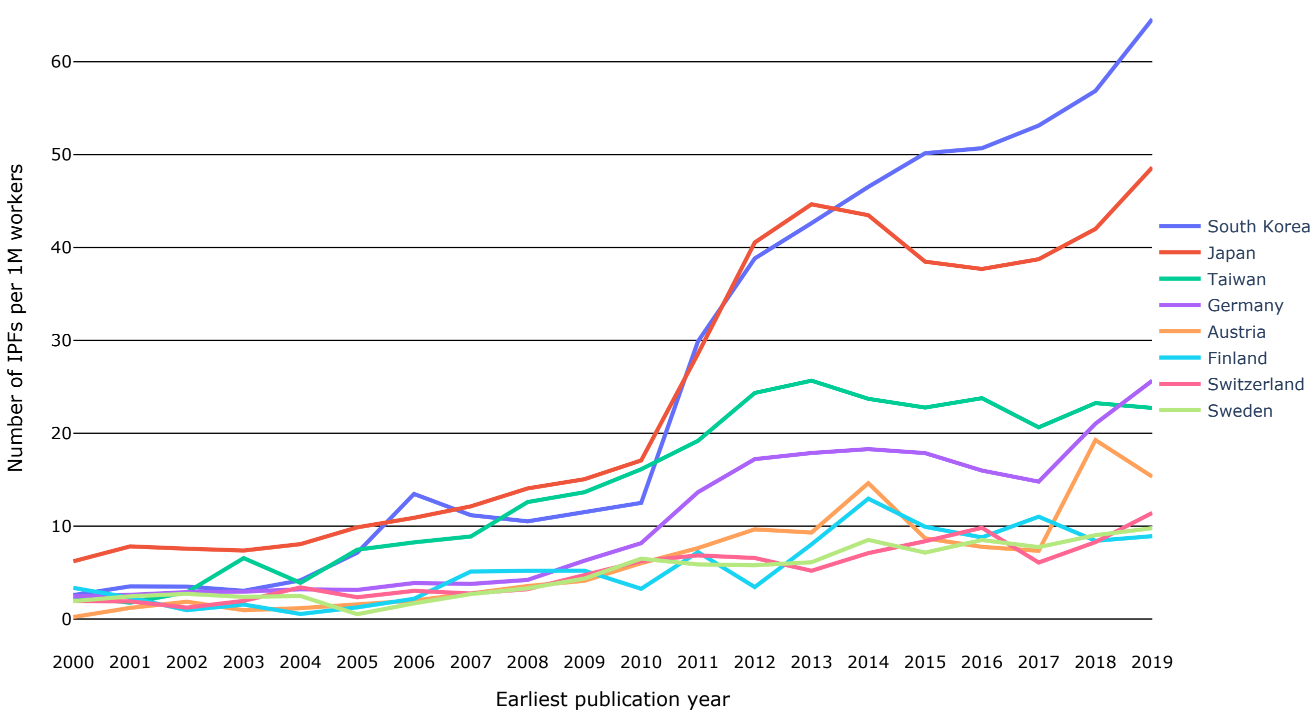

Figure 4. Battery IPFs per 1M workers by inventors' countries of origin, 2000-2019. The eight countries with the highest total battery IPF intensities over the given timeframe are displayed. In this perspective, South Korea (blue) overtook Japan (red) in 2014.

Breaking down battery IPF counts by inventors' countries of origin, the dominance of Asia becomes even more apparent. Figure 3 shows the eight countries with the highest total battery IPF output over the whole timespan. In 2019 the three top countries in terms of battery IPF output were from the far east: Japan, South Korea, and China. These were followed by the US, Germany, France, Taiwan, and the UK. Japan, the undisputed leader in battery IPF counts during the whole timeframe, is displaying a vibrant rate in the dynamics of inventive output since 2016. China is catching up fast with South Korea, which has held the second place in battery IPF output since 2011 when it surpassed the US (for the Chinese case see[18]). Germany also displays an upward trend in battery IPF output. Please note the similarity of the trajectories presented in this plot to the ones depicted in Fig. 6.2 and 6.3 of the report by IEA and EPO[1]. The higher numbers in the current study result from the underlying data being defined somewhat differently, with the largest difference being that IPFs related to the field of battery charging were included in the dataset of the current study.

By scaling the numbers shown in the previous plot by each country's and year's labor force count, one obtains battery IPF intensities.[19] This measure gives the viewer a different perspective on the IPF counts, allowing for assessment of a country's innovative output relative to the size of its working population. Figure 4 shows the eight countries with the highest scaled total battery IPF output over the whole timespan and it can be seen that in contrast to Fig. 3, a number of small European countries step up: Austria, Finland, Switzerland, and Sweden are part of the top eight. It is also worth noting that, in this light, South Korea overtook Japan in 2014, establishing itself as the global leader of battery patent intensities.

