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Trends in battery research publications 2013 - 2022

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Abstract

China dominates increasingly in the production of scientific publications relating to batteries. In 2022, the country reached a global share of 57% and this is likely to increase further in the future. Some battery technologies where China has a particularly high share is Metal-sulfur and Metal-air batteries. The strategic focus of the United States and Japan has rather been on solid-state batteries, whereas South Korea has had a relatively strong focus on redox-flow battery technologies. These and many more results emanate from a systematic study of battery-related publications retrieved from Scopus and published during the time-period 2013 – 2022. The study of different sub-fields within battery research allowed for a comparison of how different countries prioritize between battery technologies. To increase the quality of the study, interviews were carried out with nine battery experts in academia, companies, and editors of leading journals. A comparison of the results from the scientometric study and the interviews, which was the focus of a final workshop with the interviewed experts, highlighted interesting differences in which institutions are considered leading in different sub-fields of battery research. One argument for interviews is that they provide more updated input compared to publications, which due to long lead times rather mirror the situation some years ago. This study indicates that it should not be taken for granted that the interviews deliver a more updated picture of the very dynamic world of battery research.

Keywords: Battery, scientometrics, publications, research

1 Introduction

Batteries are key to the electrification of the transport system. Even though batteries today enable competitive electric vehicles in some market segments, vehicle electrification overall would benefit from cheaper and more performant batteries. In parallel to the race between countries and companies to secure market shares in the whole value chain leading to the delivery of complete battery systems, there is a research and innovation race to find new battery technologies that outperform today's batteries. Many large national and supra-national initiatives have been launched to foster battery knowledge production.

Here we present results from a study of battery research using scientific publications in Scopus, the broadest abstract and citation database [1], as input data in combination with interviews with battery experts. The key questions addressed were: How has battery research developed in different countries? Which are the leading battery research environments in the world? Selected battery technologies and other sub-groups were studied separately, thus adding details to the analysis.

Publications have been used in several other similar studies of the battery field [2-5], including our own at previous EVS conferences [6-7]. This work builds upon learnings and adds new dimensions, not least the division of battery publications into different sub-fields, as well as methodology refinement.

While using scientific publications is a well-founded proxy for research development and strategies behind, it has limitations and therefore we also performed interviews with battery experts from different domains and countries.

2 Methodology

2.1 Publication analysis

The clearly most challenging part of the study was to identify "battery" publications. There are many possible approaches but, for various reasons, not least an ambition to avoid black boxes, we used the traditional query-based approach. Queries were made in Scopus looking for the search terms in the title and abstract of each publication. The format of the query was INCLUDE (A) OR INCLUDE (B & C) AND INCLUDE NOT (D), where A were quite specific battery search terms such as "lithium-ion battery", B more general search terms such as "battery", which then also required a search term from the C group to be included in the extraction. The C group included a long list of search terms such as "state of charge". Finally, the last part of the query D excluded publications in closely related fields, such as "fuel cells". The full query included 170 search terms.

The development of the query required many iterations. Using samples of 100 random publications, it was checked whether the query returned publications that were battery-related according to our definition. We accepted a maximum of 2% questionable publications. The total production of some productive battery researchers in different countries was used to ensure that the query did not miss many publications.

Two leading battery researchers in Sweden, whereof one is a member of the project team, reviewed the resulting list of publications for Sweden. It should be noted that there will always be publications in a grey zone, which, depending on how you define battery research, either could be included or excluded. For subgroups of the battery field, the query for all batteries was used in combination with a query to find publications within a specific technology or type of activity. Overall, this approach under-estimates the total production of battery-related publications. It is also biased towards more applied research, as more generic research either not mentions battery applications at all or lists several potential applications. If this list includes for example both batteries and fuel cells, the publication will not be included.

A search query approach has advantages and disadvantages. Among the advantages are that once an acceptable query has been developed, it can easily be repeated to capture trends. Another advantage is that it is transparent, all steps in the selection process are visible. Disadvantages include the amount of work to be invested to make a good query and difficulties to use more than publication metadata.

More modern approaches using machine learning and other types of AI tools are developing quickly. To some extent, such methods are available within standard tools such as Elsevier's SciVal. For example, there is an algorithm, which clusters publications based on how they reference each other. One interesting example, which highlights opportunities and challenges with AI tools, uses text mining to shed some light on the content in battery-related publications [8].

The selection of countries represents the largest producers of battery publications as well as some countries specifically relevant for comparisons with Sweden. Two five-year periods were used to illustrate trends. The last year included was 2022, which at the time of extraction of publication data in October 2023, was the latest available year with almost complete data as regards publication volumes.

2.2 Interviews and workshop

Analyses of scientific publications have weaknesses. All research is not published, there is a lag between discovery and publication, the query to identify relevant publications for a field like batteries will never become perfect and more. To compensate for some of these weaknesses, we also carried out interviews with people being very active in the field.

