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Battery Research and Innovation—A Study of Patents and Papers

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Abstract: This study of patent applications and scientific publications related to batteries is unique as it includes the volume of as well as qualitative indicators for both types of publications. Using carefully elaborated strategies to identify publications relating to batteries, this study provides data to discuss the critical balance to strike between investments in research and the more innovation-related aspects. The results show that China's dominance in publication volumes increases and that research with Chinese involvement is highly cited, whereas patent applications are slightly less valued than the world average. Quality-related indicators for Canada and the United States are very high for both scientific publications and patent applications. National differences in the proportions of patent applications and scientific publications are large, with Japan at one end with three patent applications per scientific paper and Canada at the other with almost seven scientific papers per patent application. On an actor level, data for Sweden indicate how the automotive industry started to file many patent applications in the decade starting in 2010. Finally, it is noted that this new approach to study a technological field appears promising as it gives new perspectives of relevance for policy actors and others.

Keywords: battery; research; patents; innovation; scientometrics

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1. Introduction

Battery business is expanding rapidly. There is a global race to gain leadership along the whole battery value chain. Interestingly, even though production capacity is being scaled very rapidly, the investments in research are still also expanding dramatically. Many companies and countries are trying to gain market shares by developing competitive battery solutions. One decisive aspect is knowledge. With superior knowledge and associated intellectual property rights, the chances to gain and maintain a strong position increase.

The purpose of this study was to develop and test a method to analyze battery-related research and innovation. In this study, batteries include all types of electrochemical devices to store electrical energy, as well as super-capacitors. Through the use of two types of publications, patents and papers, this study addressed two steps in the value chain: research and innovation. By patents we mean patent applications as well as granted patents, and papers are here equal to articles, conference papers, books, book chapters, and reviews indexed in Scopus.

One challenge associated with investments in research and innovation is to find a balance between research-oriented more basic knowledge production and innovation-oriented activities leading to commercial development. Heavy investment in research but limited efforts to make use of the knowledge in new or improved products or services might lead to knowledge being wasted or exploited in other firms or countries. On the other hand, a limited involvement in research compared to subsequent steps toward the market might lead to a situation when the actors or the country is being surpassed by others working with superior technologies. In this study, we used scientific publications as a proxy for research and patent applications as an innovation indicator.

In addition to the development of a new method, we tested the method on data covering approximately two decades from 2000. For a selection of countries including Canada, China, France, Germany, Japan, Republic of Korea, Sweden and the United States, the following questions were studied:

- How do the volumes of patents and papers develop?
- How does the ratio of patents to papers develop?
- What is the share of academic–corporate papers?
- How is the quality of the patents and papers?

Moreover, but only for Sweden given the large efforts of manual work needed, it was also investigated on an actor and individual level to what extent patenting and academic publishing goes hand in hand.

Existing studies of patents and papers on batteries and vehicle electrification seldom combine and compare these two types of publications. One exception is [1], which used both types of publications to identify emerging trends. As highlighted by [2], actual patents form a small part of the total innovation activities, and by adding papers we cover a wider scope. The main contribution of our study is the combination and comparison of patent and paper data, including both volumes of publications and elaborated indicators related to their quality.

The methodology developed in this study is unique, at least in the context of batteries and vehicle electrification, and it delivers new insights relating to how different countries strike the balance between research and innovation.

The approach forwarded in this study can be used for any technology provided that it generates sufficient volumes of patents and papers. Given the broader perspective on innovation offered, it provides insights of relevance, not least for policy makers interested in the development of the innovation system.

The remainder of the paper is structured as follows. A review of previous literature follows; thereafter the methodology is described. The results section includes three sub-sections, with volumes and quality indicators on a national level in the first two sub-sections, followed by one sub-section on the actor level using data for Sweden. Finally, discussions and conclusions follow.

2. Quantitative Studies of Batteries and Vehicle Electrification

A background to the use of patent data and how it refers to papers is given in [3]. The study argues that patentometrics started to become important in the 1980s and that citations from patents to papers were used to better understand the links between science and technology.

In [1], the broader scope of energy storage was studied using both types of publications to identify emerging topics. Based on rather short search queries, publications were identified and clustered to find emerging topics. The number of citations was used to assess the relevance of each cluster, both for patents and papers. Papers were retrieved from Web of Science whereas patents were obtained from Derwent Innovation, a collection of patent data from 44 patent authorities. It can be noted that patent data for this study published in 2020 started to drop dramatically in 2016, as there is a time lag until patent applications are published. Within the battery domain, lithium–sulfur technologies were identified as emerging on the academic side, whereas multi-power systems where emerging within industry research.

Several papers use patent data for the study of batteries or their use in battery-electric vehicles. In [4], networks between organizations involved in electric and hybrid-electric vehicles were studied based on co-authorships of the patent applications. The search method was based on patent classes and patent data were from the European Patent Office's Global Patent Index Database. For the paper published in 2016, patent data until and including 2010 were used. One of their findings is that the networks toward the end of the period center around the large original equipment manufacturers, which could indicate that electric-vehicle technologies are maturing.

Using the same data source, another paper from the same year [5] addresses electric-vehicle technologies and presents which countries are most active in patenting. It also identifies some technological fields within electric-vehicle patenting. A small selection of patent classes was used to find relevant publications. Among the findings are that patenting activity within the electric-vehicle field has increased and that many innovations originate from Asian countries.