3.2 Battery technologies

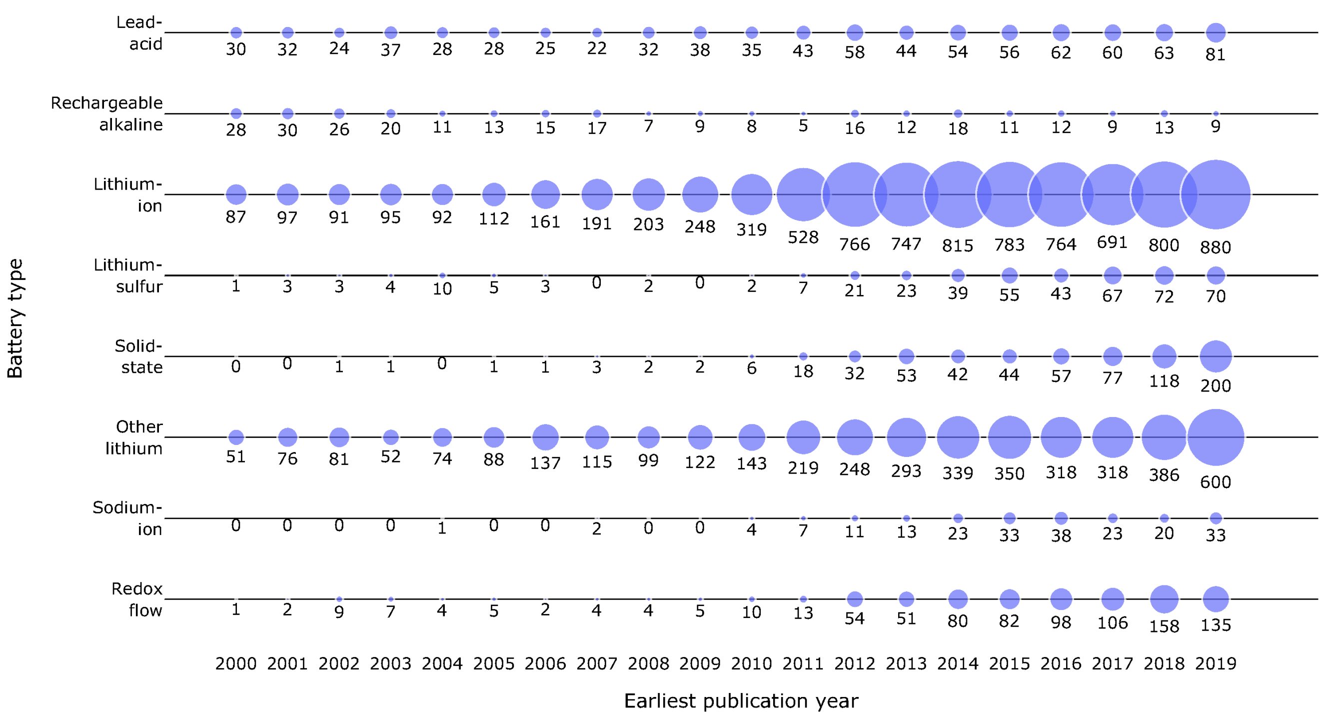

Figure 5. Global battery patenting activity for selected battery types, 2000-2019. The depicted battery IPF fractional counts are rounded to the closest integer. The eight technologies with the highest total battery IPF count over the given timeframe are displayed. The relative importance of lead-acid and rechargeable alkaline batteries decreased, whilst IPF counts for lithium-ion batteries and other lithium-based battery technologies have soared robustly. After 2010 four technologies emerge: Lithium-sulphur, solid-state, sodium-ion, and redox flow batteries.

By assigning battery technology sub-areas to patent families a disaggregation of the dataset into 19 battery cell technologies was obtained. This process is described in detail in the Supplementary Information. The technology classes used in this study are "Lead-acid", "Lithium-air", "Lithium-ion", "Lithium-sulfur", "Solid-state", "Other lithium", "Magnesium-ion", "Nickel-cadmium", "Nickel-iron", "Nickel-zinc", "Nickel-metal hydride", "Rechargeable alkaline", "Sodium-sulfur", "Sodium-ion", "Aluminium-ion", "Calcium(-ion)", "Organic radical", "Redox flow", and "Nickel–hydrogen".

