Institute for Scientific Information

Global Research Report:
China's research landscape

October 2023

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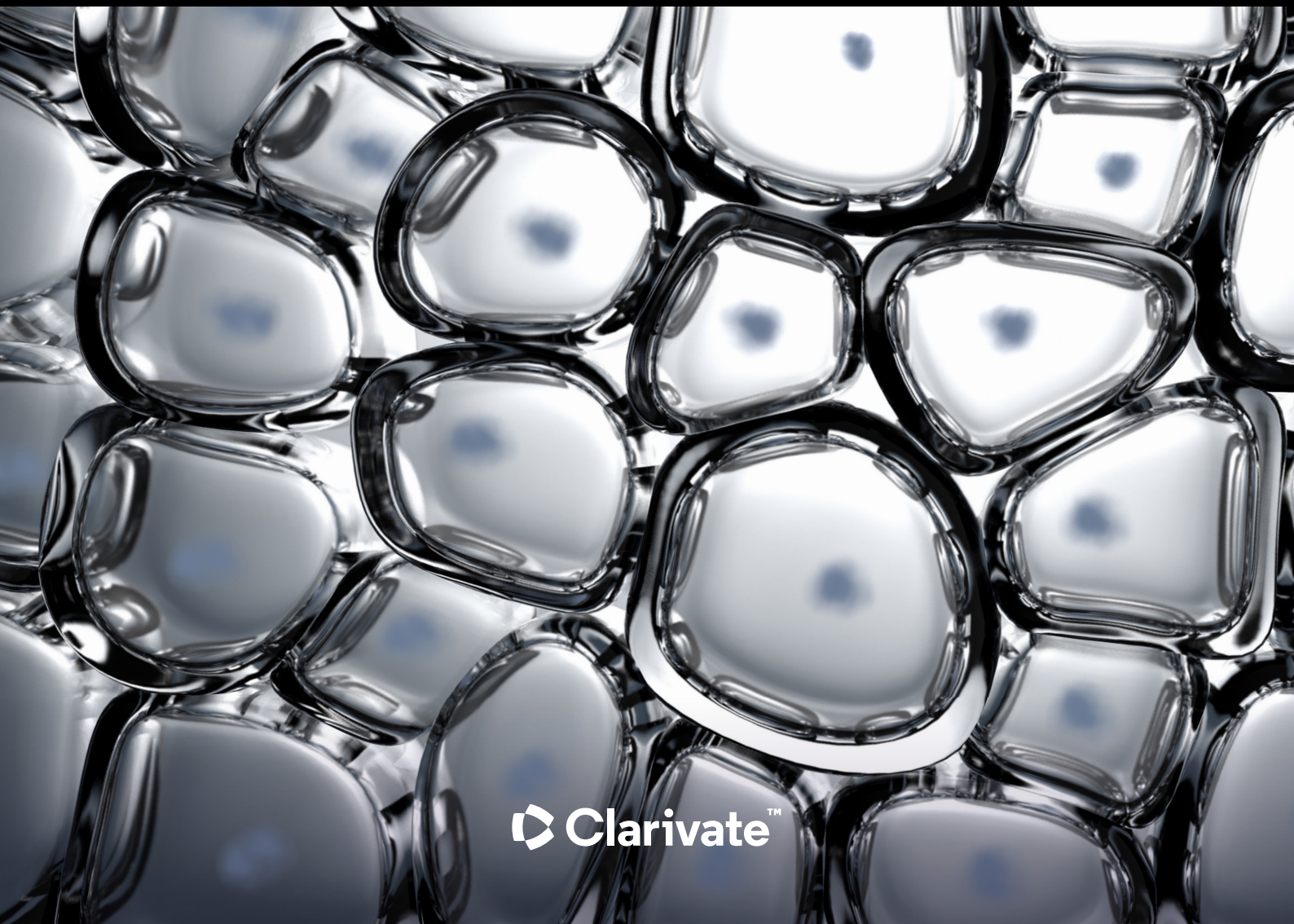

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The Institute for Scientific Information at Clarivate™ has pioneered the organization of the world's research information for more than half a century. Today it remains committed to promoting integrity in research while improving the retrieval, interpretation and utility of scientific information.

It maintains the knowledge corpus upon which the Web of Science index and related information and analytical content and services are built. It disseminates that knowledge externally through events, conferences and publications while conducting primary research to sustain, extend and improve the knowledge base.

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[*] In this report, the regional term China in technical analyses identifies the research activity of the People's Republic of China including Mainland China, Hong Kong and Macau. Some analyses cover only Mainland China excluding the latter areas. In discussion a more colloquial use of the term 'China' may be used without specific geographical reference

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Executive summary

China has transformed its research economy over the last 40 years, with its reported spending on research growing 400-fold. Its remarkable level of investment in research now exceeds that of the E.U. and is swiftly approaching parity with the U.S.

Our analysis shows this surge is mirrored by a corresponding acceleration in published research output. China now outpaces other major economies in terms of its publication of academic research articles and reviews in journals indexed in the Web of Science, including both the U.S. and the E.U. **(Figures 1.1, 1.2)**

This expansion has been accompanied by an increase in China's research subject diversity. Notably, China now publishes a greater share of the world's papers in engineering and technology than any other country/region and its activity in life sciences rivals that of the U.S. **(Figure 1.3a and b)**

An emphasis on quality as well as quantity is now clearly evident in citation analysis of China's research publications. China is now publishing as great a proportion of its research with citation impact above the global average as the U.S. and Germany. **(Figure 1.4)**

The shift in research quality is reflected in the rising number of the world's most Highly Cited Researchers based in China. This has surged from 312 in 2018 to 579 in 2022, doubling China's presence among the world's influential research elite. Over the same time span, the U.S. saw a decline in these numbers. **(Figures 2.1, 2.2)**

China's most highly cited research contributions are strongly represented in the disciplines of chemistry, engineering and materials science. Many Highly Cited Researchers are based at institutions with global reputations: the Chinese Academy of Sciences, Tsinghua University and the University of Hong Kong. China is home to 14 institutions hosting 20 or more of the world's most Highly Cited Researchers. **(Figure 2.3, Table 2.1)**

While international collaboration has experienced absolute growth, it represents only about 20% of China's total research output, a significantly lower proportion compared to other leading research economies. That share has changed little over 30 years. Its collaborations are also largely bilateral, in contrast to the increasingly multilateral research collaborations embraced by western nations. **(Figure 3.1)**

China's research impact is robust both within its domestic sphere and in collaboration with international partners. This stands in contrast to the U.S., which exhibits weaker multilateral international collaboration relative to the global average. **(Figure 3.2a and b)**

While continuing to collaborate frequently with the U.S. and E.U., China has recently emerged as a leading research partner for smaller nations across Asia and the Middle East. Egypt, Iran and Saudi Arabia have seen substantial growth in collaboration and China is the dominant research partner for Pakistan and Singapore. **(Figure 3.3)**

Research collaboration is particularly focused in technology areas, where China commands a substantial share of global output. It co-authors more than one-quarter of U.S. papers in topics such as automation control, imaging, ceramics nanoscience and telecommunications. **(Table 3.1)**

China's research landscape reflects its historical domestic strengths and its current focus on international collaboration is reflected in topics with notably high recent publication and global citation activity known as Research Fronts™. These pertain to topics in chemistry, materials and electrical engineering. China's leading Research Fronts center around green technologies, such as solar cells and fuel cells while also contributing the most core papers to Research Fronts relating to microwave absorption and electromagnetic radiation. **(Table 4.1)**

By contrast, China's citing of core research in Research Fronts is markedly greater in the realm of clinical and life sciences, pointing towards new areas of emerging interest and anticipated future expansion. The impact of China's emerging capacity and likely excellence will be of profound significance for many research developments globally. **(Figure 4.1)**

Introduction

This report on the growth and development of the research base in China is part of a series of Global Research Reports on the new geography of science.