In an ambitious patent study of three energy-related technologies, li-ion batteries, hydrogen production and thermochemical conversion of biomass, the five largest countries in terms of patenting activity were covered [2]. Relevant patents were extracted using a combination of patent classes and keyword search from the European Patent Office's database. In the literature review, a good explanation of how patent applications relate to innovations is given, arguing that only a small part of all inventions is patented and thereof only a part is becoming innovation. A total of 5822 patents relating to li-ion batteries were found for the period 1995–2018. Japan dominated with approximately 50% of the total followed by China.

There have also been several studies that used scientific publications. One such study addressed the thermal management of li-ion batteries [6]. It used keywords to identify relevant publications in Scopus, but the development of the search string was not described. For the period 2000–2021, 983 papers were identified, and Chinese institutions dominated in terms of publication volumes, followed by a Canadian university. Volumes per country, institution, journal, and author were described, as well as total citation numbers per publication.

A study on a similar topic with the same approach had an explicit very short query to identify relevant papers in the period until 2018 [7]. It used clustering to identify trends and the distribution of keywords over time to study research trends, concluding among other conclusions that thermal management for li-ion batteries was a research gap. In terms of publication volumes, Chinese institutions dominated.

Another recent study used papers from Scopus to investigate electronic waste from electric vehicles [8]. A very short query was used to identify 593 publications during the period 2015–2023. These publications were then analyzed in different dimensions such as institutions, authors, collaborations, and networks. Batteries were among the most researched topics and Chinese institutions dominated in terms of volume. The citation count was used to investigate the importance of research.

Using Web of Science and a query with approximately 10 search terms, li-ion battery subfield fault diagnosis was studied [9]. The results indicate China's rapid growth in publication volumes since 2015, surpassing the United States to become clearly the largest producer of such papers in 2021. Vosviewer and other tools were used to analyze co-citations and collaboration networks.

A different approach to identify relevant papers is to use clusters generated based on citation relations [10]. A database with a Web of Science origin was used to study six sub-fields within battery research, as well as the whole scope of the European initiative Battery 2030+. The standing of Europe was compared with other countries or groups of countries in terms of volumes of papers as well as their field-normalized citation impact. It was noted that Europe was similar to China but well below North America in citation impact.

In a study of grid-connected Li-ion batteries, a five-step search strategy was deployed to discover the 100 most-cited papers in Scopus during the period 2010–2021 [11]. The study used search terms and the language of English and used subject filters as exclusion criteria. The United States had the highest number of publications in this top list followed by China.

A very short query "electric vehicle" was used to analyze relevant themes within battery-electric-vehicle research during the period 2000–2021 using data from Web of Science [12]. China was found leading in electric-vehicle research. In [13], a search query from a previous study from 2011 was reused to study li-ion battery research in India. Different types of electrified vehicles were studied using a query with search terms such as "hybrid NEAR/2 vehicle" and data from Web of Science [14]. Some patent data were also used, and whereas Japan was found to be most active in hybrid-electric-vehicle patenting, the United States led in paper volumes. Relating to electric vehicles, China produced the highest volume of papers.

Finally, to some extent representing the future of publication studies, a paper used text mining to shed some light on the content in battery-related publications [15]. This approach, which makes use of the full content in papers, is an interesting example of the opportunities and challenges with artificial intelligence tools.

This brief review of literature using patent and or paper data to study vehicle electrification and, in most cases, batteries, highlights from a methodological perspective that a combination and comparison of both types of publications is not common. None of the studies reviewed included attempts to analyze links between patents and papers, such as citations or having the same author. Moreover, more advanced quality-related indicators are not so common. If used, a direct citation count dominates, which has limitations, as the number of citations relates to the publication year as well as to the scientific field. Clustering and network analyses were often used to identify research and innovation trends.

Search strategies for patent studies were mainly based on patent classes, whereas papers typically were identified using queries. The development of the search strategy is not always explained, and the number of search terms is often limited.

Many of the papers reviewed include large sections with descriptive data covering the papers identified. In these sections, Chinese institutions often dominate, at least in terms of volume. A rapid growth starting in the period 2010–2015 is depicted, leading to China being the largest contributor of papers.

3. Methodology and Data

Critical for the study was to identify relevant publications. Patents were selected using patent classes, in line with a method described and used in an ambitious recent project led by the IEA [16]. The Swedish Intellectual Property Office was, in April 2022, commissioned to retrieve all battery patents from the global patent database DocDB, which then were further analyzed in a database for patent value assessment. Patent data until and including 2019 were considered sufficiently complete to be used in the analysis. This approach is in line with previous literature, which often uses patent classes to identify data and illustrates the significant lag between the year of study and the availability of complete patent data, c.f. [4,5].

Papers were selected using search terms in Scopus to be matched in the title or abstract of the paper. Scopus is the broadest abstract and citation database [17]. The query was developed in an iterative process, involving manual scrutiny of randomly selected papers to ensure that only relevant papers were selected. Papers from six productive battery researchers in Canada, the United States, Japan, and Sweden were used to test whether the query covered a sufficiently large share of these researchers' battery-related papers. The iterative process is described with some details in [18]. At the time of the study (June 2022), volume data for papers were almost complete until and including 2021.

The format of the query was: (A OR (B AND C)) AND NOT D, where

- A equals search terms specific for battery research, such as "electrochemical cell";
- B equals search terms often related to battery research, such as "battery";
- C equals a high number of search terms which in combination with B make it very likely that the publication deals with battery research, such as many different battery chemistries;
- D equals search terms in neighboring fields, such as "fuel cells", and words such as "batteryless".