Figure 5 presents the developments of IPF counts in the eight major categories. They were selected based on their total IPF count in the entire timeframe of 2000-2019. While the number of IPFs related to lead-acid batteries has been relatively stable over the depicted 20 years, which resulted in its overall share in battery IPFs to decrease steadily over this time period, and whilst rechargeable alkaline batteries exhibit a slight downwards trend, lithium-ion batteries and other lithium-based battery technologies have soared drastically. Less relevant today than lithium-ion batteries but with considerably higher counts than other smaller battery technologies are the four remaining categories presented in Fig. 5: Patenting activity related to lithium-sulfur, solid-state, sodium-ion, and redox flow batteries have seen a notable increase in IPF counts in 2010-2019. In 2019 solid-state batteries reached an all-time maximum of 200 IPFs.

The observation that the recent decade displayed increased patenting activity in these four emerging technologies motivates the way the next part of the analysis is set up: The following sub-section describes the results obtained by clustering countries based on their position in a technology space computed using their technology distribution of the years of 2010-2019.

3.3 Clustering

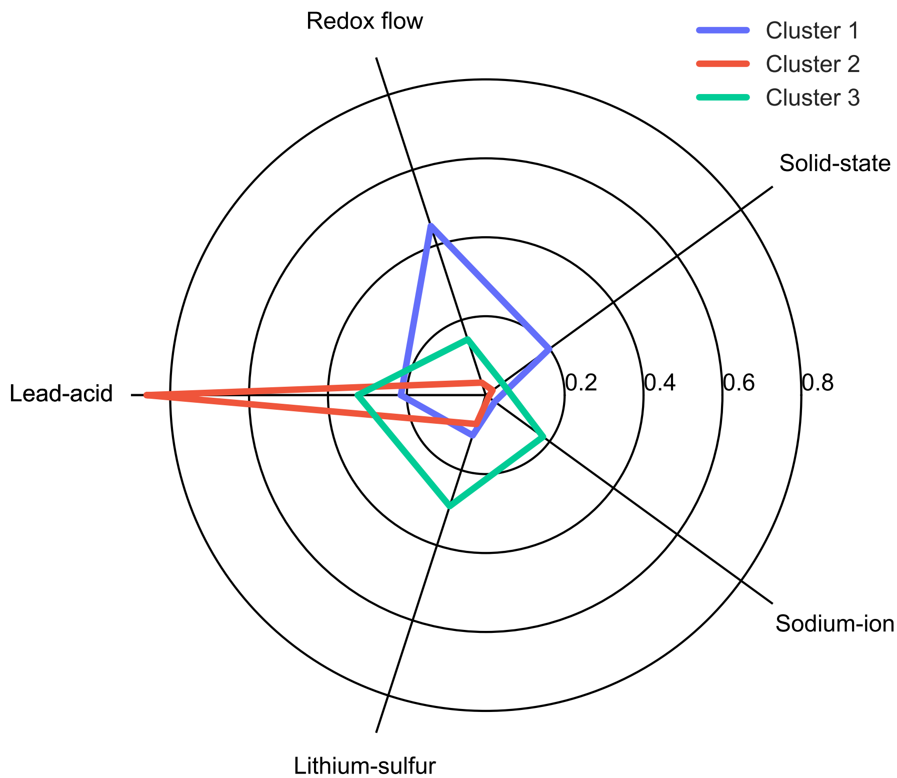

Figure 6. Cluster profiles. Inventors' countries of origin were clustered by their battery type distribution using k-means and data from 2010-2019. While countries from cluster 2 are more focused on lead-acid batteries, clusters 1 and 2 exhibit a higher patenting activity related to the four emerging technologies of redox flow and solid-state batteries (cluster 1) and lithium-sulphur and sodium-ion batteries (cluster 3).

The most suitable technology space for clustering was found to be spanned by the countries' distribution values over the four emerging technologies lithium-sulfur, solid-state, sodium-ion, and redox flow, which display increased patenting activity after 2010, alongside the older lead-acid technology.

Clustering 36 countries using data from 2010 to 2019, k-means was found to be the clustering algorithm with a better R^2 value for all relevant numbers of clusters (for details on this metric see the Supplementary Information). Setting the numbers of clusters to two, a clear separation of the dataset between countries with a high focus on lead-acid batteries (82.61% of IPFs are related to lead-acid batteries in this cluster) and countries with comparatively high shares of IPFs related to the four emerging technologies and consequently a relatively low share of lead-acid related IPFs (19.57%) was obtained.