This series reflected on the change between the research world of the 1980s, dominated by the G7 and Russia and looking much the same from year to year, and the dynamic shifts in the global network that were accelerated by the internet and among which China was a particular influence. We noted the emergence of a rich technology research base, reflected in the escalating volume of academic papers authored by Chinese researchers, published in internationally trusted journals indexed in the Web of Science. This grew from the existing industrial innovation system, the restructuring of specialist technology universities into multi-faculty campuses, a burgeoning space program and an 18% annual growth in Gross Expenditure on R&D (GERD) since our last Global Research Report on China in 2009. These developments were underpinned by comprehensive long-term planning and sustained, well-funded national programs and by a substantial expansion of both undergraduate and postgraduate training opportunities for Chinese researchers.

China's primary focus had been on core technology and physical sciences, giving it an exceptional share of global activity in important topics where other countries/regions had allocated fewer resources: for example, materials science.

We suggested that China's grip on innovative materials might have far-reaching effects, necessitating close collaboration for other countries/regions to grasp the implications of this research. Our analysis underscored new and rapid growth in bio-medical sciences — an area in which the U.S. and U.K. have invested heavily and have been recognized leaders, which was complementing China's technology strengths.

This new report builds upon our prior analysis and charts the exceptional research trajectory that China has followed. China's influence is profound, reshaping the research landscape in the Asia-Pacific region and recalibrating the global balance of capacity and innovation. The international discourse surrounding the China phenomenon has assumed a central role in research policy worldwide; its technology strengths have become dominant; and the emergence of biomolecular science that we identified has been solidified into a well-established domain.

"China's primary focus had been on core technology and physical sciences, giving it an exceptional share of global activity in important topics where other countries/regions had allocated fewer resources: for example, materials science."

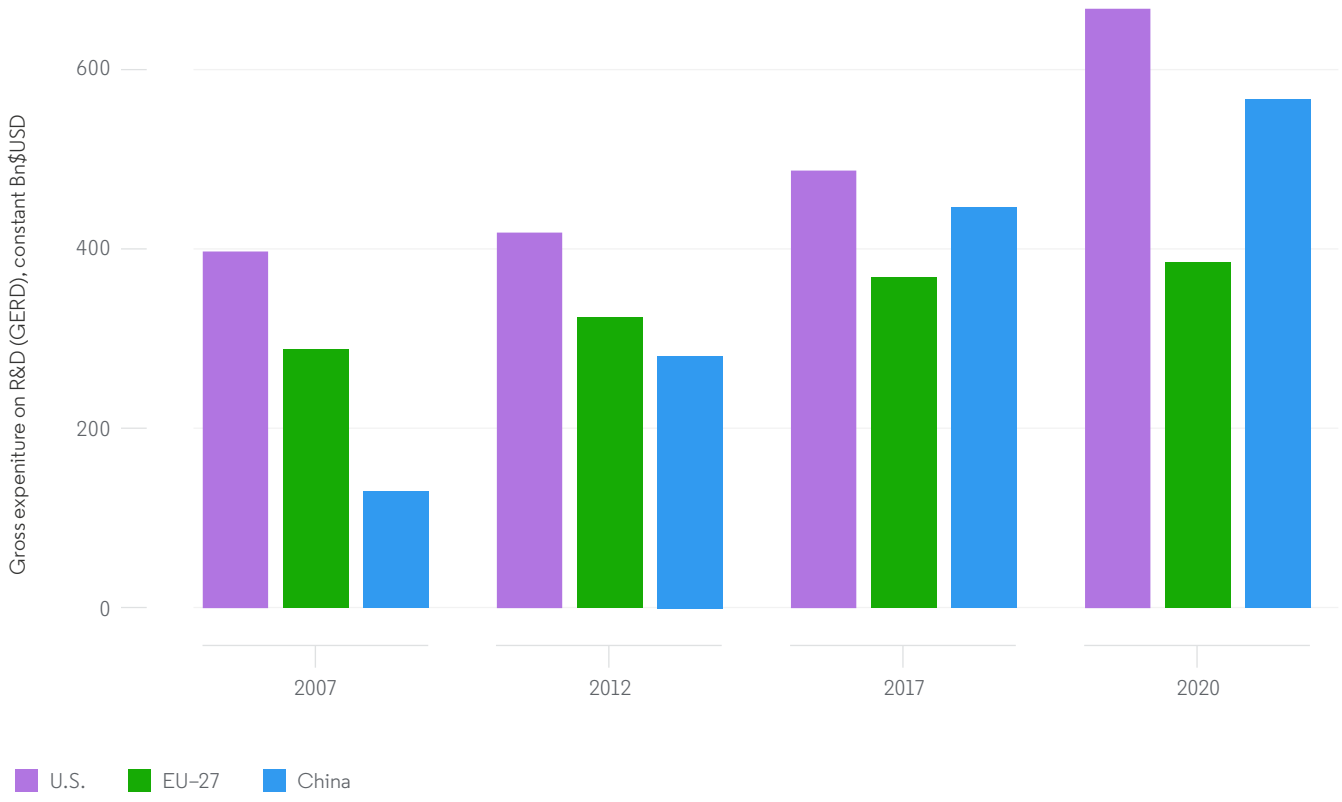
01. China's research profile

China's reported research investment in real terms has experienced a 400-fold increase in 2021 compared to the 1981 level.

This may not entirely represent the full extent of expenditure, since much prior R&D investment may not have been publicly disclosed. Nevertheless, the surge is consistent with the 300-fold growth of the research budget in South Korea.

In the last 10 years alone, China's investment has risen by a factor of 3.5, contrasting with growth rates of 1.5 for the U.K. and 1.3 for the U.S. China's investment now clearly exceeds the collective investment of the E.U. total and is swiftly approaching parity with the U.S. The overall level of research investment in the Asia-Pacific region, where China is the most influential axis, is likely to be a dominant factor in technology innovation for the foreseeable future. **(Figure 1.1)**

Figure 1.1: Gross Expenditure on Research & Development (GERD).



Source: OECD Main Science and Technology Indicators (MSTI).