The resulting query included hundreds of search terms. This approach led to an unexpected problem, as the standard query looks for matches in the title, abstract, and keywords. It was noted that the keywords include both the keywords given by the author(s) and other keywords, probably added by the journal. The latter keywords were in some cases broader, thus covering related fields not addressed in the paper. They did not work in combination with the "AND NOT" part of the query and thus a query only looking in the title and abstract was used.

In comparison to previous studies, the use of search terms to identify relevant publications is a dominating approach. However, three aspects differ. The first one is that previous studies do not always explain the strategy as to how the query was developed and how the precision of it was verified. A second difference is the use of only the title and abstract to search for relevant publications. Most other studies use the standard TITLE-ABS-KEY approach, which might work very well if "AND NOT" arguments are not used. Thirdly, the query developed differs substantially in size. Our query involved around 170 search terms plus the use of countries/regions and years to identify subsets. It is not always an advantage to use a very long query, but, for the purpose of this study, it was considered essential to ensure a reasonable coverage of all battery technologies over the 20-year period.

It is very difficult to capture all "battery-related" papers as blue-sky research, for example, does not always mention potential applications. Therefore, the resulting query underestimates the total volume and has a bias toward more applied battery research. A team of three battery experts from academy, business, and government supported in the development of the query.

The technical and economic value of patents was assessed using a composite index, the Technology Business Index (TBI), which combines several indicators, among them the patent's scope, family size, originality, generality, and backward and forward citations [19–21]. Percentiles were used to differentiate the patents, top 30% and top 10%.

We used a "full count" approach when a publication had several authors, both on individual and national levels. For example, this means that a publication with two authors, one from China and one from the United States, is counted fully for both countries. Various types of fractionalization constitute the main alternative, which, at least on the individual level, would have been rather confusing. Moreover, there are very few battery-related papers with many co-authors, which means that a full count approach does not lead to a severe bias in terms of volumes and citations.

For papers, standard citation indicators such as percentiles and the field-weighted citation impact, FWCI, were used. The latter is a normalized indicator based on the field, year, and type of publication. An average paper has FWCI 1.00 and if the paper has FWCI equaling 1.50, it is cited 50% more than the average publication.

This quality dimension was only used in a few previous studies and, typically, only with basic citation counts. To our knowledge, the quality indicator for patents has never been used in combination with different elaborated quality indicators for papers.

Given the sponsor of the project, the Swedish Energy Agency, the analysis had a focus on Sweden and the selection of countries for comparison was made from a Swedish perspective. In total, 11 countries were covered, some of which are not included in this paper, as they have relatively low patent volumes.

This study also included attempts to study institutions and individuals. For example, do researchers with many papers also have patents? This part of the study, which is unique in comparison to previous literature, was associated with a lot of manual work, and it was only carried out for Sweden. The main reason why this was laborious was the patent data quality, which made it difficult to identify people and institutions, as the names were indicated in many ways.

4. Results

4.1. National Level—Volumes of Patents and Papers

In Figure 1, the annual volumes of patent applications are indicated for all eight countries. Since 2011, China has had tremendous growth, becoming the largest patenting nation in 2014 and thereafter continued to increase the volume at the same pace. The dip in 2019 is probably due to incomplete data. Republic of Korea and Japan alternated as the number one until 2014 and thereafter as the number two. Since 2012, the United States has been in fourth place when it comes to battery-related patenting.

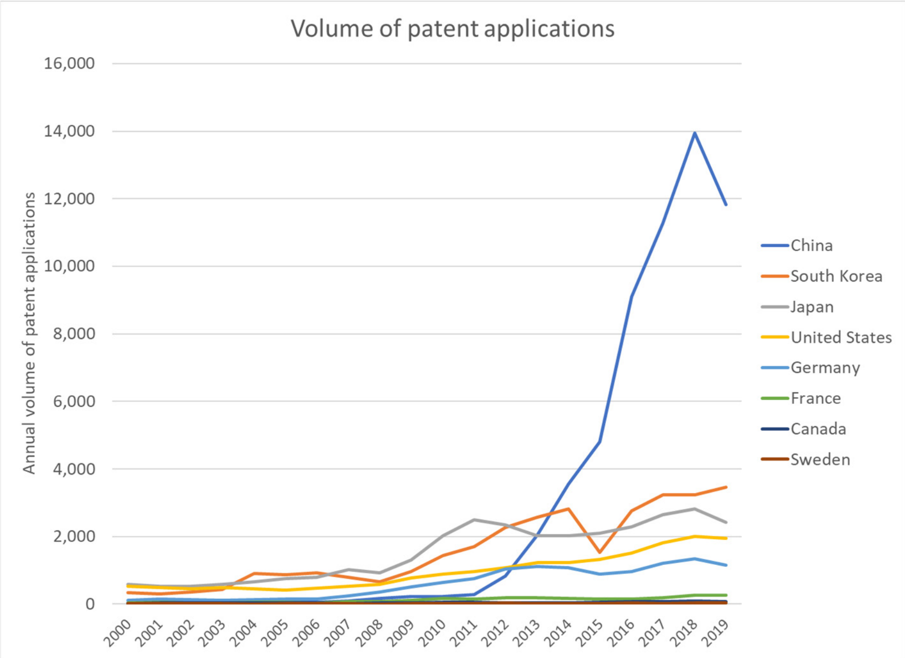

Figure 1. Development of patent volumes.