Nine semi-structured interviews were carried out, whereof five persons were leading researchers based in Germany, Spain or Sweden, two were working with battery topics at automotive companies (Polestar and Scania) and two were editors for leading journals publishing battery research. Questions were in most cases shared before the interview and notes from interviews were sent to the informant for check. Interviews were carried out in October and November 2023.

A central topic in the interviews was which research environments were considered leading in the world. The definition of leading was open for the informant to define. Given the rather detailed division of the battery field in sub-fields, the informants were invited to comment upon the sub-fields they were able to have an opinion on.

As the interviews were carried out in parallel to the publication analysis, a final workshop was organized to discuss the findings from the interviews and the publication analysis. All informants were invited to the workshop as well as managers of battery research funding at the Swedish Energy Agency. The one-hour workshop was carried out in a digital format.

3 Results

3.1 Publication volumes, citations, and scientific profiles

In Figure 1, the annual number of publications is presented for selected countries. The rapid increase in Chinese battery publications from a share of the world of 35% in 2013 to 57% in 2022 means that almost all other countries, even though their publication volumes increase substantially, have difficulties to gain an increased share of the world production. Not included in the selection but also on the world's top ten list in battery publication volume were India (ranked 3 in 2022), the United Kingdom (rank 6) and Australia (rank 8).

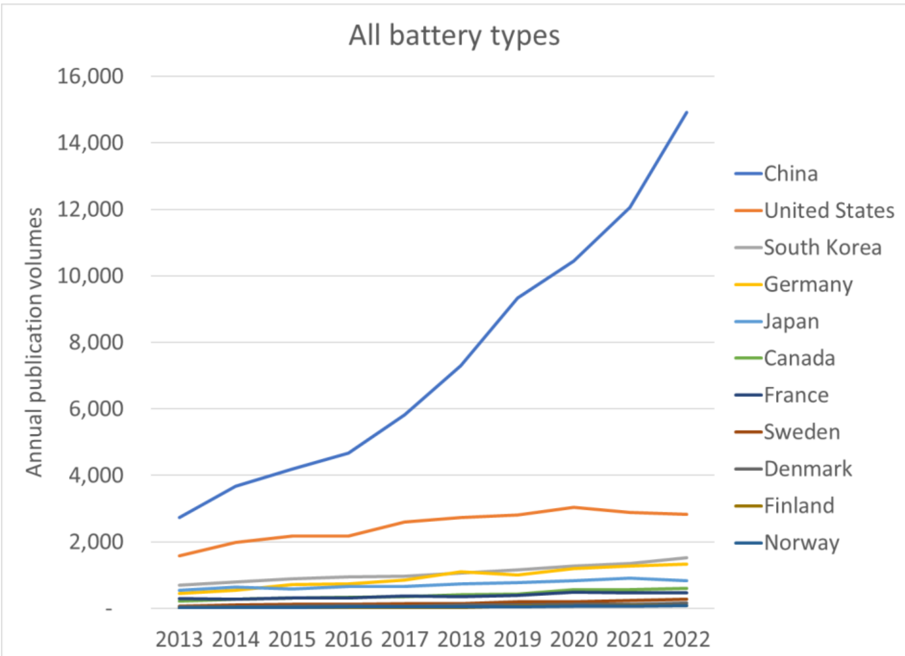


Figure 1: Annual volume of battery-related publications

The United States is a clear number two in battery-related publication volumes but since 2020, the volumes do not appear to increase. South Korea and Germany follow as number three and four, exhibiting a similar growth trend. The overall message from Figure 1 is that the volume of battery-related publications has increased rapidly during the decade studied.

One quality-related indicator is the citation impact. It is based on the number of citations a publication has generated. A citation is a reference to a previous publication. To allow for a comparison of different types of publications, the citation indicator is often normalized. The field-weighted citation impact, FWCI, means that publications within the same scientific field, published the same year in the same type of outlet are compared. If FWCI equals one, the publication is world average, if FWCI equals two, the publication is twice as cited as the average. In Figure 2, the citation impact is indicated for three types of battery-related publications.

International publications have at least two co-authors and affiliations in at least two countries. Academic-corporate publications also have at least two co-authors and at least one academic and one corporate affiliation. According to Figure 2, battery-related publications were cited much more than average publications. The largest producers of such publications, China and the United States, both have a FWCI above 2.00 for their battery-related publications.