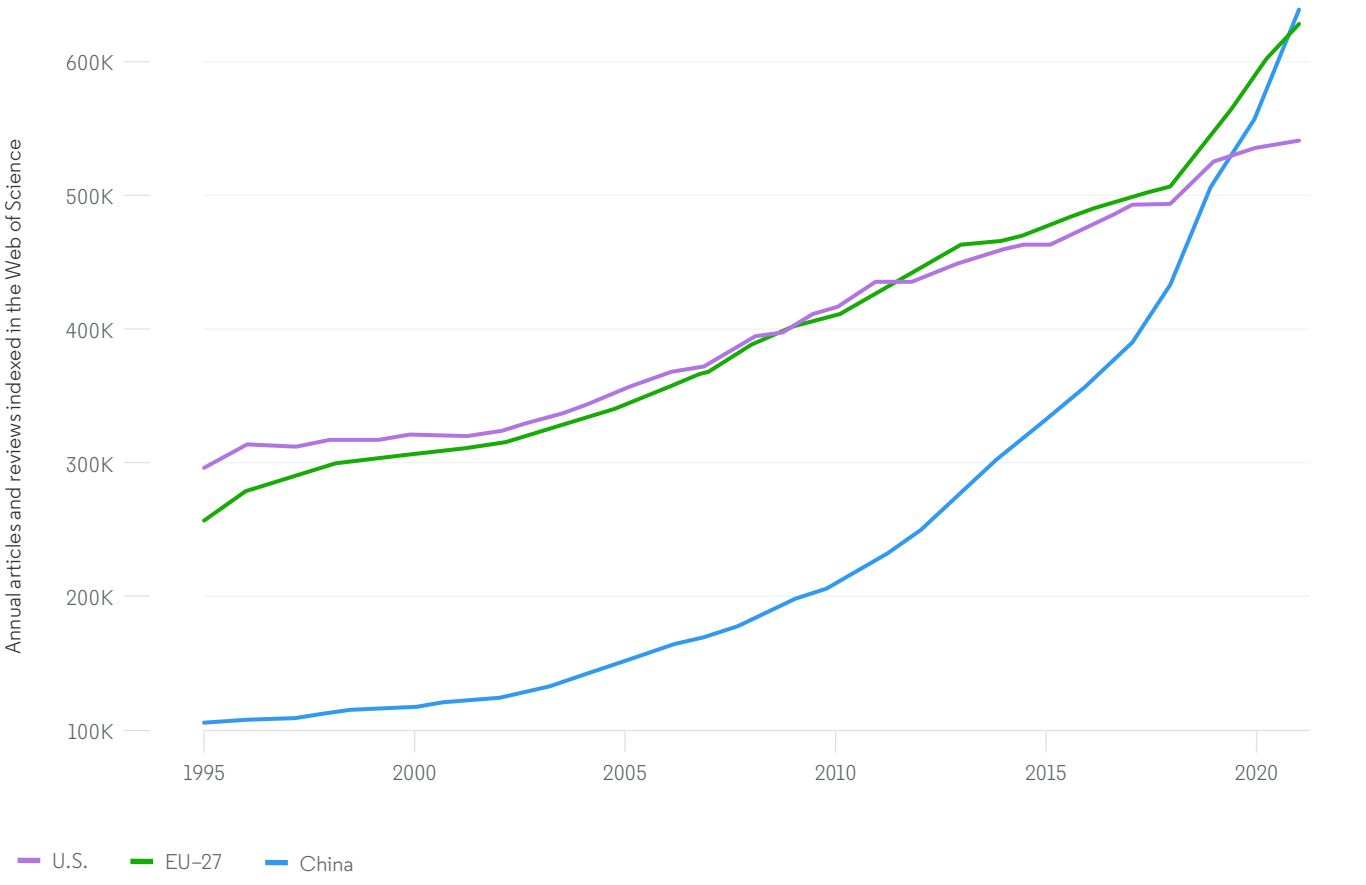
Research output

A steep rise in the output of original academic papers (that is to say, articles and reviews) reflects the shift of China's research towards more open and international engagement. To analyze this, we tracked the numbers of papers published in the 20,000-plus journals selected for indexing in the Web of Science. We counted papers for each country/region by checking the addresses of authors, assigning a paper once to each country/region for which there was an author affiliation, and using whole, not fractional, counts. Thus, a paper with five authors — two with China addresses, two with U.S. addresses and one with an Australian address — counts once for each country/region.

To provide historical context, national research output volume in the 1980s grew slowly from year to year and the relative numbers for each country/region remained much the same. From the 1990s onwards, the rise in international collaboration enabled by cheaper air travel and then the internet resulted in increased publication rates for most countries/regions. However, China's growth has been so fast as to disrupt historical norms and significantly alter the global balance.

China's publication output in 1995 was just over 12,000 papers. That rose to 120,000 by 2009 and in 2021, researchers based in China authored or co-authored around 650,000 papers. Over the same period (2009 – 2021), China produced a five-fold volume increase, U.S. output increased by less than 1.5-fold and the E.U.'s collective output increased by 1.75-fold. China now publishes more academic research papers annually than either the E.U or the U.S. **(Figure 1.2)**

Figure 1.2: Annual counts of academic papers (articles and reviews) published in journals indexed in the Web of Science.



"China has surpassed both the U.S. and the E.U. in terms of global production across various technology and physical science sectors. It exceeds U.S. output in plant and animal sciences, agricultural sciences and pharmacology and it is challenging the U.S. in molecular biology — aligned to our predictions made in 2009."

Reports often suggest that China's research growth trajectory must level out at some point. While that may be true, there is no indication of it so far. Indeed, since there are areas where China has yet to develop a significant international research publication base, it can reasonably be suggested that the trajectory could continue for some time.

The expansion of China's research was initially focused in those areas where its prior industrial base gave it momentum, including the core physical sciences and their overlap in materials science. Its research 'footprint' in 2007 – 2011 illustrates this pattern. The footprint is considered at the broad level of major subject domains covered in Clarivate Essential Science Indicators (ESI), such as chemistry, engineering and materials science. Even in those major areas where its research had developed, China was at that time producing a relatively small share of global outputs while in other areas, around clinical medicine, life sciences and social sciences, it had yet to develop as extensive a publication profile. **(Figure 1.3a)**

The footprint for 2017 – 2021 shows how much this has changed. Note that these data always show 'share' (percentage) of world output, so a country/region may be producing more papers in a subject than it had in the past but still have a relatively reduced share if the global total has grown faster. **(Figure 1.3b)**

China has surpassed both the U.S. and E.U. in terms of global production across various technology and physical science sectors. It exceeds U.S. output in plant and animal sciences, agricultural sciences and pharmacology and it is challenging the U.S. in molecular biology — aligned to our predictions made in 2009. Only in the medical sciences and in social science research does China deliver a modest share of world activity, and the latter may be accounted for by both distinct regional priorities and the obvious language barrier. In medicine, however, it is difficult not to believe that China's contribution will grow much further, boosted by its existing technology strengths. Indeed, as we note in **Section 4** of this report, it is anticipated that China's technological proficiency will contribute to important innovations in the biomolecular sciences where its approach may be a novel and complementary strand to pathways followed in Europe and North America.

The dominance of China's technology research can also be tracked at a more granular level, where it becomes clear that research output in many key topics recognized in the E.U. and U.S. as critical to the economy — and to many areas of innovation — is now led by China's researchers. Indeed, research collaboration with China has been a substantial part of the research growth that has been realized in many western nations. We explore the focus of these collaborations in **Section 3**.

Figure 1.3a: Research Footprints for China, the E.U. and the U.S. for the five-year period 2007 – 2011. Data are shown as each region's share (%) of world total output.

Figure 1.3b: Research Footprints for China, the E.U. and the U.S. for the five-year period 2017 – 2021. Data are shown as each region's share (%) of world total output.

"Because of lagging recognition, China's annual average CNCI initially appeared to decline, implying a potential inability to maintain research quality. However, our subsequent analysis revealed that with growing awareness, each year's research was in fact increasingly valued beyond its borders."

Research quality

The issue of research quality has been a topic of discussion raised by numerous commentators and policy analysts in the discourse surrounding China's research expansion. It has been asserted that while China demonstrates impressive productivity, it has not yet delivered a corresponding level of excellence.

One of the reasons for such assumptions has been the lag in recognition for China's research in other parts of the world. This was reflected in annual citation indicators. Citations are a sound indicator of the amount of attention that research receives, particularly for larger collections of papers, such as at national level. In turn, attention is often an indicator of significance and novelty of research. Citations accumulate over time at a rate that is field dependent, so raw data are 'normalized' to take variables such as document type, publication date and research category into account by comparing each paper's observed citation count with the relevant expected global average. This is referred to as a Category Normalized Citation Impact (CNCI).