A closer look at the countries with lower volumes, see Figure 2, shows that Germany started patenting at an increasingly higher frequency in 2006, leaving the other countries included far behind. Sweden is clearly the country with the lowest volumes in the sample. Canada has, since 2012, developed to have approximately twice the annual volume compared to Sweden.

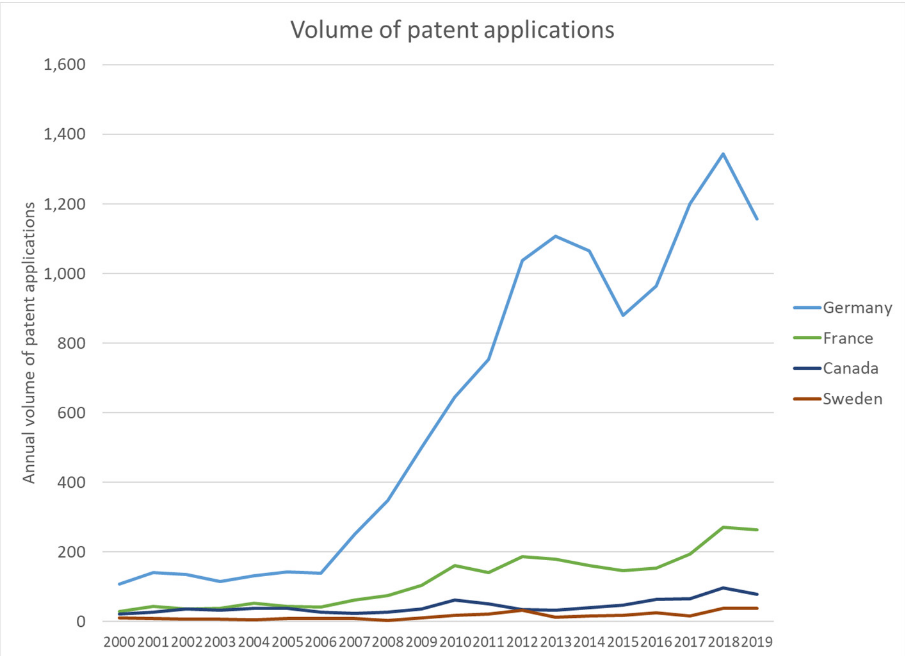

Figure 2. Development of patent volumes (countries with lower volumes).

On average there are approximately the same volumes of scientific publications relating to batteries as there are patent applications. When comparing Figure 1 with Figure 3 (below), it can be noted that China took the lead earlier in papers, in 2005, and that the United States since then has been the number two.

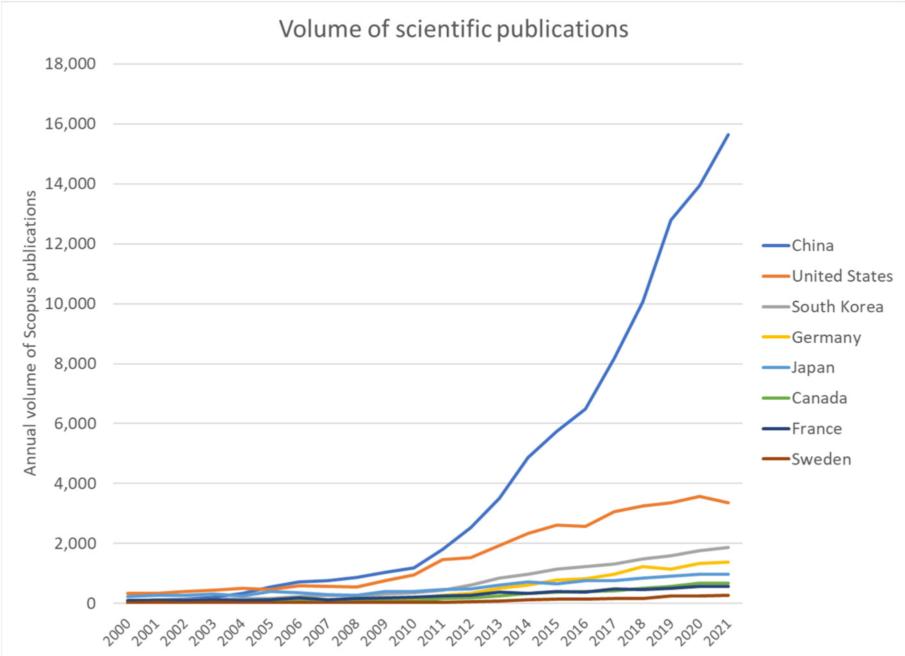

Figure 3. Development of paper volumes.

When China and the United States are removed, see Figure 4, the steep trajectory of Republic of Korea's papers becomes visible, overtaking Japan in 2011 and ten years later it had approximately twice the volume. A similar dramatic increase is also valid for Germany, which has more than quadrupled its paper volume in the last decade.