Setting the number of clusters to three, to achieve a more granular separation, one finds that the lead-acid focused cluster from the previous stage is still fairly intact, whilst the "emerging technologies" cluster has been separated in two: one cluster that displays a stronger focus on redox flow and solid-state batteries and another that has a higher relative focus on sodium-ion and lithium-sulfur-related IPFs. Figure 6 shows the distribution profiles of the three-clusters solution generated with the k-means variable "random_state" set to zero. The variable "random_state" determines the centroid initialization of k-means and results in deterministic runs of the algorithm when a value is assigned to it.

While the approximate shape of the clustering profile depicted in Fig. 6 is fairly insensitive to alterations or non-assignation of "random_state", the affiliation of the countries to their clusters varied enough to motivate running k-means a higher number of times (with the variable "random_state" undefined) in order to compute each country's cluster affiliation distribution for assessing which cluster each country belongs to in the majority of events. Running k-means 10,000 times results in the following most probable cluster affiliations:

- Cluster 1 (12 countries):
  USA, Germany, Taiwan, Austria, Netherlands, Thailand, Switzerland, South Korea, Japan, Belgium, Italy, Australia.
- Cluster 2 (17 countries):
  India, Russia, Turkey, Bulgaria, New Zealand, Luxembourg, Poland, Sweden, Malta, Mexico, North Korea, Serbia, Greece, Hungary, Kazakhstan, Israel, Norway.
- Cluster 3 (7 countries):
  Canada, Spain, Ukraine, UK, France, China, Hong Kong.

Inside each cluster, countries are ordered by (1) their probability p to be in this cluster, and (2) their total IPF count in the five categories. Each country's name is colored according to the following schema, indicating its probability p for belonging to the respective cluster:

$p = 1$ $p \in [0.95,\ 1)$ $p \in [0.9,\ 0.95)$ $p \in [0.85,\ 0.9)$

A value of $p = 1$ indicates that a country was assigned to this cluster during each of the 10,000 runs, meaning that its cluster affiliation appears to be quite insensitive to the centroid initialization of the algorithm. The following section describes the results obtained by scanning the abstracts of the patent applications contained in this study's dataset for key phrases.

3.4 Title and abstract mining

The content material of patents is relevant evidence that can be mined, processed, and sorted for purposes of leveraging classic patent analysis.[20] Two methods were implemented in order to use patent wordage as empirical material. Both patent abstracts and titles were searched for meaningful phrases. The first approach, henceforth called *n-gram counts* was to simply count occurrences of n-grams in patent abstracts and titles for each year. The second approach, from now on referred to as *n-gram intensities* was to additionally scale these counts by the respective year's number of abstracts or titles, respectively. The resulting unit of measure for n-gram intensities is occurrences per 1,000 abstracts or titles, respectively, and all depicted n-gram intensities are rounded to the closest integer. Unigrams, bigrams, and trigrams were counted. The resulting n-gram counts and n-gram intensities were sorted in three different ways, which are described in detail in the Supplementary Information. The result that we found most meaningful and thus selected for presentation in this paper are the top 50 increasing trigrams extracted from battery patent abstracts. The terms are displayed in descending order of total increase over the given 20-years time period in Tables 1 (trigram counts) and 2 (trigram intensities). A holistic analysis is provided by considering the different analyses jointly.

Trigram counts display several expectable trends like the surge of "lithium secondary battery" and "lithium ion battery". The occurrence counts for these two trigrams increased from 46 to 844 and from 15 to 685, respectively, between 2000 and 2019 and the trigram intensities of "lithium ion battery" indicate a robust upward dynamic not only in absolute terms but also relative to battery patenting activity. The increase of the term "energy storage system", which is also confirmed by its intensity's trajectory, hints at an increase in the importance of increasingly complex systems for managing the storage of energy. This is buttressed by the term "battery management system" that also occurs in both counts' and intensities' top 50 trigrams. As already established by Fig. 5, solid-state batteries have been growing in relevance, especially in the past decade. This is confirmed by the increasing counts and intensities for the terms "solid electrolyte layer" and "solid state battery" after 2010. Notable trigrams in the subfields of battery charging and electric vehicles are "wireless power transmission" and "electric vehicle charging", which have both increased considerably in both counts and intensities. The surge in relevance for redox flow batteries (see Fig. 5) is also confirmed by both counts and intensities ("redox flow battery"). The trigrams "plurality battery cell" (results from "plurality of battery cells" due to stop word removal and lemmatization) and "battery module plurality" (both are present in both counts and intensities) hint at a substantial increase in innovative output related to compositions of cells and modules inside battery packs. An unexpected, yet reasonable, appearance in the top 50 trigram intensities is the term