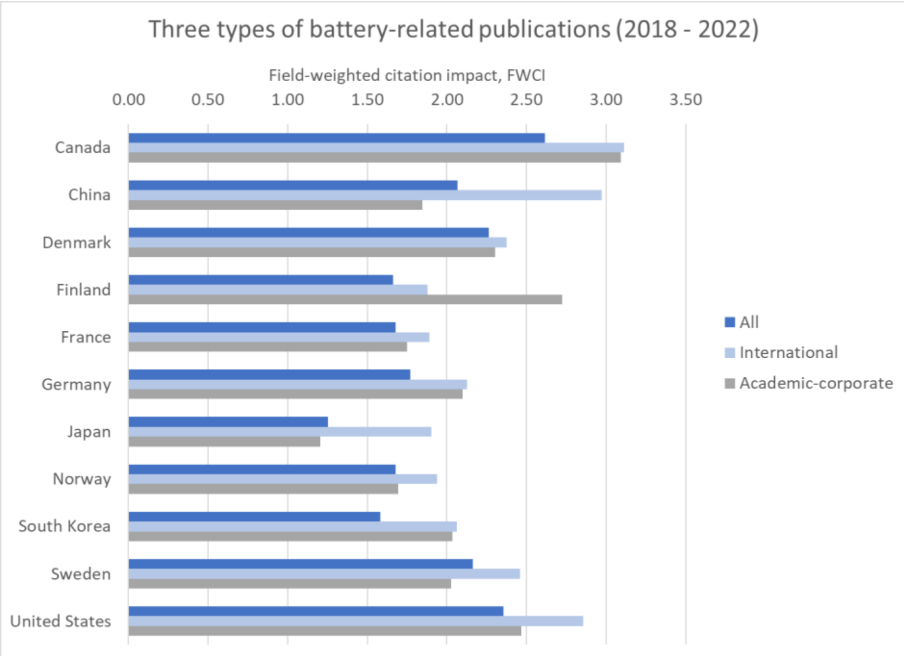


Figure 2: Citation impact for battery-related publications

Another message in Figure 2 is that international battery publications were even more cited in all countries in the selection. Academic-corporate co-publications were also more cited than all battery-related publications with the exceptions of China and Sweden. It should be noted that there is an overlap between international and academic-corporate co-publications.

The following categories of battery technologies were used:

A All battery-related publications

B Lithium but not Li-sulfur or Li-air

C Na, K, Mg, Ag, Zn, Ca or Al but not *-sulfur or *-air

D *-sulfur or *-air

E Organic and water-based

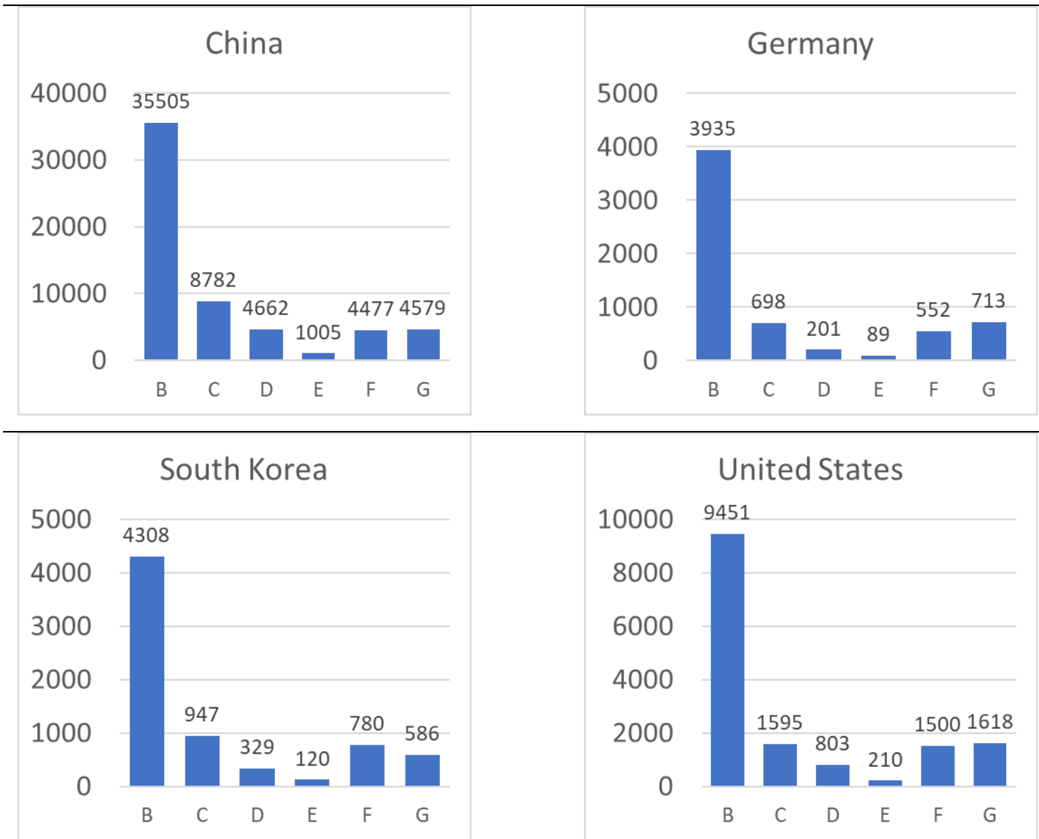
F Redox-flow

G Solid-state

Categories B – G may overlap to some extent. For example, it might be so that a publication about a novel battery technology also mentions lithium-ion batteries as a reference technology.