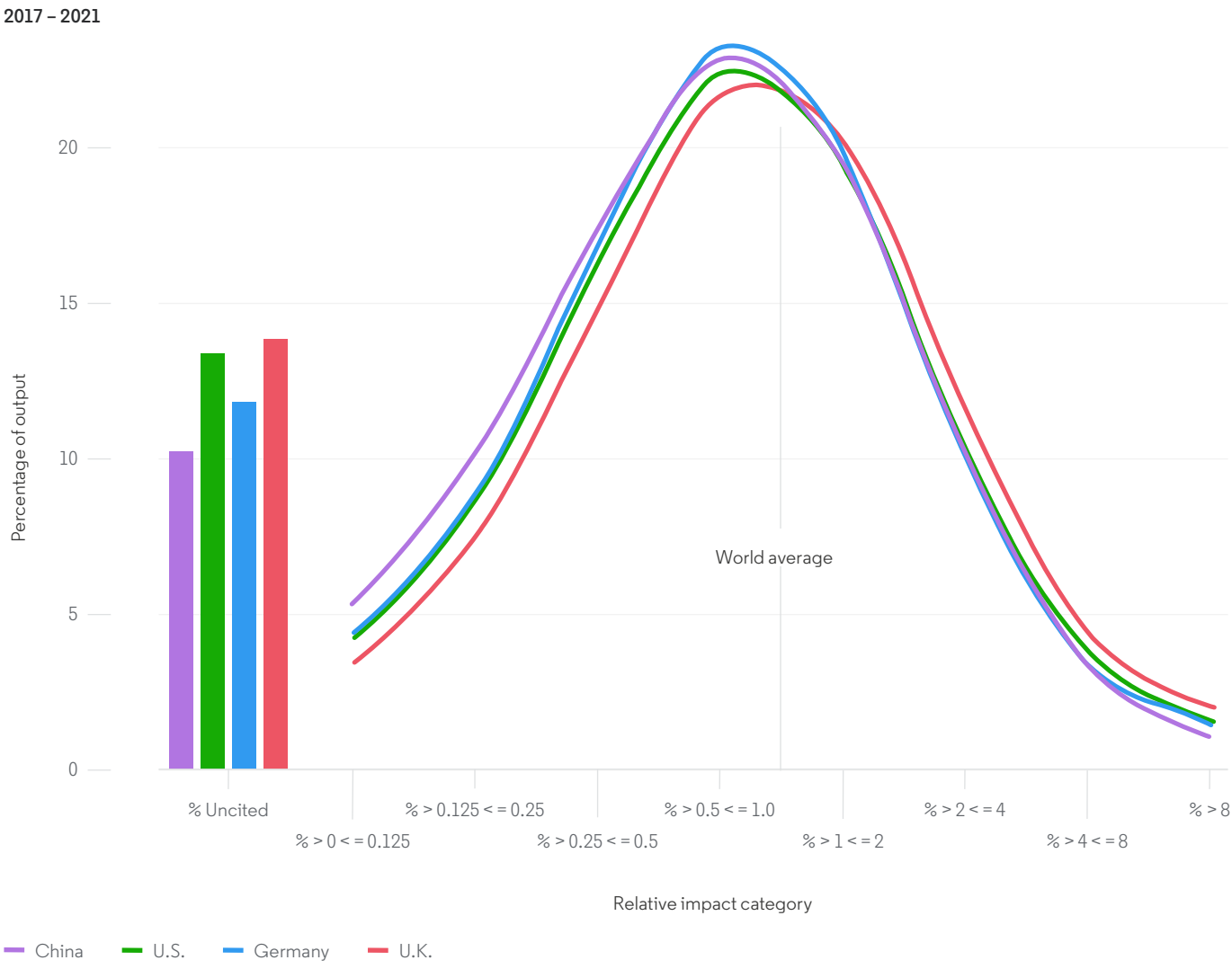
Because of lagging recognition, China's annual average CNCI initially appeared to decline, implying a potential inability to maintain research quality. However, our subsequent analysis revealed that with growing awareness, each year's research was in fact increasingly valued beyond its borders. Now, we can assess the overall performance of China's much expanded research base across an Impact Profile, which juxtaposes the distribution of well-cited and less-cited papers with those of other countries/regions. Although China still has relatively more papers in impact categories below world average, it is now publishing as great a proportion of its research as the U.S. and Germany in most CNCI categories above world average. Only in the elite category that exceeds eight times world average impact does it trail and then only marginally at around 1% of output compared to around 1.5% for its major competitors.

Because China is now so prolific, the absolute count of these Highly Cited Papers is in excess of 1,000 per year. Such a substantial volume of exceptional research provides a sound reason for both taking note of what China is doing and seeking to collaborate with the people who are delivering this.

It is also reflected in the increase in the numbers of China's individual researchers who are now recognized as 'highly cited'. **Section 2** discusses this and notes the institutions that host these peaks of research excellence.

"Exceptional research provides a sound reason for both taking note of what China is doing and seeking to collaborate with the people who are delivering this."

Figure 1.4: Impact Profiles of research output for China, the U.S., the U.K. and Germany for the five-year period 2017 – 2021. Individual papers are indexed and grouped by Category Normalized Citation Impact into citation impact categories below and above world average. Uncited papers are shown to the left. Data are shown by percentage output for each region or country for visual comparison, since their absolute publication output differs substantially.



02. Highly cited research in China

The dramatic rise in publication output from China over the past three decades and its production of Highly Cited Papers™ during the last decade have transformed the global scientific landscape.

In several domains and specialty areas, China now contributes as many or more Highly Cited Papers as the U.S. and other G7 nations with mature scientific and scholarly research systems **(Figure 1.2)**. At the very highest levels of publication citation impact, China has moved strongly ahead and has effectively dispelled the notion that China emphasizes quantity above quality **(Figure 1.4)**. Of course, every paper reflects the work of individual people, indicating a rise in the number of Chinese researchers producing work of a caliber comparable to that of elite researchers in other countries/regions.

Each year since 2014, Clarivate has issued a list of people recognized as Highly Cited Researchers. The methodology for identification involves a count of papers (articles and reviews) published during an 11-year period that rank in the top 1% by citations for each of 21 fields employed for their Essential Science Indicators (ESI) and by year of publication. In 2018, Clarivate also introduced a new Cross-Field category in its Highly Cited Researchers list. The inclusion of the Cross-Field category recognizes the interdisciplinary nature of modern research and the fact that groundbreaking work often spans traditional disciplinary boundaries — this category captures researchers whose contribution of Highly Cited Papers spans multiple fields, equivalent to exceptional performance in any one field. With this modification in method, the number of Highly Cited Researchers approximately doubled.

In 2022, the list comprised 7,221 Highly Cited Researcher awards: 3,981 category awards for the 21 ESI fields and 3,240 Cross-Field awards. Some individuals achieved recognition across multiple ESI categories (a few excelling in three or even four fields). Cross-Field recognition is only attainable when a researcher does not qualify for a single ESI field or category award.

In compiling the list of Highly Cited Researchers from each nation, Clarivate considers an author's primary affiliation only, as reported by them. In the case of China, we count Highly Cited Researchers who report a primary affiliation in the regions of Mainland China, Hong Kong, and Macau.

In the analysis for this report, we analyzed the Highly Cited Papers from the years 2007 – 2021 which formed the basis for the Highly Cited Researchers lists from 2018 – 2022. Each of these five annual lists (2018 – 2022) surveyed an 11-year window: for example, the 2018 list examined the papers that were highly cited in each ESI category from 2007 – 2017.

In 2018, Chinese researchers were recognized for 312 Highly Cited Researcher category awards across one or more of the 21 ESI fields. By 2022, this number had surged to 579, or an increase of 85.6%. These figures may be compared with U.S. researchers, who were awarded 1,818 awards in specific subject categories in 2018 and 1,566 in 2022. In percentage terms, China's world share jumped from 7.7% to 14.9% while the U.S. world share of Highly Cited Researchers declined from 44.8% in 2018 to 40.2% in 2022.

Taking into account the Cross-Field category, the total Highly Cited Researcher awards to Chinese researchers numbered 536 in 2018 and 1,289 in 2022, an increase of 140.5% - an increase in world share from 8.8% in 2018 to 17.9% in 2022. In contrast the U.S. world share of Highly Cited Researchers in both ESI fields and the Cross-Field category dropped from 43.4% to 38.1% over the same period **(Figure 2.1)**.

Analyzing only the Cross-Field category shows Highly Cited Researchers awards to Chinese researchers numbered 224 in 2018 and 710 in 2022, an increase of 217.0%. China's world share of Cross-Field Highly Cited Researchers increased from 11.1% in 2018 to 21.9% in 2022, almost a doubling **(Figure 2.2)**.

Figure 2.1: Highly Cited Researcher awards for China, the U.S., the U.K. and Germany for 2018 – 2022, where the awards are made for research output in a single subject category in Essential Science Indicators. Columns show the numbers of awards; lines show each country/region's share (%) of the total of awards in that year.