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
electrode active material	89	82	72	121	136	157	241	278	294	356	427	991	1253	1288	1323	1386	1273	1308	1382	1990
active material layer	17	9	29	27	37	96	114	143	134	188	186	364	419	553	499	383	336	510	619	883
lithium secondary battery	46	91	72	65	112	128	192	140	124	178	222	340	451	487	490	410	492	374	540	844
lithium ion battery	15	26	41	31	16	49	58	83	99	121	197	321	476	421	449	520	618	568	702	685
energy storage device	5	41	27	39	33	20	44	70	109	94	147	183	224	367	367	277	370	538	576	648
secondary battery electrode	29	27	21	25	55	82	113	109	95	122	146	286	417	422	384	400	419	441	435	593
electrode current collector	7	7	10	12	15	15	24	46	57	104	96	135	206	171	155	172	215	226	412	539
power storage device	11	3	7	10	2	8	4	30	69	37	183	166	317	310	361	311	311	520	293	394
electrolyte secondary battery	25	27	41	36	65	74	110	118	180	129	113	214	301	269	437	425	412	287	264	405
aqueous electrolyte secondary	24	38	45	46	67	75	111	116	182	135	121	216	307	289	456	427	421	285	248	390
plurality battery cell	3	1	3	1	7	9	10	28	26	29	32	135	175	229	177	206	212	232	314	351
ion secondary battery	10	25	15	23	32	58	68	73	75	81	162	261	331	409	428	468	388	337	300	357
power supply device	11	3	25	7	20	28	35	28	84	60	80	140	227	259	285	222	228	256	281	348
lithium ion secondary	12	29	18	30	33	63	72	74	76	84	164	270	366	418	442	506	379	342	291	345
current collector electrode	5	8	6	4	8	11	12	27	37	45	56	127	113	114	138	97	137	138	217	323
active material lithium	17	24	16	28	27	36	36	43	48	65	100	168	256	183	225	255	222	177	160	266
cathode active material	6	10	23	31	9	28	59	49	44	64	92	79	146	168	199	182	168	198	211	247
power supply system	7	20	25	18	27	21	32	52	47	59	82	150	187	162	165	145	166	185	218	241
energy storage system	0	7	0	8	2	11	6	25	35	32	46	93	80	116	121	106	138	165	200	222
electrode mixture layer	0	0	0	3	0	0	4	14	25	38	26	56	87	93	89	111	151	98	170	219
solid electrolyte layer	5	2	1	0	3	0	3	3	19	11	21	48	46	92	43	70	68	105	126	208
solid state battery	0	0	0	1	0	0	1	2	5	4	3	11	29	58	49	29	33	53	95	198
layer electrode active	3	1	2	3	3	5	6	17	12	20	30	60	71	93	85	112	102	105	120	200
battery management system	0	3	3	1	2	3	11	30	39	20	22	61	91	113	97	147	107	139	163	185
material layer electrode	2	0	1	3	3	11	15	19	9	30	34	76	79	89	82	86	74	101	91	178
energy storage unit	1	1	21	1	4	7	20	16	26	47	43	81	78	78	44	94	92	101	201	176
secondary battery lithium	6	15	4	10	8	13	10	13	21	25	40	46	69	69	90	96	106	70	125	177
anode active material	6	2	4	15	14	20	58	61	65	55	77	80	92	113	211	108	74	117	166	175
transition metal oxide	3	7	3	9	3	10	20	18	13	28	38	49	54	68	91	132	106	80	83	167
active material particle	4	6	12	6	14	19	41	32	32	36	38	57	94	93	93	150	161	213	199	164
collector electrode active	1	2	4	1	3	6	4	15	13	15	28	68	44	92	109	67	67	72	82	157
active material electrode	27	23	13	15	20	20	32	34	37	40	52	107	119	126	118	161	128	131	123	182
electrical energy storage	1	3	10	15	18	3	16	38	15	28	52	32	89	116	74	77	79	100	125	153
wireless power transmission	0	0	0	0	0	0	0	0	2	13	23	33	115	105	183	172	154	223	143	148
redox flow battery	0	0	8	12	2	1	0	0	0	2	2	22	44	30	50	93	86	102	120	146
power storage element	1	0	0	0	0	0	0	0	13	11	10	4	46	58	93	112	160	162	170	143
aqueous electrolyte solution	4	11	5	0	11	13	12	12	22	14	31	42	64	62	70	47	55	38	89	143
material electrode active	7	4	4	5	5	14	11	18	17	33	27	50	82	77	69	84	89	70	84	146
material lithium ion	5	10	3	13	5	17	12	18	23	33	63	106	162	134	153	181	142	125	126	140
power transmission device	0	0	0	2	0	0	0	0	2	30	27	41	53	92	121	173	96	113	136	134
lithium transition metal	8	16	6	19	24	31	20	19	36	29	42	74	75	82	106	138	112	87	112	138
battery module plurality	1	4	0	2	0	5	17	3	15	15	18	52	62	71	65	71	60	64	117	127
material lithium secondary	11	22	21	21	33	32	27	27	26	50	54	81	125	105	134	99	102	80	84	130
electric vehicle charging	0	0	0	0	0	0	1	0	5	9	25	48	93	113	65	53	38	50	64	118
battery electrode active	5	7	9	13	21	14	22	44	25	36	39	77	128	120	115	133	111	133	102	122
battery cell electrode	0	1	4	1	1	2	2	8	2	11	14	24	30	59	42	43	53	47	72	117
power supply circuit	10	12	27	14	11	25	12	44	38	26	31	59	71	59	73	37	63	101	100	127
control unit configured	0	0	0	0	0	2	1	2	6	6	9	13	34	34	42	46	50	62	61	114
state secondary battery	0	4	2	1	3	3	4	5	9	9	16	23	31	41	28	27	57	96	45	112
electrode lithium secondary	4	8	11	10	17	19	8	13	17	19	29	39	31	48	35	28	38	39	74	114

