A bibliometric analysis of battery research with the BATTERY 2030+ roadmap as point of departure

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Abstract

In this bibliometric study, we analyze the six battery research subfields identified in the BATTERY 2030+ roadmap: *Battery Interface Genome, Materials Acceleration Platform, Recyclability, Smart functionalities: Self-healing, Smart functionalities: Sensing*, and *Manufacturability*. In addition, we analyze the entire research field related to BATTERY 2030+ as a whole, using two operationalizations. We (a) evaluate the European standing in the subfields/the BATTERY 2030+ field in comparison to the rest of the world, and (b) identify strongholds of the subfields/the BATTERY 2030+ field across Europe. For each subfield and the field as a whole, we used seed articles, i.e. articles listed in the BATTERY 2030+ roadmap or cited by such articles, in order to generate additional, similar articles located in an algorithmically obtained classification system. The output of the analysis is publication volumes, field normalized citation impact values with comparisons between country/country aggregates and between organizations, co-publishing networks between countries and organizations, and keyword co-occurrence networks. For the results related to (a), the performance of EU & associated (countries) is similar to China and the aggregate Japan-South Korea-Singapore and well below North America regarding citation impact and with respect to the field as a whole. Exceptions are, however, the subfields *Battery Interface Genome* and *Recyclability*. For the results related to (b), there is a large variability in the EU & associated organizations regarding volume in the different subfields. For citation impact, examples of high-performing EU & associated organizations are ETH Zurich and Max Planck Society for the Advancement of Science.

1 Introduction

Uppsala University is coordinating an EU-funded Horizon 2020 large scale research initiative, BATTERY 2030+, which started September 1st 2020.[1] The project is a continuation of a previous project that recently published a battery research roadmap[2]. One of the aims of the BATTERY 2030+ initiative is to monitor the progress towards the goals set out in the battery research roadmap, as well as emerging areas, opportunities and challenges. The monitoring will include two bibliometric analyses of European and international battery research subfields: the analysis described in this report and a second analysis executed at the end of the project.

In this report, we treat the six battery research subfields identified in the BATTERY 2030+ roadmap. These fields are *Battery Interface Genome (BIG)*, *Materials Acceleration Platform*

[1] https://battery2030.eu/

[2] https://battery2030.eu/research/roadmap/

(MAP), Recyclability, Smart functionalities: Self-healing, Smart functionalities: Sensing, and *Manufacturability*. In addition, we analyze the BATTERY 2030+ field as a whole. The overarching aims of the analysis are:

(a) to evaluate the European standing in the subfields/the BATTERY 2030+ field in comparison to the rest of the world,
(b) to identify strongholds of the subfields/the BATTERY 2030+ field across Europe.

The output of the analysis is indicated in the following list:

- Publication volumes.
- Field normalized citation impact values with comparisons between country/country aggregates and between organizations.
- Co-publishing networks, both between countries and organizations.
- Keyword co-occurrence networks.

The country/country aggregates referred to above and used in the report are defined in Table 1.

Table 1. Definitions of country/country aggregates.

Country aggregate	Included
EU & associated	EU 27 + Horizon 2020 associated countries[3]
China	China
JKS	Japan, South Korea, Singapore
North America	Canada, US

The remainder of this report is structured as follows. Section 2 treats data and methods, whereas Section 3 reports the results of the analysis. In Section 4, we reflect on the results, put forward limitations and give conclusions.

2 Data and methods

In this section, the main data source of the analysis is described, as well as the methods used.

2.1 Data source

The data source of the analysis is the KTH Library database Bibmet, a relational database that constitutes a bibliometric version of Web of Science (WoS). Bibmet contains about 64 million publications, with the earliest publication year equal to 1980, and is updated quarterly. The publication period of the analysis is 2010-2019, and the WoS document types taken into account are “Article” and “Review”. In the remainder of this work, we use the term “article” to stand for articles and reviews.

Bibmet involves a classification system, algorithmically obtained by use of a methodology proposed by Waltman and van Eck (2012). The system is hierarchical and has four levels of clusters, where, for each level, the clusters are pairwise disjoint. Only articles are clustered, based on direct citation relations between them, and the clustering technique used is similar to modularity-based clustering (Newman 2004a, 2004b). 35.7 million articles are included in the

[3] Albania, Armenia, Bosnia and Herzegovina, Faroe Islands, Georgia, Iceland, Israel, the former Yugoslav Republic of Macedonia, Moldova, Montenegro, Norway, Serbia, Switzerland, Tunisia, Turkey, and Ukraine.

system. Each cluster, regardless of hierarchical level, has been algorithmically assigned three labels, where a label is an author keyword, a journal name, a WoS subject category name or a word derived from author addresses. The purpose of these labels is to indicate the subject orientation of the clusters.

2.2 Article sets for the six subfields and the BATTERY 2030+ field

For each of the six subfields, and the BATTERY 2030+ field as a whole, we used the classification system to define a set of articles to analyze. BATTERY 2030+ roadmap includes, for each subfield, a publication list. These lists were used as starting points in the process of defining article sets for the subfields. Let S be a subfield. The following five steps were carried out to define a set of articles for S:

1. From the publication list for S in the BATTERY 2030+ roadmap, the subset of articles covered by Bibmet was selected. Let S_r be this subset. If deemed desirable, S_r was expanded with additional articles selected by the BATTERY 2030+ consortium.
2. For each article x in S_r, each article cited by x and covered by Bibmet was added to S_r. Let S_a be the resulting set. The articles in S_a were considered as *seed articles*: articles that can be used in order to obtain additional, similar publications.
3. The articles in S_a were located in the classification system with respect to the most fine-grained level of the system, level-1 (with 158,783 clusters) and the next to most fine-grained level, level-2 (with 5,053 clusters). For both levels, Excel sheets were created, in which the identified clusters were ordered descending after the number of articles in S_a, i.e. the number of seed articles for S, that a cluster contains. Besides information on number of seed articles were, for instance, cluster labels included in the sheets. Moreover, sheets with bibliographic information on the articles belonging to the identified clusters were created.
4. For the clusters with the highest frequencies of articles from S_a, keyword co-occurrence networks and co-publishing networks of countries and organizations were created. The networks were visualized, and the visualizations stored in image files.
5. At least one subject expert, with regard to the subfield S, analyzed the sheets from step 3 and the image files from step 4. The subject expert(s) marked the clusters that in her/his view are relevant, i.e. should be included in the analysis, and provided this and other feedback to the authors of this report.
6. The union of the clusters that were marked as relevant by the subject expert(s), say U_S, was obtained, and U_S constitutes the set of articles assumed to represent the subfield S in the analysis.[4]

Thus, the execution of steps 1-5 for each subfield yielded six article sets, where each such set is our operationalization of the corresponding subfield.

For the part of the analysis that treats the BATTERY 2030+ field as a whole, we took two operationalization approaches. In the first approach, the union of the six article sets (the U_S sets) was used as an operationalization of the field. Let POOL denote this set. However, since

[4] However, if the feedback given in step 5 indicated that additional articles should be added to the set S_a, S_a was expanded and steps 3-5 were iterated one time (in this case, the same subject expert(s) performed the new analysis).

POOL may represent the BATTERY 2030+ field quite narrowly, we used a larger set of articles (compared to POOL) in the second approach. This set, say WIDE, is based on a wider selection of larger level-2 clusters, which cannot necessarily be directly tied to the specific subfields of BATTERY 2030+, but which are relevant to the broader battery field as defined from the articles in the six sets of seed articles. Further, the selected level-2 clusters are ranked high, with respect to the number of seed articles they contain, for at least one of the six subfields. More precisely, for each included level-2 cluster *C*, (1) there are at least two subfields *S* and *S'* such that *C* belongs to the five highest ranked clusters in both *S* and *S'* with respect to number of seed articles, or (2) *C* has been selected by subject experts for at least one subfield. Table A1 in Appendix 1 lists the clusters used for the definition of WIDE, also indicating if these clusters belong to the 10 highest ranked clusters in each respective subfield, with respect to number of seed articles. In Figure 1, a conceptual view of the two approaches is given. Note that not all articles in POOL are included in WIDE.

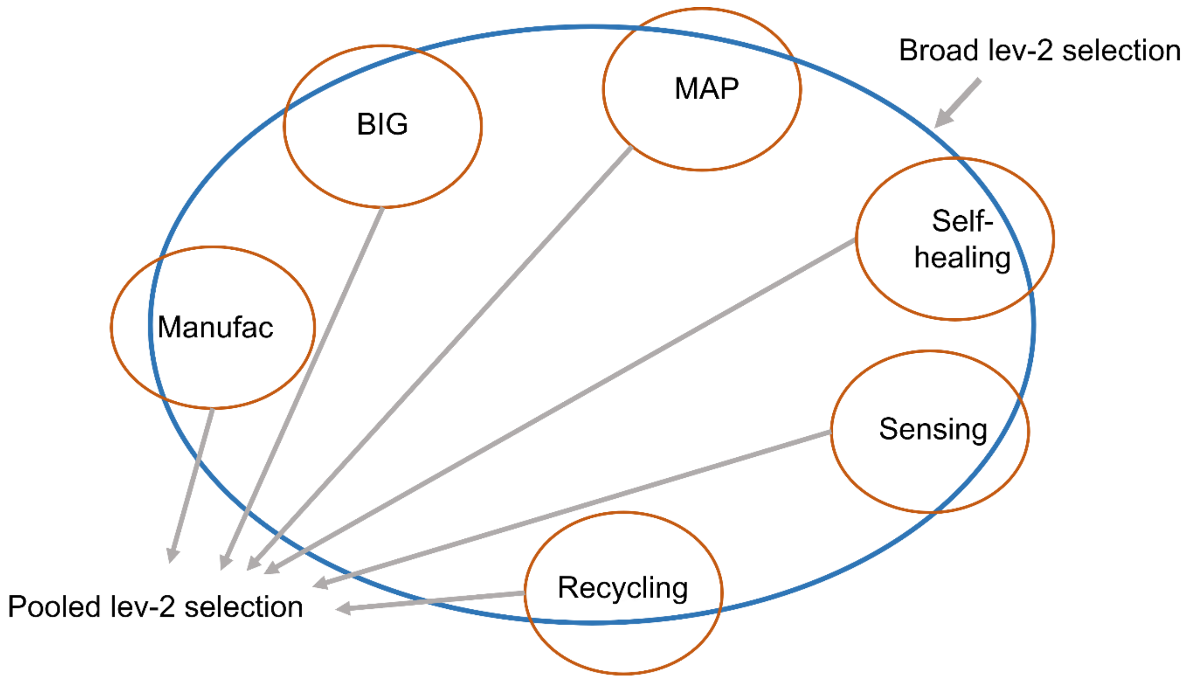

Figure 1. Conceptual view of the two approaches to the operationalization of the whole BATTERY 2030+ field, based on the cluster selection method. The red circles represent article sets based on selected clusters for the specific subfields and the blue circle represents an article set based on a wider selection of larger level-2 clusters.

2.3 Indicators

For selected countries/country aggregates and organizations, and for each subfield and the BATTERY 2030+ field, the indicators put forward in Table 2 are used to describe performance. Regarding the four citation-based indicators, cf and Ptop10% are publication-level indicators, whereas jcf and Jtop25% are journal-level indicators. Jcf is a field normalized counterpart to the well-known Journal Impact Factor.

The four citation-based indicators are calculated by the use of fractional counting. An author's fraction of an article is counted as 1/*n*, where *n* is the number of authors of the article. A unit's (e.g. an organization's) fraction of the article is then given by the sum of the author fractions of the authors affiliated to the unit in the article. However, if an author is affiliated to more than one unit in the article, the fraction of the author is distributed uniformly across these units. Fractional counting yields a more proper field normalization of citation impact indicators compared to full counting.

Table 2. Indicators and their descriptions.

Denotation	**Description**
P full	Full counts of articles.
P frac	Fractional counts of articles.
cf	Mean field normalized citation rate. This indicator normalizes for the variation of citation patterns between subject fields. Each article is compared to a reference group of articles. In our case, for an article *a* in the set U_S (the set of articles assumed to represent the subfield *S* in the analysis), the reference group consists of all articles in U_S published the same year as *a*. The number of citations of *a* is divided by the average number of citations across the articles belonging to U_S and published the same year as *a*, which results in a field normalized citation rate for *a*. For a given country/country aggregate/organization represented in U_S and a given publication year, the cf value expresses the average field normalized citation rate of the country's/country aggregate's/organization's articles in U_S that are published in the year. The weighted average of the cf values of all countries/country aggregates/organizations for a given year, where the weight of a country/country aggregate/organization is given by its fractionalized number of articles, is equal to 1. Therefore, a citation rate above 1 for a country/country aggregate/organization indicates that its set of articles is cited above world average, e.g. a citation rate of 1.2 indicates that its articles are cited 20 percent above world average.
Ptop10% (expressed as share)	The share of articles among the 10 percent most cited. The same reference group as for the field normalized citation rate is used for the indicator. Articles can partly belong to the 10 percent most cited articles if several articles have the same citation value as the percentile limit. The weighted average of the Ptop10% values of all countries/country aggregates/organizations for a given year, where the weight of a country/country aggregate/organization is given by its fractionalized number of articles, is equal to 10.
jcf	Mean field normalized citation rate for journals. This indicator shows the citation impact of the journals in which the unit has published. It is calculated as an average of the field normalized citation rate of the set of journals in which the analyzed unit has published. If the unit has published multiple articles in the same journal, the journal's field normalized citation rate is counted multiple times. This journal indicator is normalized for field differences by the same principles as the mean field normalized citation rate (cf). However, in this case the Web of Science Subject categories for journals are used as a basis for obtaining reference groups. For an article *b* in a given journal *J*, the reference group consists of all articles appearing in the journals belonging to the same Web of Science Subject category (or categories) as *J* and published the same year as *b*. For an article *a* in the set U_S and published in the year *y*, the value of the journal of *a* is based on the years *y*-5 to *y*-1. The weighted average of the jcf values of all countries/country aggregates/organizations for a given year, where the weight of

	a country/country aggregate/organization is given by its fractionalized number of articles, is equal to 1.
Jtop25% (expressed as share)	The share of articles that have been published in journals, which are among the 25 percent most cited. The same reference group as for the mean field normalized citation rate for journals (jcf) is used for the indicator. The journals in the top 25 category publish 25 percent of the articles in the reference group. A journal can partly belong to the top 25 percent if it stretches over the percentile limit or if it has been classified into multiple fields with different percentile limits. The weighted average of the Jtop25% values of all countries/country aggregates/organizations for a given year, where the weight of a country/country aggregate/organization is given by its fractionalized number of articles, is equal to 25.
IntColl%	This indicator shows the number of articles that has been co-published between two or more countries. The default presentation of this indicator is by full counts.

In Table 2, regarding the field normalized citation indicators cf and Ptop10%, we only describe the reference group of articles for an article in a given U_S, corresponding to the subfield *S*. For POOL as an operationalization of the BATTERY 2030+ field and an article *a* in POOL, *a* belongs to exactly one U_S. The reference group of articles for *a*, with respect to the two indicators, is U_S. For WIDE as an operationalization, and an article *a* in WIDE, the reference group of articles for *a*, with respect to the two indicators, is WIDE, regardless of if *a* belongs to a U_S or not. Note that the calculation of the two journal-level field normalized citation indicators, jcf and Jtop25%, are not affected by whether subfields or the BATTERY 2030+ field are analyzed.

Notice that for the citation part of the study, the last considered publication year is 2018. The rationale for this is to avoid an improperly short citation window for the last publication year of the study (i.e. 2019). Citations are counted with an open window until the time for the analysis (last quarterly update of the database Bibmet), hence all citations from articles registered in the database at this point in time will been counted. For all citation statistics, author self-citations are excluded, defined as citations where any of the author names are the same in the citing and cited article.

For detailed documentation of the calculation of the two publication-level field normalized citation indicators and the two corresponding journal-level indicators, see Ahlgren et al. (2021) and the openly available document “Formal definitions of field normalized citation indicators and their implementation at KTH Royal Institute of Technology”[5], respectively.

3 Results

In this section, we present the results of the analysis. Each of the sections 3.1-3.8, which correspond to the six subfields (sections 3.1-3.6) and the BATTERY 2030+ field (sections 3.7 and 3.8), has three subsections. The first subsection treats the country/country aggregate level. A table with indicator values by country/country aggregate is put forward, as well as line graphs for publication volume (P full) and citation impact (cf and Ptop10%). In these graphs, the horizontal axis corresponds to publication year. For all cf and Ptop10% graphs, a dashed,

[5] URL: https://www.kth.se/polopoly_fs/1.544479!/Formal%20definitions%20of%20field%20normalized%20citation%20indicators%20at%20KTH.pdf

grey line indicates world average. The second subsection concerns the organization level and contains a table that corresponds to the table in the first subsection. 13 organizations are taken into account in the table: the top 10 organizations among EU & associated with respect to publication volume (the indicator P full), and the top 1 organization from China, North America and JKS regarding the same indicator. The subsection also gives information on the frequency of occurrence of companies in the articles of the subfield/field. Note that identifying organizational types in bibliometric studies can be difficult. This is especially the case for companies. Therefore, highlighted companies constitute samples, which do not give the complete picture.

In the third subsection, three bibliometric networks are visualized. First, a co-occurrence network with regard to author keywords is visualized, where the visualization was done using VOSviewer, a publically available program from CWTS, Leiden University (van Eck & Waltman, 2010). Unification of keywords was done by VOSviewer based on manually created thesaurus files: files in which keyword variants are mapped to a standard variant. In the network, the nodes represent keywords, and the larger a node is the higher is the weight of the node, where *weight* in this case is defined as the number of articles in which the keyword occurs. A link between two nodes indicates that the corresponding two keywords co-occur in at least one article. Moreover, the thicker the link is the higher its strength, where *strength* in this case is defined as the number of articles in which the two keywords co-occur. The distance between the nodes approximately indicates the strength of the co-occurrence relation between the corresponding keywords. However, a normalized link strength, *association strength*, is used as default by the VOSviewer layout technique: the link strength divided by the product of the two node weights. Note that VOSviewer cluster the keywords. VOSviewer uses modularity-based clustering (Newman 2004a, 2004b), where in our case the underlying relatedness measure between two keywords is association strength. All nodes in a given cluster have the same color, whereas nodes in different clusters have different colors.

The third subsection further contain visualizations of co-publishing networks for both the country level and the organization level. Here, the nodes represent countries (organizations), and a link between two nodes indicates that there is at least one article in which the corresponding two country names (organization names) co-occur. In this case, the weight of the node is defined as the number of articles in which the country name (organization name) occurs, whereas the link strength in this case is defined as the number of articles in which the two country names (organization names) co-occur. The nodes were clustered by VOSviewer with the same methodology as in the author keywords clustering. For layout, association strength was used, as in the keyword case.

Table 3 reports the number of articles per subfield and for the BATTERY 2030+ field, i.e. the number of articles in the six articles sets, in POOL and in WIDE over the whole publication period 2010-2019.

Table 3. Number of articles per subfield, POOL and WIDE, 2010-2019.

Field	P full
BIG	1,069
MAP	1,683
Recyclability	1,090
Self-healing	7,127
Sensing	2,818
Manufacturability	1,361
POOL	15,148
WIDE	66,574

3.1 Battery Interface Genome (BIG)

In this section, we give the results for BIG. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

3.1.1 Country/country aggregates

In Table 4, indicator values by country/country aggregate and for the whole publication period are given.

North America has a fairly stable publication volume from 2013 onwards (Figure 2). China has, though, caught up during later years. Note that the publication volumes for EU & associated and JKS are small for each year, especially in the first part of the study period. Regarding cf and Ptop10%, the values fluctuate considerably, more so when the number of publications is low, and it is difficult to see a clear pattern (Figures 3 and 4).

Table 4. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	151	125.3	1.36	17.4%	1.35	44.0%	50.3%
China	344	296.4	0.86	6.7%	1.28	45.1%	25.9%
JKS	69	60.1	0.57	3.1%	1.19	41.8%	20.3%
North America	481	426.8	1.12	11.6%	1.40	46.7%	32.6%

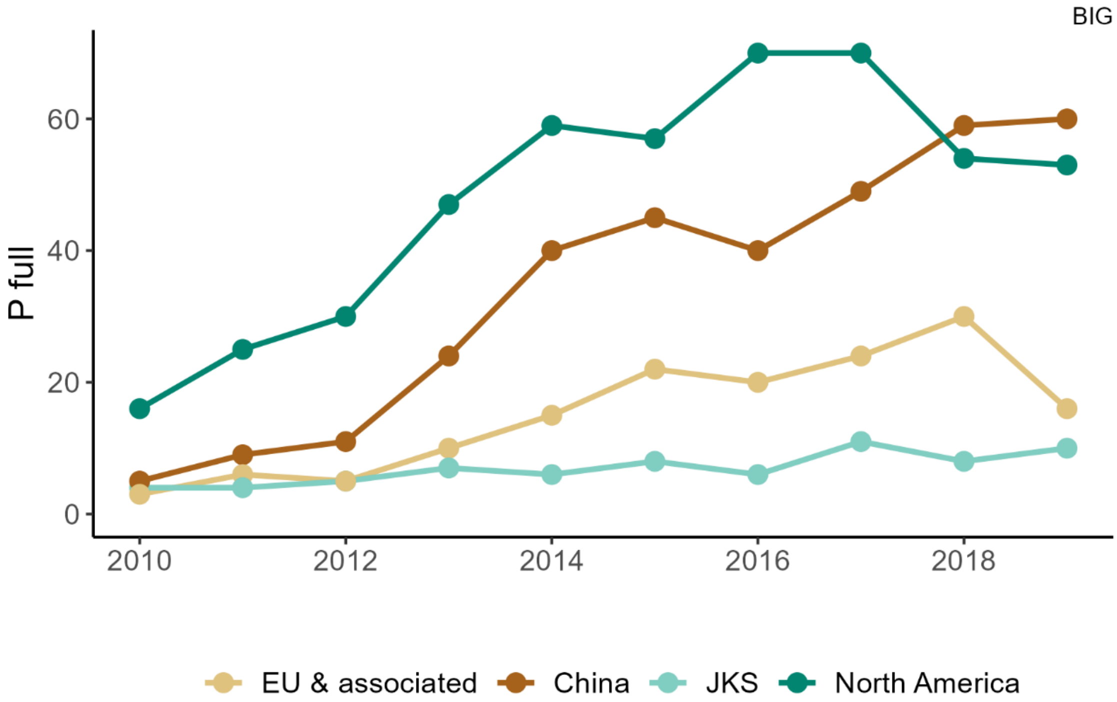

Figure 2. Publication volume (P full) development by country/country aggregate.

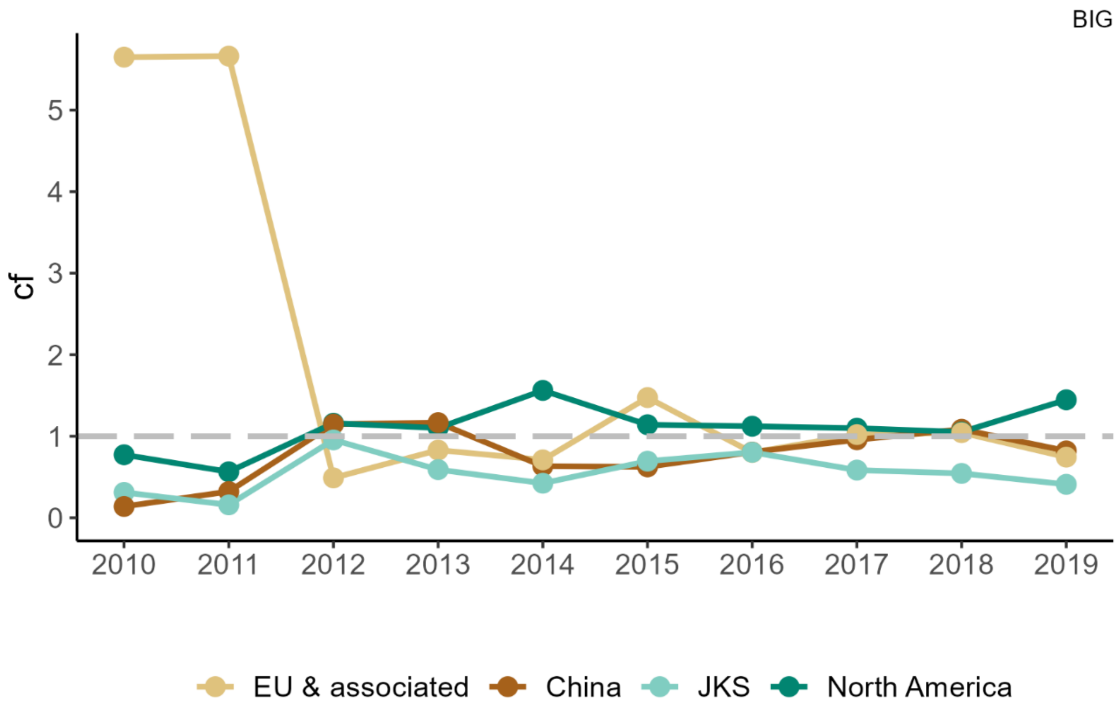

Figure 3. Publication-level citation impact (cf) development by country/country aggregate.

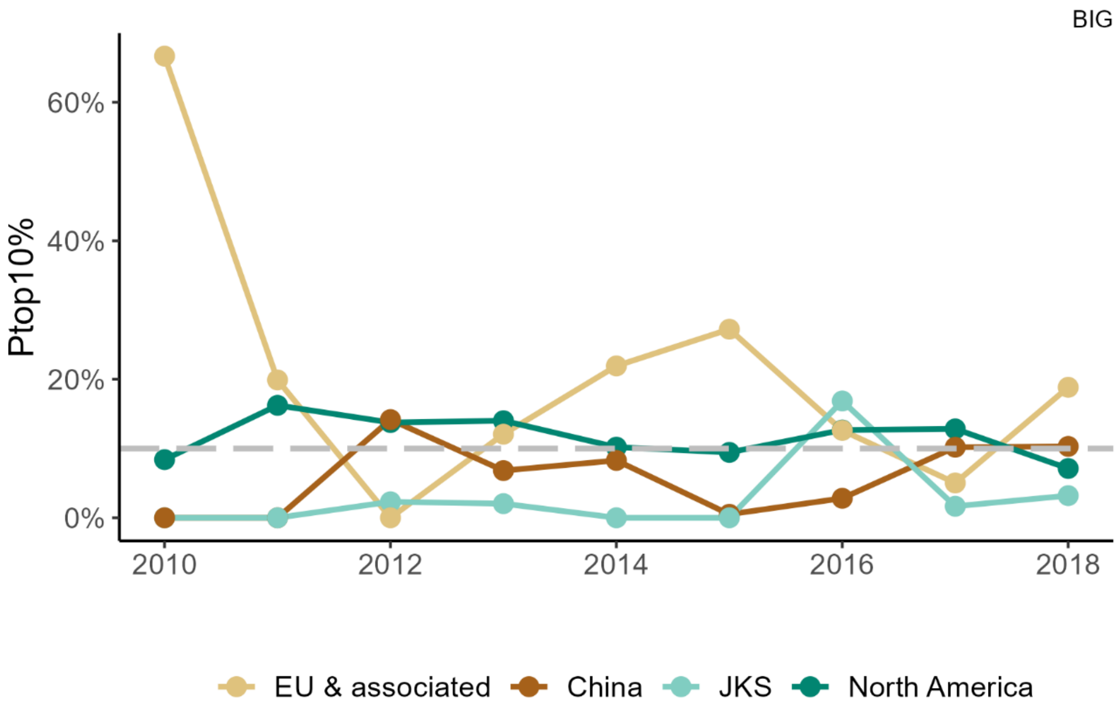

Figure 4. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.1.2 Organizations

Table 5 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

There is a large variability in performance among the organizations in EU & associated with regard to cf and Ptop10%. It should be kept in mind, however, that the publication volumes are very small for these organizations, and it is therefore difficult to draw any firm conclusions.