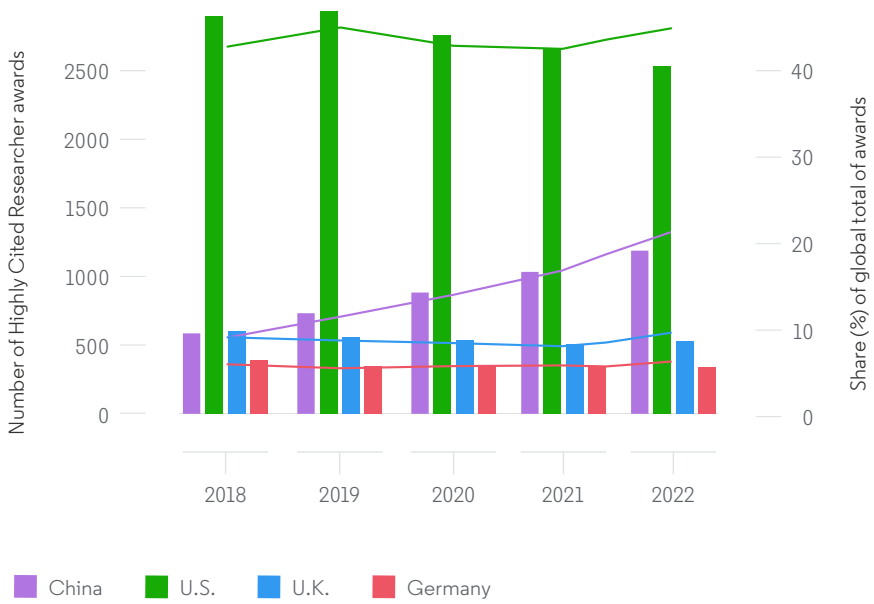
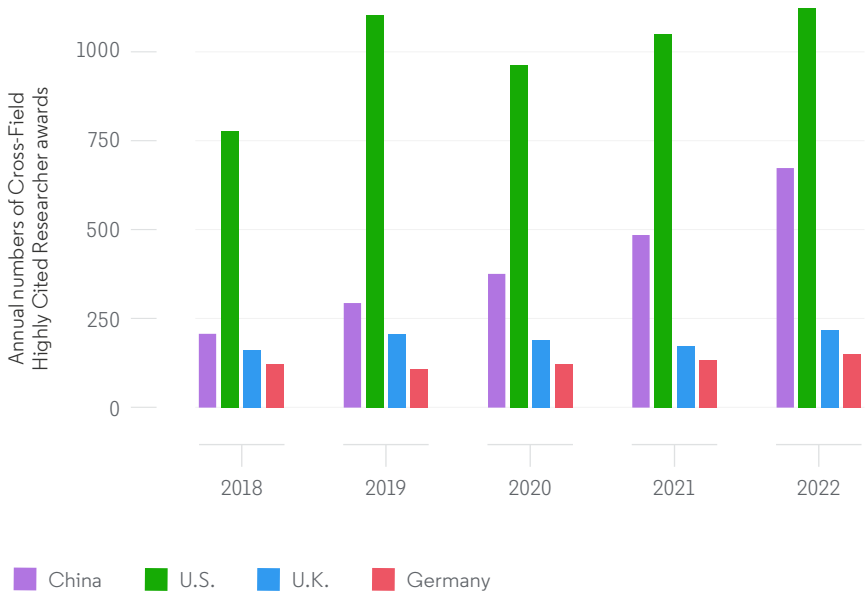


Figure 2.2: Awards to Highly Cited Researchers in the Cross-Field category, for China, the U.S., the U.K. and Germany for 2018 – 2022.



Of course, as China's output of Highly Cited Papers and authors of those papers has outpaced the world average, it is almost inevitable that the share of top-ranked papers and people associated with nations with a slower growing research base will fall.

Whether we analyze a particular field or consider them collectively, (as is the case with Cross-Field), Chinese researchers have successfully accrued more citations and thus more Highly Cited Papers in the observation period of 2022 compared to that of 2018. We have witnessed a remarkable doubling in total awards granted to Chinese researchers from 2018 – 2022.

Of course, this growth is not evenly distributed across China: there are evident concentrations, or hotspots, of research excellence, but the distribution of institutions is also changing. In 2018, 115 unique Chinese institutions were identified as primary affiliations by Highly Cited Researchers. By 2022 that number surged to 201, signifying that China's expansion in Highly Cited Researchers awards is both deepening and diversifying.

It is important to note that the Chinese Academy of Sciences (CAS) stands as a unique and sizeable institution, warranting separate consideration. Among the universities, Tsinghua University maintains a prominent second ranked position behind CAS in terms of numbers of Highly Cited Researchers and stands out as the premier Chinese university. Over the period of analysis from 2018 – 2022, the University of Hong Kong and City University of Hong Kong have both moved ahead by three positions, and Beijing Institute of Technology advanced by five places, from 13th to eighth. **(Table 2.1)**

Table 2.1: Chinese institutions identified to Clarivate as primary affiliations by Highly Cited Researchers: 2018 and 2022 domestic ranks, sorted by 2022 ranks; and the numbers of 2018 and 2022 Highly Cited Researcher awards.

2018 domestic rank	2022 domestic rank	Primary institution name	2018 Highly Cited Researcher awards	2022 Highly Cited Researcher awards
1	1	Chinese Academy Sciences (CAS)	90	177
2	2	Tsinghua University	26	71
6	3	University of Hong Kong	14	39
15	4	Hunan University	4	31
3	5	Peking University	20	30
9	6	City University Hong Kong	10	29
4	7	Zhejiang University	19	28
16	8	Fudan University	14	27
13	8	Beijing Institute of Technology	6	27
5	10	Suzhou University	18	26
7	10	University Science & Tech China (CAS)	12	26
5	12	University Electronic Science & Tech	18	25
8	13	Shanghai Jiao Tong University	11	21
11	14	Sun Yat Sen University	8	20
10	15	South China University of Technology	9	19
11	15	Nankai University	8	19
15	17	Tianjin University	4	18
12	18	Harbin Institute of Technology	7	17
15	18	Wuhan University	4	17
15	18	Central South University	4	17

From 2018 to 2022, the total number of awards assigned to Chinese institutions listed as primary affiliations (excluding the Chinese Academy of Sciences) increased by 149.3%. As of the latest ESI full-year data for 2022 (6th bimonthly for November and December 2022), Highly Cited Papers listing an address in China totaled 55,998 while those with an address in the U.S. totaled 76,500.

By ESI category, the U.S. led China in Biology and Biochemistry (BBI), Clinical Medicine (CLM), Economics and Business (ECB), Geosciences (GSC), Immunology (IMU), Microbiology (MIC), Molecular Biology and Genetics (MOL), Neuroscience and Behavior (NEB), Pharmacology and Toxicology (PHT), Physics (PHY), Plant and Animal Science (PLA), Psychiatry and Psychology (PSS), Space Science (SPA), and Social Sciences (SSS). **(Figure 2.3)**