Obviously, the volumes differ between the categories. Below in Table 1, the profiles in absolute numbers for 2018 – 2022 are presented for the four largest countries in terms of overall volume of battery-related publications. Here, it should be noted that the volumes in some categories are relatively small, not least publications relating to E, Organic and water-based batteries.

Table 1: The number of publications per battery category for four countries (2018 – 2022)



Similar data is presented in Figure 3 as a share of the world. For each sub-group, the two lines of dots represent the averages for the time periods 2013 – 2017 and 2018 – 2022 respectively. China dominates increasingly in all battery categories. It appears to be especially active in Metal-air and Metal-sulfur batteries, with a large increase in the share of the world from the first to the second period and almost three quarters of the world's publications. In relative terms, the United States was most active in solid-state and redox-flow batteries with 18% of the world's production. South Korea had a relatively large share of publications in redox-flow batteries. Japan's portfolio exhibits an emphasis on solid-state batteries, where its share was 9% of the world in the latter period.

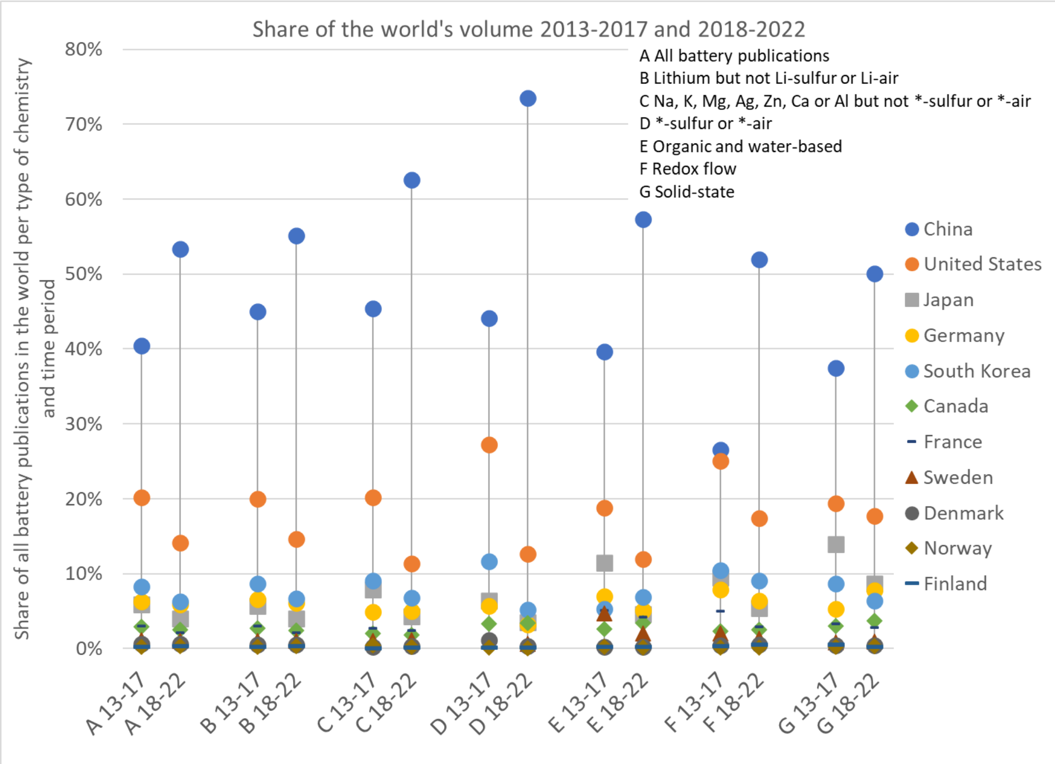


Figure 3: Share of the world's production per type of battery and country

In another dimension we divided the publications in the following three groups:

- Production and manufacturing
- Recycling and second life
- Applications within the automotive industry

The volumes of publications relating to battery manufacturing were relatively small and it is possible that the search method was less reliable for this group. Figure 4 shows an exception to all other comparisons as China did not have the highest volume. Germany had the highest volume, followed by China and the United States. The historically dominating countries in battery manufacturing, Japan and South Korea, did not seem to publish very much.