Table 1. Trigram occurrences in battery patent abstracts. The top 50 trigrams in terms of their count increase between 2000 and 2019 are displayed. The color gradients represent intra-row relationships.

"unmanned aerial vehicle", which exhibited 4, 13, 16, and 8 occurrences per 1,000 abstracts in the years of 2016, 2017, 2018, and 2019, respectively. It indicates an increased field of application related to the deployment of battery technology in drones.

Results obtained by using the data and methods combinations not presented in this paper (i.e. application titles and other sorting methods) can best be viewed by opening the HTML file "03_title_and_abstract_mining.html", which is part of the GitHub repository associated with this study. The said repository can be accessed by following the link provided in the Data Availability statement.

4 Discussion

Assessing Fig. 1, one could infer that the inflection point between 2011 and 2012 may be a result of the global financial crisis and the subsequent recession. Assessing Fig. 1, Fig. 3, and Fig. 4 jointly, one can identify a clear difference in yearly battery patenting activity between the two decades assessed in this study (2000-2009 and 2010-2019) both on global level and for several countries. Combining this knowledge with Fig. 2, it becomes clear that the major part of the increase in battery patenting activity is driven by Asia.

The observation obtained from Fig. 2 that the Asian continent has by far the highest battery IPF output worldwide should

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
electrode active material	91	70	64	102	106	100	123	129	119	127	126	192	185	173	167	179	163	155	143	181
active material layer	17	8	26	23	29	61	58	67	54	67	55	71	62	74	63	50	43	60	64	80
energy storage device	5	35	24	33	26	13	23	33	44	33	44	36	33	49	46	36	47	64	60	59
lithium ion battery	15	22	36	26	12	31	30	39	40	43	58	62	70	56	57	67	79	67	73	62
electrode current collector	7	6	9	10	12	10	12	21	23	37	28	26	30	23	20	22	27	27	43	49
lithium secondary battery	47	78	64	55	87	82	98	65	50	63	66	66	67	65	62	53	63	44	56	77
plurality battery cell	3	1	3	1	5	6	5	13	10	10	9	26	26	31	22	27	27	27	32	32
power storage device	11	3	6	8	2	5	2	14	28	13	54	32	47	42	45	40	40	62	30	36
current collector electrode	5	7	5	3	6	7	6	13	15	16	17	25	17	15	17	13	17	16	22	29
secondary battery electrode	30	23	19	21	43	52	58	51	38	43	43	56	62	57	48	52	54	52	45	54
ion secondary battery	10	21	13	19	25	37	35	34	30	29	48	51	49	55	54	61	50	40	31	32
power supply device	11	3	22	6	16	18	18	13	34	21	24	27	34	35	36	29	29	30	29	32
energy storage system	0	6	0	7	2	7	3	12	14	11	14	18	12	16	15	14	18	20	21	20
electrode mixture layer	0	0	0	3	0	0	2	7	10	14	8	11	13	12	11	14	19	12	18	20
lithium ion secondary	12	25	16	25	26	40	37	34	31	30	49	52	54	56	56	65	48	41	30	31
solid state battery	0	0	0	1	0	0	1	1	2	1	1	2	4	8	6	4	4	6	10	18
battery management system	0	3	3	1	2	2	6	14	16	7	7	12	13	15	12	19	14	16	17	17
cathode active material	6	9	20	26	7	18	30	23	18	23	27	15	22	23	25	24	21	23	22	22