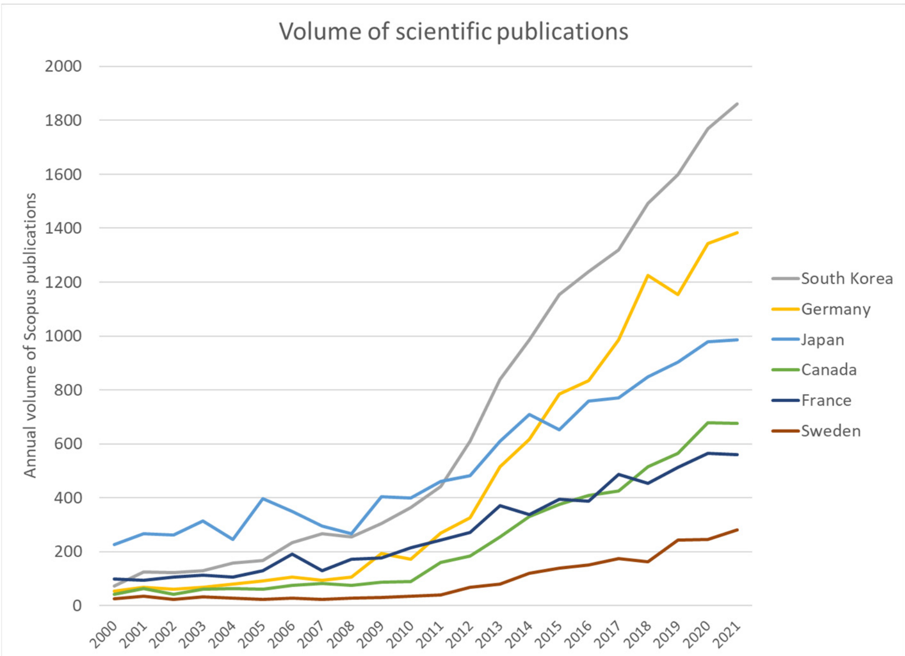

Figure 4. Development of paper volumes (excluding China and the United States).

A final times series is presented in Figure 5. Here the development of the volumes of patents and papers are possible to compare for China and the United States.

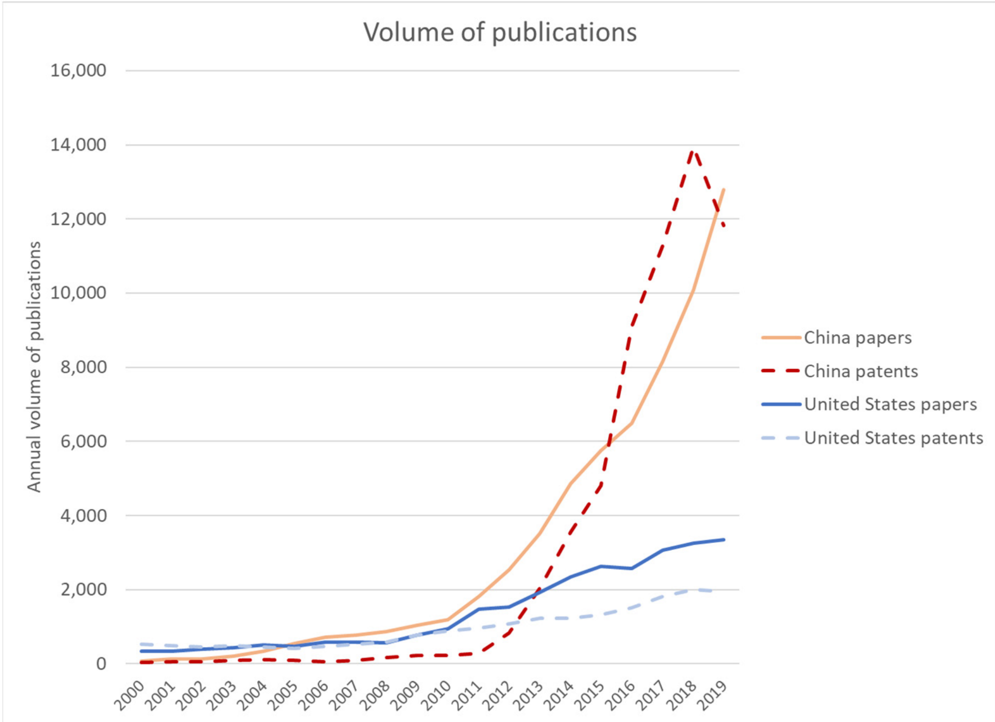

Figure 5. Development of patent and paper volumes for China and the United States.

The two countries show very different developments. China's paper volumes are much larger than the patent volumes until 2012, and thereafter the patent volumes after only a few years surpass the paper volumes. The United States had in the beginning of the period higher volumes of patents than papers. In 2010, the paper volumes started to increase more rapidly, and in the last period it clearly had higher volumes of papers. The dip in patent volume for China 2019 is probably due to incomplete data.

Three six-year periods were used to obtain a sufficient volume of patents for each period. In Table 1, the volumes of patents and papers for these three periods are presented.

Table 1. Comparison of paper and patent volumes.

	2002–2007			2008–2013			2014–2019		
	Paper	**Patent**	**Paper/Patent**	**Paper**	**Patent**	**Paper/Patent**	**Paper**	**Patent**	**Paper/Patent**
Canada	389	194	2.01	849	240	3.54	2619	390	6.72
China	2717	479	5.67	10,937	3,772	2.90	48,138	54,485	0.88
France	778	274	2.84	1452	845	1.72	2572	1188	2.16
Germany	499	915	0.55	1582	4391	0.36	5604	6608	0.85
Japan	1862	4349	0.43	2621	11,117	0.24	4643	14,300	0.32
Republic of Korea	1076	4267	0.25	2813	9590	0.29	7788	17,026	0.46
Sweden	159	43	3.70	284	97	2.93	988	149	6.63
United States	2984	2818	1.06	7182	5489	1.31	17,216	9796	1.76
World	13,775	14,939	0.92	33,831	38,541	0.88	102,132	111,518	0.92

Globally, the number of battery patents is slightly higher than the number of papers leading to a ratio around 0.9. A similar ratio applies for China in the last period included. In some countries, patent production dominates, among them Japan, Republic of Korea, and Germany. In others, the volumes of papers are clearly larger. Canada, Sweden, France, and the United States appear to focus more on research than patenting. For China, the share of patents per paper has increased over the periods, whereas, in Canada and the United States, the trend has been in the opposite direction. Globally, the ratio has been rather stable.