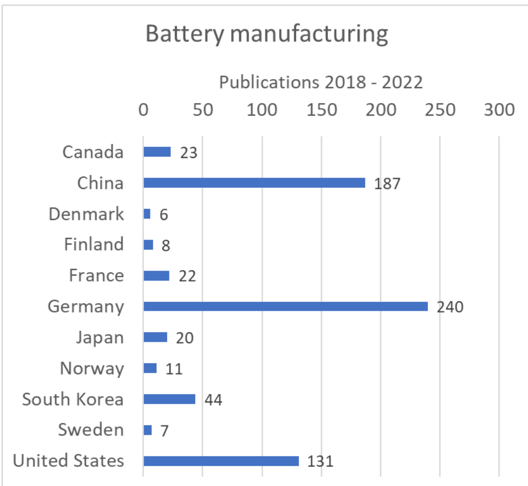


Figure 4: Publications relating to battery manufacturing

The publication volumes were clearly higher when it comes to recycling and second life, see Figure 5. China made the highest number of publications, followed by the United States and Germany. However, in relative terms, China's share of the world was 42%, to be compared with 54%, which is China's share when all battery-related publications are counted. Sweden had twice as many publications related to recycling and second life as could be expected given its overall share of battery-related publications.

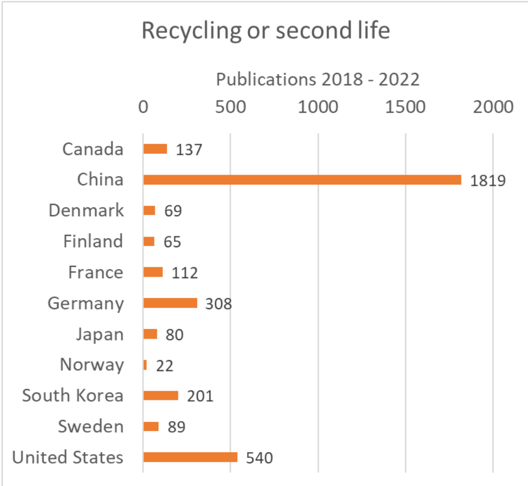


Figure 5: Publications relating to recycling or second life

Finally, in Figure 6, the volumes of battery-related publications mentioning automotive applications are indicated. The top three are China, the United States and Germany. In relative terms, Canada had 4% of such publications in the world, which is somewhat higher than 3% of battery-related publications overall. Denmark's volume was relatively high, considering the minor role of the automotive industry in the country.

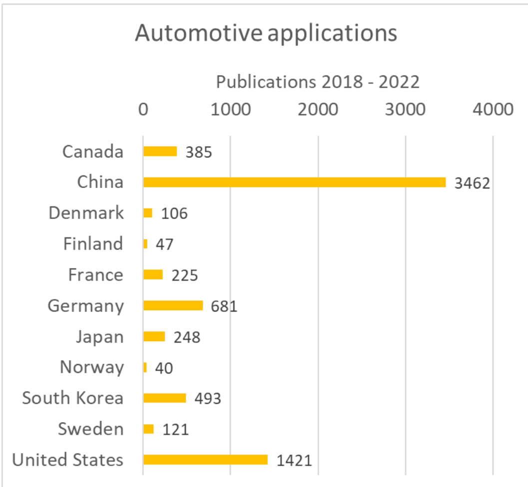


Figure 6: Battery-related publications mentioning automotive applications

3.2 Leading research environments

When asked about leading research environments, the respondents in the interviews often mentioned the names of leading researchers. For practical reasons, this study was on the institutional and not on the individual level.

The interviewed battery experts provided slightly different definitions of what constitutes a leading research environment. It was emphasized that such an environment carries out front edge research with an ability to combine breadth with focus. In publication indicator terms, this corresponds relatively closely to publications with a high citation impact. A common theme was also the longevity of research in the area, the environment should have published consistently over a long time. This corresponds to some extent to a high publication volume. Two informants also mentioned an industry perspective. To keep it simple, we did not include the industry dimension in the mapping of leading research environments.

One challenge with publication data is that the attribution of publications to institutions differ. Some organizations, such as the Chinese Academy of Sciences, the US Department of Energy or the French CNRS are stated as affiliations in combination with several other organizations. Researchers stating these affiliations also state another affiliation, a university or a research laboratory for example. This leads to massive publication volumes for this type of organizations. In the following, we list them in the tables but do not adapt the scale for the volume axis to show them.

All different battery technologies mentioned above as well as the other dimensions were analyzed with interview and publication data. However, given the restrictions in the length of the paper, we only give two examples below. The first example is lithium(-ion) batteries.