Table 5. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	Jcf	Jtop25%	IntColl%
Uppsala University	16	11.4	0.94	9.3%	1.04	24.2%	68.8%
Karlsruhe Institute of Technology	14	7.0	0.84	16.2%	1.39	61.3%	42.9%
Technical University of Munich	10	6.9	2.23	53.7%	1.16	23.6%	30.0%
University of Tours	10	5.4	0.54	10.2%	1.06	29.1%	30.0%
University of Münster	9	5.4	0.93	12.0%	1.33	46.6%	55.6%
University of Ulm	9	3.7	1.28	30.1%	2.08	55.7%	22.2%
BMW Group	9	2.9	3.52	41.0%	1.78	68.8%	77.8%
Forschungszentrum Julich	8	2.8	1.27	5.6%	1.18	61.3%	75.0%
University of Picardy Jules Verne	8	2.2	0.37	0.0%	1.36	77.0%	62.5%
Chalmers University of Technology	8	1.8	0.28	0.0%	1.18	44.0%	87.5%
South China Normal University (CH)	99	83.0	0.81	4.8%	1.45	59.2%	19.2%
Kyoto University (JKS)	22	8.1	0.67	3.5%	1.20	43.2%	9.1%
Dalhousie University (NA)	146	122.6	0.65	3.1%	1.17	37.0%	41.8%

Regarding companies publishing in BIG, the four largest ones with respect to publication volume are Guangzhou Tinci Materials Technology (30) Samsung (28), 3M (24) and GM (13). We note that for the last three companies, the publishing is associated with the US branches, whereas the Guangzhou Tinci Materials Technology publishing is coming from China.

3.1.3 Bibliometric networks

The network in Figure 5 gives an overview of the author keywords used in the articles selected for the BIG subfield. Most research in the field thus far has focused on Li-ion batteries, clearly represented by the largest node in the center. On the left-hand side of the figure, in green and yellow clusters, keywords mostly associated with chemical engineering of the positive Li-ion electrode interface to the electrolyte are discerned. Typical electrode materials (such as $LiCoO_2$) and electrolyte components (especially the well-known fluorinated compounds) active at their interfaces are found here. On the bottom right-hand side in red, concepts primarily associated with the negative electrode interface to the electrolyte cluster. The “solid electrolyte interphase” is expectedly a major node here.

The networks in Figures 6 and 7 show the collaboration networks between countries and organizations within BIG, respectively. A relatively strong connection between North America and China can be observed, both in the country network and in the organization network, where most Chinese and North American organizations can be found to the left (Figure 7). One can note that there is a strong connection between Japanese and South Korean organizations. For Figure 7, most European organizations are found in the upper part of the network (light blue and purple).

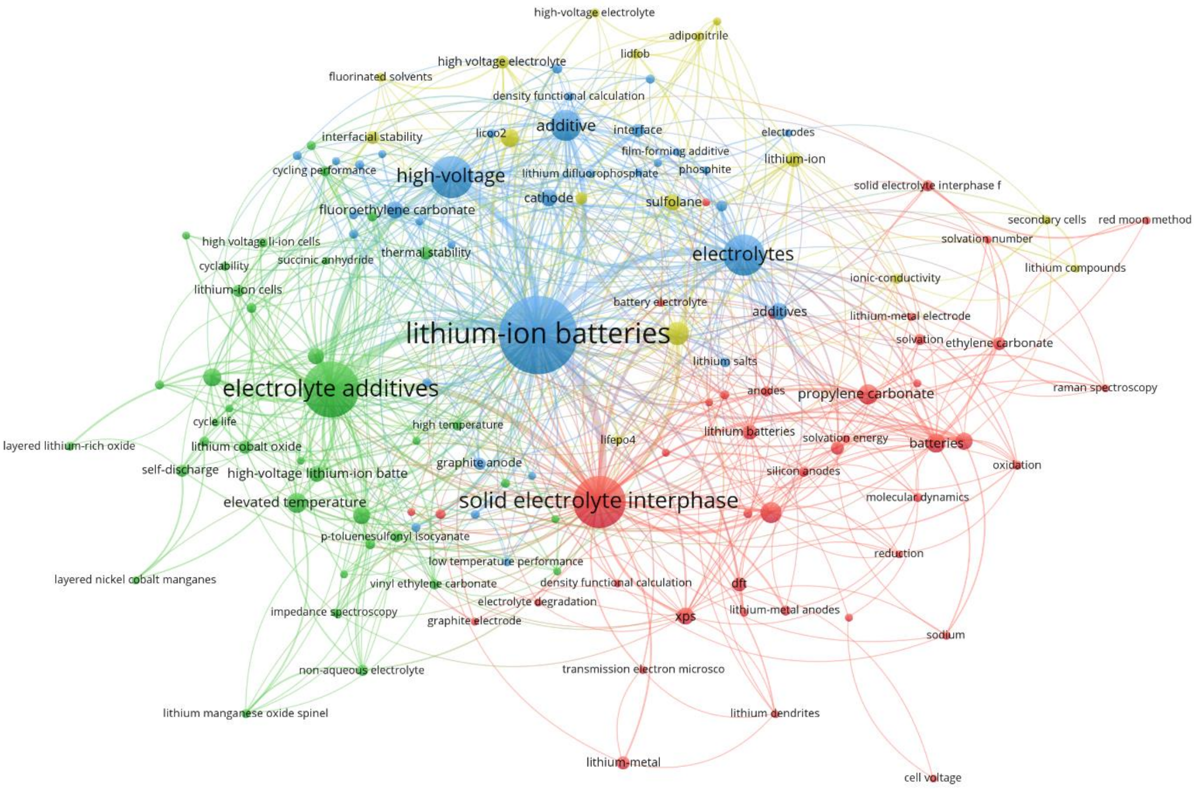

Figure 5. Author keyword co-occurrence network for BIG. Minimum node (author keyword) weight is set to 3.

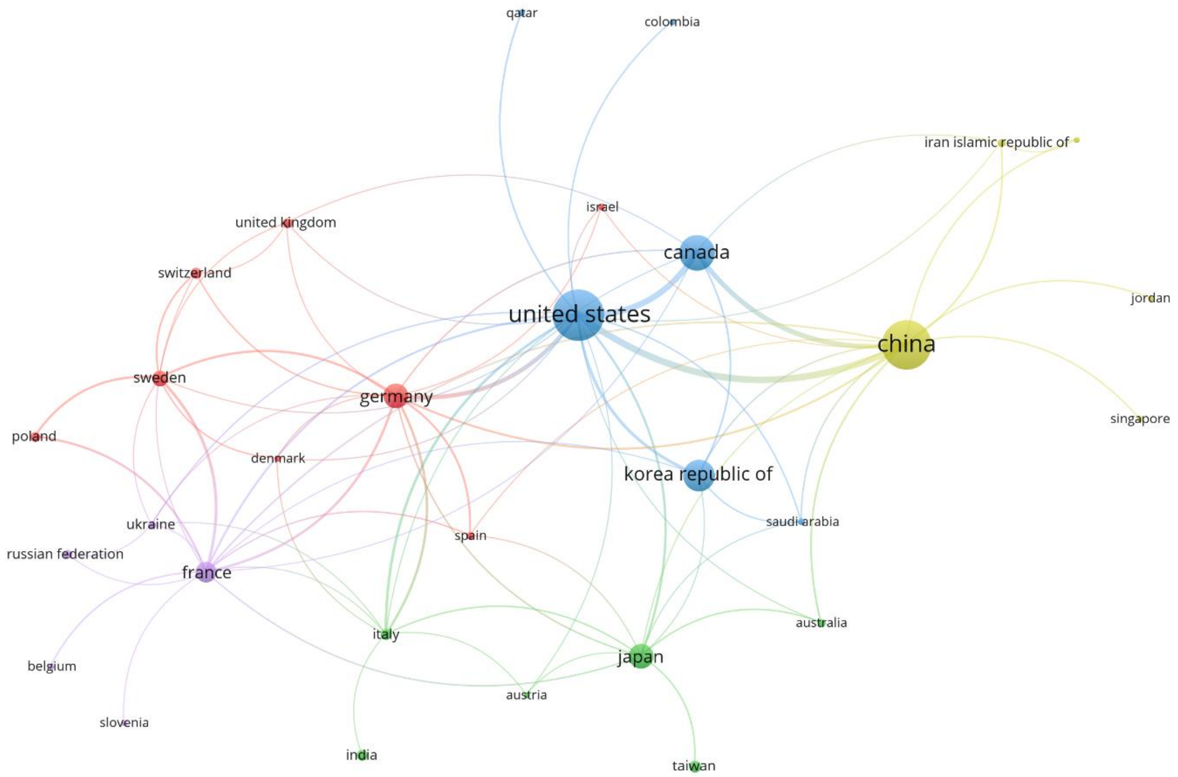

Figure 6. Country co-publishing network for BIG. Minimum node (country name) weight is set to 2.

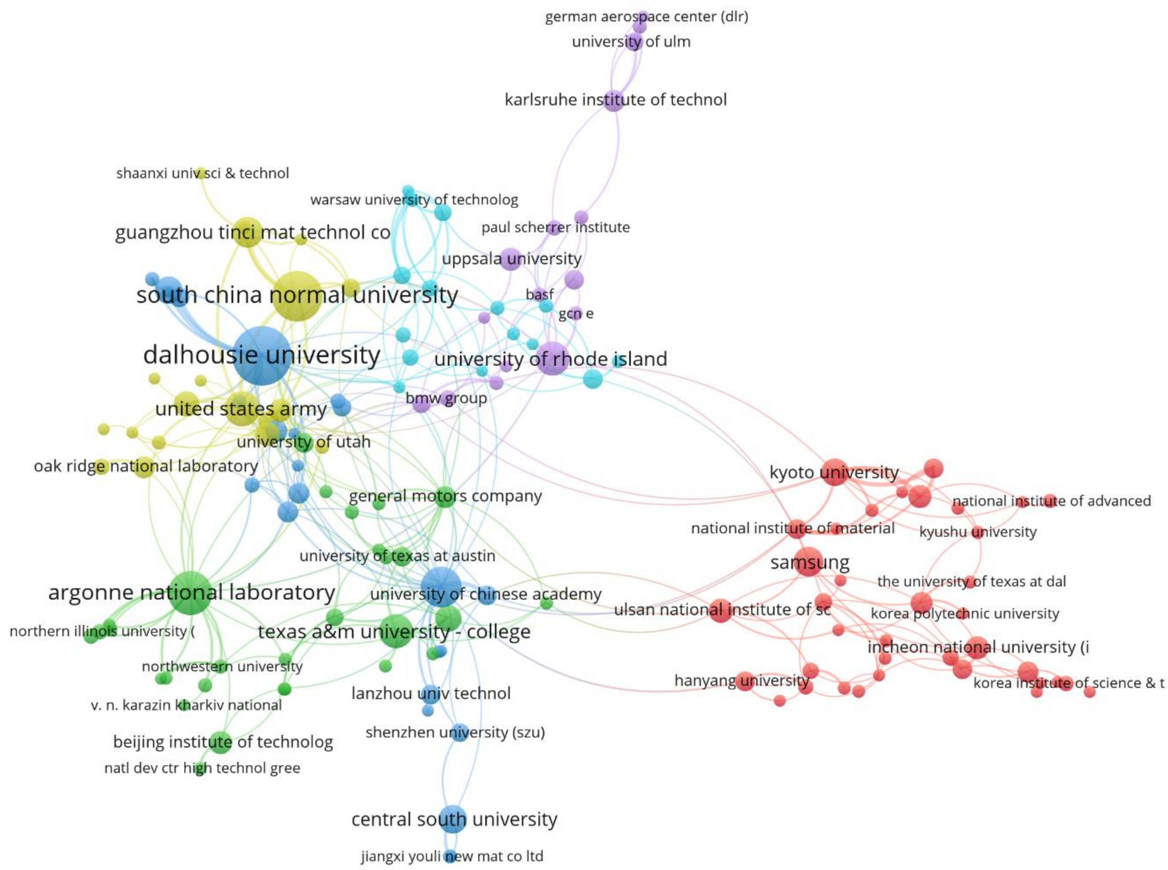

Figure 7. Organization co-publishing network for BIG. Minimum node (organization name) weight is set to 3.

3.2 Materials Acceleration Platform (MAP)

In this section, we give the results for MAP. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

3.2.1 Country/country aggregates

In Table 6, indicator values by country/country aggregate and for the whole publication period are given. MAP is clearly a very strong subfield for North America: regardless of citation impact indicator, North America has by far the best performance among the four units. China and JKS perform poorly for cf and Ptop10%, and China is lagging compared to some other subfields analyzed in this report.

Interestingly, MAP is growing for all four units from 2016 onwards (Figure 8). For cf and Ptop10% trends (Figures 9 and 10), EU & associated has caught up compared to US in the later years and is relatively strong compared to China. The gap in Ptop10% between North America and China is considerably less year 2018 compared to the earlier years.

Table 6. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	559	420.4	0.99	11.5%	1.36	41.3%	56.7%
China	228	160.4	0.63	4.8%	1.25	36.1%	52.6%
North America	848	699.1	1.27	12.8%	1.60	49.0%	38.3%
JKS	254	194.3	0.47	1.8%	1.16	31.8%	36.2%

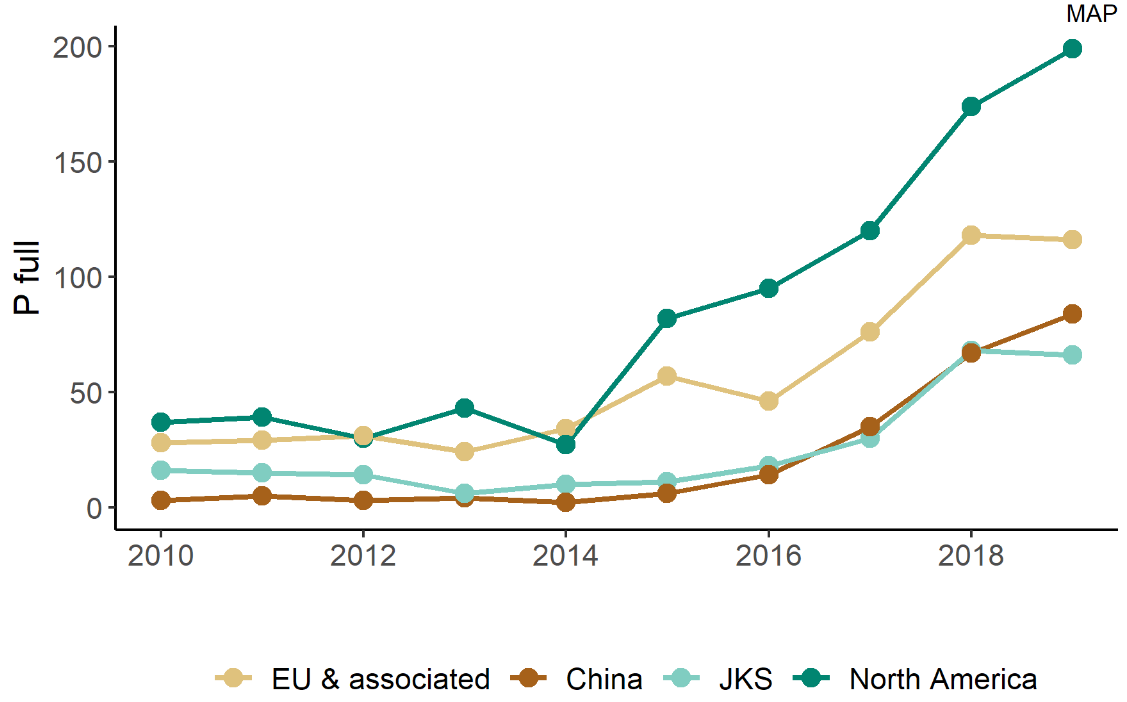

Figure 8. Publication volume (P full) development by country/country aggregate.

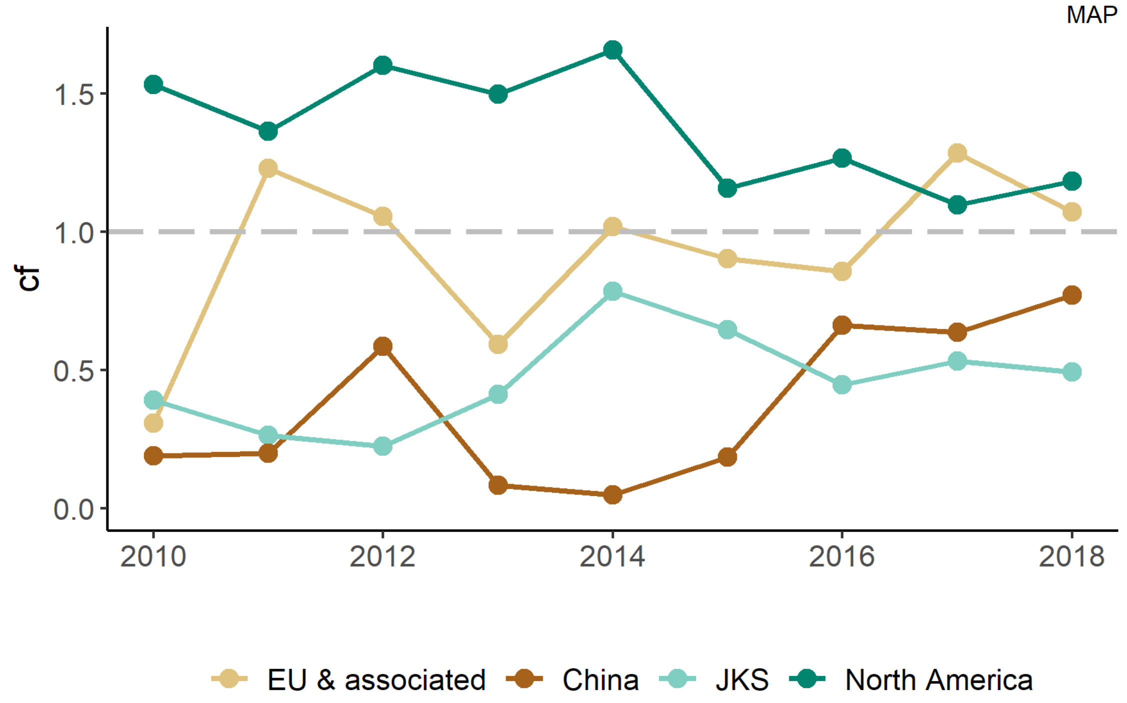

Figure 9. Publication-level citation impact (cf) development by country/country aggregate.

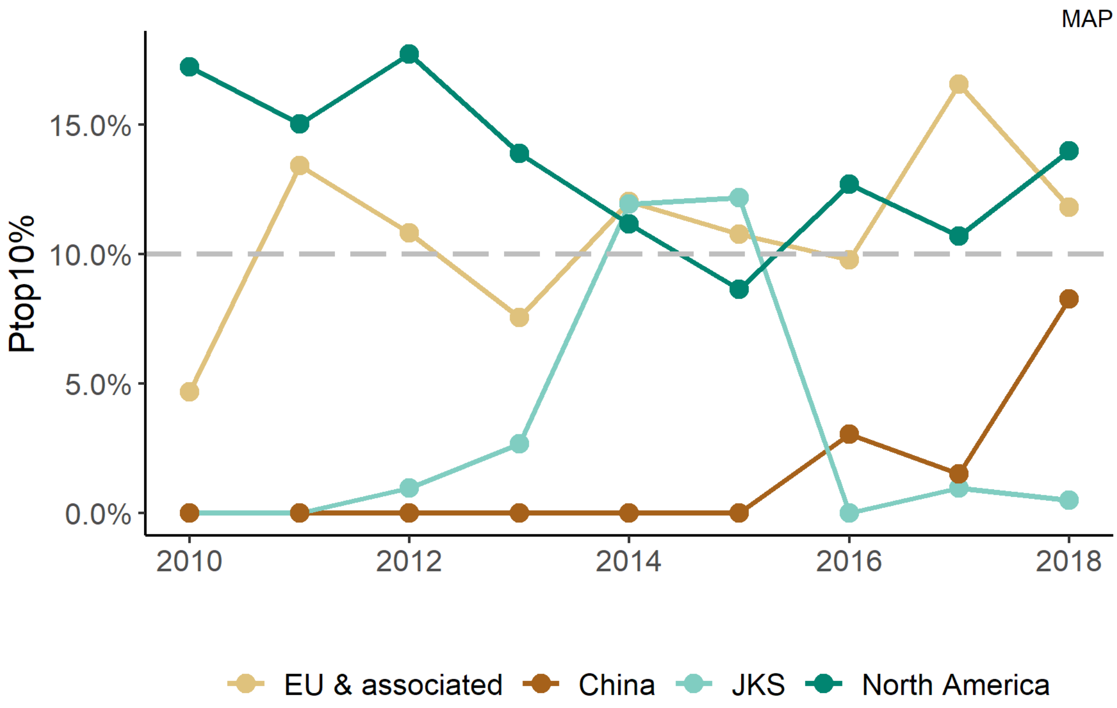

Figure 10. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.2.2 Organizations

Table 7 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

Among the 10 organizations from EU & associated and country origin, Germany and Switzerland dominate. There is a large variability in performance among these 10 organizations with regard to cf and Ptop10%. Technical University of Berlin has the highest values on the two indicators. Further, all 24 articles in which this organization has participated have been internationally co-authored (IntCollab% equal is to 100.0%). University of California, Berkeley has the highest number of articles (P full) and has also a strong performance regarding the citation impact indicators. Generally, EU & associated organizations have very high values on the two journal-level citation impact indicators, jcf and Jtop25%.

Table 7. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	Jcf	Jtop25%	IntColl%
Max Planck Society[6]	72	26.9	1.76	29.8%	1.61	58.1%	84.7%
University of Basel	49	28.0	1.45	16.4%	1.15	33.7%	73.5%
Ruhr-Universität Bochum	44	33.9	1.48	18.3%	1.14	38.0%	29.5%
Swiss Federal Institute of Technology Lausanne	32	20.2	1.05	21.1%	1.38	50.1%	62.5%
Bar-Ilan University	30	25.6	0.29	0.0%	1.29	31.3%	20.0%
ETH Zurich	29	14.9	1.93	20.3%	2.40	57.2%	69.0%
Technical University of Berlin	24	7.7	4.27	65.4%	1.79	67.8%	100.0%
Technical University of Denmark	18	13.4	2.44	28.5%	1.95	59.7%	38.9%
Université Catholique de Louvain	18	6.1	1.24	6.3%	1.10	32.5%	83.3%
Free University of Brussels	17	8.5	0.26	1.8%	1.25	43.4%	82.4%
University of California, Berkeley (NA)	78	25.5	2.23	15.5%	1.64	49.9%	24.4%
Chinese Academy of Sciences (CH)	46	23.5	0.61	3.6%	0.94	25.8%	28.3%
National Institute of Materials Science (JKS)	53	20.8	0.50	2.0%	0.99	22.7%	22.6%

For MAP, the company publication volumes are relatively low. A notable exception is Citrine Informatics with 14 publications. This company focuses on AI in relation to material development.

3.2.3 Bibliometric networks

The network in Figure 11 gives an overview of the author keywords used in the articles selected for the MAP subfield. It is quite evident from the figure that there is a strong focus on computer science in MAP, an article set that is composed of one level-2 cluster. Several keywords, like "machine learning" and "high-throughput experimentation", are connected to AI-related subjects. This in line with the outlined vision in the BATTERY 2030+ roadmap, a vision inspired by the route of pharma industry in drug discovery processes where state-of-the-art computational schemes are coupled with combinatorial material screening methodologies. The clusters are strongly nested and likely reflect that MAP is currently undergoing a strong exploratory phase in which large number of ideas are combined and evaluated.

The networks in Figures 12 and 13 show the collaboration networks between countries and organizations within MAP, respectively. As is clear from Figure 12, US is dominating MAP. Relative to what one may expect, China has rather low publication volume. For Germany and Japan, the opposite is the case.

[6] We use "Max Planck Society" as an abbreviation for "Max Planck Society for the Advancement of Science".

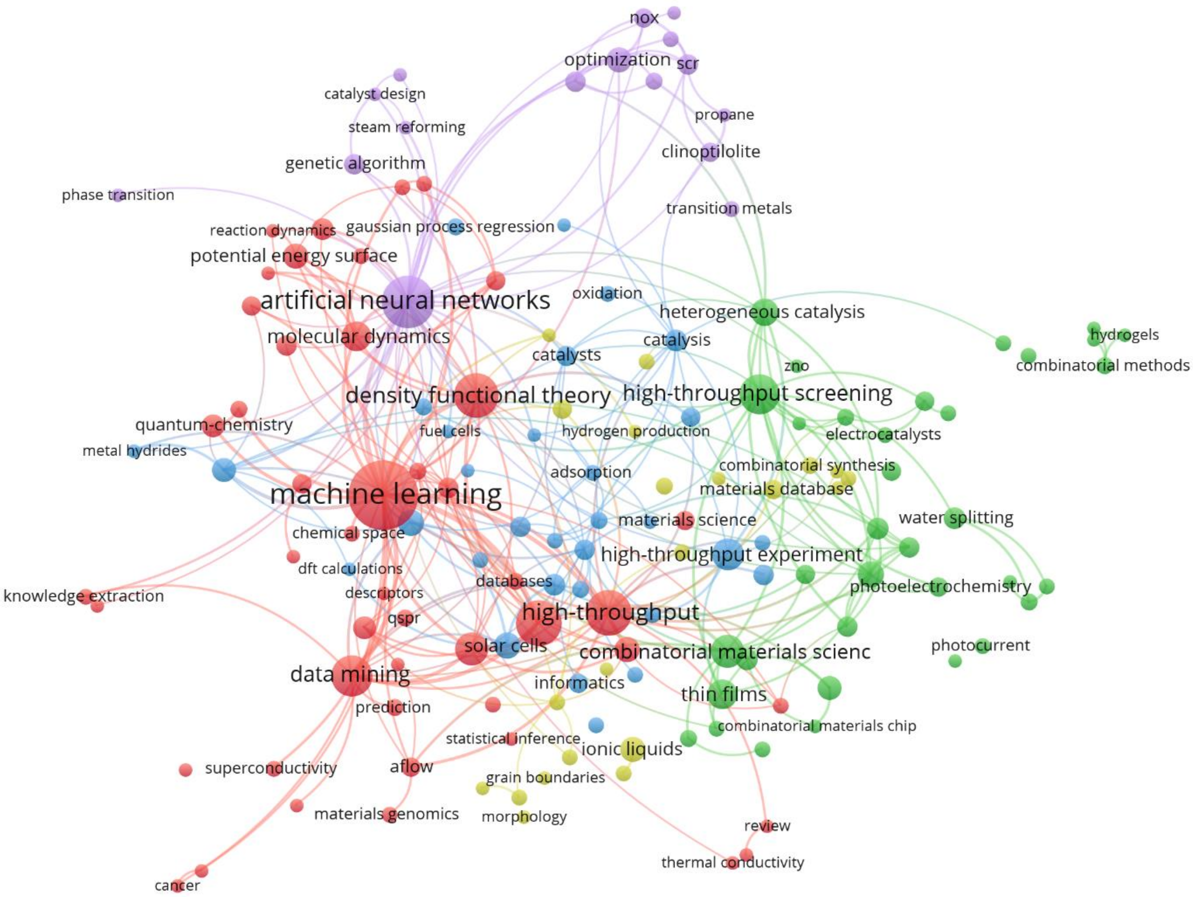

Figure 11. Author keyword co-occurrence network for MAP. Minimum node (author keyword) weight is set to 3.