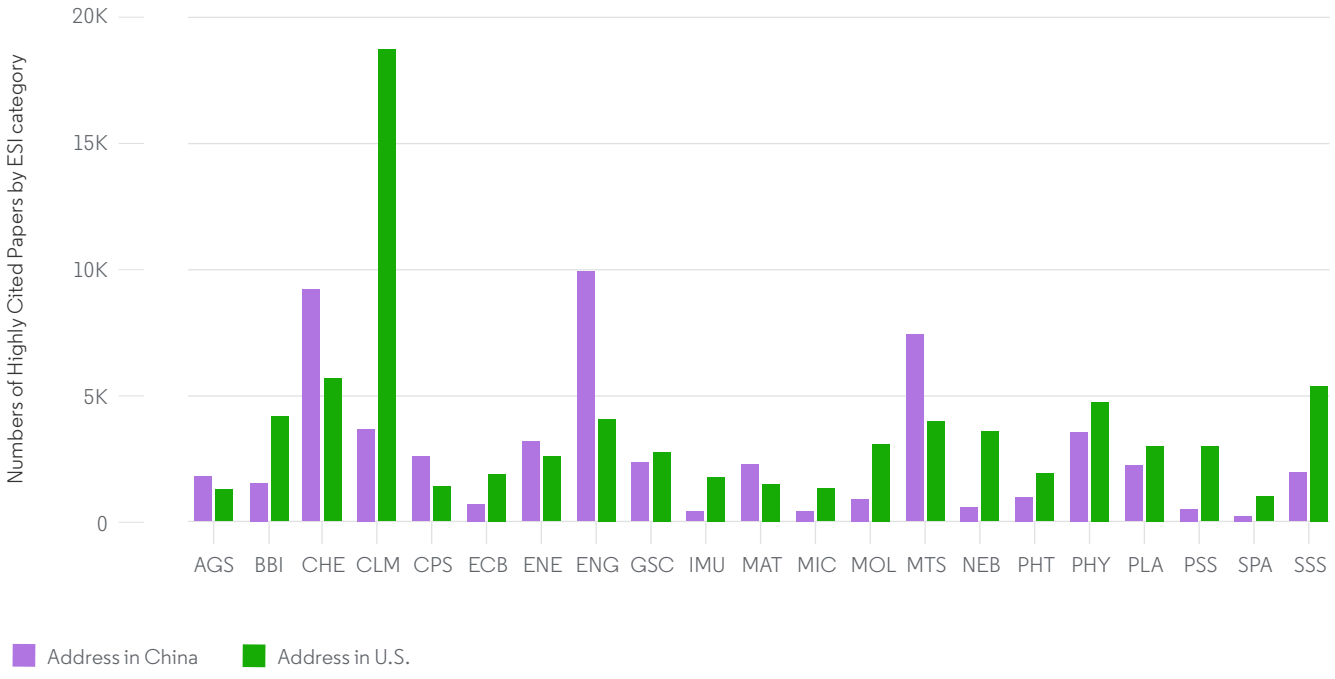
China led the U.S., — and sometimes substantially so — in Agricultural Sciences (AGS), Chemistry (CHE), Computer Science (CPS), Environment and Ecology (ENE), Engineering (ENG), Mathematics (MAT), and Materials Science (MTS).

Much of the U.S.'s lead in Highly Cited Papers can be attributed to the expansive Clinical Medicine category (about a fifth of all Highly Cited Papers), where the U.S. boasts 15,328 more Highly Cited Papers than China, constituting 74.8% of its total 20,502 paper advantage over China. In terms of Highly Cited Papers, the U.S. exhibits strength in biomedical sciences, physics and space science, as well as social sciences. On the other hand, China's research impact is focused on agricultural and environmental sciences, technology and engineering related fields.

The surge in China's tally of Highly Cited Researchers can be attributed to many factors, such as augmented investment in education and research facilities, strategic concentration on specific and significant topics that garner international recognition and citations and the overall improvement of its scientific and scholarly research base, whether in organization, strategic planning, or administrative efficiency.

As shown in **Section 3**, China's publications are heavily weighted to domestic collaborations as compared, for example, with European nations. Shifting from a mostly domestic to international collaboration may further boost China's Highly Cited Papers and people, since international co-authorship attracts citations at higher rates, for reasons of visibility, merit, or a combination of both.

Figure 2.3: Total Highly Cited Papers with at least one address in either China or the U.S. (as of the Essential Science Indicators) and summarized by ESI field. The field codes are identified and described in the text. Some papers have author addresses in both China and the U.S.



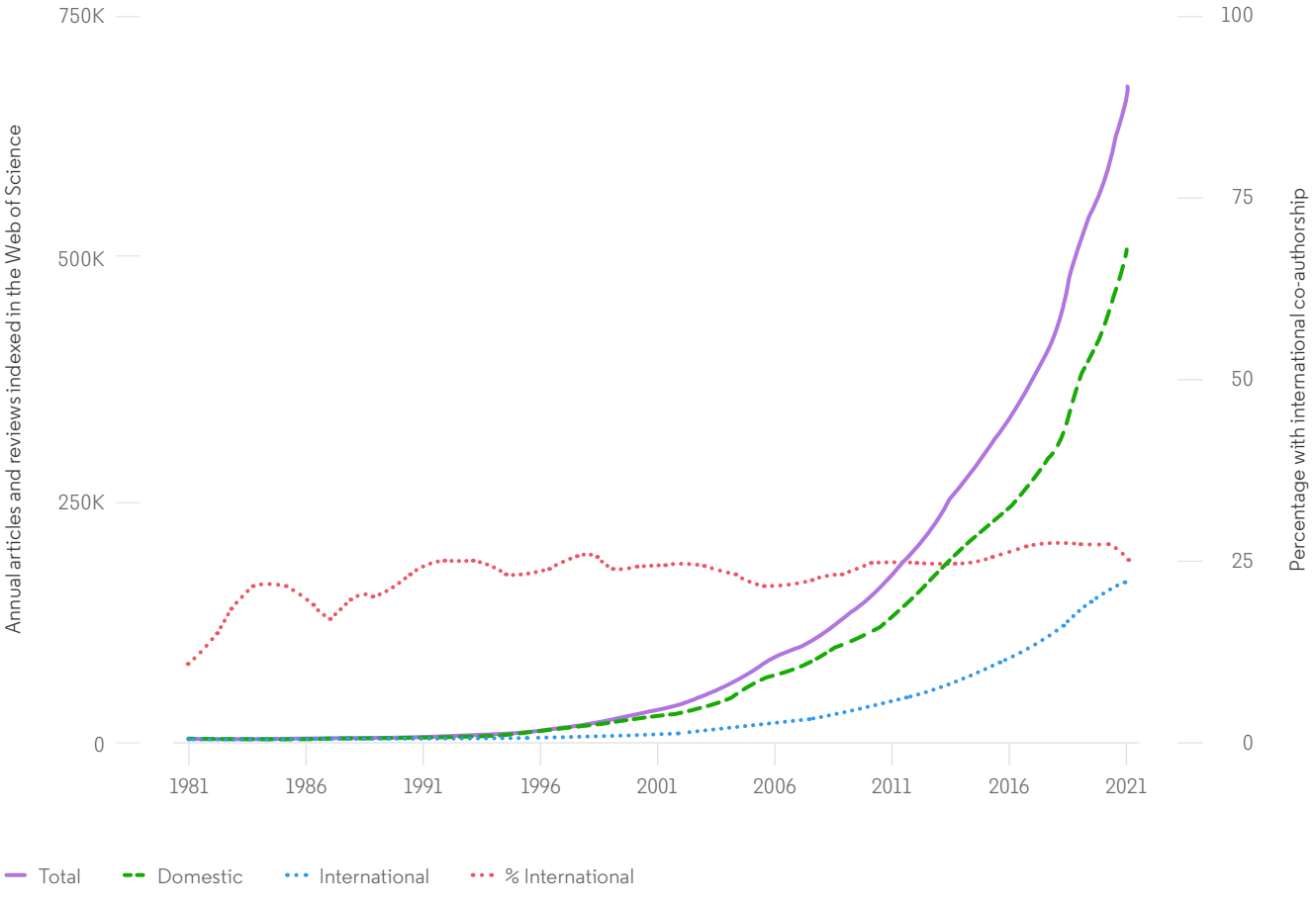
03. Research collaboration

Research quality

China is now such a substantial global presence as a research economy that few other countries/regions bear sensible comparison. As we discussed in the first section of this report, China has seen significant growth in its article output since 2013, outpacing all other global regions. Indeed, it is more informative to use other global 'regions' as benchmarks for China's activity.

The growth rates of China's output regionally (i.e., solely within China) and via international collaboration (i.e., collaborating with at least one other country/region) have been similar **(Figure 3.1)**. China's focus remains largely domestic, with the proportion of journal articles produced without any international collaborative partners fluctuating between 70% and 80%. This makes it the most internally focused global region since others have generally seen a progressive shift towards international collaboration. For comparison, U.S. domestic output is now below 60%, while the U.K. and E.U. economies typically demonstrate less than 40% domestic output.

Figure 3.1: Annual total of articles and reviews published in journals indexed in the Web of Science and with at least one author based in China. The right axis shows the percentage of this output that has at least one international co-author.



"It is widely recognized that articles with collaborative co-authorship are — on average — cited more frequently than similar articles with a single author."

Collaboration impact

It is widely recognized that articles with collaborative co-authorship are — on average — cited more frequently than similar articles with a single author. Similarly international collaboration provides — again, on average — a further boost to citation counts. The possible reasons for this are contested but it is likely that the relative costs of collaboration, both in terms of time and the inherent need for shared agendas and benefits, dictate that researchers only collaborate when there is the strong likelihood of producing innovative and impactful work that could not be achieved alone.