When looking at the period 2014–2019, Canada and Sweden are rather extreme with almost seven scientific papers per patent, whereas Japan is extreme in the other direction with approximately three patents per paper.

Another type of innovation indicator is academic–corporate co-publications, which are defined as scientific publications with at least two co-authors and at least one with an academic and one with a corporate affiliation. A high share of such publications is considered positive for innovations to materialize.

In Table 2, all countries except China have a higher share of academic–corporate papers within the battery field than the average for all papers in the country. In Canada, Germany, and Japan, the share is around twice as high.

Table 2. Academic–corporate collaboration (2014–2019).

Academic–Corporate Co-Publications (Share of)		
	Batteries	**All**
Canada	9.0%	4.3%
China	2.0%	2.7%
France	8.3%	6.3%
Germany	11.4%	6.5%
Japan	11.8%	6.4%
Republic of Korea	5.9%	4.9%
Sweden	9.3%	7.5%
United States	5.8%	4.7%

4.2. National Level—Quality-Related Indicators

In Table 3, two citation-based indicators for papers are presented, as well as TBI percentiles for patents. These indicators are explained above in the Section 3. Among the listed countries, battery papers are clearly more cited than all papers. The United States had the highest field-weighted citation impact, FWCI, as well as the highest share of papers in the top 10% citation percentile. Canada had the second highest FWCI and China the second highest share of papers in the top 10% percentile. Given China's dominance in paper production, it is interesting that the quantity does not come at the expense of quality, rather the opposite.

Table 3. Comparison of quality-related indicators for papers and patents (2014–2019).

	Paper Citation Data		**Patent TBI Value**	
	FWCI	**Top 10%**	**Top 10%**	**Top 30%**
Canada	2.47	43%	25%	54%
China	2.30	44%	7%	28%
France	1.89	32%	9%	24%
Germany	2.10	37%	6%	16%
Japan	1.60	29%	12%	34%
Republic of Korea	1.89	39%	8%	25%
Sweden	2.24	40%	16%	29%
United States	2.79	46%	23%	50%

Red (high value) to blue (low value).

The patent TBI values differ more between the countries than the citation impact indicators. Canada had the highest TBI values in both percentiles followed by the United States. Germany and China had the lowest TBI values. Japan, which was active in patenting, did so with a slightly better than average patent value.

A high share of academic–corporate papers is, as stated above, considered positive for innovation and it is also of interest to study whether the papers are cited. In Table 4, the citation impact for all battery papers and battery papers with academic–corporate collaboration are compared.

Table 4. Comparison of different types of battery papers.

Field-Weighted Citation Impact (2014–2018)		
	All	**Academic–Corporate Collaboration**
Canada	2.47	2.89
China	2.30	1.89
France	1.89	2.20
Germany	2.10	2.85
Japan	1.60	1.54
Republic of Korea	1.89	2.17
Sweden	2.24	1.49
United States	2.79	2.68

On a global level, academic–corporate co-publications are typically more cited [22]. In the battery field, this was also the case in four of the eight countries, with Germany exhibiting the largest positive difference. Sweden had a relatively large difference in the other direction; here, the academic–corporate collaboration clearly did not bring citation benefits.

4.3. Actor Level—Sweden

The number of patent applications and Scopus publications for the most recent period with reliable data is presented in Figure 6. The volumes vary between the years, but it is rather clear that both types of publications increase. The ratio between them is approximately 0.2, which means that for every patent application there are five scientific papers.

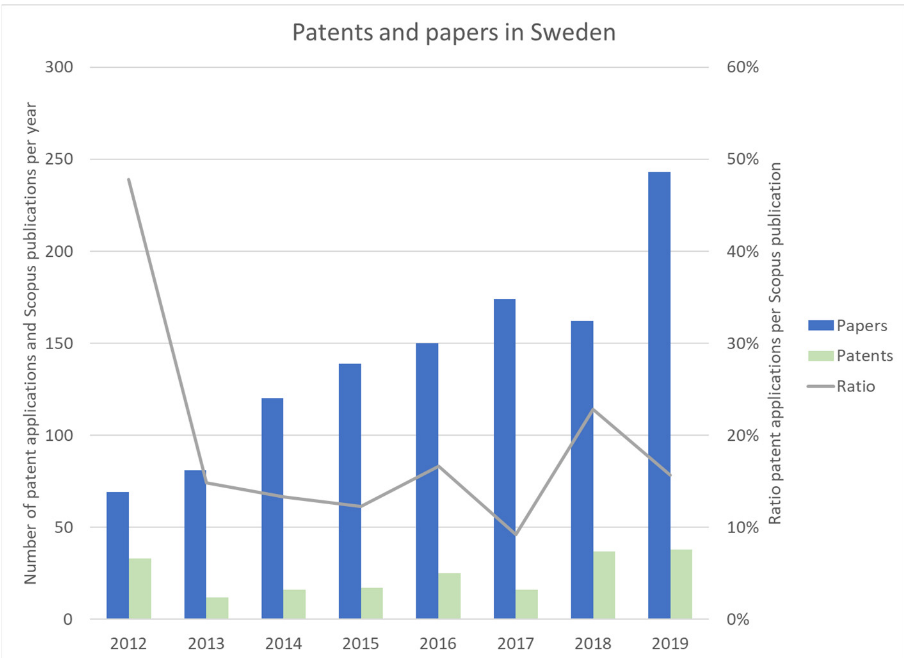

Figure 6. Development of patent and paper volumes for Sweden.