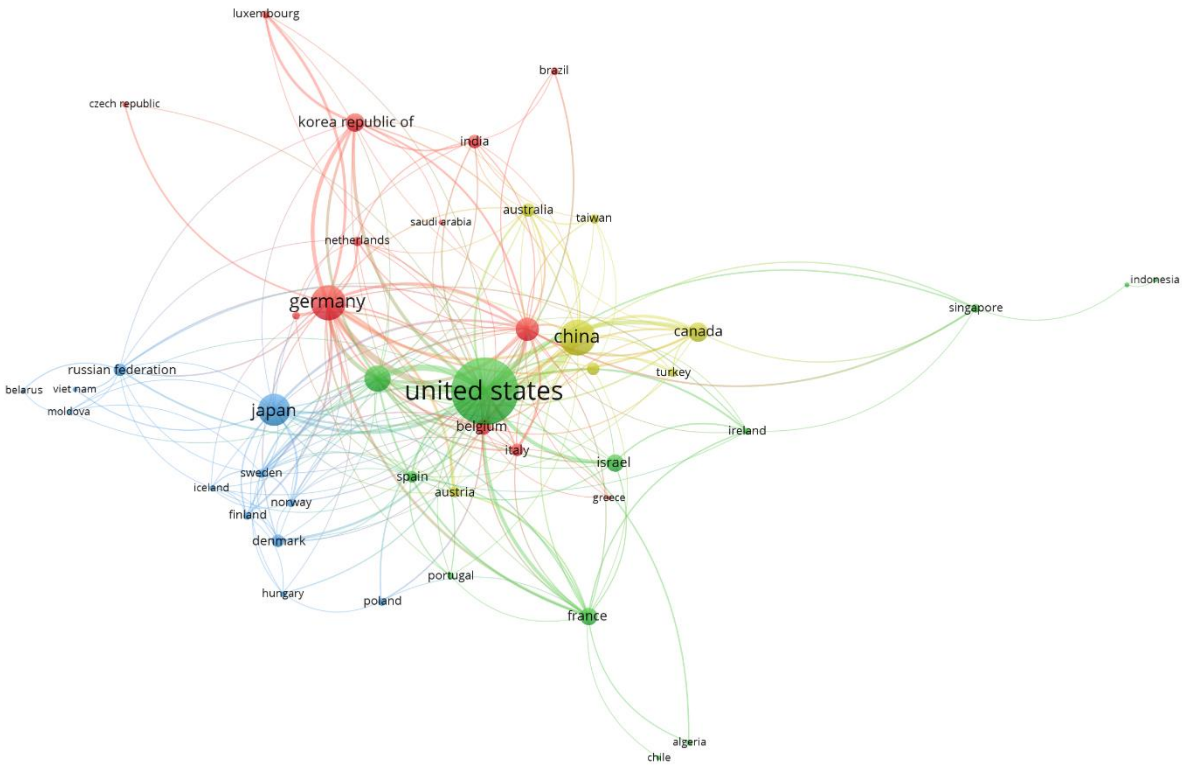

Figure 12. Country co-publishing network for MAP. Minimum node (country name) weight is set to 2.

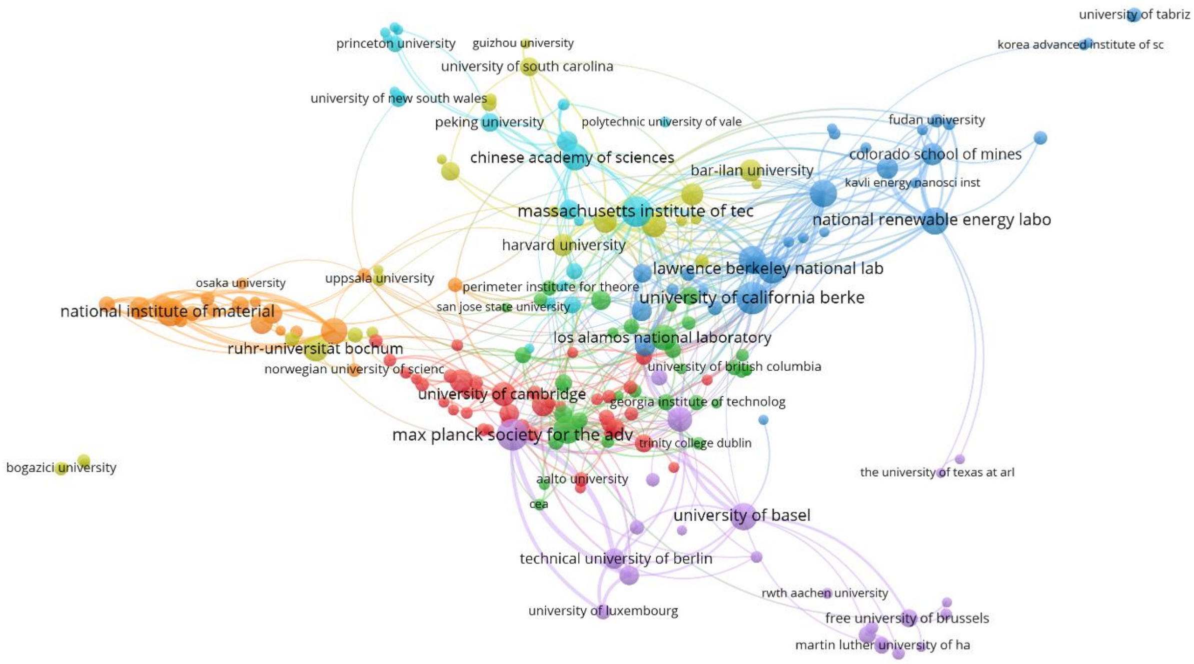

Figure 13. Organization co-publishing network for MAP. Minimum node (organization name) weight is set to 4.

3.3 Recyclability

In this section, we give the results for Recyclability. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

3.3.1 Country/country aggregates

In Table 8, indicator values by country/country aggregate and for the whole publication period are given. North America is surprisingly weak regarding the publication-level citation impact indicators, cf and Ptop10%, compared to several other subfields. China has by far the best performance for these two indicators.

As for several other subfields, China has a remarkable increase in publication volume in later years (Figure 14). By contrast, the volume values are quite stable for JKS. For both cf and Ptop10%, EU & associated has possibly negative trends (Figures 15 and 16).

Table 8. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	273	243.1	1.07	10.6%	1.31	41.3%	34.4%
China	374	343.8	1.29	14.9%	1.24	43.9%	21.4%
North America	231	184.2	1.01	9.6%	1.56	55.5%	35.9%
JKS	96	84.6	0.46	1.8%	1.00	27.9%	30.2%

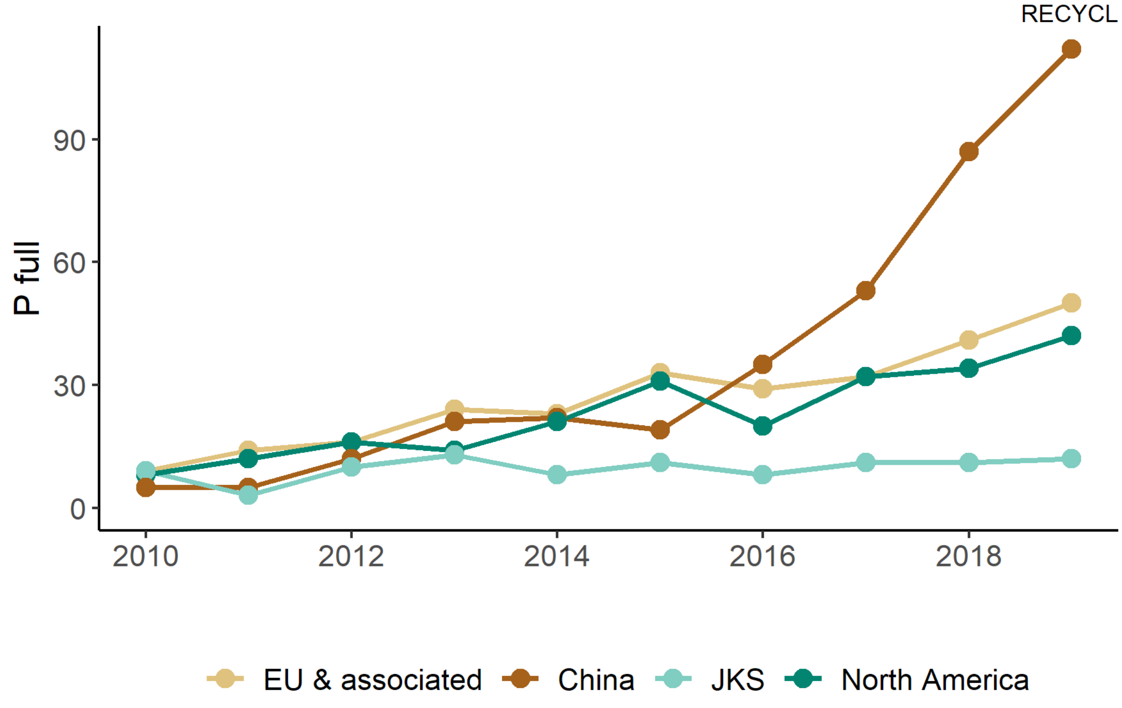

Figure 14. Publication volume (P full) development by country/country aggregate.

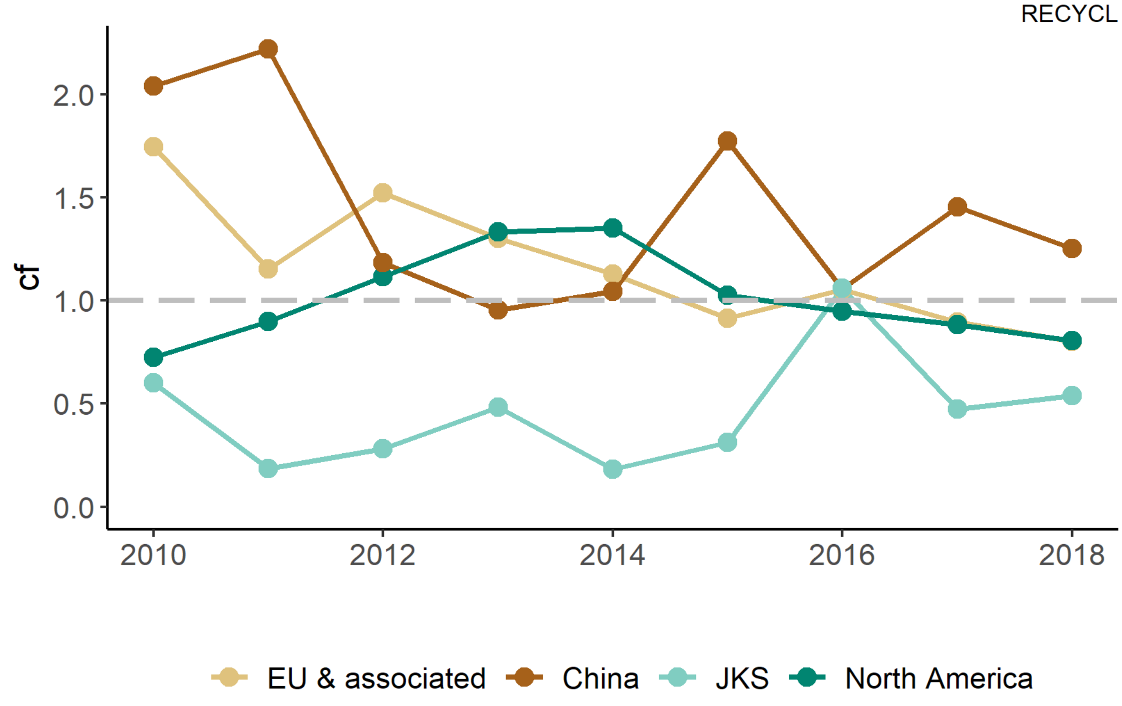

Figure 15. Publication-level citation impact (cf) development by country/country aggregate.

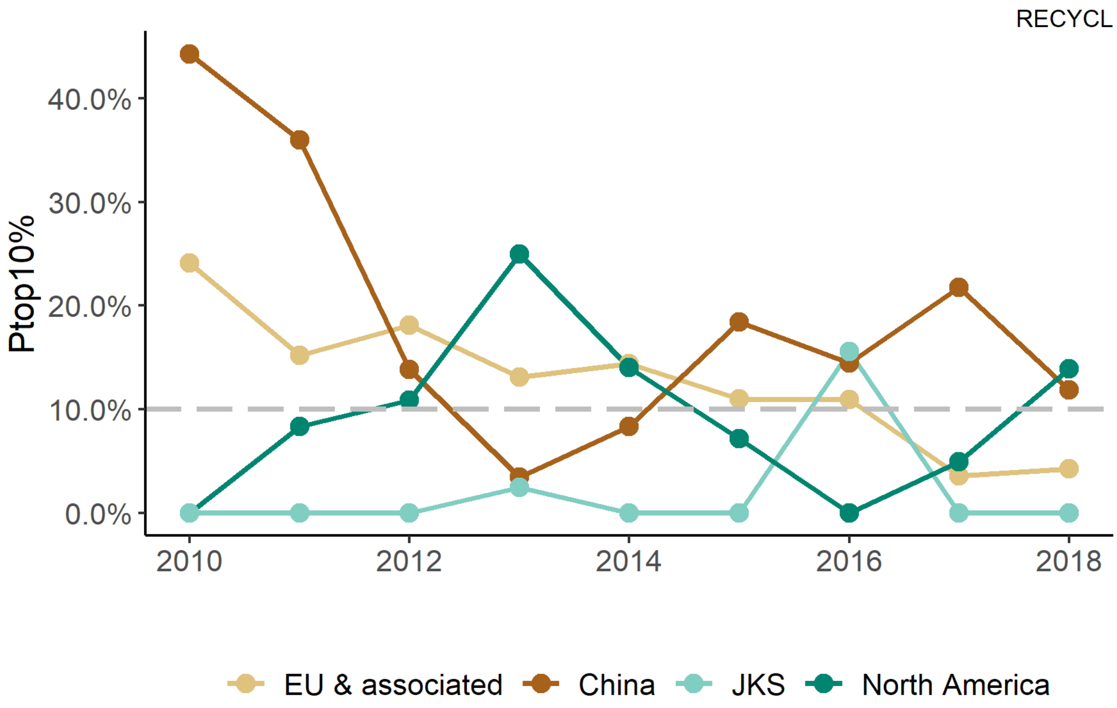

Figure 16. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.3.2 Organizations

Table 9 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

EU & associated has relatively few articles per organization. Among these organizations, Karlsruhe Institute of Technology has the highest number of articles, 20. Note that Chinese Academy of Sciences is not the Chinese organization with the highest number of articles (which is usually the case). Instead, Tsinghua University has the highest number, 55. There is a large variability in performance among the 13 organizations with regard to cf and Ptop10%. However, the values are uncertain due to small publication volumes.

Table 9. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
Karlsruhe Institute of Technology	20	13.3	1.22	12.3%	1.19	31.3%	20.0%
University of Lisbon	19	15.5	0.46	0.0%	1.35	46.9%	15.8%
Free University of Brussels	13	8.5	0.81	3.6%	1.15	26.7%	53.8%
Chalmers University of Technology	12	10.8	0.65	8.9%	1.40	46.6%	16.7%
Norwegian University of Science and Technology	12	8.6	3.85	48.2%	1.94	46.3%	41.7%
Aalto University	11	8.9	0.79	0.0%	1.23	47.4%	54.5%
University of Coimbra	11	8.1	1.29	20.0%	1.32	36.9%	36.4%
Sapienza University of Rome	9	7.3	1.04	0.0%	1.19	38.2%	33.3%
RWTH Aachen University	8	5.9	0.86	8.2%	0.97	30.6%	12.5%
European Commission	7	3.3	3.29	45.2%	1.25	36.0%	85.7%
Argonne National Laboratory (NA)	23	9.6	2.06	39.1%	2.16	74.2%	65.2%
Tsinghua University (CH)	55	42.4	1.46	10.8%	1.42	53.7%	32.7%
Korea Inst Geosci & Mineral Resources (JKS)	20	12.3	0.63	0.0%	1.20	42.9%	50.0%

For Recyclability, the company publication volumes are relatively low. The only exception company is Ford Motor Company with 9 publications.

3.3.3 Bibliometric networks

The network in Figure 17 gives an overview of the author keywords used in the articles selected for the Recyclability subfield. The network is clearly separated into two themes, one dealing with aspects of electric vehicles, the other with more chemistry- and process-oriented aspects of battery recycling. These two themes are bridged by the node lithium-ion batteries. The label of the largest green node, “recyclability”, is not shown.

The networks in Figures 18 and 19 show the collaboration networks between countries and organizations within Recyclability, respectively. In Figure 18, a strong collaboration link is visible between China and US. The organization network within Recyclability (Figure 19) is more disconnected compared to the corresponding networks for the other subfields. Therefore, we choose to show the full disconnected network, in which about 24% of the nodes are not connected to main network. Possible causes for the disconnectedness are a narrow cluster selection, and thereby a smaller article set, and that the cluster selection seems to represent two quite distinct themes in battery recycling (cf. the comments on the author keyword co-occurrence network).

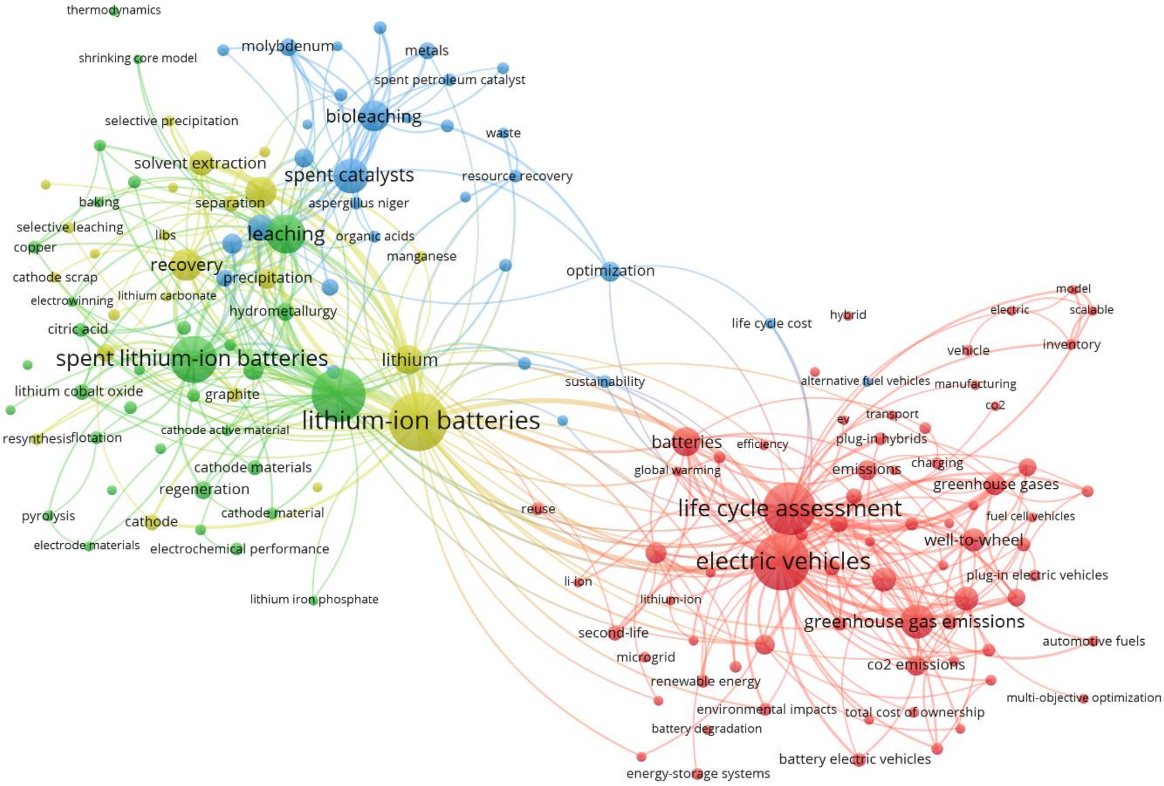

Figure 17. Author keyword co-occurrence network for Recyclability. Minimum node (author keyword) weight is set to 4.

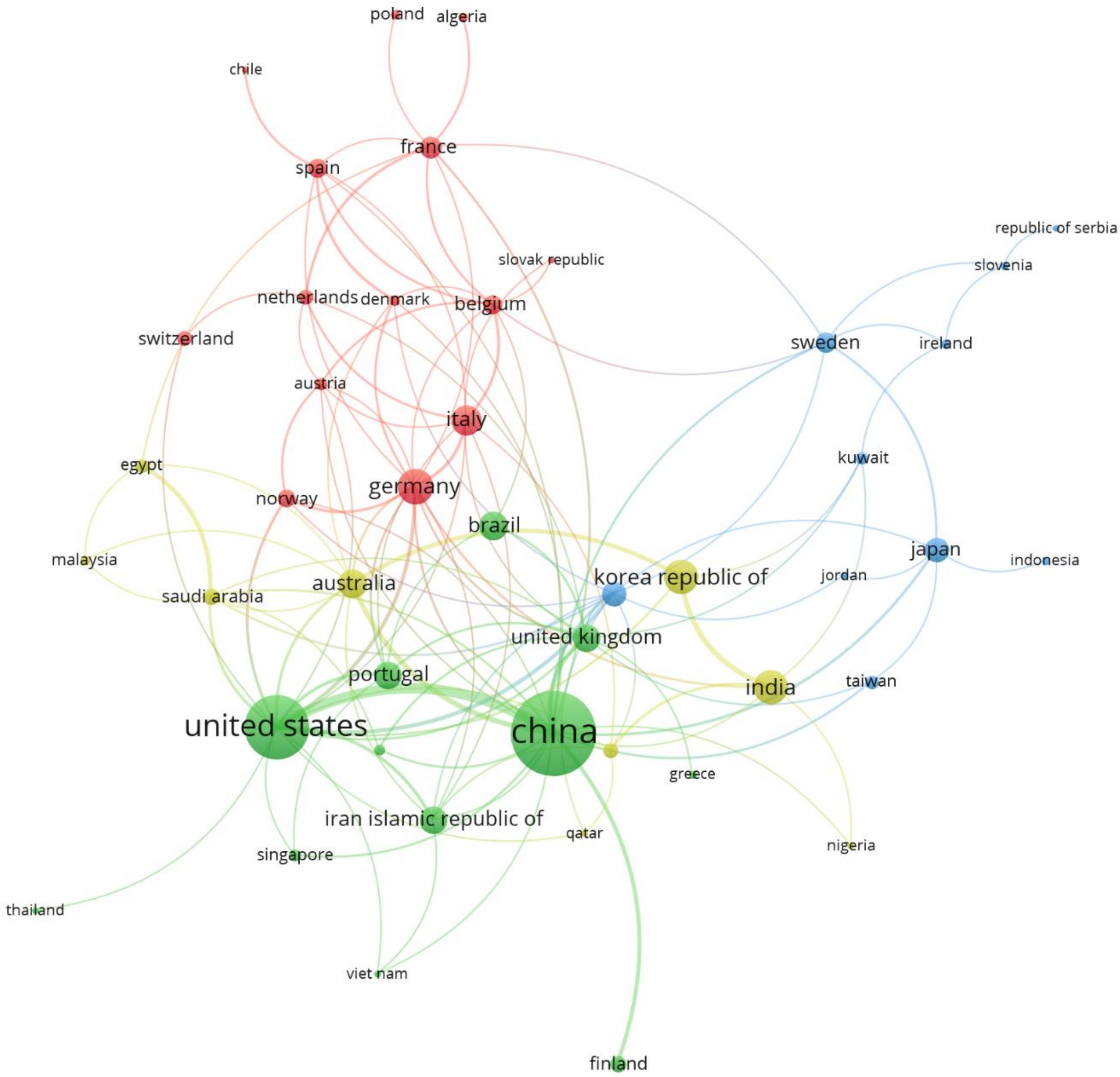

Figure 18. Country co-publishing network for Recyclability. Minimum node (country name) weight is set to 2.