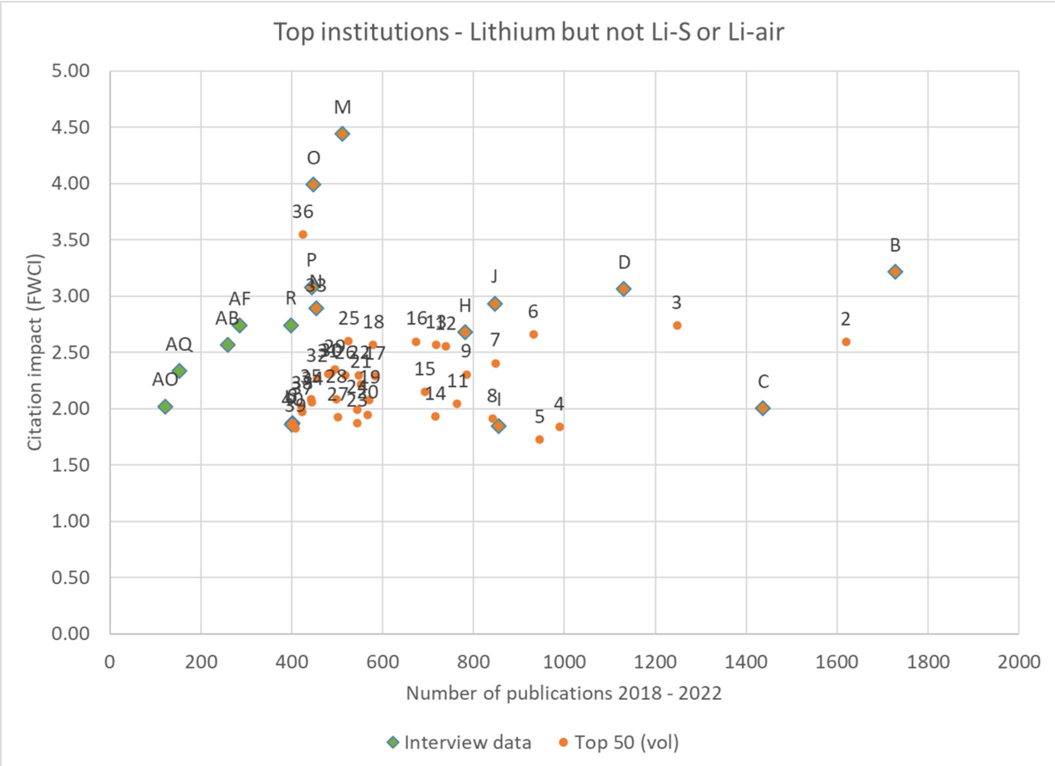


Figure 7: Leading institutions within lithium(-ion) batteries but not Li-S or Li-air batteries

In Figure 7, the institutions mentioned in the interviews are plotted with letters as labels. The red dots with numbers are institutions not mentioned in the interviews but in the top 50 of all institutions worldwide in terms of publication volume. In Table 2, all institutions mentioned in the interviews plus some of the others are listed.

Table 2: Leading lithium(-ion) battery, but not Li-S or Li-air battery institutions

	Institution	Total	FWCI		Institution	Total	FWCI
A	Chinese Academy of Sciences	4009	2.52	15	Xi'an Jiaotong University	693	2.15
1	United States Department of Energy	2555	3.02	16	Shandong University	674	2.60
B	Tsinghua University	1728	3.22	17	Nankai University	583	2.29
2	University of Chinese Academy of Sciences	1619	2.60	18	University of Science and Technology Beijing	579	2.57
C	Central South University	1437	2.01	19	Wuhan University of Technology	571	2.08
3	University of Science and Technology of China	1248	2.74	20	Jülich Research Centre	567	1.94
D	Beijing Institute of Technology	1131	3.06	21	Beijing University of Chemical Technology	552	2.22
4	Harbin Institute of Technology	989	1.84	22	Soochow University	548	2.29
5	CNRS	946	1.73	23	Guangdong University of Technology	544	1.87
6	Zhejiang University	932	2.66	24	Sichuan University	544	1.99
I	Karlsruhe Institute of Technology	856	1.84	25	Hunan University	525	2.60
7	Zhengzhou University	849	2.41	M	Stanford University	512	4.44
J	Argonne National Laboratory	847	2.93	O	University of Texas at Austin	448	3.99
8	Shanghai Jiao Tong University	842	1.91	P	University of California at Berkeley	444	3.08
9	Huazhong University of Science and Technology	785	2.31	R	Oak Ridge National Laboratory	398	2.74
H	Peking University	781	2.68	S	Seoul National University	402	1.88
11	South China University of Technology	764	2.04	U	University of Münster	400	1.86
12	Tianjin University	739	2.55	AB	Ulsan National Institute of Science and Technolog	259	2.57
13	Xiamen University	717	2.57	AF	The Faraday Institution	285	2.74
14	Shanghai University	716	1.93	AO	Université de Picardie Jules Verne	122	2.02
15	Xi'an Jiaotong University	693	2.15	AQ	Dalhousie University	153	2.34

One interesting aspect is that all plotted institutions had a good or very good citation impact. There is a tendency that many of the institutions mentioned in the interviews were based outside China and had relatively low publication volumes.

A more representative illustration of the typically rather large mismatch between the scientometric approach and the interview data is the next category of post-lithium batteries, or all other metals but not in combination with sulfur or air, see Figure 8.