The gross list with patent applications for Sweden included more than 5000 items. It was associated with a lot of work to take care of all the name variants for people and organizations. Approximately 600 people and 124 companies had at least one patent application. Among them, 137 had both patent applications and scientific papers in the period 2000–2021. In Table 5, all people with at least 5 patent applications or 60 papers are included. Whereas all people with patent applications also have at least one paper in Scopus, the opposite is not always the case.

Table 5. Individuals with patent applications and/or papers.

Battery Researchers in Sweden with Minimum 5 Patents or 60 Papers 2000–2021			
	Battery Related		
Name	**Patents**	**Papers**	**Affiliation**
Legnedahl, Niklas	7	3	CEVT
Sturk, David	7	3	Autoliv
ASP, Leif	6	26	Chalmers University of Technology
Leijonmarck, Simon	6	13	KTH
Lindbergh, Goeran	5	116	KTH
Bryngelsson, Hanna	5	8	AB Volvo
Edstrom, Kristina	2	203	Uppsala University
Brandell, D.	0	150	Uppsala University
Johansson, P.	0	140	Chalmers University of Technology
Strömme, M.	0	73	Uppsala University
Younesi, Reza	2	62	Uppsala University
Matic, A.	0	62	Chalmers University of Technology

A long time series for companies is presented in Figure 7. During the oil crises in the 1970s, battery patenting was rather intensive. Since 2010, patenting activity has increased again.

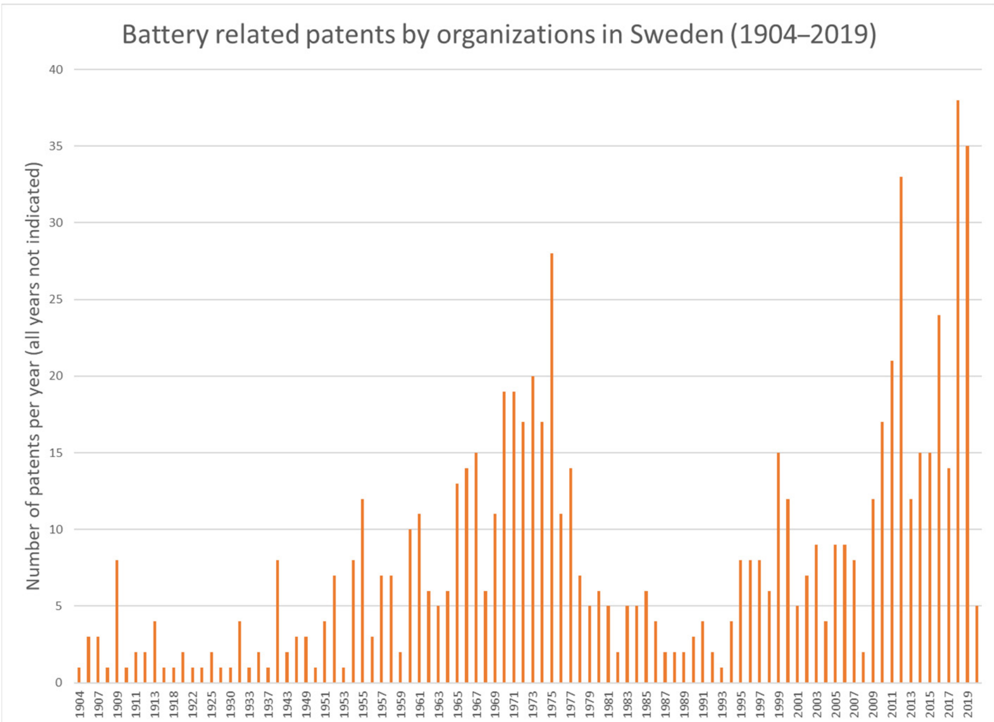

Figure 7. Development of patent applications in Sweden 1904–2019.

In Table 6, all companies with at least five patent applications during 2000–2020 are listed and divided into two time periods.

Table 6. Companies with patent applications in Sweden.

Battery Related Patents in Sweden (Minimum 5)		
Company	**2000–2010**	**2011–2020**
AB Volvo	5	34
Husqvarna	4	31
Scania CV	4	28
Nilar	16	5
Volvo Car Corporation	2	18
Ericsson Mobile Communications	7	7
Autoliv Development	3	8
Alelion Batteries	3	6
Effpower	5	1
Sony Mobile Communications	4	2
Lunalec	1	4

The automotive industry with AB Volvo, Scania CV, and Volvo Car Corporation appears to have increased its patenting activity substantially. Husqvarna, a company making garden equipment, has also intensified patenting. There are some battery manufacturers in Sweden, Northvolt probably being the most famous. Nilar, a battery company, filed for bankruptcy in December 2023. Another battery maker is Alelion Batteries, which also filed for bankruptcy in the autumn of 2023. Effpower terminated their operations in 2012.

Another very manual step in the analysis was to check which scientific publications were referenced in the patent applications. Slightly more than 100 papers could be identified in Scopus, where 92 were published in 1996 or later. In Table 7, the affiliations of the authors in these 92 papers are listed, including countries with at least 3 papers.