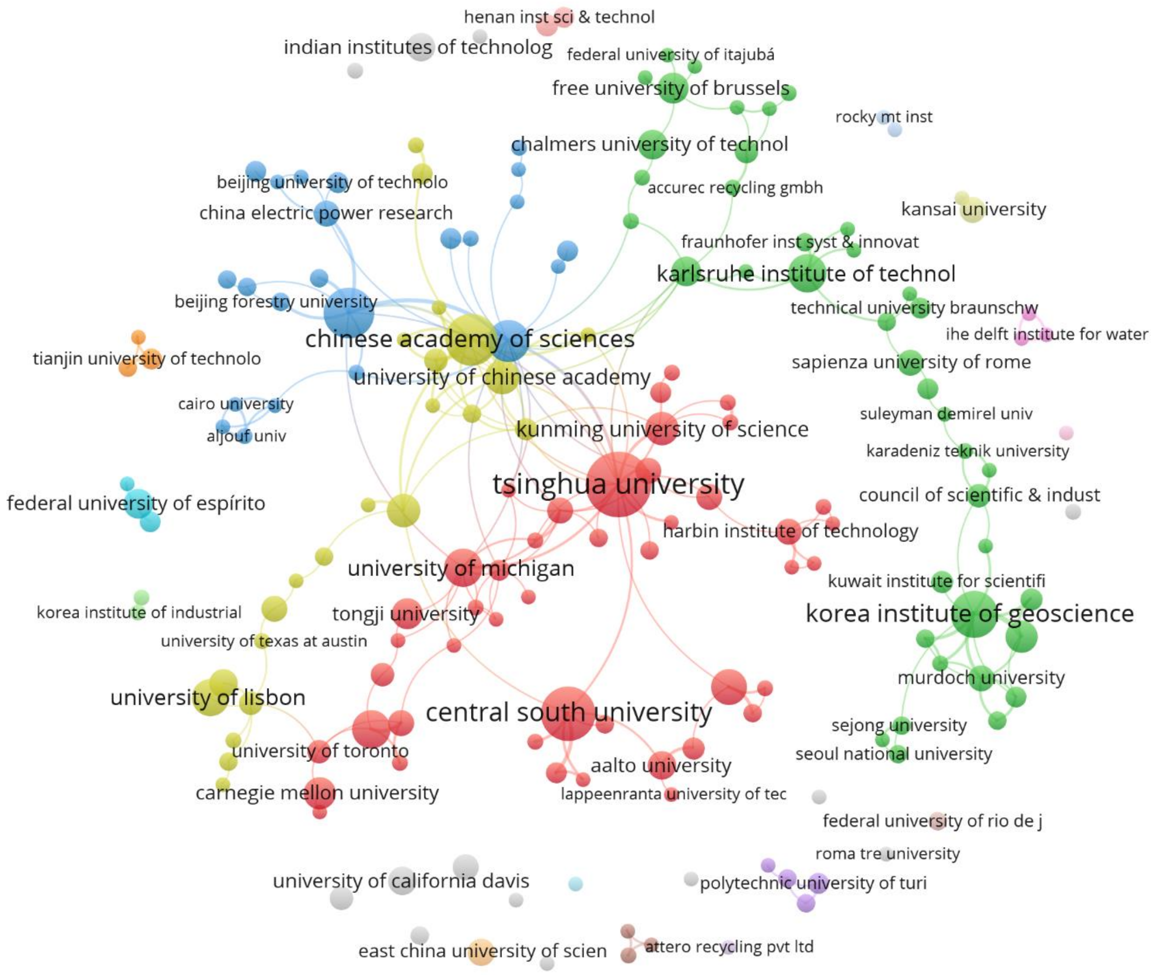

Figure 19. Organization co-publishing network for Recyclability. Minimum node (organization name) weight is set to 3. Note that it is the full disconnected network that is visualized.

3.4 Smart functionalities: Self-healing

In this section, we give the results for Self-healing. The section has three subsections. The first one, which concerns results for country/country aggregate, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

Note that the cluster selection for Self-healing is rather broad compared to the other five subfields. This is due to the areas deemed relevant by the subject experts. Therefore, this subfield comprises self-healing in a general sense, and not only self-healing directly to related battery research.

3.4.1 Country/country aggregates

In Table 10, indicator values by country/country aggregate and for the whole publication period are given. Regardless of citation impact indicator, EU & associated has the worst performance among the four units. For instance, the Ptop10% value is only 5.6%, which is almost 50% below world average. North America has the highest citation impact values, regardless of indicator.

For Self-healing, China has a remarkable increase in publication volume in later years (Figure 20). However, this is a general trend for Chinese research (Cao et al., 2020). Noteworthy is that JKS has a very good Ptop10% performance, and a good cf performance, for the last considered publication year, almost as good as the performance of North America (Figures 21 and 22).

Table 10. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	1,392	1207.6	0.74	5.6%	1.41	39.0%	38.2%
China	3,294	2946.8	1.06	10.9%	1.50	45.7%	24.1%
North America	1,608	1246.2	1.39	15.9%	1.90	57.9%	41.0%
JKS	1,103	892.5	0.96	10.3%	1.60	46.1%	36.2%

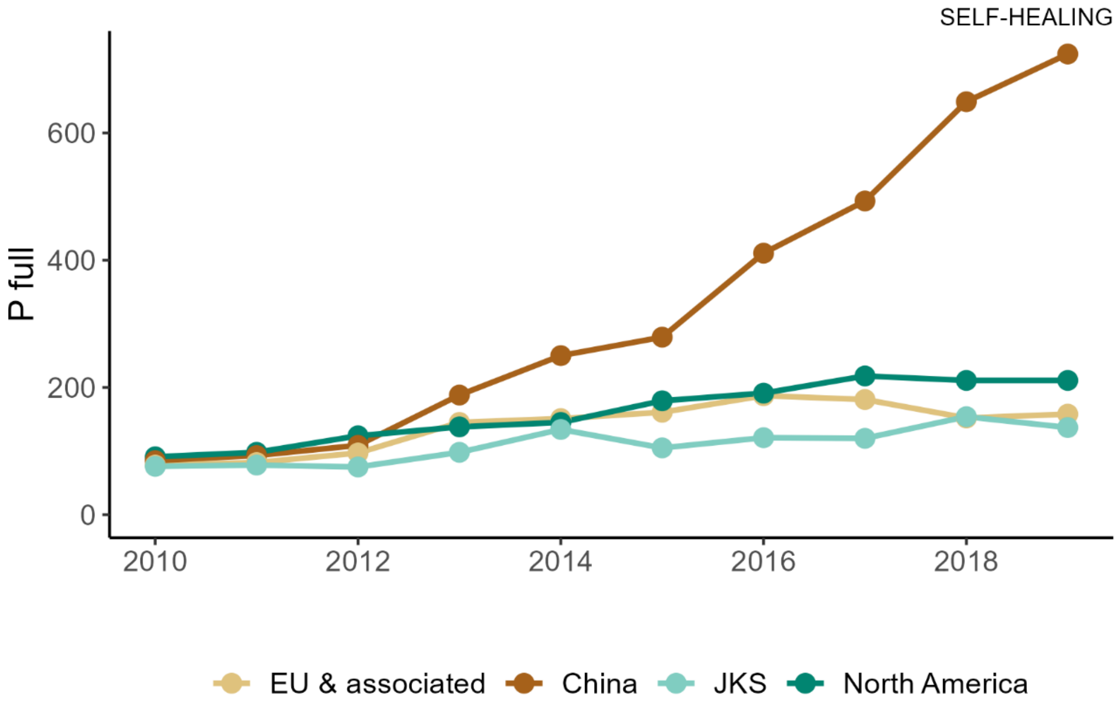

Figure 20. Publication volume (P full) development by country/country aggregate.

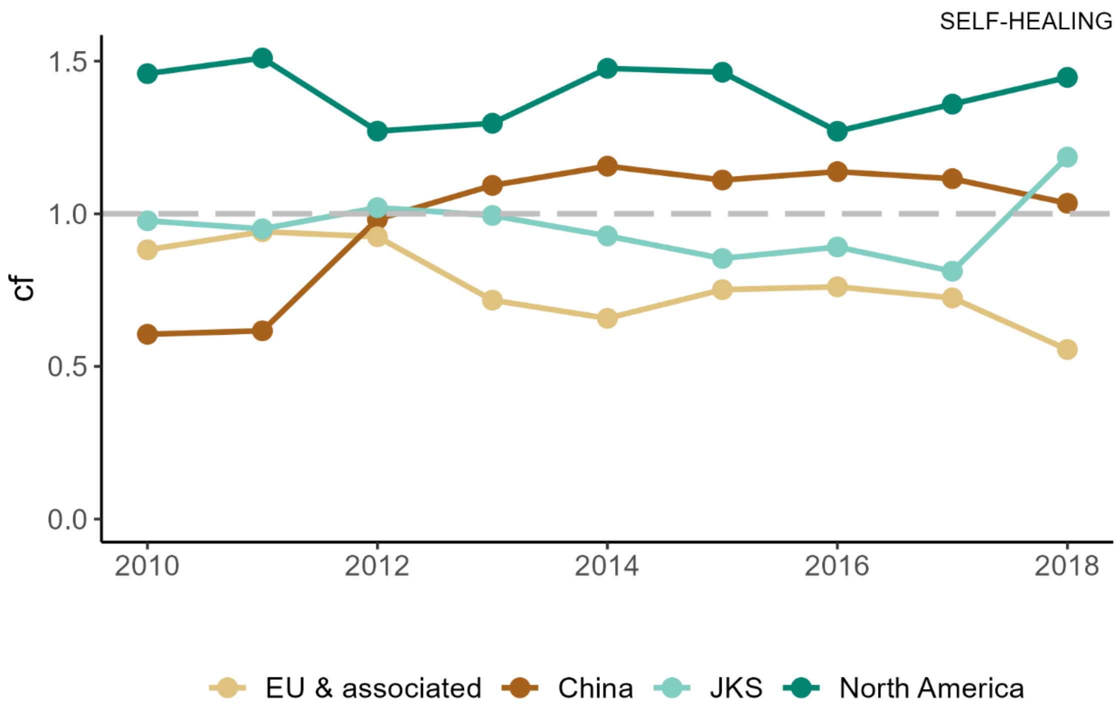

Figure 21. Publication-level citation impact (cf) development by country/country aggregate.

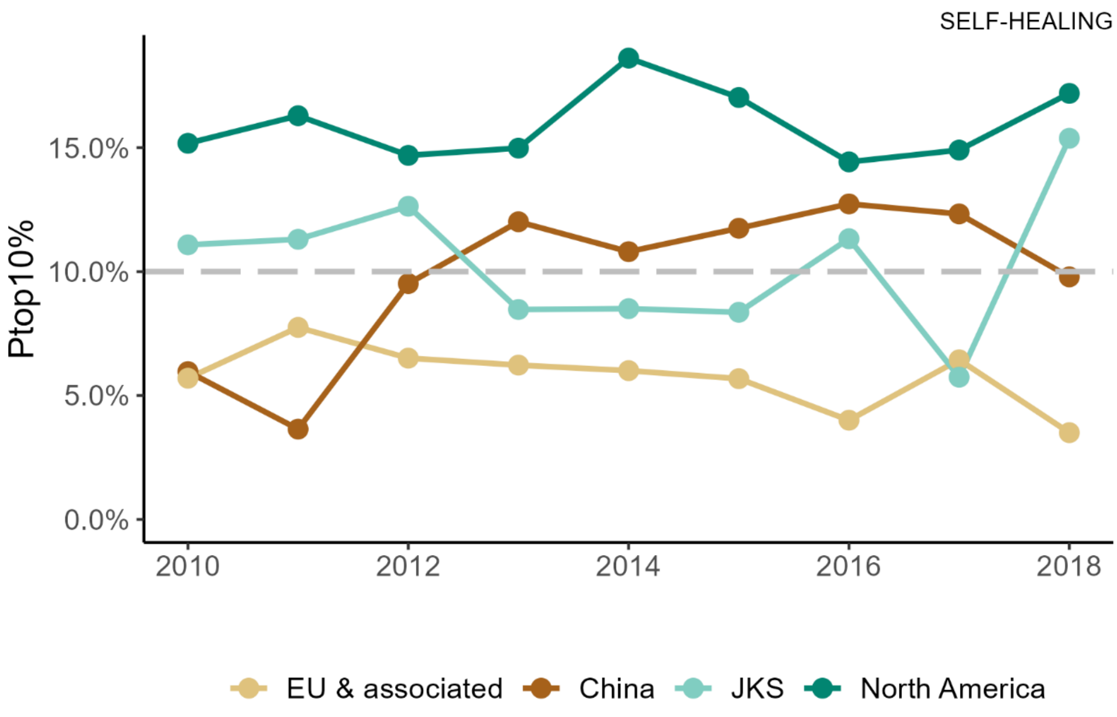

Figure 22. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.4.2 Organizations

Table 11 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

The poor EU & associated performance in cf and Ptop10% is indicated Table 11. However, the selected EU & associated organizations perform considerably better with respect to the two journal-level citation impact indicators, jcf and Jtop25%. This gap between publication-level and journal-level citation impact can be seen as problematic (publishing in good venues but not attracting much citations).

Table 11. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
University of Strasbourg	58	39.6	0.73	4.3%	1.71	50.9%	48.3%
Delft University of Technology	58	37.0	0.74	0.3%	1.46	42.1%	56.9%
University of Groningen	55	36.9	0.69	5.8%	1.66	47.0%	54.5%
Helmholtz-Zentrum Geesthacht Center for Materials and Coastal Research	47	37.7	0.74	7.9%	1.89	50.3%	12.8%
Istanbul Technical University	41	32.5	0.75	5.9%	1.26	42.1%	26.8%
KTH Royal Institute of Technology	35	28.9	0.40	0.0%	1.52	39.5%	28.6%
University of Jena	34	25.3	0.86	8.7%	1.40	31.4%	47.1%
Martin Luther University of Halle-Wittenberg	33	23.1	0.86	8.8%	1.23	29.7%	24.2%
Petru Poni Institute of Macromolecular Chemistry	31	24.1	0.21	0.0%	0.68	10.0%	19.4%
University of the Basque country	31	20.5	0.67	0.0%	1.20	23.0%	35.5%
University of Colorado Boulder (NA)	93	59.6	1.32	14.6%	1.78	59.7%	44.1%
Chinese Academy of Sciences (CH)	423	241.5	1.30	12.3%	1.70	50.6%	17.3%
Nanyang Technological University (JKS)	146	86.4	1.75	23.7%	2.02	59.6%	66.4%

For Self-healing, the companies with the highest publication volumes are Samsung (27) and General Motors Company (15).

3.4.3 Bibliometric networks

The network in Figure 23 gives an overview of the author keywords used in the articles selected for the Self-healing subfield. It is clear that this subfield is not primary dealing with battery research but is rather more oriented towards self-healing in soft materials research. However, there is an emerging bridge over to battery research (indicated by the blue cluster) in form of next-generation materials such as graphene and carbon nanotubes. Overall, the network also indicates some of the broader topical trends in the self-healing area, such as mechanical properties (often dealing with non-biomaterials), microcapsule delivery in pharmaceuticals and hydrogels.

The networks in Figures 24 and 25 show the collaboration networks between countries and organizations within Self-healing, respectively. Again, China and US are the most prominent nodes (Figure 24), with South Korea in collaborating neighborhood. Germany and France are the largest European countries. The Chinese presence is even more apparent in the organization network (Figure 25). However, this network is relatively unstructured and it is difficult so see a clear pattern.

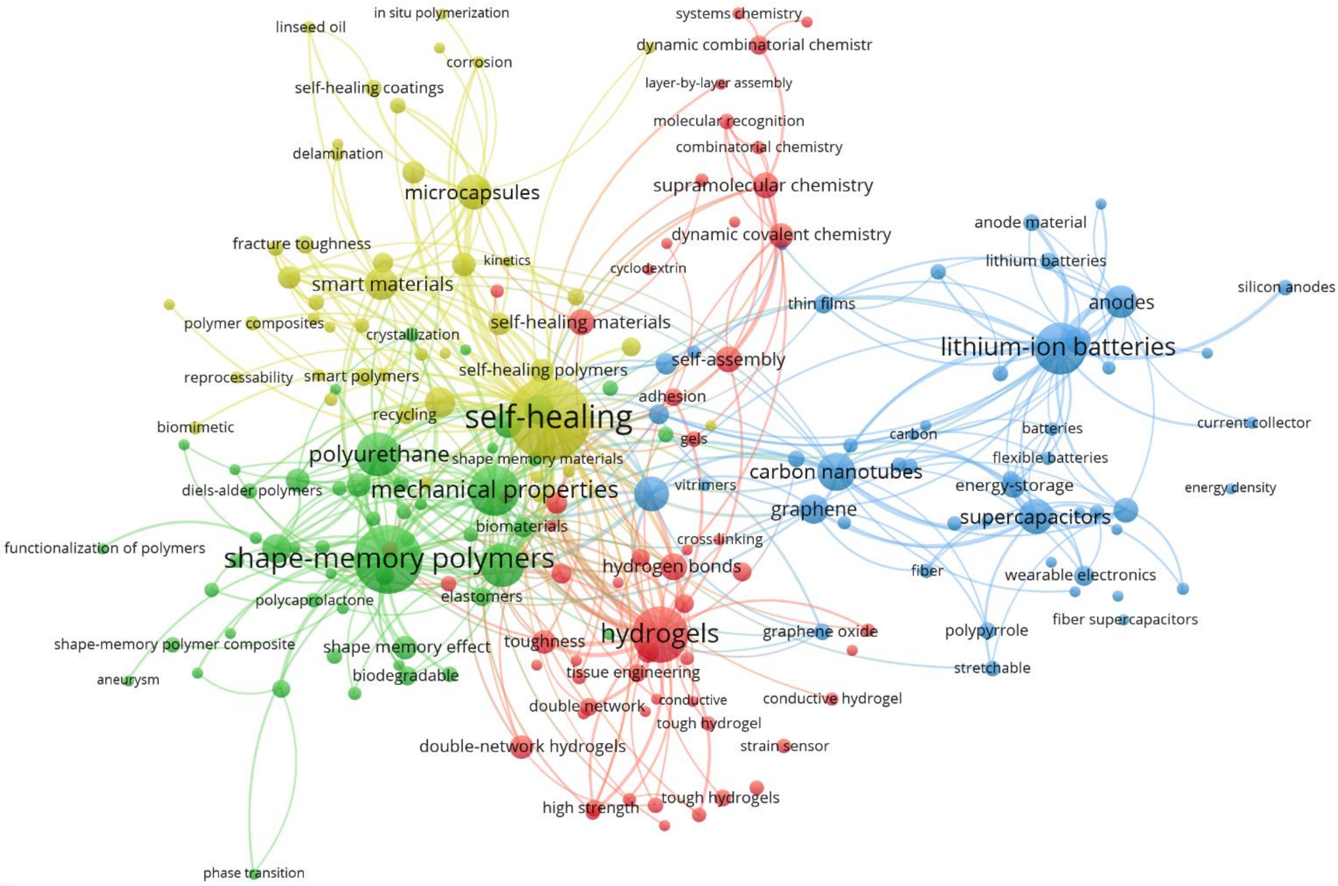

Figure 23. Author keyword co-occurrence network for Self-healing. Minimum node (author keyword) weight is set to 11.

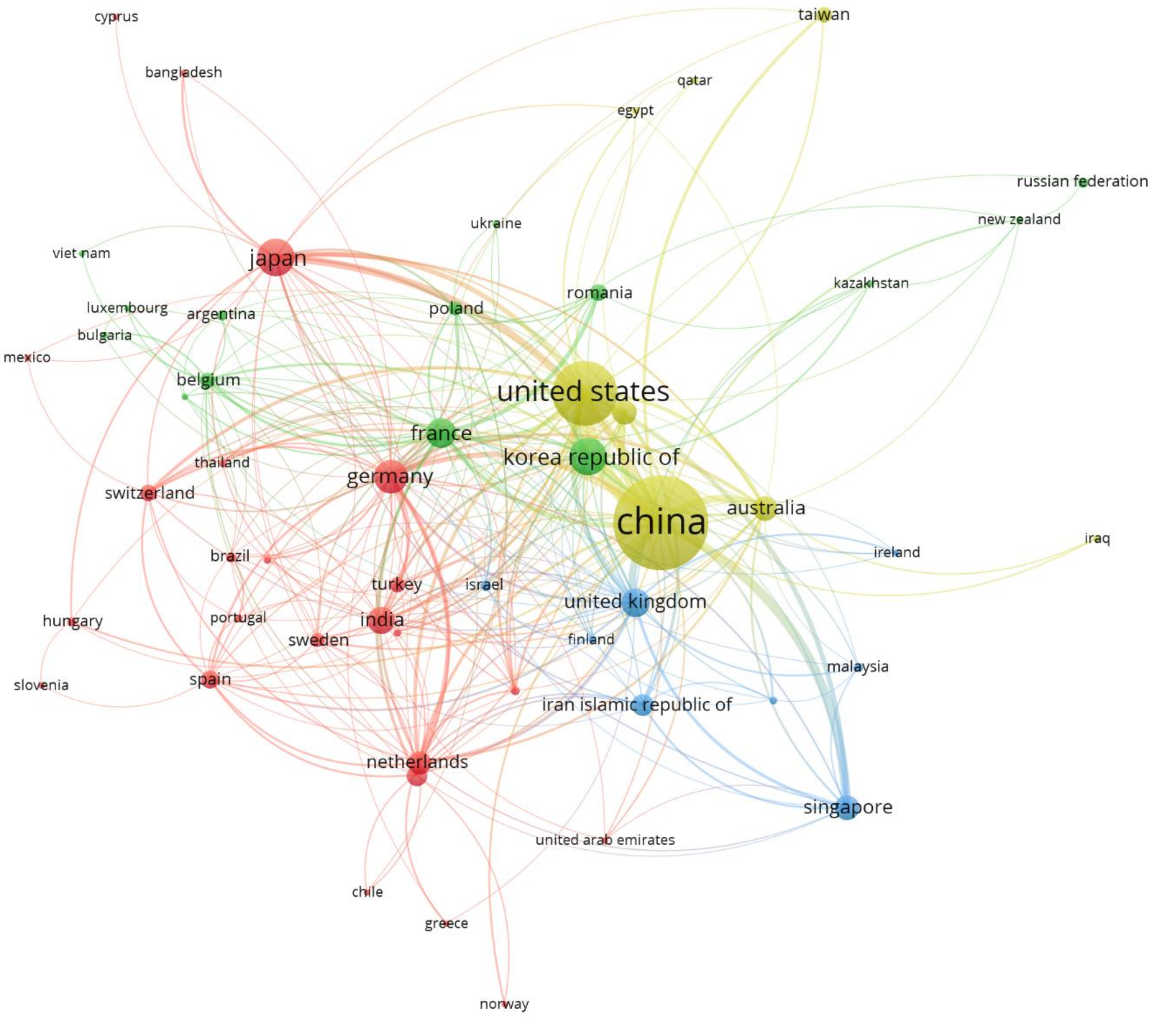

Figure 24. Country co-publishing network for Self-healing. Minimum node (country name) weight is set to 3.

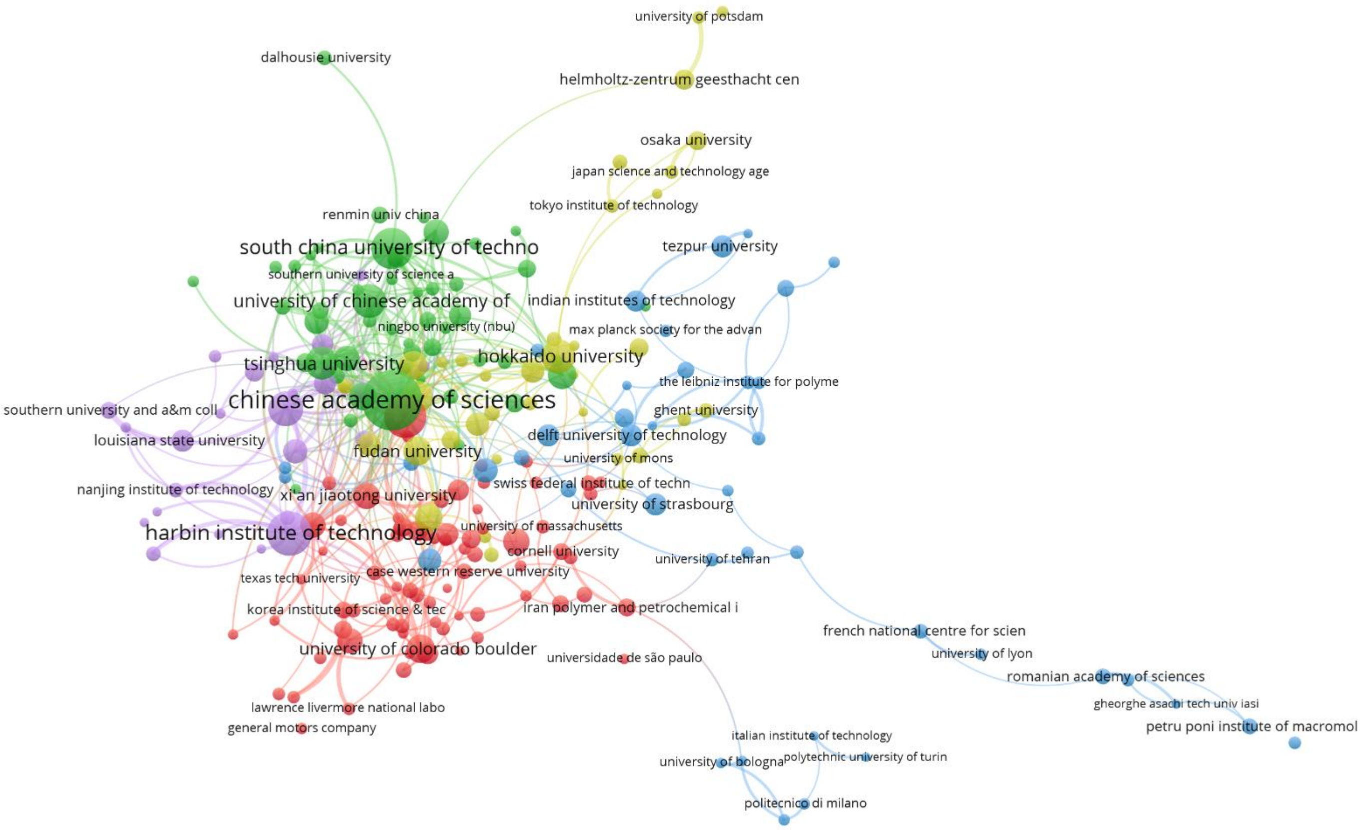

Figure 25. Organization co-publishing network for Self-healing. Minimum node (organization name) weight is set to 12.

3.5 Smart functionalities: Sensing

In this section, we give the results for Sensing. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

3.5.1 Country/country aggregates

In Table 12, indicator values by country/country aggregate and for the whole publication period are given. It is clear from the table that JKS is lagging, both in volume and in citation impact (regardless of indicator). EU & associated performs worse than China and North America for the publication-level citation impact indicators cf and Ptop10%. EU & associated performs better with respect to the two journal-level citation impact indicators, jcf and Jtop25%, compared to cf and Ptop10%.

As in several of the analyzed subfields, China has a remarkable increase in publication volume over time (Figure 26). There is a decrease in publication volume for North America in later years. This outcome is perhaps surprising. Note that China, EU & associated and North America have similar cf and Ptop10% performance for the last considered publication year, 2018 (Figures 27 and 28).