layer electrode active	3	1	2	3	2	3	3	8	5	7	9	12	11	12	11	14	13	12	12	18
energy storage unit	1	1	19	1	3	4	10	7	10	17	13	16	12	10	6	12	12	12	21	16
power supply system	7	17	22	15	21	13	16	24	19	21	24	29	28	22	21	19	21	22	23	22
material layer electrode	2	0	1	3	2	7	8	9	4	11	10	15	12	12	10	11	9	12	9	16
solid electrolyte layer	5	2	1	0	2	0	2	1	8	4	6	9	7	12	5	9	9	12	13	19
wireless power transmission	0	0	0	0	0	0	0	0	1	5	7	6	17	14	23	22	20	26	15	13
redox flow battery	0	0	7	10	2	1	0	0	0	1	1	4	7	4	6	12	11	12	12	13
collector electrode active	1	2	4	1	2	4	2	7	5	5	8	13	7	12	14	9	9	9	8	14
electrical energy storage	1	3	9	13	14	2	8	18	6	10	15	6	13	16	9	10	10	12	13	14
power transmission device	0	0	0	2	0	0	0	0	1	11	8	8	8	12	15	22	12	13	14	12
transition metal oxide	3	6	3	8	2	6	10	8	5	10	11	10	8	9	11	17	14	9	9	15
power storage element	1	0	0	0	0	0	0	0	5	4	3	1	7	8	12	14	20	19	18	13
electrolyte secondary battery	26	23	36	30	50	47	56	55	73	46	33	42	45	36	55	55	53	34	27	37
aqueous electrolyte secondary	25	33	40	39	52	48	57	54	73	48	36	42	45	39	57	55	54	34	26	35
active material particle	4	5	11	5	11	12	21	15	13	13	11	11	14	12	12	19	21	25	21	15
electric vehicle charging	0	0	0	0	0	0	1	0	2	3	7	9	14	15	8	7	5	6	7	11
battery cell electrode	0	1	4	1	1	1	1	4	1	4	4	5	4	8	5	6	7	6	7	11
battery module plurality	1	3	0	2	0	3	9	1	6	5	5	10	9	10	8	9	8	8	12	12
control unit configured	0	0	0	0	0	1	1	1	2	2	3	3	5	5	5	6	6	7	6	10
state secondary battery	0	3	2	1	2	2	2	2	4	3	5	4	5	5	4	3	7	11	5	10
secondary battery lithium	6	13	4	8	6	8	5	6	8	9	12	9	10	9	11	12	14	8	13	16
anode active material	6	2	4	13	11	13	30	28	26	20	23	16	14	15	27	14	9	14	17	16
current collector layer	0	0	1	2	2	1	2	0	0	0	1	1	1	5	2	1	2	4	10	9
aqueous electrolyte solution	4	9	4	0	9	8	6	6	9	5	9	8	9	8	9	6	7	5	9	13
unmanned aerial vehicle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	4	13	16	8
electrode active substance	1	2	9	0	14	10	3	1	1	2	4	4	7	6	11	7	8	4	7	9
plurality battery module	1	4	1	6	1	2	4	6	1	4	3	10	7	7	6	4	8	5	11	9
solid state secondary	0	0	0	0	0	0	1	1	0	0	1	2	1	2	1	1	6	8	3	8
power receiving device	0	0	0	0	2	3	0	3	1	12	6	8	11	16	22	14	10	10	12	8
present electrode active	0	2	2	2	1	1	1	2	1	2	2	7	5	3	7	7	9	8	7	8
solid electrolyte material	0	0	0	0	0	0	0	0	2	0	2	3	4	5	3	1	2	4	4	8
power storage system	0	0	1	0	0	1	0	4	0	1	1	4	7	7	10	6	9	4	8	8

Table 2. Trigram occurrence intensities in battery patent abstracts. The unit of measure is occurrences per 1,000 abstracts and all values are rounded to the closest integer. The top 50 trigrams in terms of their intensity increase between 2000 and 2019 are displayed. The color gradients represent intra-row relationships.

be accompanied by the remark that the countries classified as "Asia" in PATSTAT account for approximately 60% of the world's labor force. When computing each continents' battery IPF intensities, one observes that Asia falls behind both Europe and North America. For interested readers, IPF intensities for each continent are displayed in Fig. S1 in the Supplementary Information.