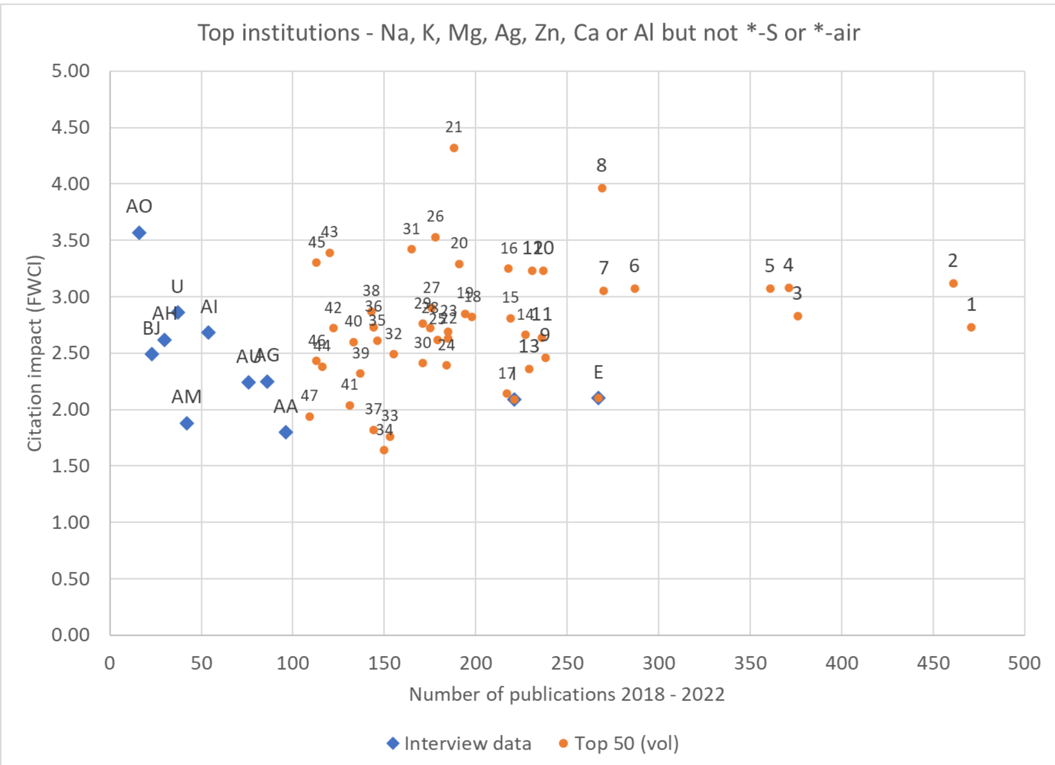


Figure 8: Leading institutions in post-lithium batteries

Some of the institutions indicated in Figure 8 are listed below in Table 3.

Table 3: Leading post-lithium institutions

	Institution	Vol	FWCI		Institution	Vol	FWCI
A	Chinese Academy of Sciences	1112	2.89	19	Xiamen University	194	2.85
1	United States Department of Energy	471	2.73	20	Hunan University	191	3.29
2	Central South University	461	3.12	21	CAS - Institute of Physics	188	4.32
3	University of Chinese Academy of Sciences	376	2.83	22	Fudan University	185	2.63
4	University of Science and Technology of China	371	3.08	23	South China University of Technology	185	2.69
5	Zhengzhou University	361	3.07	24	National University of Singapore	184	2.39
6	Nankai University	287	3.07	25	Soochow University	179	2.62
7	Peking University	270	3.05	26	City University of Hong Kong	178	3.53
8	University of Wollongong	269	3.96	27	Wuhan University of Technology	176	2.90
E	CNRS	267	2.10	28	Argonne National Laboratory	175	2.72
9	Shanghai University	238	2.46	29	Beijing University of Chemical Technology	171	2.76
10	Tsinghua University	237	3.23	30	Xi'an Jiaotong University	171	2.41
11	Huazhong University of Science and Technology	236	2.64	AA	Uppsala University	96	1.80
12	Tianjin University	231	3.23	AG	CIC energigune	86	2.25
13	Harbin Institute of Technology	229	2.36	AU	Tokyo University of Science	76	2.24
14	Beijing Institute of Technology	227	2.66	AI	Deakin University	54	2.68
I	Karlsruhe Institute of Technology	221	2.09	AM	The University of Tokyo	42	1.88
15	Zhejiang University	219	2.81	U	University of Münster	37	2.86
16	Shandong University	218	3.25	AH	Chalmers University of Technology	30	2.62
17	Shanghai Jiao Tong University	217	2.14	BJ	CSIC - Institute of Materials Science of Barcelona	23	2.49
18	Guangdong University of Technology	198	2.82	AO	Justus Liebig University Giessen	16	3.57

Three institutions in the top 50 by volume were mentioned in the interviews. Almost all institutions not mentioned in the interviews were based in China.