Clearly, the collaboration effect has consequences for the analysis of citation impact. It is therefore more informative if research output is deconstructed by collaboration types and ISI uses five types for this purpose: domestic single institutional; domestic multi-institutional; international bilateral, with the country/region of interest and one partner country/region; international trilateral; and international quadrilateral-plus. There are relatively few papers that have five or more countries/regions among author addresses.

The methodology has been applied to articles from the U.S. and China. China's domestically focused research (73% of output) over the decade accounts for 64% of all China's citations. More than three-quarters of its international collaboration is bilateral. U.S. output is less domestic than China (~61%) but, as with China, most international partnerships are bilateral in nature (73%). **(Figure 3.2a)**

A greater proportion of multilateral collaborations, compared to China, will tend to produce a higher average citation impact (CNCI) for other countries/regions. To improve comparability, we can further normalize the CNCI values by collaboration type; publication year, subject area and document type have already been taken into account by conventional CNCI. This modified citation index is called Collab CNCI and is described in detail by Potter et al. (2020, 2022).

Collab CNCI not only normalizes citation counts by the type of collaboration, but also incorporates the aforementioned factors. For example, the conventional CNCI of a domestic paper is compared in Collab CNCI with the global average CNCI for other domestic papers whereas a paper with international bilateral authorship is compared with other internationally bilateral papers. This not only modifies the CNCI value (and Collab CNCI is typically less than the standard CNCI value for the same set of papers), but also enables us to see whether a country/region's domestic papers are more or less impactful compared to other domestic papers. In other words: are they good for their type?

When the ISI examined the Collab CNCI values across the five different collaboration types for China and the U.S. **(Figure 3.2)** it became apparent that China's Collab CNCI values are broadly consistent (between 1.12 and 1.22), whereas U.S. values decrease as collaboration increases from 1.35 for domestic single institution articles to 0.97 — below world average — for international quadrilateral-plus articles. This suggests that China's research impact consistently surpasses world average - regardless of collaboration type. Both China and the U.S. exhibit higher Collab CNCI values for their domestic research compared to their collaborative research. This indicates that both have a strong domestic base. While both are now also frequent research partners for many countries/regions, it is noteworthy that the most highly multilateral U.S. papers do not perform as well, relatively speaking. **(Figure 3.2b)**

Figure 3.2. Article and citation data (2013-2022) for China and the U.S. deconstructed by collaboration type (dom:single – domestic single institutional; dom:multi – domestic multi-institutional, int:bilat international bilateral; int:trilat – international trilateral; int:quad+ – international quadrilateral plus).

Figure 3.2a: The balance of different publication modes across the research portfolios of China and the U.S.

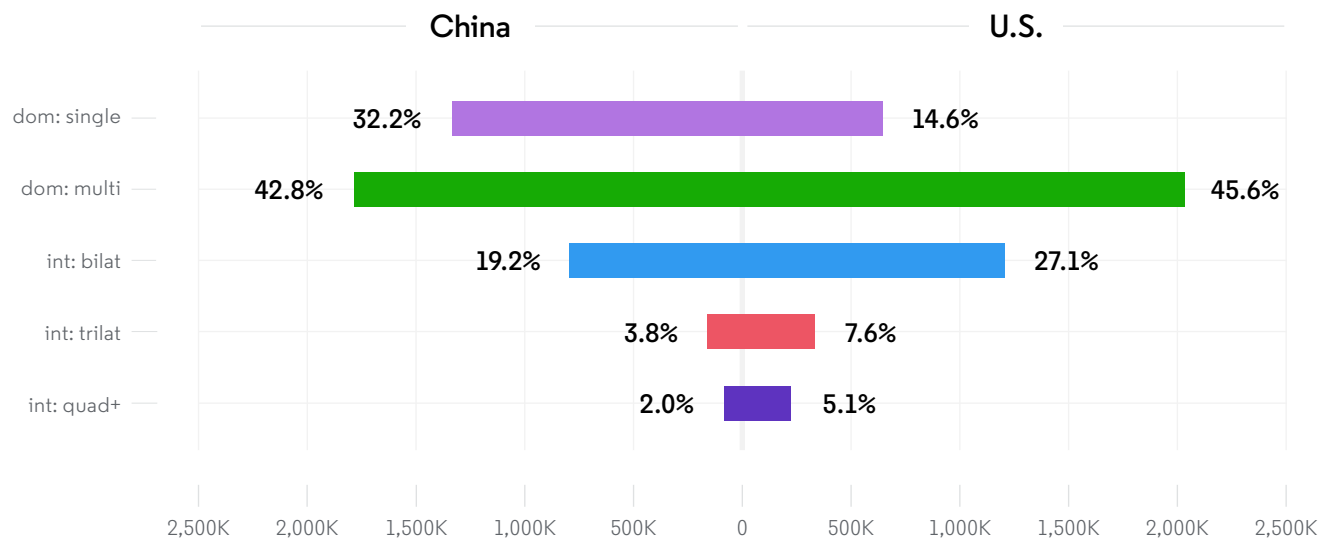
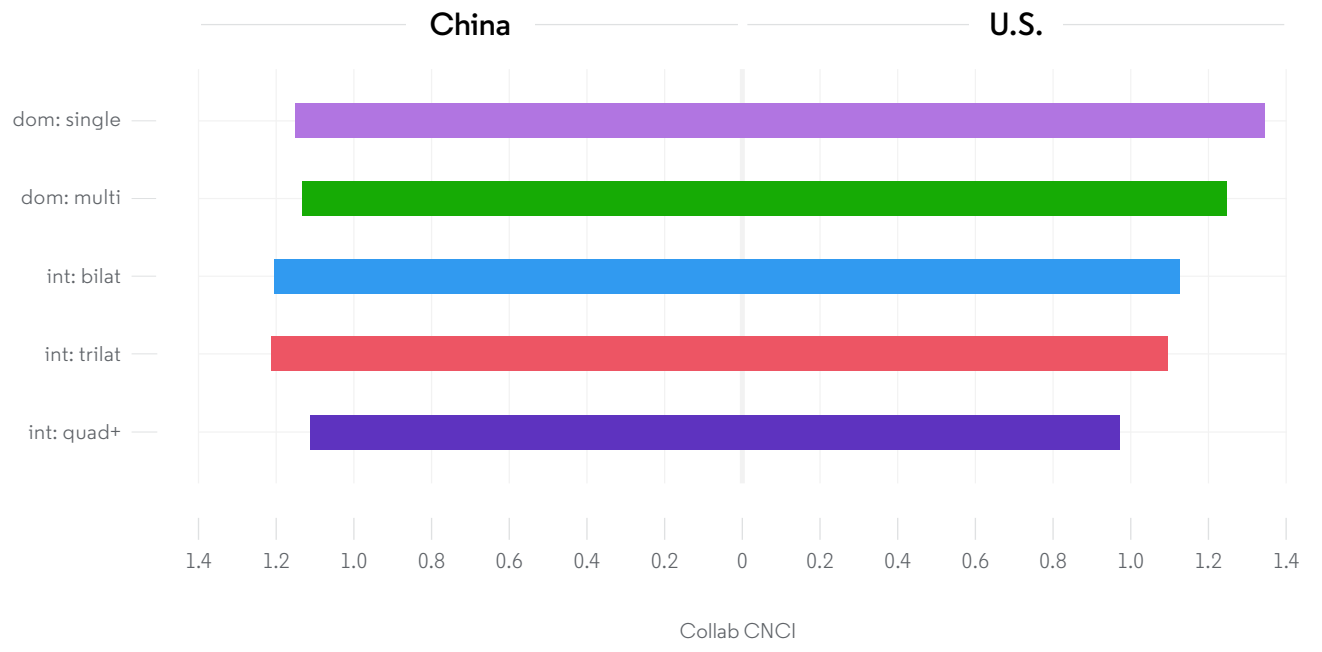


Figure 3.2b: Category Normalized Citation Impact (CNCI) of each publication mode across the two portfolios.