Table 12. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	557	476.2	0.95	8.8%	1.31	48.0%	34.8%
China	1,338	1184.6	1.08	11.0%	1.19	42.1%	27.5%
North America	727	575.3	1.07	11.4%	1.49	60.8%	39.9%
JKS	256	206.7	0.73	6.2%	1.10	36.5%	37.9%

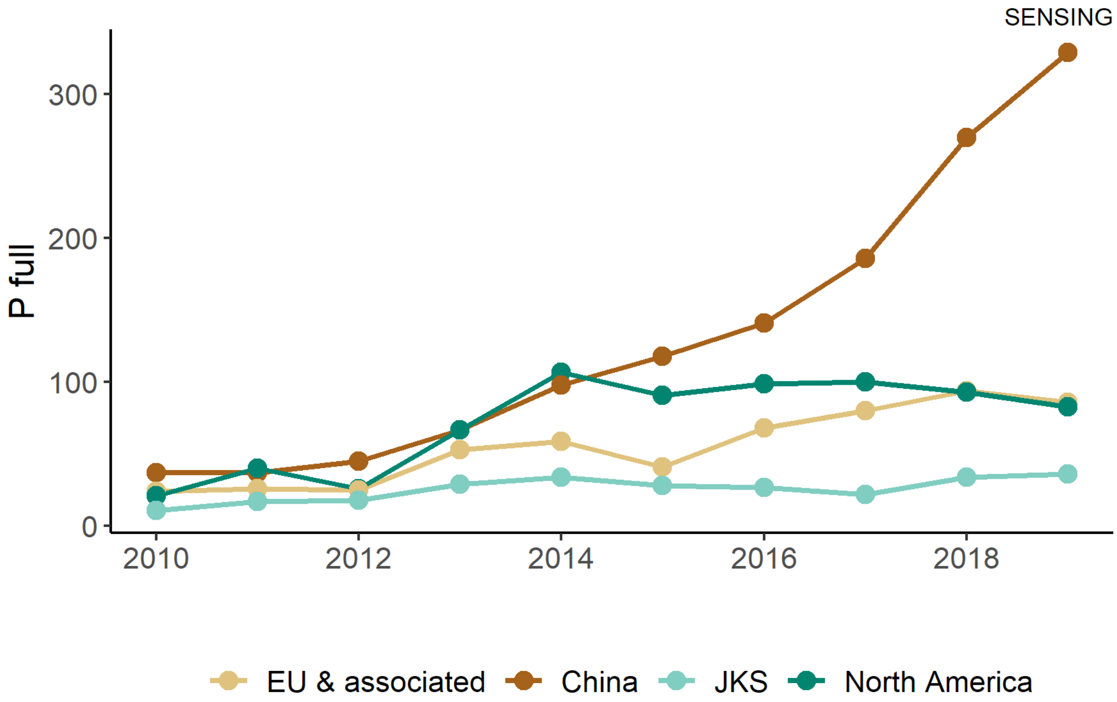

Figure 26. Publication volume (P full) development by country/country aggregate.

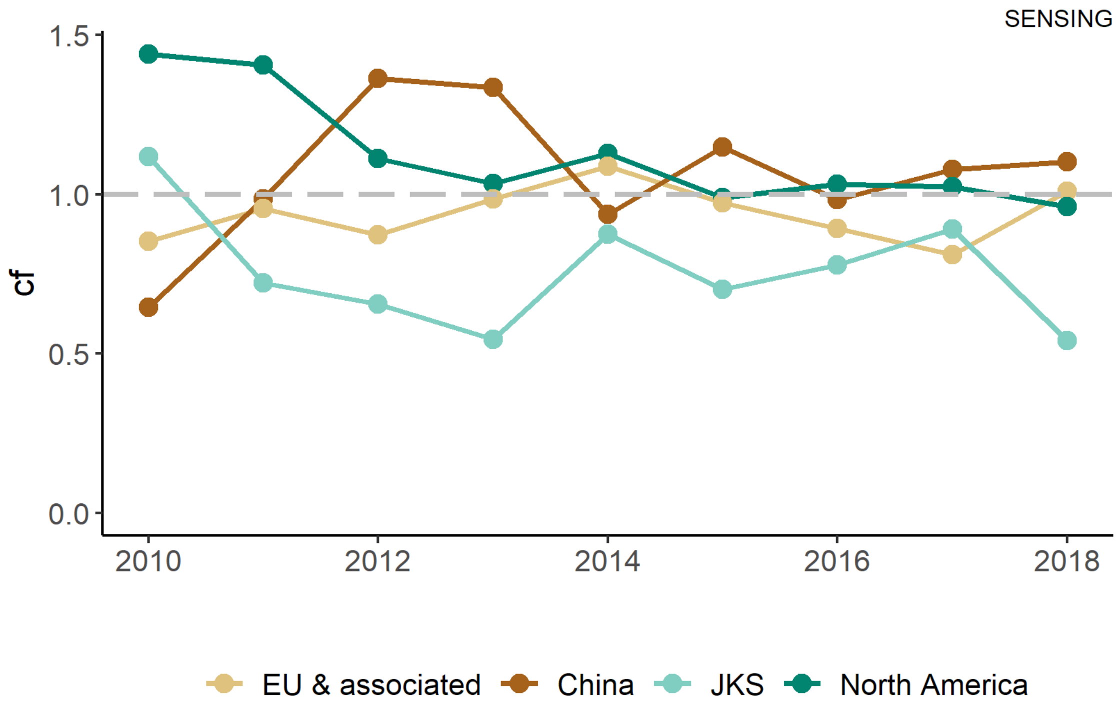

Figure 27. Publication-level citation impact (cf) development by country/country aggregate.

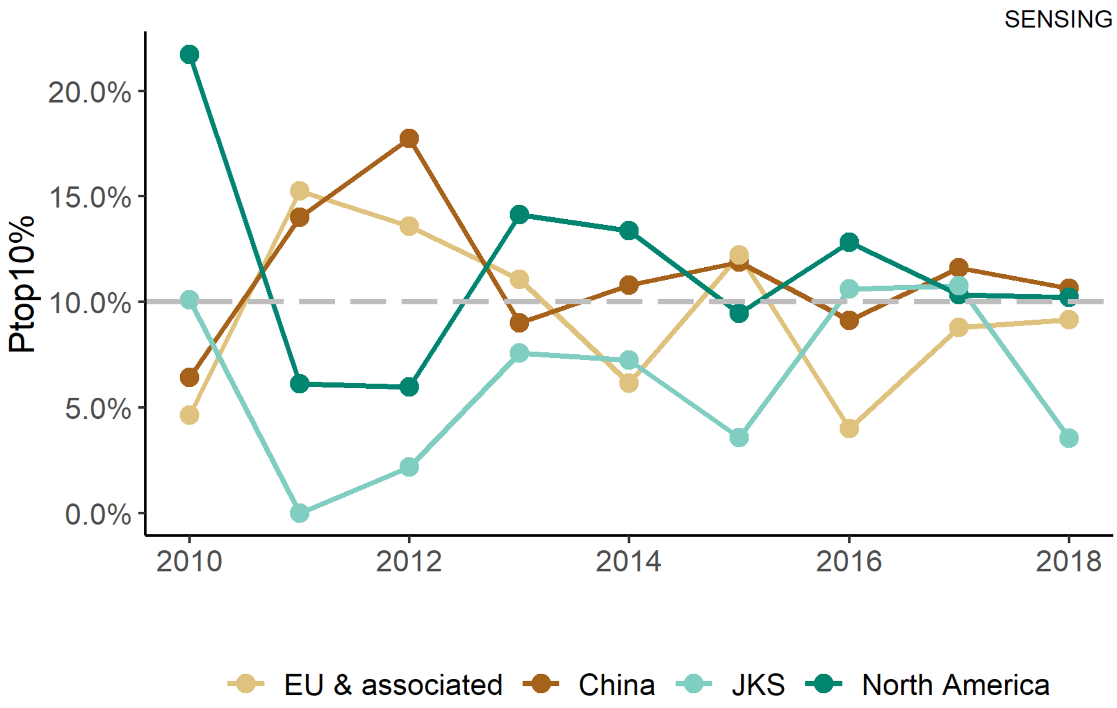

Figure 28. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.5.2 Organizations

Table 13 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

Among the 10 organizations from EU & associated, Chalmers University of Technology, Jülich Aachen Research Alliance, JARA and RWTH Aachen University all have strong citation impact performance, regardless of indicator. Perhaps somewhat surprisingly, the number of articles (P full) per organization in EU & associated is small. Tsinghua University, China, has a very competitive performance regarding citation impact indicators, especially for the publication-level indicators cf and Ptop10%.

Table 13. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	**P full**	**P frac**	**cf**	**Ptop10%**	**jcf**	**Jtop25%**	**IntColl%**
University of Mons	36	24.0	0.86	6.4%	1.48	57.0%	58.3%
RWTH Aachen University	34	18.5	1.88	18.3%	1.52	67.3%	8.8%
Free University of Brussels	32	24.0	1.19	13.2%	1.21	43.5%	34.4%
Chalmers University of Technology	30	11.3	1.87	33.0%	1.56	67.7%	53.3%
Technical University of Munich	21	16.6	0.46	0.0%	0.90	20.3%	28.6%
Karlsruhe Institute of Technology	15	12.0	0.74	0.0%	1.47	72.2%	13.3%
Aalborg University	15	8.6	0.95	2.3%	1.15	33.3%	80.0%
Jülich Aachen Research Alliance, JARA	15	6.7	2.14	15.2%	1.64	81.9%	6.7%
RISE - Research Institutes of Sweden	11	5.0	1.12	20.1%	1.11	47.1%	0.0%
Ikerlan	10	5.3	1.57	8.7%	1.52	65.4%	30.0%
Tsinghua University (CH)	134	81.2	1.91	20.2%	1.30	52.6%	26.9%
Nanyang Technological University (JKS)	37	22.6	1.26	14.9%	1.48	45.2%	62.2%
Carleton University (NA)	68	42.0	0.93	10.8%	1.45	60.4%	58.8%

Sunwoda Electronic Co, which is a battery producer also for the vehicle industry, is the company with the highest publication volume (21). In general, many car companies publish in Sensing, for instance General Motors Company and Mitsubishi Corporation.

3.5.3 Bibliometric networks

The network in Figure 29 gives an overview of the author keywords used in the articles selected for the Sensing subfield. The left side of the network is dealing with applied battery performance-related aspects of sensing. The blue cluster is primarily associated with concepts related to battery charge state (i.e. state of charge, open circuit voltage). The yellow cluster relates to battery lifetime aspects (i.e. state of health), whereas the green cluster clearly represents battery safety-related topics (i.e. heat generation, fire behavior). On the other side, the purple cluster is more directly dealing with specific sensing technologies. The optical methods indicated should primarily be seen as examples (e.g. Fiber Bragg grating-based sensing).

The networks in Figures 30 and 31 show the collaboration networks between countries and organizations within Sensing, respectively. In terms of publication volume, Canada and United Kingdom are more prominent in relation to China and US in comparison to the other five subfields (Figure 30; the node for Canada is the relatively large, green node near the node for US). The network of Figure 31 is somewhat unstructured but dominated by Chinese organizations. Most of the European organizations seem to be located in the lower part of the map, close to several Canadian organizations.

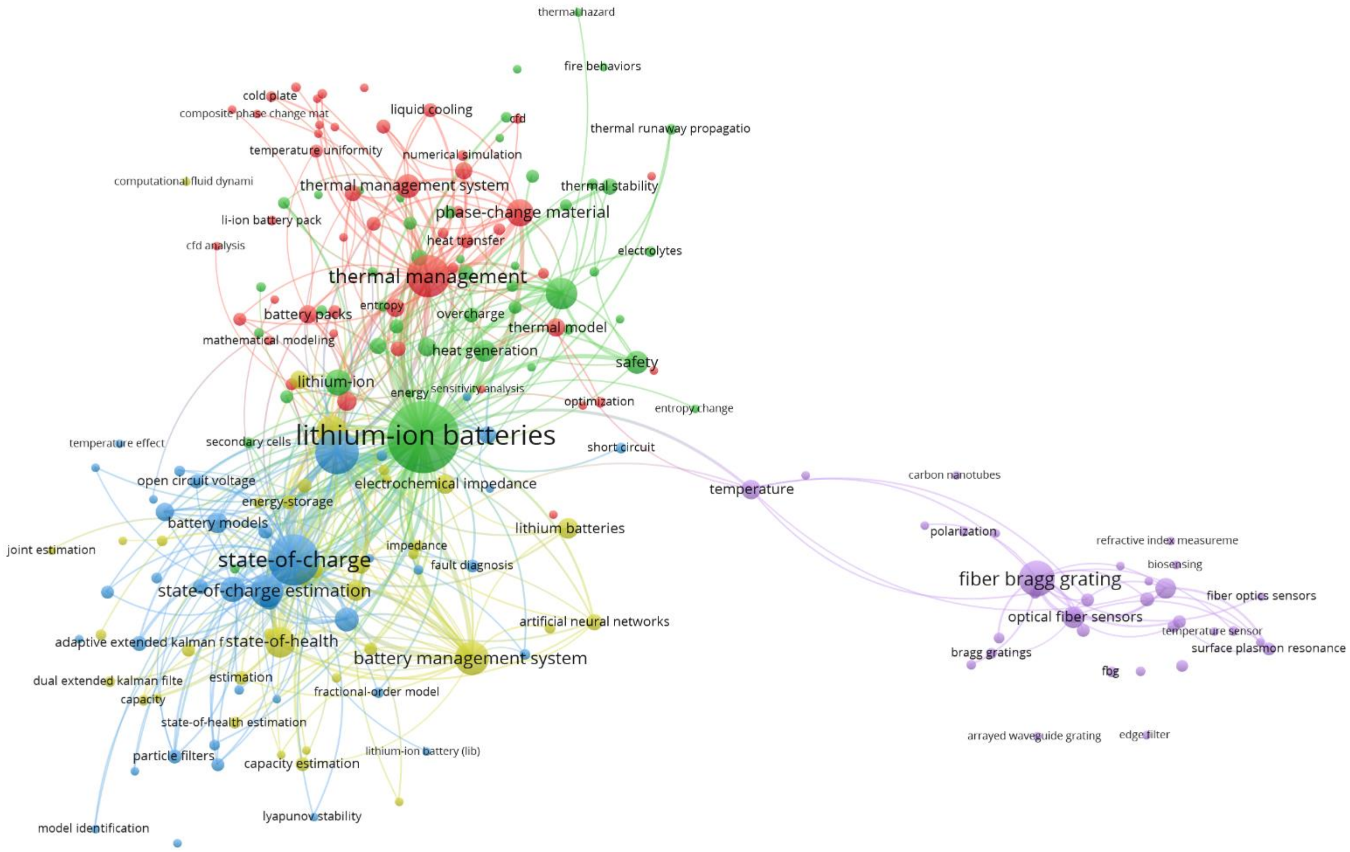

Figure 29. Author keyword co-occurrence network for Sensing. Minimum node (author keyword) weight is set to 6.

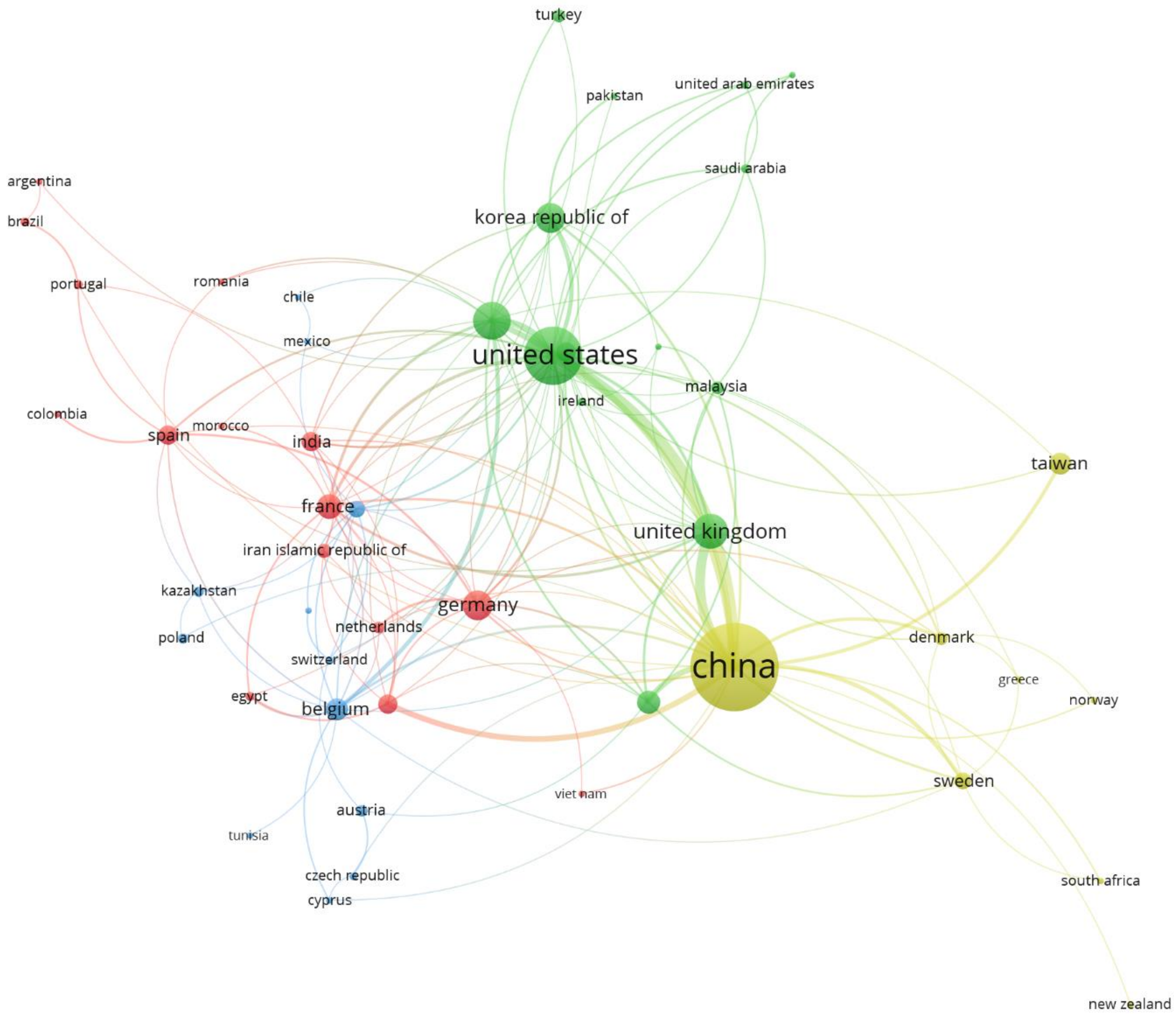

Figure 30. Country co-publishing network for Sensing. Minimum node (country name) weight is set to 3.

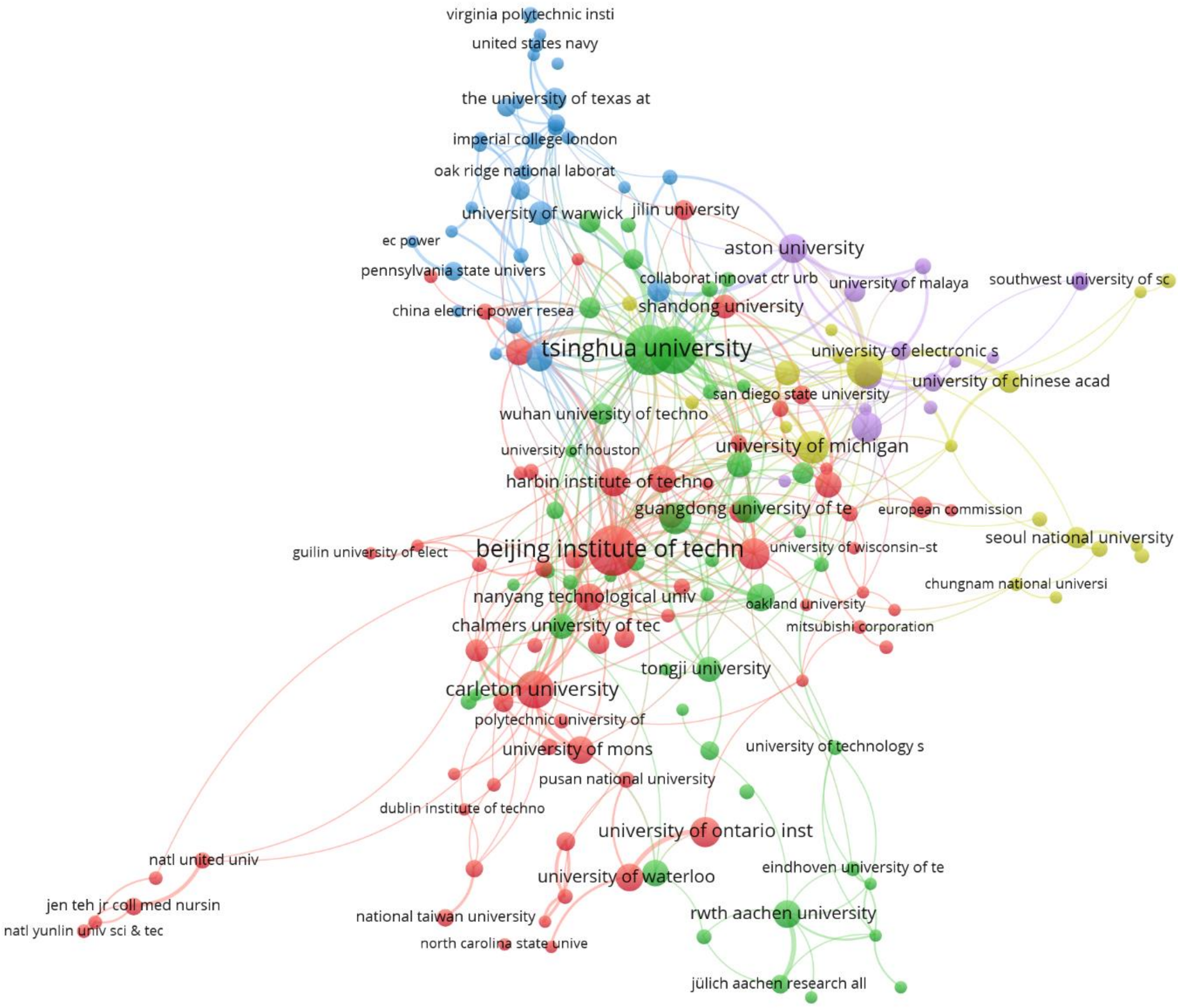

Figure 31. Organization co-publishing network for Sensing. Minimum node (organization name) weight is set to 6.

3.6 Manufacturability

In this section, we give the results for Manufacturability. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table is given. The third subsection visualizes three bibliometric networks.

We point out that problems in defining the set of articles for the subfield Manufacturability were faced. Indeed, given our seed methodology, there was an overlap in the potential clusters between the subfields BIG, Manufacturability, and MAP. We will return to this issue in the section "Discussion".

3.6.1 Country/country aggregates

In Table 14, indicator values by country/country aggregate and for the whole publication period are given. The volume (P full) for China is comparably low, whereas the cf and Ptop10% performance of North America is surprisingly poor. Compared to other subfields, JKS is doing well regarding the citation impact indicators.

As in several of the analyzed subfields, China has a remarkable increase in publication volume over time (Figure 32). For the last considered citation impact year, 2018, EU & associated has the lowest values on cf and Ptop10% (Figures 33 and 34).

Table 14. Indicator values by country/country aggregate.

Region	**P full**	**P frac**	**cf**	**Ptop10%**	**jcf**	**Jtop25%**	**IntColl%**
EU & associated	338	292.4	1.13	8.3%	1.66	51.9%	37.9%
China	451	392.7	1.09	13.2%	1.60	50.6%	25.9%
JKS	184	151.6	1.20	14.0%	1.93	58.7%	33.7%
North America	453	369.4	0.90	9.3%	1.63	55.0%	38.4%

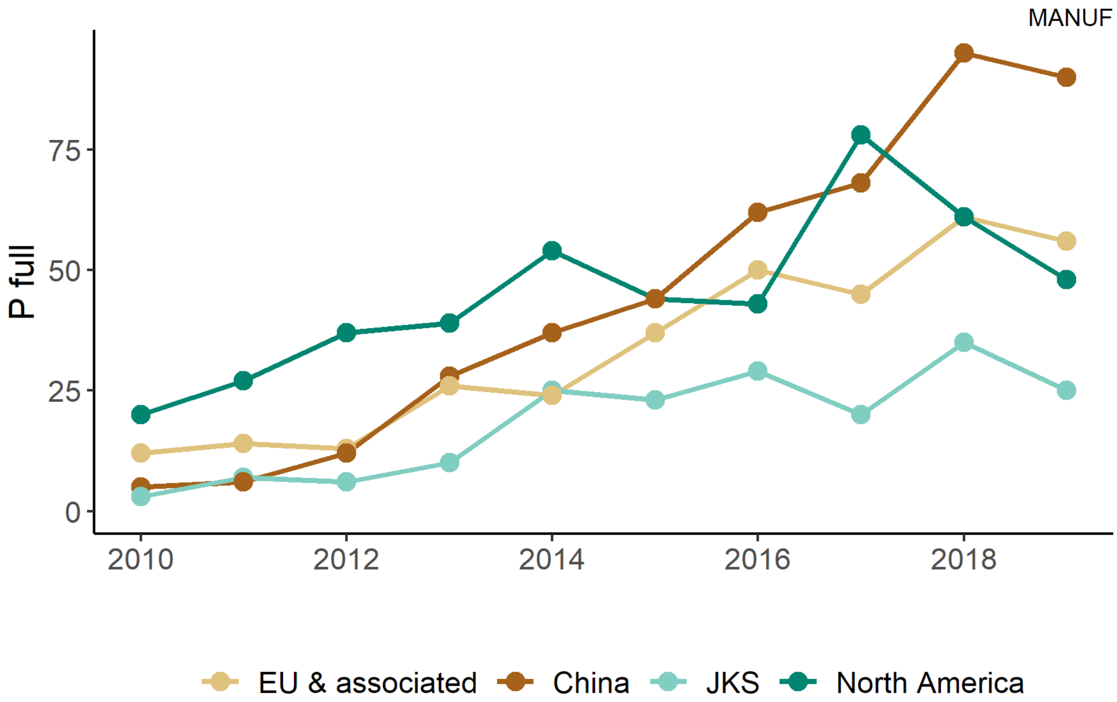

Figure 32. Publication volume (P full) development by country/country aggregate

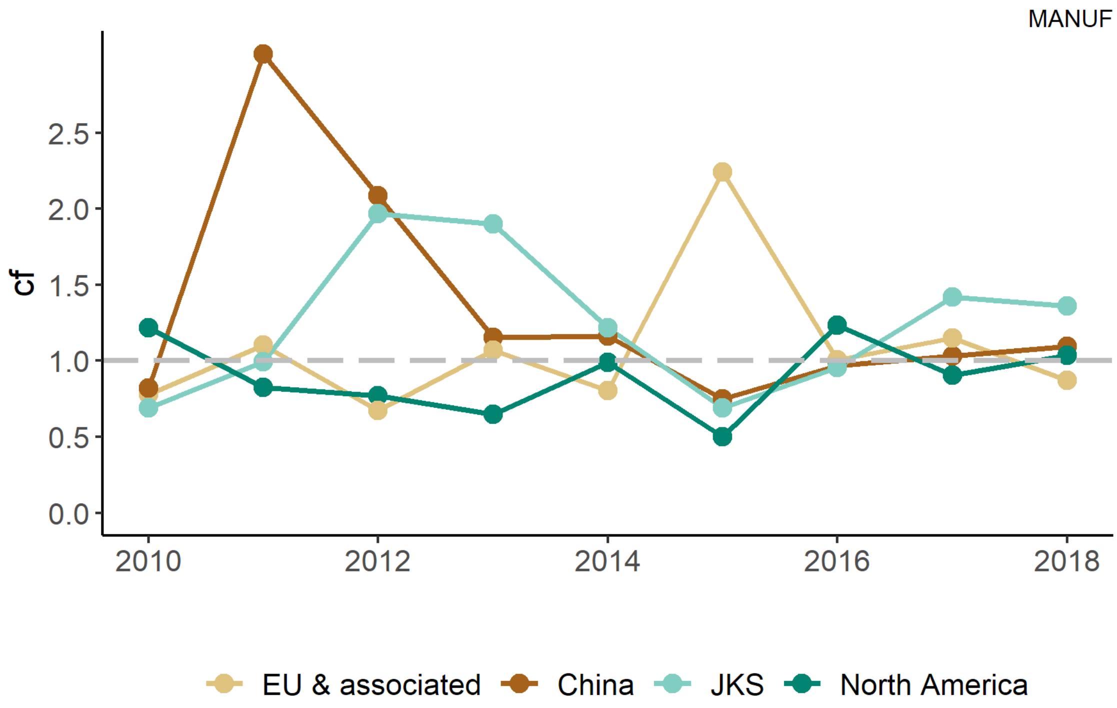

Figure 33. Publication-level citation impact (cf) development by country/country aggregate.