Table 7. Where scientific publications referenced in patent applications come from.

Papers	**Country**
32	United States
19	China
13	Sweden
10	Germany
8	United Kingdom
7	Australia
3	France
3	Italy
3	Taiwan

The United States dominates with one-third of the papers, followed by China and then Sweden. As the references are largely added by the reviewers of the patent applications, this reflects which literature they consider relevant.

Among the institutions affiliated in the papers, Linköping University in Sweden is included in seven papers, followed by institutions in the United States and the United Kingdom, see Table 8.

Table 8. Which institutions scientific publications referenced in patent applications come from.

Papers	Institution	Country
7	Linköping University	Sweden
4	Drexel University	United States
4	Imperial College London	United Kingdom
4	United States Department of Energy	United States
3	CNRS	France
3	RWTH Aachen University	Germany
3	University of New South Wales	Australia
3	University of Wollongong	Australia

5. Discussion—What Do the Numbers Say?

Quantitative studies have limitations and should be interpreted with care. It is often a good idea to use them as an input to generate an informed discussion among the actors in the field.

From a methodological perspective, the chosen approach appears promising. It is important to select a technological field that is large enough to result in reasonable volumes of publications. Analyses based on small numbers of publications seldom lead to solid results. One critical ingredient in the method was to involve experts in the battery field. The methodology for this study was developed in line with previous studies but added several unique or at least not so common features as explained in the Section 3. Among them, the combination of patents and papers to cover a broader range of innovation activities and the use of elaborated quality-related indicators are probably the most important ones.

The study confirms the massive development of Chinese patenting and research within the battery field. Whereas this has been indicated in several studies of papers, c.f. [6–9], the development in patenting activity is new to some extent. It is somewhat surprising how different the proportions of patents versus papers are in the countries studied and the diverging trends. The linear innovation model suggests a gradual development from research toward innovation, which in terms of patents and papers would mean that the ratio of patents per paper increases over time as the field matures. Data do not indicate such a trend, even though some countries, not least China, clearly had an increasing share of patents from 2002 to 2019. One possible interpretation is that the battery field is still developing rapidly with many new questions arising relating to everything from new chemistries to production methods.

The citation indicators and TBI percentiles highlight that the United States and Canada are strong in both patents and papers. China is stronger in papers, whereas Japan is somewhat stronger in patents. It should be noted that high quantity does not necessarily mean low quality. China, which made almost 50% of the global volume of battery papers in 2014–2019, did so with a high citation impact. Japan, which made three times more patents than papers in the same period also managed to achieve higher TBI values than the global average.

Academic–corporate collaboration is more frequent in the battery field than in general, at least when it comes to such co-publications. The associated citation impact varies between countries; some result in higher values and some in lower values than for all battery papers. As the citation impact is an important indicator for researchers, countries with a lower citation impact for academic–corporate papers might consider a closer study of how the collaborations are performing.

The actor level analysis focusing on Sweden provides interesting perspectives. Links between research and innovation are important and papers and patents provide data for a quantitative analysis of such links. It could be expected that a certain type of paper is more frequently referenced in patent applications. Potentially, it could be possible to trace an innovation from the original paper to one or several patent applications. In this study, we have not managed to make such a chronological ordering of the publications. But partly linked to the topic is the data for individuals with both patent applications and papers. Some individuals, but not many, carry out battery research resulting in many papers in combination with the writing of a few patent applications.

One policy implication of the study is that the battery field attracts large investments in knowledge production. Several countries show ambitions to secure a dominant position in the production of batteries for automotive and other applications. China dominates. Given the parallel investments in battery knowledge development and battery production, there appears to be an intricate balance between launching products onto the market and betting on the right technology. What if the massive investments in battery production become obsolete because they are not compatible with a new battery technology?

On a lower level, it appears rather easy to identify productive researchers. It might be relevant to nurture a dialogue with them to understand how research can be implemented. Even though there is a no right or wrong mix of patents and papers, a heavy focus on the latter indicates that there might be some missed opportunities.

In the case of Sweden, the battery companies with several patent applications since 2000 have not been successful. None of them were in operation in December 2023. This is worrying but should not be given too much emphasis. The battery industry is in a formative stage and a lot of changes are to be expected.

6. Conclusions

The purpose of this study was to develop and test a method to analyze the volumes of as well as qualitative aspects of patent applications and scientific publications. Battery development in several countries was used as a case. One conclusion is that this approach gives perspectives on battery research and innovation that are new and constitutes a valid starting point for further discussions on a policy level. For example, the substantial variations between countries in the volumes of papers versus patents triggers questions. What is the correct balance? How should we interpret China's rapidly increasing share of patents? By including the quality dimension for both types of publications, an estimation of whether it is only quantity or also quality is enabled. For clarity, we do not think that there is one ideal balance between the volumes of patents and papers. The balance depends on many factors, not least the speed of technology development. A publication study has many limitations, and one natural next step would be to discuss the findings with practitioners in the battery field. By doing so, the results can be scrutinized, and more nuances can be added. At the same time, the results have been communicated and potentially implemented to some extent. The results show that China during 2014–2019 dominated quantitatively and increasingly in both types of publications with a development toward a higher ratio of patent applications per scientific publications. The quality-related indicators show that the United States and Canada during the same period made highly cited scientific publications as well as patent applications with leading Technology Business Index values. On an actor level, the study illustrated how Swedish individuals and companies publish patents and papers. Automotive companies have recently started to file many patents relating to batteries.

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