With regard to the country-wise patent counts and intensities presented in Fig. 3 and Fig. 4, is worthwhile to mention that comprehensive analyses that were undertaken before defining the final dataset resulted in the observation that the majority of battery patent applications from China in the considered timeframe of 2000-2019 are filed only nationally. Given the IPF constraint deployed for this study and the report by IEA and EPO[1], these solely nationally filed applications are not taken into account in either one. In fact, in the dataset used for the current study, IPFs make up only 19.41% of all battery patent families. It is reasonable to define the data for the current study as such (the same for the recent analysis undertaken by IEA and EPO) because it can be expected that patents filed in only one country are of considerably lesser "value" than international patent families, thus including them would result in a rather inhomogeneous dataset. Nonetheless, it is worth noting that if the IPF restriction was to be discarded and one-country patent families were to be considered, China (which in fact is the world's largest producer and market) would take the first place in battery patent counts in the majority of years of the recent decade. As a resulting thought, it would be worthwhile to study the battery patenting dynamics of China in detail within the context of future research in order to shed light on why China's battery patenting behavior is so nationally-focused and what implications this has for technology analyses in this field.

In this study, we find robust country clusters as they advance along emergent battery innovation pathways. This means there is country variation in terms of technological capabilities. We are thus witnessing specialization and heterogenous technological trajectories in regards to this dimension of the energy transition. Interpreting the clustering solution presented in section 3.3, the three resulting clusters could be characterized as follows:

- Cluster 1–Redox advantage:

  These countries are putting an increased focus on the two emerging technologies of solid-state and redox flow batteries. Their patent output related to lead-acid batteries is the lowest out of the three clusters and their sodium-ion-related IPF share is close to zero. This cluster contains high-tech industrial nations like the US, Germany, and Taiwan that are known to have explicitly expressed their ambitions in the field of battery technology.

- Cluster 2–Lead-acid based:

  A large portion of these countries' battery innovation results is made up of lead-acid battery patents. Their share of battery patents related to the four analyzed emerging technologies are close to zero, except for their lithium-sulfur component, which accounts for approximately 10% of their IPF output in 2010-2019. This cluster contains countries like India, Russia, and Turkey that are considerably industrialized but are not known for their innovative impact on the world's technology sector.

- Cluster 3–Lithium-sulfur-driven:

  These countries' focus lies on lead-acid and lithium-sulfur batteries, which account for about 30% each. They have almost no innovative output in solid-state batteries and exhibit a considerably greater share in sodium-ion batteries than the other two clusters. This cluster is made up of countries like Canada, Spain, and China; countries that have a considerable economic impact.

5 Conclusions

We found that the global battery patenting activity has shown a robust upward trend in 2000-2019, which briefly came to a halt in the early 2010s, probably due to the global financial crisis and the subsequent recession. The majority of battery patents originates from Asia and several Asian and European countries exhibit high battery patent intensities in the given timeframe. Comparing the two decades of 2000-2009 and 2010-2019, a considerable increase in yearly battery patenting activity is observed. Furthermore, we found that four battery technologies—redox flow, solid-state, sodium-ion, and lithium-sulfur batteries—have displayed increased patenting activity in the recent decade. Lithium-ion and other lithium battery technologies have also surged, whilst lead-acid and rechargeable alkaline batteries' share in battery patenting activity has decreased over the timeframe of 2000-2019. Countries can be separated in a meaningful way using their patenting distribution over the four emerging battery types and the already established lead-acid technology making it possible to cluster them in three groups, one containing lead-acid-focused countries, one with a higher focus on redox flow and solid-state batteries and a third group that contains countries with higher sodium-ion and lithium-sulfur-related patenting shares. Lastly, a text mining approach yielded the conclusions that the battery-related technologies energy storage systems, battery management systems, wireless power transmission, electric vehicle charging, and unmanned aerial vehicles (i.e. drones) are growing in relevance both in absolute terms and relative to general battery patenting activity.

Data Availability

The raw data used for this study is available via subscription at PATSTAT Online. The data subset generated and used for this work can be reproduced using the queries and code made available at the GitHub repository associated with this work, which can be accessed by following this link: `https://github.com/ph1001/battery_patents.git`. On reasonable request said data subset is available from the corresponding author.

Author contributions statement

Philipp Metzger: Software, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. Sandro Mendonça: Conceptualization, Supervision, Writing - Review & Editing. José A. Silva: Conceptualization, Supervision, Writing - Review & Editing. Bruno Damásio: Conceptualization, Supervision, Writing - Review & Editing.

Competing interests

The authors declare no competing interests.

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Figure legends

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