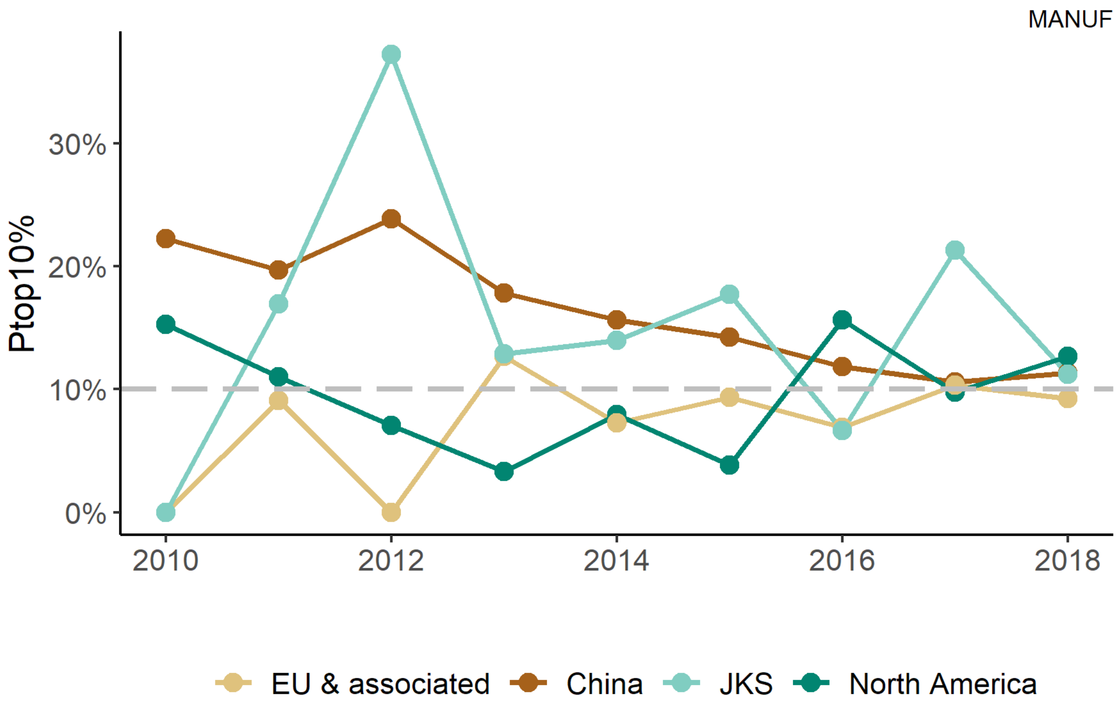

Figure 34. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.6.2 Organizations

Table 15 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

Among the 10 organizations from EU & associated, five organizations are from Germany and three from France. Note that the publication volumes are quite low overall.

Table 15. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
University of Picardy Jules Verne	36	16.5	1.04	6.8%	1.83	62.5%	36.1%
Technical University Braunschweig	25	17.4	0.49	0.0%	0.99	14.7%	12.0%
University of Ulm	25	12.6	0.33	0.5%	0.90	14.1%	36.0%
ETH Zurich	21	12.8	1.67	24.6%	2.52	61.3%	52.4%
Uppsala University	18	16.2	0.78	6.6%	1.66	62.9%	22.2%
Helmholtz-Zentrum Berlin	18	4.8	0.45	0.0%	1.53	46.5%	22.2%
French National Centre for Scientific Research	16	3.9	0.56	0.0%	1.61	60.7%	37.5%
Technical University of Munich	15	13.8	1.32	33.3%	1.29	36.9%	20.0%
Karlsruhe Institute of Technology	15	11.1	0.62	8.6%	1.47	77.2%	13.3%
University of Nantes	15	6.6	0.88	0.0%	2.89	73.3%	33.3%
Chinese Academy of Sciences (CH)	60	34.2	0.94	14.5%	1.51	44.8%	10.0%
National Institute of Advanced Industrial Science and Technology (JKS)	22	15.2	1.94	24.9%	1.76	48.7%	50.0%
University of Michigan (NA)	27	20.1	0.96	5.0%	1.26	47.7%	40.7%

The four companies with the highest publication volumes are General Motors Company (12), Samsung (11), Robert Bosch (10) and Ford Motor Company (7).

3.6.3 Bibliometric networks

The network in Figure 35 gives an overview of the author keywords used in the articles selected for the Manufacturability subfield. This network is quite hard to interpret and does not show a clear grouping of subjects. The left hand side of Figure 35 however includes a few aspects, such as microstructure and electrode thickness, which are important in the field of manufacturability. Also, a number of analysis- and simulation methods that can be used to improve production processes can be seen. We discuss further challenges in defining and identifying the Manufacturability subfield in the discussion.

The networks in Figures 36 and 37 show the collaboration networks between countries and organizations within Manufacturability, respectively. For the country network (Figure 36), as indicated above in this section, the publication volume of China is relatively low. Other than that, Germany stands out both compared to US and to other European countries. With regard to the organization network (Figure 37), European organizations are located to right of the map, whereas the Chinese and the US organizations are intermingled to the left. Many organizations from United Kingdom are located centrally in the map and can be seen as bridge between China-US and Europe.

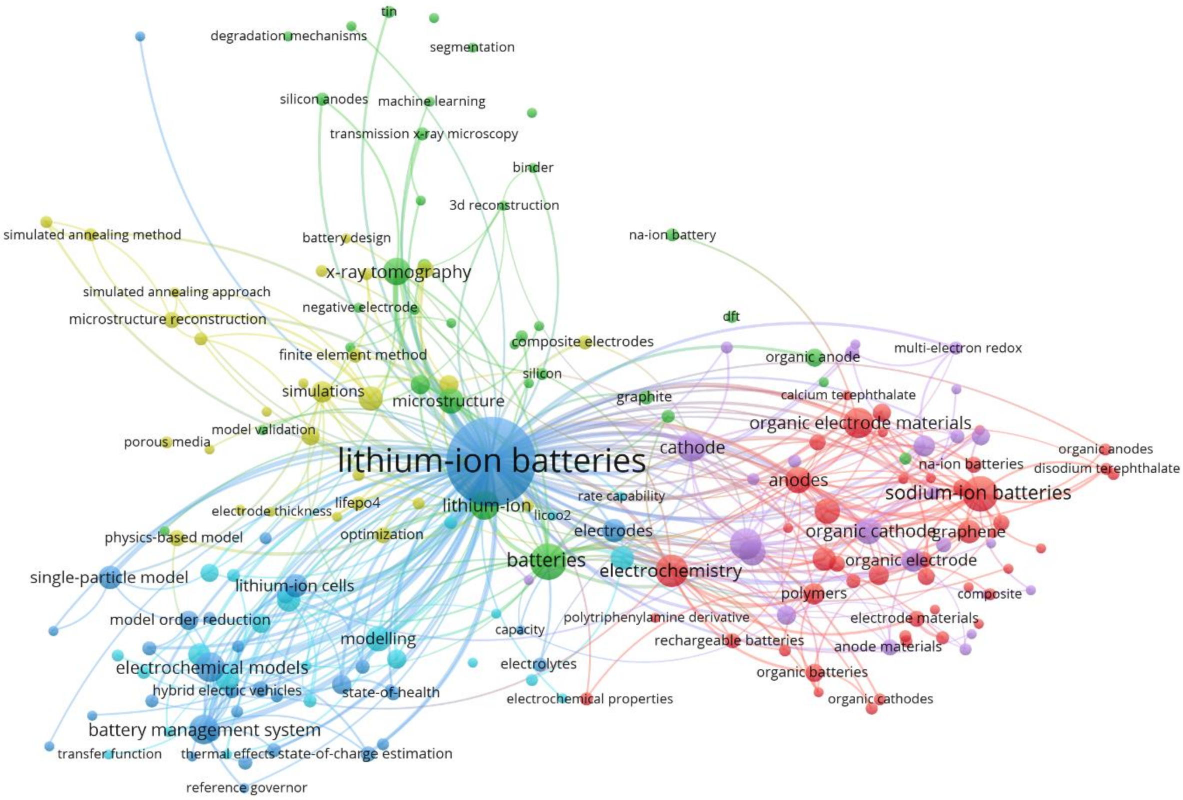

Figure 35. Author keyword co-occurrence network for Manufacturability. Minimum node (author keyword) weight is set to 3.

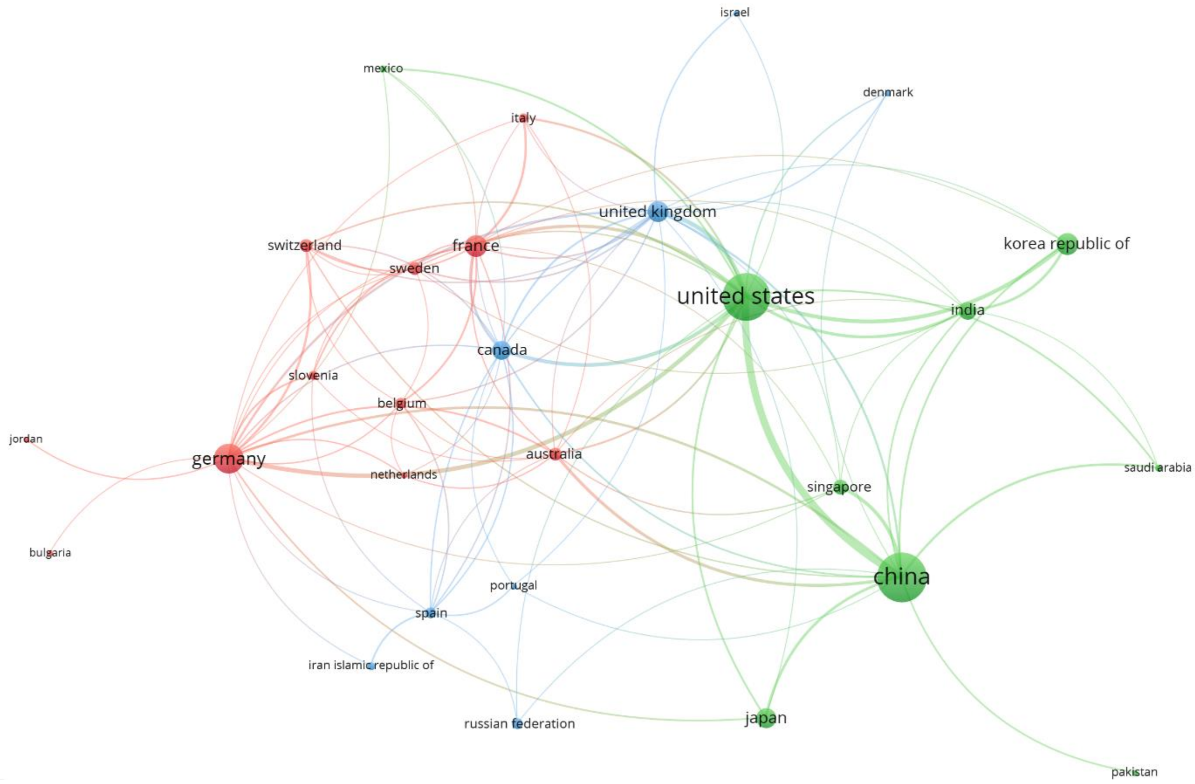

Figure 36. Country co-publishing network for Manufacturability. Minimum node (country name) weight is set to 2.

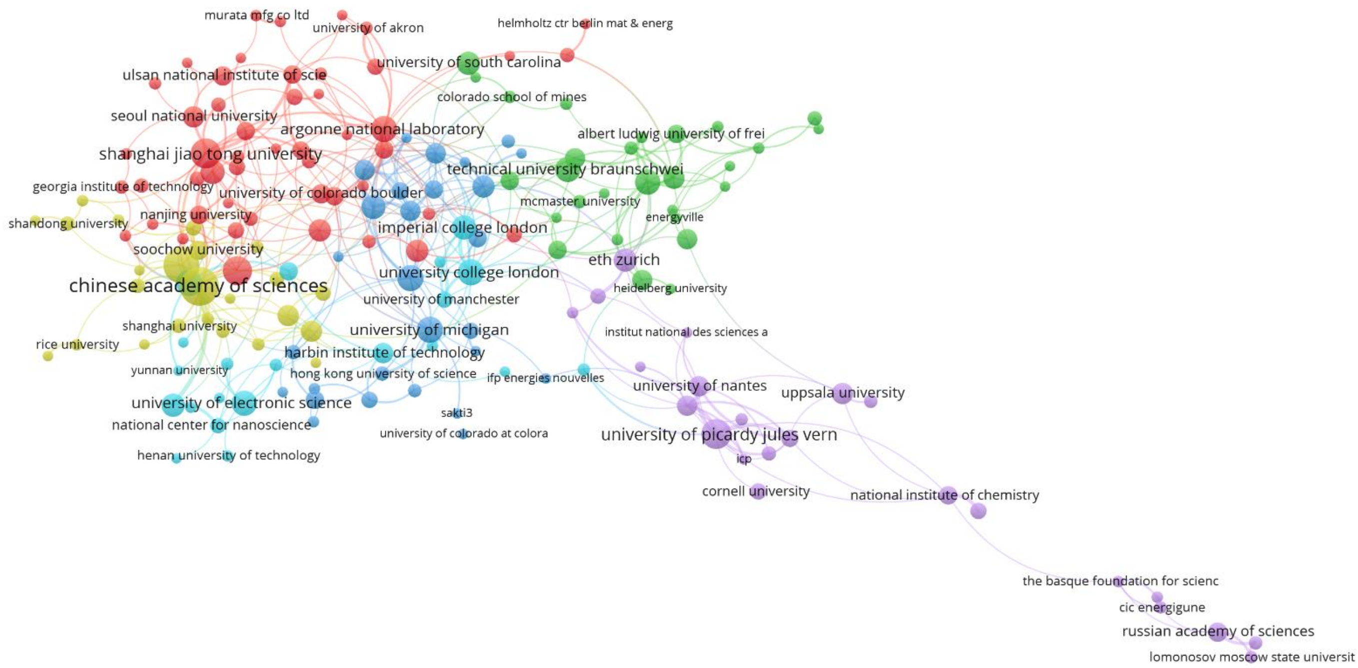

Figure 37. Organization co-publishing network for Manufacturability. Minimum node (organization name) weight is set to 4.

3.7 The BATTERY 2030+ field-POOL

In this section, we give the results for the BATTERY 30+ field as a whole, operationalized as the article set POOL. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, one table are given. The third subsection visualizes three bibliometric networks.

Note that the article sets for the subfields are of different size, and therefore the pooled set will be most influenced by the subfields with larger sets (also see the section "Discussion"). Consequently, the pooled results are strongly influenced by the results in Self-healing, a set with 7,127 articles.

3.7.1 Country/country aggregates

In Table 16, indicator values by country/country aggregate and for the whole publication period are given. EU & associated and JKS are lagging North America and China regarding volume indicators (P full and P frac) and publication-level citation indicators (cf and Ptop10%). For instance, the Ptop10% value for North America is 13%, which is 30% above world average, whereas the value for EU & associated is 8.2%, 18% below world average. For international co-publishing (IntColl%), EU & associated has the highest share among the four units, 41%, whereas China has the lowest, 26%.

Table 16. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	3,260	2,752.8	0.91	8.2%	1.40	42.7%	41.0%
China	6,029	5,324.7	1.06	10.9%	1.40	44.8%	26.0%
JKS	1,188	937.5	0.91	9.6%	1.48	45.4%	38.2%
North America	4,348	3,500.9	1.21	13.0%	1.66	54.8%	38.8%

China's publication volume development from 2012 onwards is quite remarkable (Figure 38). For a majority of the last seven publication years, EU & associated has a similar cf performance as JKS (Figure 39). From 2013, China and North America consistently outperform EU & associated and JKS. This is generally also the case for Ptop10% (Figure 40). For this indicator, and the last considered publication year, North America has, by far, the best performance. China has a considerable increase from 2010 to 2013 for both cf and Ptop10%. However, for both these indicators, and in contrast to P full, China's indicator values are fairly stable from year 2013.

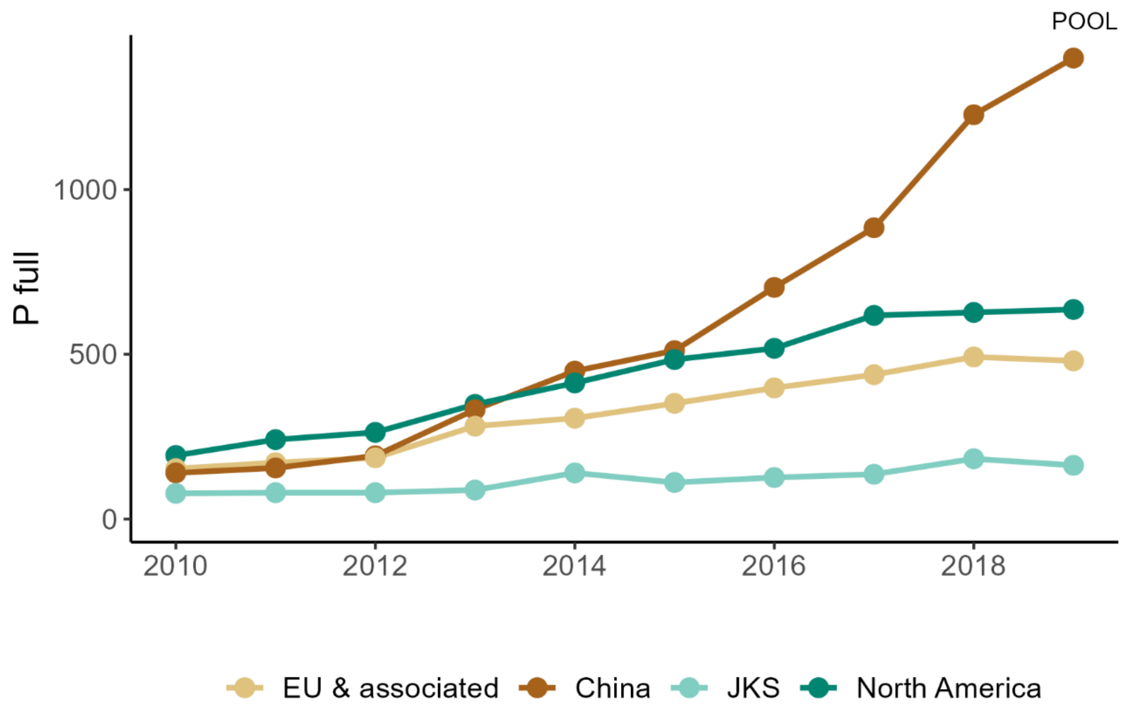

Figure 38. Publication volume (P full) development by country/country aggregate.

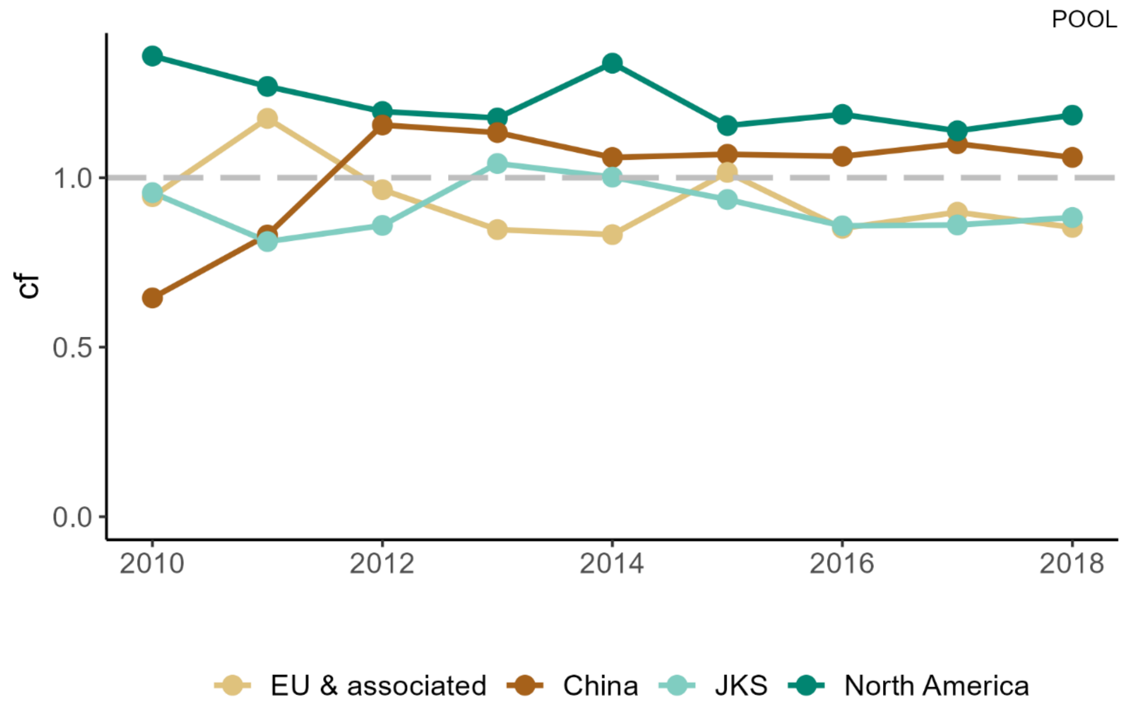

Figure 39. Publication-level citation impact (cf) development by country/country aggregate.

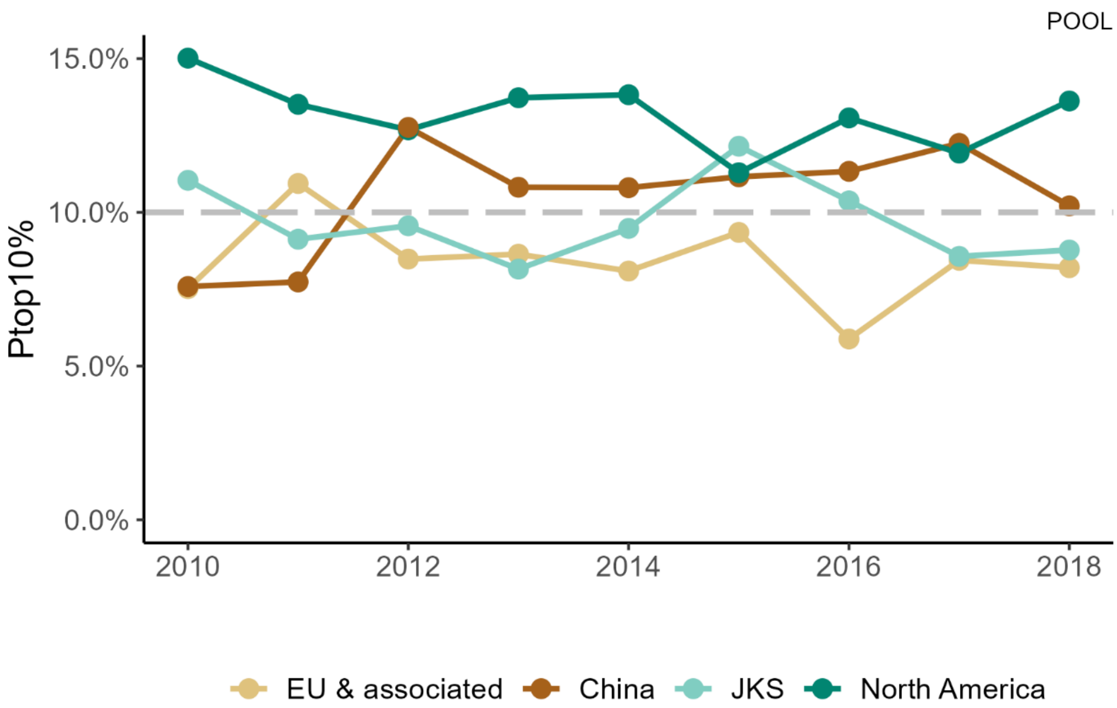

Figure 40. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.7.2 Organizations

Table 17 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10, jcf and Jtop25%) compared to the selected organizations. Note that the organization counts here are dependent of the counts within the constituent subfields. Therefore, the organizations found under POOL are mainly determined by the Self-healing subfield due to the relatively high publication volume of this subfield.

The performance of the organizations in EU & associated is better for the journal-level citation impact indicators (jcf and Jtop25%) compared to the publication-level ones. This suggests that the organizations perform better with regard to publishing in highly cited journals compared to the extent to which their articles are cited. Nanyang Technological University, in JKS, has high indicator values for all four citation impact indicators.

Table 17. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	**P full**	**P frac**	**cf**	**Ptop10%**	**jcf**	**Jtop25%**	**IntColl%**
Max Planck Society	95	37.9	1.46	25.3%	1.62	54.7%	77.9%
Free University of Brussels	90	58.2	0.83	6.5%	1.22	37.0%	43.3%
Karlsruhe Institute of Technology	89	54.0	0.82	7.6%	1.47	59.4%	34.8%
Swiss Federal Institute of Technology Lausanne	69	47.9	0.77	10.1%	1.56	54.6%	46.4%
Delft University of Technology	67	40.9	0.73	0.6%	1.43	42.1%	58.2%
Ruhr University Bochum	62	48.6	1.04	12.5%	0.94	29.0%	24.2%
ETH Zurich	62	33.9	1.59	18.6%	2.26	57.6%	58.1%
University of Strasbourg	59	40.0	0.73	4.2%	1.71	50.9%	49.2%
RWTH Aachen University	59	35.1	1.30	11.2%	1.33	50.8%	11.9%
Technical University of Munich	58	41.8	1.05	20.6%	1.15	27.6%	34.5%
Chinese Academy of Sciences (CH)	689	388.4	1.17	12.3%	1.57	48.8%	19.9%
Nanyang Technological University (JKS)	208	126.6	1.68	24.1%	1.93	57.9%	65.4%
Dalhousie University (NA)	184	153.3	0.67	3.2%	1.16	35.6%	40.8%

When it comes to companies in POOL, the most prominent ones, based on publication volume, are represented by research activities in US. The two companies with the highest publication volumes are Samsung (97) and General Motors Company (65). Among the top 15, only two EU companies, both in Germany, are represented: BMW Group and PSA Group.