4 Discussion

4.1 Why do the interviews indicate other leading institutions than the scientometric analysis?

Even though the informants obviously use publication data to assess their own and others research, the results differ substantially between their top lists and what the publication data tells. One explanation of this difference could be that the publication analysis was not correct. Among others, it might be that it did not identify relevant battery-related publications. Or that the scientometric definition of a leading research environment based on publication volume and citation impact lacks important aspects. However, when the results were discussed with the informants, they did not consider these explanations very relevant. It should, however, be acknowledged that a scientometric study has many limitations and that we in this study have further simplified the analysis by just using volume and citation impact to define a leading research environment. The battery experts interviewed most probably base their opinions on many more types of data – both hard and soft.

Another potential explanation might be that the people interviewed did not represent the global battery research community. There was a strong bias towards the Western world with no person from China, South Korea, or Japan among those interviewed. If this explanation is valid, it also indicates that the battery research world might have become too large for people to have in-depth knowledge about all parts of it. One lesson for future research of this type is to be more careful when selecting people to interview.

Partly linked to this, it could also be so that as battery research develops very rapidly and that the period 2018 – 2022 is too short. It appears likely that the opinions about leading research environments from the interviews were based on a longer history of achievements. It typically takes many years to become broadly known and accepted by the community as a leading researcher. If this is true, it is somewhat problematic, as the interviews among others were added to the publication analysis to allow for a more updated view on the field.

From a methodological perspective, a standard approach is to use a publication study to get a quick overview and thereafter discuss it with people in the innovation system to add details and confirm or reject the results of from the publications. In this case, we *did not* follow the standard approach. No results from the publication analysis were shared with the informants before or during the interview. This has the advantage of in this aspect unbiased data and in the end to substantial differences in the lists of top battery research environments. As a workshop with the informants was carried out in the end of the project, potential explanations for the differences as listed above were collected, but it could for a reader still be considered problematic that our results are not coherent. We do advocate to allow for more than one perspective on what a leading environment is. Thus, depending on the research question, we consider it very important to consider alternatives to the standard approach when publication data and interviews are combined.

4.2 What does the scientometric study tell us about the world of battery research?

In line with other studies, our study confirms the increasingly dominant position of China. The country had the highest number of publications in all battery technologies studied as well as in most other dimensions. The only exception was battery manufacturing research, where Germany had the highest number of publications.

The total volume of battery-related publications increased very much in the period 2013 – 2022. Almost all countries studied exhibit a high growth rate but only a few managed the same growth rate as China. The consequence was that their share of the global volume of battery-related publications decreased.

It should also be noted that quantity did not come at the expense of quality. The citation impact for battery-related publications with Chinese participation was not the highest among the countries included in the study but still very high. Canada had the highest citation impact followed by the United States.

One contribution of our study is that it divided the battery field into different sub-groups. Thereby it highlights differences in priorities between countries, which, as illustrated above, are substantial. The profiles illustrate preferences on the technology readiness level scale, if the country prefers research on more mature technologies such as lithium-ion batteries or rather invest in potential future battery technologies, *etc*. To some extent, these decisions are probably influenced by the type of industry in the country. If it has a large automotive industry heavily committed to electrification, then a focus on battery technologies being mature to manufacture at large scale relatively soon might be more motivated. Another important factor influencing the profile could be whether the country is aiming for the establishment (or survival) of an industry producing batteries. It would also be interesting to investigate to what extent the different profiles relate to national strategies.

For the smaller countries in the study, it could be questioned if they should be active in all battery technologies or if they would benefit from a focus on a few, to obtain critical volumes.

International co-publications were clearly more cited than fully domestic ones. One part of a national strategy could be to foster international collaborations with research environments having complementary expertise. Our lists of leading research environments per battery field could in fact serve as an inspiration.

From a methodology perspective, the division of battery-related publications into sub-fields leads to relatively small publication volumes in some sub-fields. Obviously, this is mainly a problem for smaller countries and caution is recommended when the volumes are small.

5 Conclusions

Our study leads to the conclusion that the research world addressing batteries is in a very dynamic phase with a quick development towards higher publication volumes following many parallel trajectories to find new even better battery technologies. China dominates increasingly in publication volumes and many of the largest institutions in terms of battery-related publications in 2018 – 2022 were in the country. The study of which battery technologies and other dimensions that each country pursued provided possibilities to compare potential national strategies in the battery domain. The approach to carry out a scientometric study in parallel with interviews resulted in two different rankings of the leading research environments in each of the studied battery technologies. In the final workshop comparing the rankings and other results from interviews and the publication analysis, it was concluded that the scientometric analysis was providing important insights not least in relation to how quickly the world of battery research changes.

Acknowledgments

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