3.7.3 Bibliometric networks

The network in Figure 41 gives an overview of the author keywords used in the articles selected for POOL. This network captures many of the aspects covered by the corresponding networks for the six subfields. Self-healing is still distinct (red cluster), and most aspects of recycling is in the lower part of the network. Sensing aspects are mostly to the right. In contrast to the corresponding network for Recyclability, electric vehicles is here placed more closely to sensing than to general recycling. The network suggests that BIG and MAP are less distinct and have connections to several other subfields. It should be kept in mind that Self-healing might have a disproportionate weight in the network, since that subfield consists of a relatively large number of articles.

The networks in Figures 42 and 43 show the collaboration networks between countries and organizations within POOL, respectively. As in several subfields, China and US dominate the country network (Figure 42). Regarding EU & associated, the countries with the largest publications volumes are Germany, France, Italy, Switzerland and Belgium. In the organization network, organizations in EU & associated are located mainly to the left but with connections to China, Japan and US (Figure 43). US organizations are placed quite centrally, Indian and South Korean at the top, and Japanese towards the bottom.

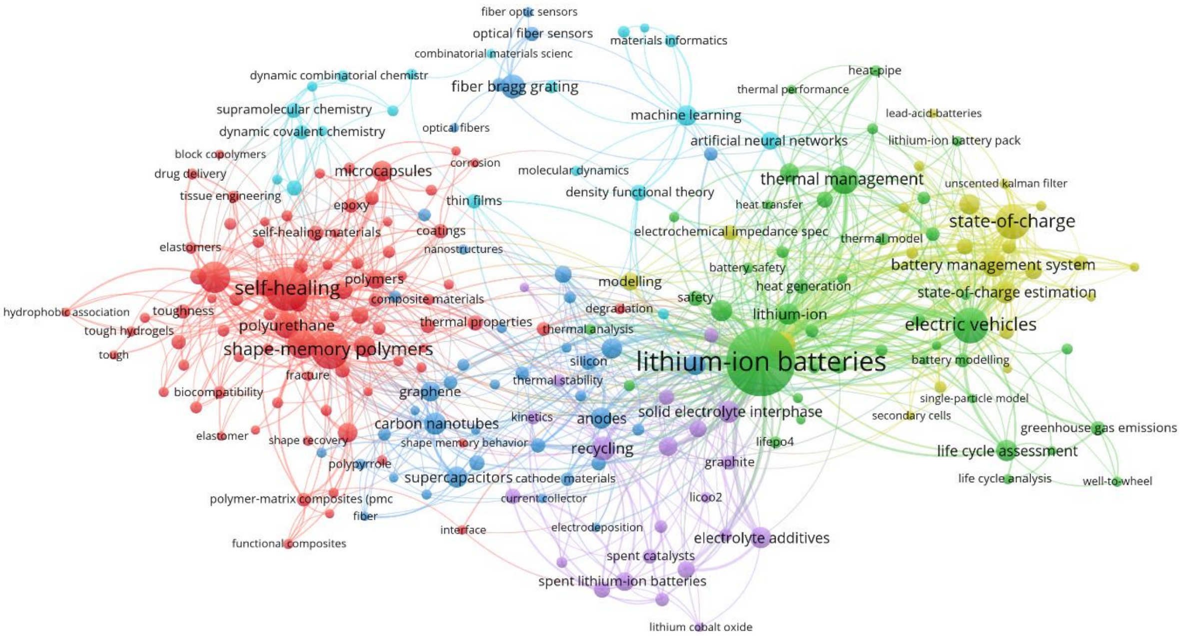

Figure 41. Author keyword co-occurrence network for POOL. Minimum node (author keyword) weight is set to 20.

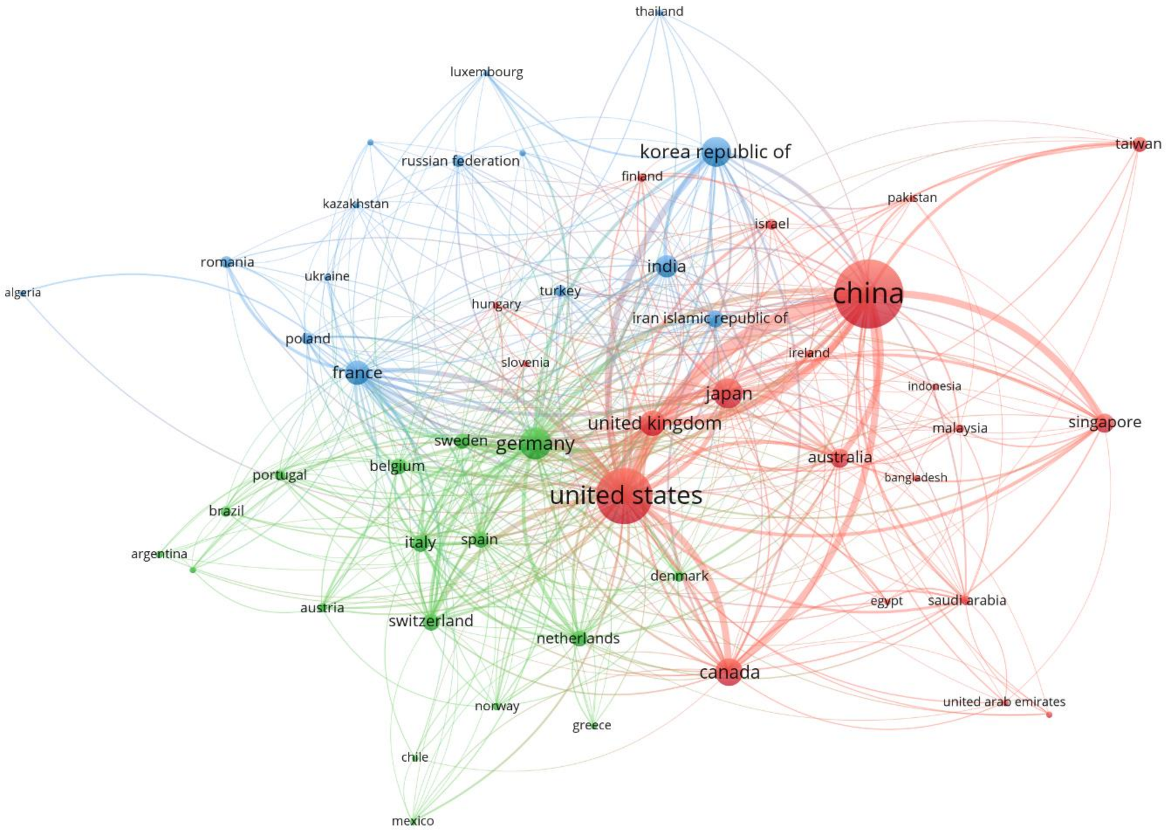

Figure 42. Country co-publishing network for POOL. Minimum node (country name) weight is set to 10.

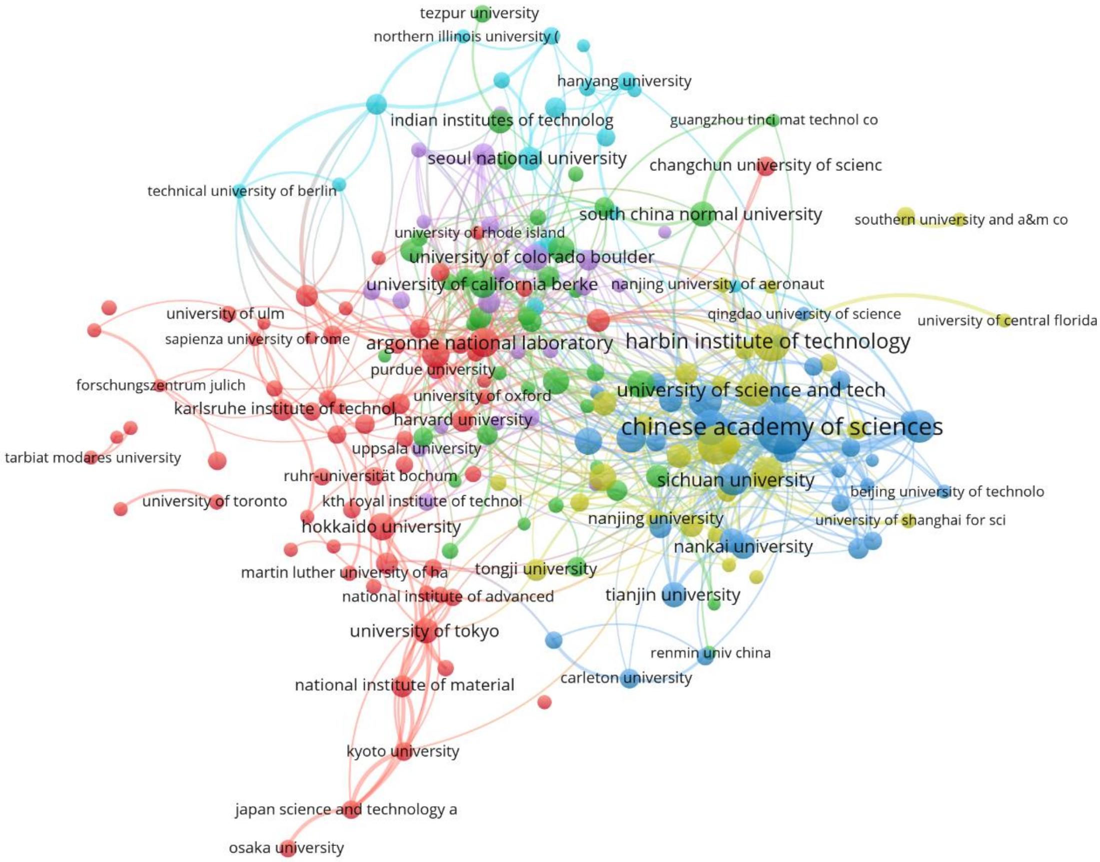

Figure 43. Organization co-publishing network for POOL. Minimum node (organization name) weight is set to 30.

3.8 The BATTERY 2030+ field-WIDE

In this section, we give the results for the BATTERY 2030+ field as a whole, operationalized as the article set WIDE. The section has three subsections. The first one, which concerns results for country/country aggregates, puts forward one table and three graphs. In the second subsection, in which we deal with results for the organization level, two tables are given. The third subsection visualizes three bibliometric networks.

3.8.1 Country/country aggregates

In Table 18, indicator values by country/country aggregate and for the whole publication period are given. It is clear from the table that North America is very strong in all four citation impact indicators, also in comparison to the corresponding North America results for POOL. EU & associated, China and JKS have a similar overall citation impact performance. Regarding volume and P full values over time (Figure 44), China has a remarkable increase. Moreover, for each considered year, China has a higher P full value than North America. For cf and Ptop10% values over time, North America has considerably higher values than EU & associated, China and JKS for all considered years (Figures 45 and 46). EU & associated exhibits a weak Ptop10% trend from 2014 onwards. For international co-publishing (IntColl%), EU & associated and North America have the highest shares among the four units, 47.3% and 45.6%, respectively, whereas China has the lowest, 23%.

Table 18. Indicator values by country/country aggregate.

Region	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
EU & associated	10,624	8,573.5	0.88	7.8%	1.49	47.0%	47.3%
China	32,837	29,718.4	0.95	9.4%	1.43	44.9%	23.0%
JKS	11,682	9,739.1	0.90	8.8%	1.49	48.3%	33.2%
North America	14,491	10,865.3	1.52	17.1%	2.01	63.4%	45.6%

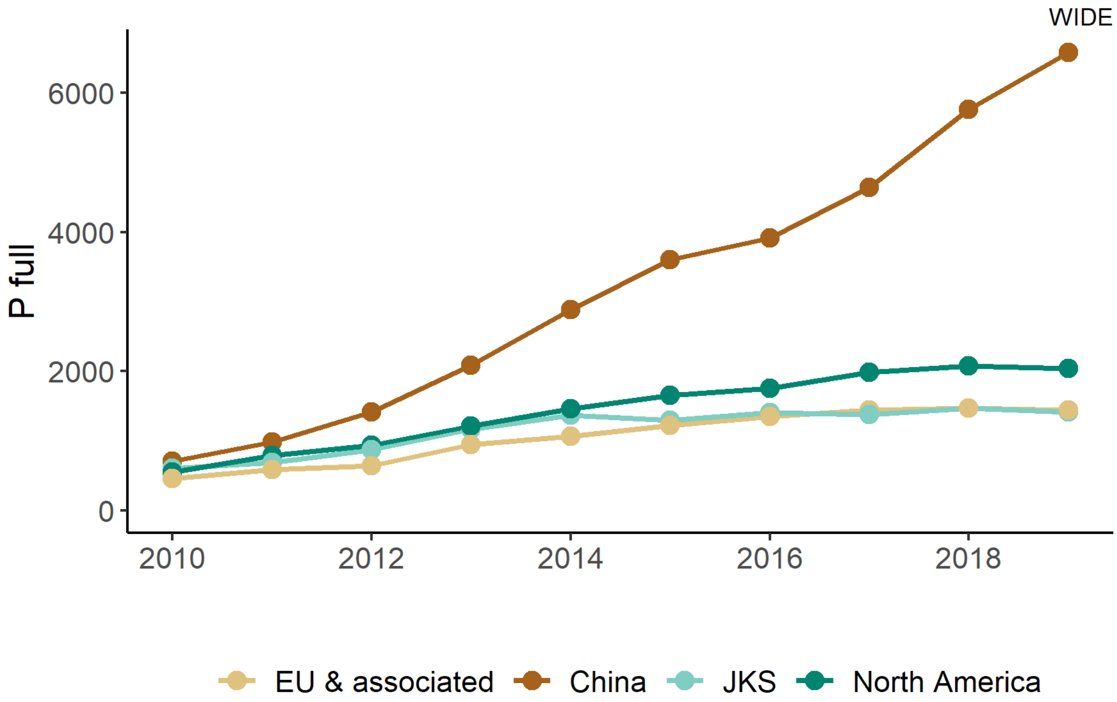

Figure 44. Publication volume (P full) development by country/country aggregate.

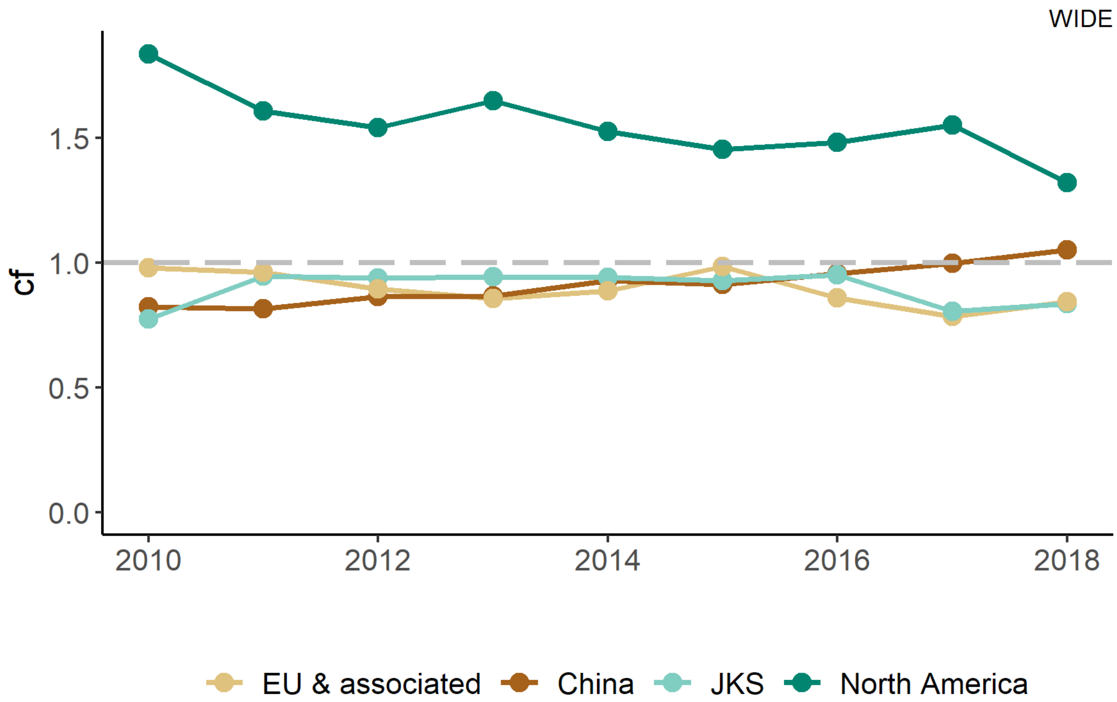

Figure 45. Publication-level citation impact (cf) development by country/country aggregate.

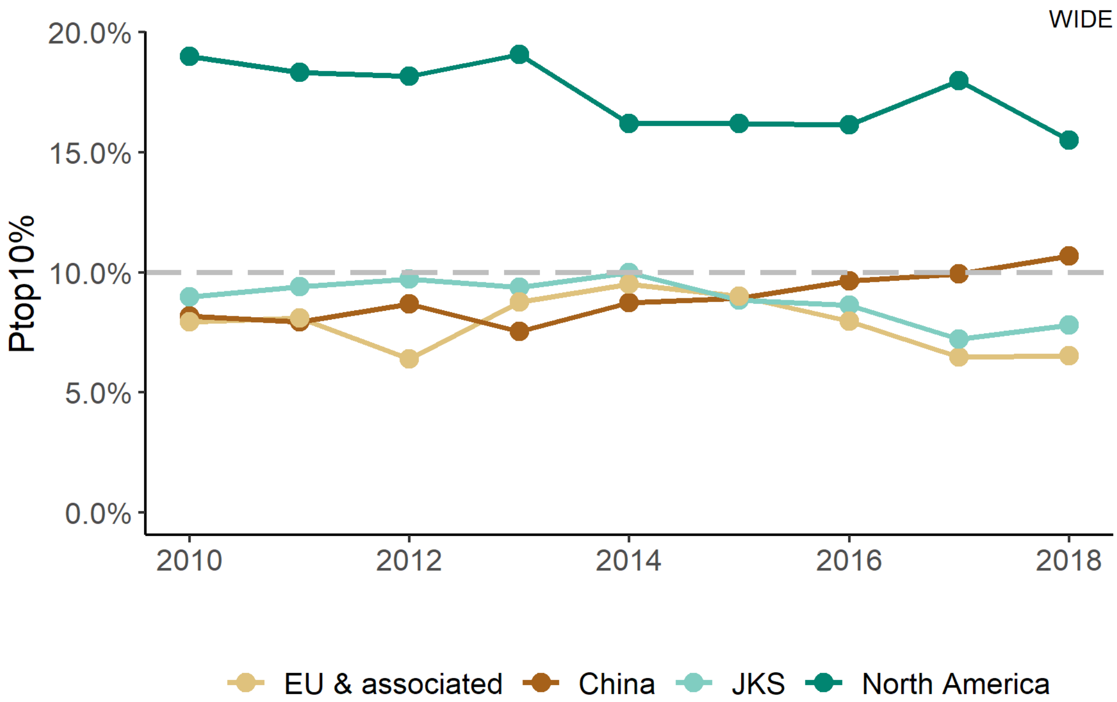

Figure 46. Publication-level citation impact (Ptop10%) development by country/country aggregate.

3.8.2 Organizations

Table 19 puts forward indicator values for the top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full. It should be kept in mind that other organizations from China, EU & associated, JKS and North America can have widely different citation impact values (the indicators cf, Ptop10%, jcf and Jtop25%) compared to the selected organizations.

There are some clear differences in citation impact performance for some of the organizations represented both in Table 19 and in the corresponding POOL table (Table 17). Karlsruhe Institute of Technology and Uppsala University have negative changes in cf and Ptop10% compared to POOL whereas Max Planck Society has a positive change. This outcome, though, is related to differences in field normalization. Max Planck Society has a lot of its articles in the subfield MAP, which might have a higher citation density than some other subfields. Recall that the articles in POOL are normalized against their subfields (and not against POOL), while the articles in WIDE are normalized against WIDE itself. Germany has a strong foothold in the WIDE: five out of ten in EU & associated are German universities or research institutes.

Table 19. Indicator values by organization. The top 10 organizations among EU & associated and the top 1 organization from China, North America and JKS with respect to P full.

Organization	P full	P frac	cf	Ptop10%	jcf	Jtop25%	IntColl%
Karlsruhe Institute of Technology	660	322.6	0.97	8.3%	1.54	54.7%	42.7%
University of Münster	447	301.5	0.87	6.9%	1.44	49.6%	22.8%
Technical University of Munich	325	195.8	0.99	9.1%	1.36	37.6%	41.2%
Max Planck Society	325	149.6	2.19	34.6%	2.52	73.0%	72.9%
Uppsala University	324	207.5	0.71	4.5%	1.61	57.6%	55.9%
Forschungszentrum Julich	311	94.2	0.79	4.1%	1.41	44.5%	37.0%
University of Picardy Jules Verne	289	108.8	1.26	15.6%	1.91	64.8%	55.4%
French National Centre for Scientific Research	250	73.7	1.15	5.8%	1.97	60.7%	52.4%
Bar-Ilan University	211	150.2	1.70	12.1%	1.63	51.9%	66.4%
Sapienza University of Rome	210	98.2	1.40	10.3%	1.56	54.6%	63.3%
Chinese Academy of Sciences (CH)	4,200	2,286.2	1.39	15.2%	1.73	55.8%	22.2%
Nanyang Technological University (JKS)	871	507.0	2.40	33.2%	2.15	70.0%	64.1%
Argonne National Laboratory (NA)	1,043	518.4	1.38	16.0%	2.21	69.8%	45.3%

When it comes to companies in WIDE, and based on publication volume, many of the most prominent ones are represented by research activities in US. The four companies with the highest publication volumes are Samsung (324), Toyota (223), General Motors Company (213) and BASF[7] (150). Among the top 15, two EU companies are represented, based on research activities from within Europe, both in Germany: BMW Group and Daimler AG.

[7] Based on research from their US branch.

3.8.3 Bibliometric networks

The network in Figure 47 gives an overview of the author keywords used in the articles selected for WIDE. In this wider, compared to POOL, operationalization of the BATTERY 2030+ field as a whole, we observe that the network is not very differentiated. The green cluster seems to be related the negative electrode and possibly to the next-generation electrodes. The blue cluster deals more with classical Li-ion batteries with a focus on the positive electrode. The red cluster seems to focus on the electrolyte but is less material-oriented compared to the blue and green clusters. In the red cluster also the link between electrolyte concepts and the topics in BIG and MAP, such as machine-learning and neural networks, is discerned. The yellow cluster mainly captures self-healing. Overall, the six subfields are less visible in this network compared to the corresponding network for POOL, which is expected. Instead, this network provides a broader general overview of battery research, especially related to lithium batteries.

The networks in Figures 48 and 49 show the collaboration networks between countries and organizations within WIDE, respectively. For the country network (Figure 48), China dominates even more, and the position of US is weaker, regarding publication volume and compared to POOL (Figure 42). For the organization network (Figure 49), the different regions are more separated compared to the corresponding network of POOL (Figure 43).

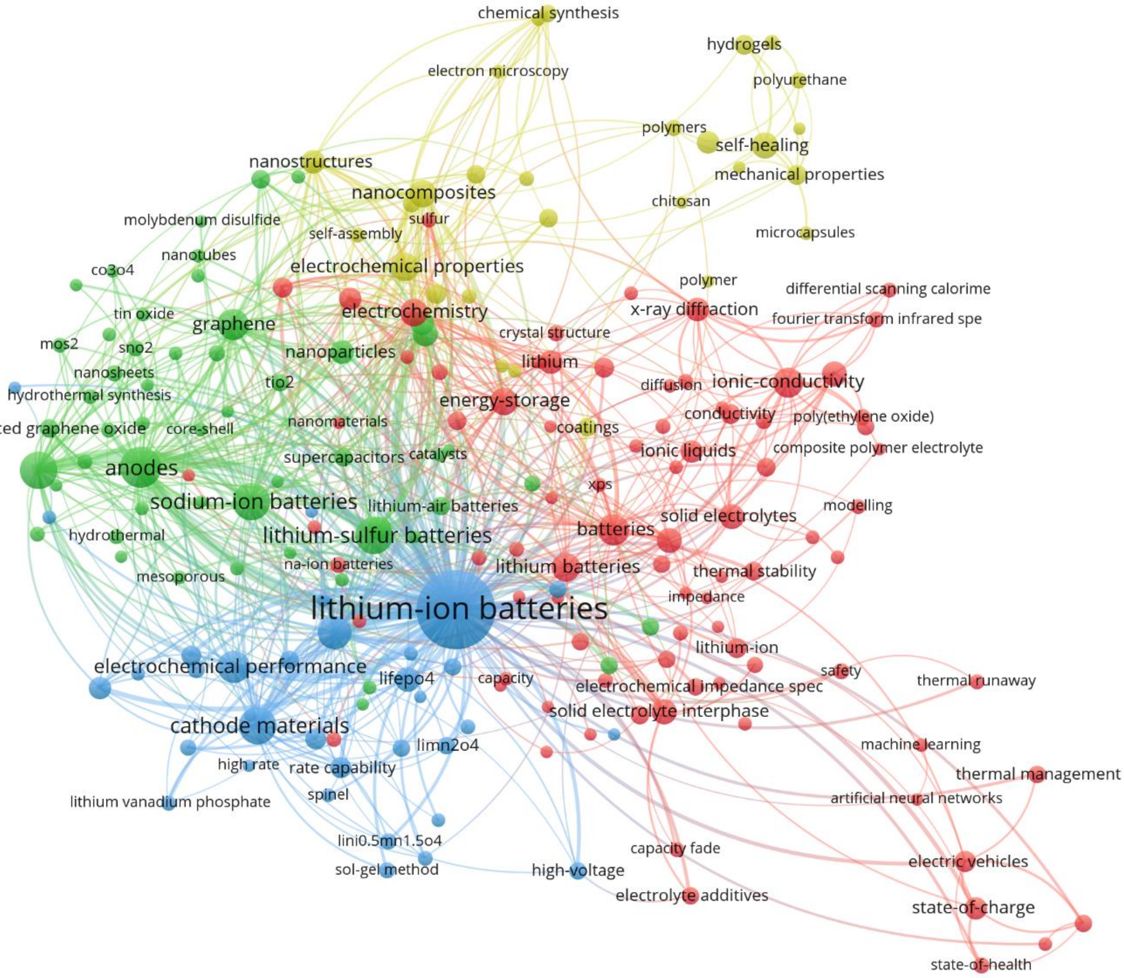

Figure 47. Author keyword co-occurrence network for WIDE. Minimum node (author keyword) weight is set to 100.

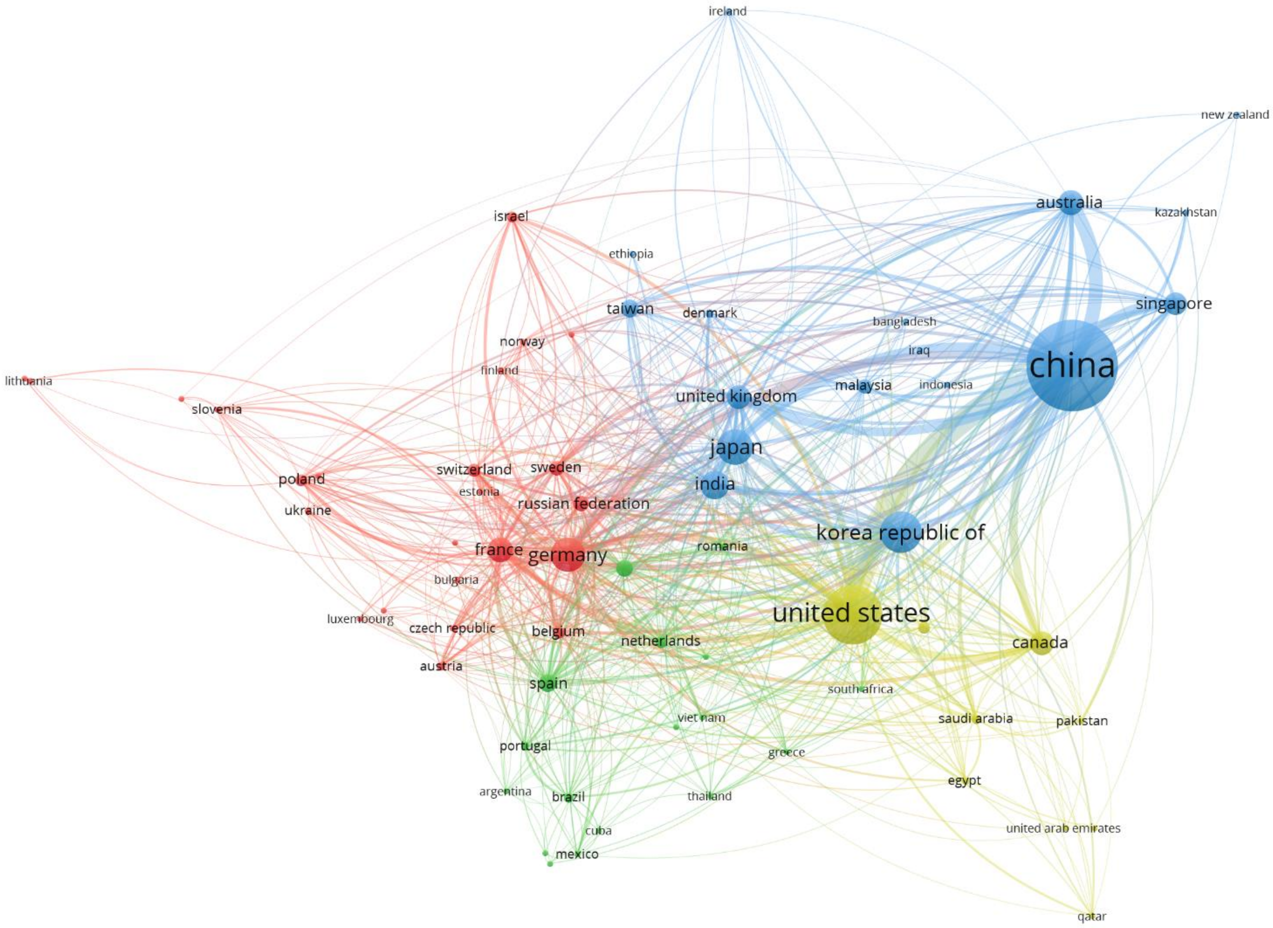

Figure 48. Country co-publishing network for WIDE. Minimum node (country name) weight is set to 15.

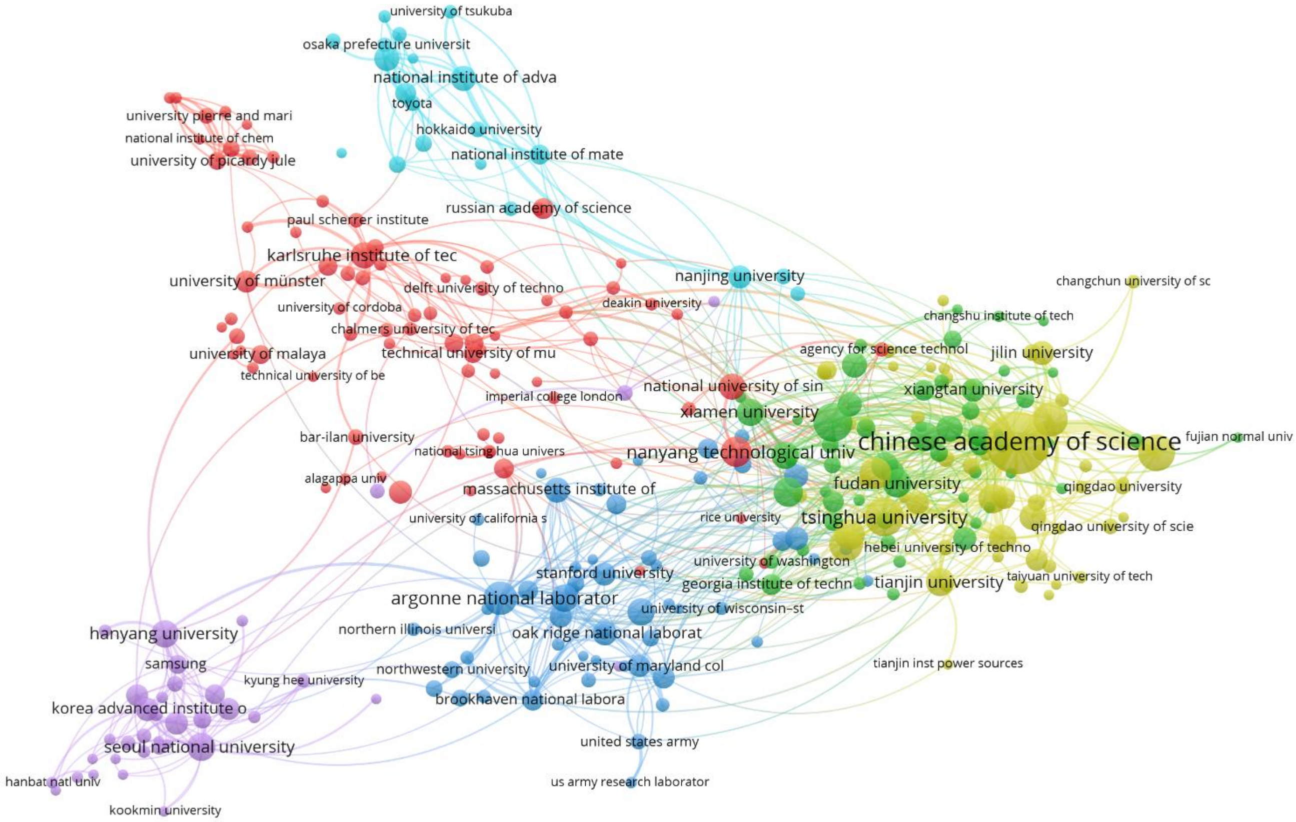

Figure 49. Organization co-publishing network for WIDE. Minimum node (country name) weight is set to 85.

4 Discussion

In this work, we have used bibliometric methods to analyze battery research with the BATTERY 2030+ roadmap as point of departure. We treated the six battery research subfields identified in the BATTERY 2030+ roadmap: *Battery Interface Genome (BIG), Materials Acceleration Platform (MAP), Recyclability, Smart functionalities: Self-healing, Smart functionalities: Sensing, and Manufacturability*. Moreover, we analyzed the BATTERY 2030+ field as a whole, where two operationalizations of the whole were used. In the following list, we repeat the overarching aims of the analysis:

(a) to evaluate the European standing in the subfields/the BATTERY 2030+ field in comparison to the rest of the world,
(b) to identify strongholds of the subfields/the BATTERY 2030+ field across Europe.

In the remainder of this section, we reflect on the results, put forward methodological limitations and give conclusions.

4.1 Reflections on the results

For point (a) above, EU & associated has similar but slightly lower publication volumes compared to North America for both POOL and WIDE and for most subfields. However, in BIG and especially MAP, the publication volume from North America is considerably larger. One exception where EU & associated has a higher publication volume is Recyclability. Also note that MAP is the only subfield in which both North America and EU & associated have a higher volume than China. The citation performance (cf and Ptop10%) of EU & associated is similar to China and JKS and well below North America with regard to POOL and WIDE. Subfield exceptions are Recyclability, where EU & associated performs (cf) above North America and 7% above world average, and BIG, where EU & associated has the highest citation performance (cf), 36% above world average. Focusing on the end of the study period, EU & associated has the strongest citation performance, in relative terms, in MAP, while Self-healing is by far the weakest subfield.

For point (b) above, Karlsruhe Institute of Technology and Max Planck Society are EU & associated organizations with high publication volumes in both POOL and WIDE. In the different subfields, there is a large variability in the top EU & associated organizations regarding volume. For citation impact (cf and Ptop10%), the performance of the EU & associated organizations is quite variable with some performing well above world average and some with a more modest performance. Examples of high-performing (cf and Ptop10%) EU & associated organizations are ETH Zurich and Max Planck Society.

Regarding publication volume, China and JKS are strengthened in WIDE compared to POOL. However, China is weakened with regard to citation impact in WIDE compared to POOL. One possible interpretation of this difference is that WIDE is gathering a wider selection of publications, where some may have a more national focus or lower levels of international collaboration. This could have led to the outcome that China has a lower citation impact in WIDE relative to POOL.

The identification of subfields, based on seed articles followed by selection of relevant clusters, was more straightforward for some subfields and in some cases challenging. For instance, the subfields Recycling, Sensing and Self-healing had a rather strong cluster signal, and relevant clusters could be selected with relative ease. One the other hand, the subfields BIG and Manufacturability were more challenging. This was due to a number of reasons. First, the potential clusters identified for these subfields (along with MAP) showed a large extent of overlap, and it was not easy to assign clusters to subfields. Since we aimed to have non-overlapping cluster selections for subfields this meant that clusters were only selected for one subfield. Second, some subfields from the Battery 2030+ roadmap are easier to define from a conceptual view and other less so. For instance, aspects of sensing and self-healing are easier to pinpoint than the more process-oriented and conceptual subfields BIG and MAP. Therefore, the selection of clusters for some of the more forward-looking subfields (BIG, MAP) was more challenging. The selection for Manufacturability was especially difficult, for two reasons: 1) it shared several potential clusters with BIG that were later used in the analysis for BIG, and 2) it is a newly emerging scientific field without a fundamentally strong academic tradition. Historically, the subject has been closely tied to a few international companies, but not necessarily with results published in academic journals, which will make it more difficult to identify using our data and methodology.

Although the scope of BATTERY 2030+ is essentially chemistry neutral, lithium-based rechargeable battery chemistries are today associated with large publication volumes and as representative for the highest performing battery systems act as benchmark and take-off point for alternative chemistries. This up to present dominance of lithium-based chemistries is clearly reflected in the available literature in the field.

One thing to comment on is the overall scope of the study. The methodology used here, going from seed articles to potential clusters, followed by selection of clusters for each subfield (with the aim of targeting these specific subfields), probably leads to a relatively narrow interpretation of the battery field, primarily targeting the perceived scope of Battery 2030+. We also use two definitions of Battery 2030+ as a whole, POOL and WIDE, where the former creates the union of the subfields and WIDE selects a group of more general level-2 clusters that are connected to several of the subfields, but which are not tied specifically to any of them. However, to view the battery field as a whole, a much wider perspective could also have been utilized, where not only battery research but also related research and technologies from e.g. applied physics, chemistry and recycling technology could have been included. If using the same type of cluster methodology, such a study could have selected clusters at a higher level (level-3) or pooled a much larger set of level-2 clusters. Clearly, such a study would be more loosely tied to Battery 2030+, but might be relevant for an even wider overview of the relative strength of different geographical regions and research organizations.

4.2 Methodological limitations

Our approach is based on publication clustering, which in turn is based on direct citation relations. This has the advantage of providing a relatively objective basis for subject delineation, and it also does not require time consuming compilation and expert curation of publication sets that are deemed relevant for different subject areas. As such, the method is not sensitive to human biases on notions of subject field relations, literature from different parts of the world etc. However, a crucial step in using clusters to represent subject fields lies in the identification and selection of clusters. In this study, we have used seed articles from the Battery 2030+ roadmap for identification of potential clusters and expert-based screening of clusters.

Another thing to keep in mind is that each article in the modularity-based clustering is placed in exactly one cluster. This means that articles that fall in-between two subject areas will be placed in exactly one cluster. Among many potential ways to delineate subject areas, one will also dominate, based on the citation relations within the literature. As an example, of interest in this study, sensors in batteries can be approached both from a technical point of view (i.e. sensing technology, and ways to measure aspects of battery state) or from the approach of the battery states that need to be monitored and measured (i.e. state of charge, state of health etc.). In the article clusters, the second perspective dominates, mainly because of citation practices within the fields. However, this places a clear limitation on the selection of clusters, and it also means that studies of the technical perspective in the sensor example above will be more challenging to identify.

Another approach to obtaining article sets for subfields is to use search queries. However, an advantage of the approach followed in this work compared to the search query approach is that the former is not dependent on the identification of search terms standing for the same or nearly the same concept. This is because the articles in the classification system have been clustered based on direct citation relations between them, and not based on textual similarity. The article set for a given subfield may contain articles (pertinent to the subfield) that treat a certain topic but doing this by using partially different terminologies. With the search query approach, the used query may fail to retrieve some of these articles. On the other hand, a possible advantage with search queries is the ability for fine grained control over the selection, when this is needed, for a user with deep knowledge of the subject field.
One further caveat worth mentioning is that the cluster selection for subfields has been relatively independent and can follow slightly different principles. For instance, the relevant literature can be seen in more broad terms or more narrowly, as only directly relevant to e.g. lithium-ion batteries. As an example, the cluster selection for the subfield Self-healing is relatively broad, with the intention of selecting technologies probably relevant to self-healing

in batteries, but not limited to batteries. Therefore, this selection of articles is quite large. On the other hand, in the subfield Recyclability a number of smaller clusters is instead selected, which are directly related to the recycling of batteries in general, and specifically to lithium-ion batteries. For recycling, a wider perspective could have been chosen, for instance including metal recycling from mining runoffs or circuit-board recycling, but this was not done here. However, these different perspectives in subfield scope must be kept in mind when interpreting results, and especially in the POOL set, where the subfields with a broader selection will dominate the set and therefore also the mean-based indicators used.

4. 3 Conclusions

We put forward tentative conclusions and observations in the list below. These can in part be considered in the planned second bibliometric analysis, referred to in the section "Introduction".

- EU & associated are relatively well represented (as countries and organizations) in most subfields, but is often lagging North America in publication volume and citation impact. In POOL and WIDE, China is also showing stronger citation impact than EU & associated towards the end of the study period.
- Looking at the specific subfields and focusing on the end of the study period, EU & associated has the strongest citation performance, in relative terms, in MAP, while Self-healing is by far the weakest subfield.
- None of the themes in Battery 2030+ are established but rather emerging multidisciplinary scientific fields, which vary strongly in the degree to which they are connected to traditional subfields in battery research.
- The themes are expected to become more nested with time. For instance, the topics of recyclability and self-healing are until today primarily applied in other areas of research (such as biomaterials) with only a few links over to batteries.
- From our study it is also clear that topics in BIG and MAP, such as neural networks, are currently mostly applied to battery electrolytes, but aspects associated with the electrodes are expected to receive increasing future focus.
- For Recyclability, the areas of traditional battery recycling and electric vehicles with life cycle analysis are clearly observed as two distinct networks. The intensive research efforts on both batteries and electric vehicles today will likely reduce this separation as a more holistic approach to recyclability is needed.
- Although the concepts of importance for future manufacturability, such as microstructure and various simulation approaches, are found as small nodes, they are present in existing literature and expected to grow in importance, surely as a result of the growing efforts within Battery 2030+.
- The clusters in the Sensing subfield are clearly divided into two parts. One related to battery performance characteristics, which are intended to be probed by sensors, and the other related to the technical aspects of sensor operation. Although optically based methods are primarily represented, there are a number of other sensing technologies gaining momentum (e.g. acoustic emission sensing) and expected to result in significantly higher future publication volumes.

Acknowledgements

The authors thank Elixabete Ayerbe, Ivano Eligio Castelli, Robert Dominko, Alexis Grimaud, Philippe Jacques, Marcel Meeus, and Tejs Vegge for their contributions to the selection of articles for the subfields of the study.

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Appendix 1. Clusters used for the definitions of WIDE, the subfields, and POOL

Table A1. Clusters used for the definition of WIDE. The subfield columns indicate whether the cluster is ranked highly within the respective subfield, based on the seed articles (cf. Section 2.2).

Cluster label	**Cluster level**	**BIG**	**MAP**	**Self-healing**	**Sensing**	**Recycling**	**Manufac-turability**
LITHIUM ION BATTERY// CATHODE MATERIAL// LI ION BATTERY	2	1	1	1	1	1	1
POLYMER ELECTROLYTE// IONIC CONDUCTIVITY// SOLID POLYMER ELECTROLYTE	2	1	1				1
SOLID ELECTROLYTE//NASICON// ALL SOLID STATE BATTERY	2	1	1				1
LITHIUM SULFUR BATTERIES// LITHIUM SULFUR BATTERY// LI S BATTERY	2	1	1	1	1		1
LITHIUM ION BATTERY// SODIUM ION BATTERIES//ANODE	2	1	1	1	1		1
HIGH THROUGHPUT EXPERIMENTATION// MATERIALS INFORMATICS// COMBINATORIAL CATALYSIS	2	1	1				1
SHAPE MEMORY POLYMER// SELF HEALING//SHAPE MEMORY	2			1			

Table A2. Clusters used for the definitions of the subfields, as well as for POOL.

Cluster -id	Cluster level	Subfield	Cluster label
2666	1	big	ELECTROLYTE ADDITIVE// ENGN MTEES// PHYS ATMOSPHER SCI
24036	1	big	ELE OCHEM BRANCH// RED MOON METHOD// METAL ION BATTERY
18660	1	big	LITHIUM ELECTRODE// LITHIUM POWDER// LITHIUM METAL SECONDARY CELL
10642	1	manuf	SINGLE PARTICLE MODEL// PSEUDO TWO DIMENSIONAL MODEL// ELECTROCHEMICAL MODEL
37669	1	manuf	STOCHASTIC 3D MICROSTRUCTURE MODELING// ELECTRODE MICROSTRUCTURE// LITHIUM ION BATTERY ELECTRODES
5756	1	manuf	ORGANIC ELECTRODE MATERIALS// ORGANIC ELECTRODES// ORGANIC CATHODE
3248	2	map	HIGH THROUGHPUT EXPERIMENTATION// MATERIALS INFORMATICS// COMBINATORIAL CATALYSIS
12124	1	recycl	SPENT LITHIUM ION BATTERIES// SPENT LIBS// SPENT LI ION BATTERIES
37750	1	recycl	SPENT CATALYST// SPENT PETROLEUM CATALYST// SPENT HDS CATALYST
20131	1	recycl	WELL TO WHEEL// MOBIL AUTOMOT TECHNOL GRP MOBI// ELECTRIC VEHICLES
135737	1	recycl	RETIRED EV BATTERIES// BATTERY SECOND LIFE// SECOND LIFE BATTERY
1918	2	self-healing	SHAPE MEMORY POLYMER// SELF HEALING// SHAPE MEMORY
11757	1	self-healing	FIBER SUPERCAPACITORS// FIBER SHAPED SUPERCAPACITORS// YARN SUPERCAPACITOR
3972	1	self-healing	SI C COMPOSITE// NANOSIZED SI// SILICON GRAPHITE COMPOSITES
36417	1	self-healing	FLEXIBLE BATTERIES// STRETCHABLE BATTERIES// FLEXIBLE LITHIUM ION BATTERIES
87418	1	self-healing	MICROSPHERE BASED SCAFFOLDS// MICROSPHERE BASED SCAFFOLD// POLYLACTIC ACID GLYCOLIC ACID
300	1	sensing	STATE OF CHARGE// STATE OF CHARGE SOC// STATE OF CHARGE ESTIMATION
1617	1	sensing	BATTERY THERMAL MANAGEMENT// BATTERY THERMAL MANAGEMENT SYSTEM// THERMAL MANAGEMENT SYSTEM
134948	1	sensing	SENSORLESS TEMPERATURE MEASUREMENT// BATTERY CONVERTER// BATTERY THERMAL MANAGEMENT BTM
10704	1	sensing	THERMAL RUNAWAY// OVERCHARGE// LITHIUM ION BATTERY SAFETY
25403	1	sensing	TILTED FIBER BRAGG GRATING// TILTED FIBER BRAGG GRATINGS// ELE OMAGNETISM TELECOMMUN
9091	1	sensing	FIBER BRAGG GRATING// WAVELENGTH DETECTION// FIBER BRAGG GRATING FBG

Appendix 2 Most frequent terms in the author keyword co-occurrence networks per subfield, POOL and WIDE

This appendix contains tables of the 30 most frequent terms in the author keyword co-occurrence networks for each subfield, POOL and WIDE to aid in the interpretation of the these networks.

BIG

Term	No. occcurrences
lithium-ion batteries	260
electrolyte additives	136
solid electrolyte interphase	115
high-voltage	76
electrolytes	72
additive	41
graphite	23
density functional theory	19
elevated temperature	17
propylene carbonate	17
batteries	16
cyclic stability	15
lini0.5mn1.5o4	14
additives	13
cathode	13
fluoroethylene carbonate	13
lithium	13
vinylene carbonate	13
xps	13
cathode electrolyte interphase	12
high-voltage lithium-ion battery	11
sulfolane	11
lithium batteries	10
lithium-ion	10
dft	9
electrochemistry	8
ethylene carbonate	8
high voltage electrolyte	8
interface	8
interfacial stability	8

MAP

Term	No. occurrences
machine learning	107
artificial neural networks	57
high-throughput	42
materials informatics	41
density functional theory	40
data mining	34
high-throughput screening	31
combinatorial materials science	20
materials design	20
high-throughput experiment	19
molecular dynamics	16
thin films	16
heterogeneous catalysis	14
combinatorial chemistry	12
qsar	12
solar cells	12
ionic liquids	11
materials discovery	11
optimization	11
potential energy surface	11
artificial intelligence	10
phase diagrams	10
materials genome initiative	9
quantum-chemistry	9
catalysis	8
photovoltaics	8
potential energy surfaces	8
solar fuels	8
water splitting	8
x-ray diffraction	8

Recyclability

Term	No. occurrences
lithium-ion batteries	162
electric vehicles	151
recycling	138
life cycle assessment	129
spent lithium-ion batteries	103
leaching	71
spent catalysts	56
greenhouse gas emissions	52
recovery	46
bioleaching	44

cobalt	43
batteries	39
lithium	37
kinetics	30
solvent extraction	28
life cycle analysis	26
plug-in hybrid electric vehicles	25
well-to-wheel	23
greenhouse gases	20
energy-storage	19
co2 emissions	18
emissions	18
valuable metals	18
environmental impact	17
optimization	17
precipitation	17
spent libs	17
nickel	16
china	15
energy consumption	15

Self-healing

Term	No. occurrences
self-healing	704
shape-memory polymers	472
hydrogels	321
lithium-ion batteries	270
mechanical properties	257
polyurethane	193
shape memory	192
carbon nanotubes	140
microcapsules	122
nanocomposites	122
supercapacitors	121
smart materials	105
anodes	101
diels-alder reactions	90
graphene	85
polymers	81
stimuli-sensitive polymers	80
composites	77
hydrogen bonds	73
self-healing materials	65
self-assembly	64
silicon	63

supramolecular chemistry	63
dynamic covalent chemistry	57
flexible	57
crosslinking	55
double-network hydrogels	54
epoxy	54
shape memory effect	54
toughness	54

Sensing

Term	No. occurrences
lithium-ion batteries	873
state-of-charge	391
electric vehicles	273
thermal management	254
fiber bragg grating	171
battery management system	151
state-of-charge estimation	134
thermal runaway	132
batteries	117
state-of-health	116
phase-change material	93
lithium-ion	78
extended kalman filter	74
equivalent circuit model	70
thermal management system	69
safety	57
heat generation	52
optical fiber sensors	51
lithium batteries	50
battery models	48
tilted fiber bragg grating	48
kalman filters	47
electrochemical impedance spectroscopy	44
parameter identification	41
temperature	41
hybrid electric vehicles	40
battery modelling	38
battery packs	37
modelling	37
thermal model	37

Manufacturability

Term	No. occurrences
lithium-ion batteries	385
batteries	49
sodium-ion batteries	47
electrochemistry	36
lithium batteries	35
organic electrode materials	31
battery management system	30
cathode	30
electrochemical models	30
lithium-ion	30
x-ray tomography	26
anodes	24
organic cathode	24
energy-storage	23
modelling	22
electrochemical performance	21
microstructure	21
tortuosity	19
lithium	18
organic electrode	18
reduced-order model	18
single-particle model	18
electrodes	17
graphene	17
lithium-ion cells	17
organic electrodes	17
parameter identification	17
capacity fade	16
organic cathode materials	15
polymers	15

POOL

Term	No. cccurrences
lithium-ion batteries	1961
self-healing	705
shape-memory polymers	472
electric vehicles	432
state-of-charge	404
hydrogels	326
mechanical properties	261
thermal management	254
batteries	241
polyurethane	194

shape memory	192
battery management system	183
recycling	178
fiber bragg grating	171
carbon nanotubes	149
solid electrolyte interphase	141
state-of-charge estimation	141
electrolyte additives	138
lithium-ion	137
thermal runaway	136
anodes	135
supercapacitors	135
life cycle assessment	129
nanocomposites	129
lithium batteries	124
microcapsules	123
state-of-health	122
machine learning	121
energy-storage	117
graphene	109

WIDE

Term	**No. occurrences**
lithium-ion batteries	15637
anodes	2732
sodium-ion batteries	2103
cathode materials	1980
anode materials	1961
lithium-sulfur batteries	1961
cathode	1537
electrochemical performance	1440
graphene	1296
batteries	1185
ionic-conductivity	1110
electrochemical properties	1044
lithium batteries	979
electrochemistry	910
energy-storage	884
nanocomposites	845
self-healing	725
solid electrolytes	697
lifepo4	670
polymer electrolytes	660
solid electrolyte interphase	653
carbon nanotubes	641

electrolytes	641
x-ray diffraction	597
electrospinning	567
lithium-oxygen batteries	563
nanostructures	561
lithium	559
nanoparticles	557
silicon	529

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