China's collaboration network

The United Nations comprises 193 sovereign states. China collaborated with 164 of these in 2013 and its expanding network encompassed 191 by 2022. Newer collaborations generally involved developing countries/regions, characterized by smaller researcher populations, lower GDPs or relatively modest R&D expenditure (GERD). These collaborations frequently extended to regions such as Africa, the Pacific and the Caribbean. Most of these collaborations were small in volume: only Libya (37), Tajikistan (40), and Palestine (92) collaborated with China on 30 or more papers in 2022. For Libya and Pakistan, this represented about 10% of their international collaborations — but for Tajikistan it constituted a significant 36%.

Over the past decade, the U.S. has stood as China's most frequent international research partner, contributing as a co-author on over 40% of China's collaborative output. This surpasses that of other key partners (the U.K. ~12% and Australia ~10%) but the U.S. has a far larger output total. While many of China's major collaborators are from Asia, others are from northern and western Europe, including many G20 member nations.

Given China's rapid growth in research output, our analysis extends beyond the absolute numbers of collaborative papers to examine how those numbers scale as a share of China's total international collaboration. As China's collaborative network has grown, the percentage of their collaborations with the U.S. surged to more than 40% after 2011, but then fell back to approximately 30%. Japan's share also decreased. However, there was an increased share over 2012 – 2021 for Australia (from 7.5% to 9.9%) and the U.K. (from 8.9% to 11.8%).

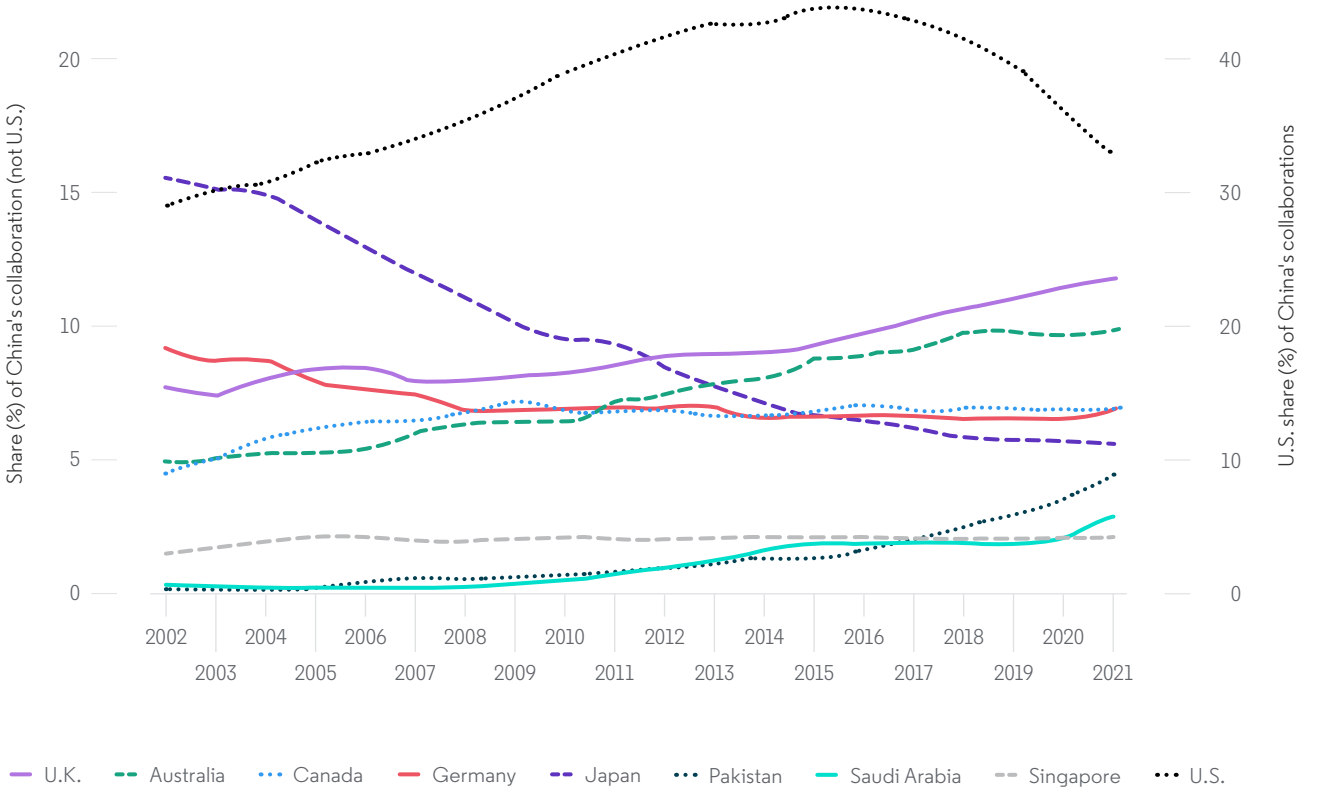
Only two other nations increased their share of China's international collaborations by more than two percentage points over the decade: Pakistan (share growth from 0.8% to 4.4%) and Saudi Arabia (from 0.8% to 2.8%). Saudi Arabia's increased share was demonstrated by a tenfold increase in volume, resulting in 4,695 collaborative papers. Other Middle Eastern nations have also witnessed recent substantial growth in their absolute collaboration volume with China: Egypt (12-fold increase to 2,585 papers in 2021); Iran (15-fold to 2,814 papers); and Iraq (30-fold increase to 365 papers). **(Figure 3.3)**.

Another perspective on international collaboration is obtained by considering not only the share of China's activity that a partner secures **(as shown in Figure 3.3)** but also the share that these collaborations represent for the partner country/region's own output. In other words, what does the balance in the relationship look like? Typically, the ratio of collaborations as a percentage of the partner's output and as a percentage of China's output will be greater than one due to the substantial size of China. But the trend in that ratio and comparisons between partners can offer valuable insights.

We analyzed the absolute percentage point difference between a country/region's share of China's collaborative output **(Figure 3.3)** and China's share of the country/region's collaborations for the 12 countries/regions that collaborated most frequently with China in 2022 **(Figure 3.4)**. The U.K. serves as an exemplary case, maintaining a remarkable balance: 10% of its collaborations in 2014 were with China and 10% of China's collaboration were with U.K. Most instances reflect changes in relationships with China.

"Over the past decade, the U.S. has stood as China's most frequent international research partner, contributing as a co-author on over 40% of China's collaborative output."

Figure 3.3: Percentage share of China's internationally co-authored papers for the more frequent collaborating partners during the latest year (2021). Note that the U.S. data are shown on a separate axis as the U.S. has an exceptional share compared to others.



For the U.S., the percentage point difference declined: a trend unique to the U.S. In 2013, the U.S. accounted for ~47% of Chinese collaborations, while China contributed to ~18% of U.S. collaborations, resulting in a difference of 30 points. By 2022, the U.S. accounted for 32% of Chinese collaborations and China accounted for 25% of U.S.'s, reducing the difference to just seven points. If this trend continues, the two will reach collaboration parity within a few years.

Singapore, renowned for its excellent relative international research profile, has seen a very different pattern to the U.S. with a percentage point difference that increased from <30 to ~48. It is notable that Singapore's share of China's collaborations has remained constant over the period (~4.5%) which indicates this partnership grew at the same rate as China's overall international portfolio. However, looking at this from a Singapore perspective, whereas one-third of Singapore's collaborations were with Mainland China in 2013 this increased to more than one-half by 2022. Singapore may be increasingly engaged with China as a collaboration partner.

Pakistan's collaborations with China increased substantially, from fewer than ten papers in 2001 to almost 7,500 articles and reviews in 2021, which compares to fewer than 5,000 China collaborative papers in 2021 for its neighbor India. Pakistan's share of China's collaborations grew five-fold to 2022 (from 1.1% to 5.1%), making it one of the ten most frequent collaborators with China, while its internal percentage with China only doubled (from 18% to 34%) between 2014 and 2019. Pakistan and China are evidently increasing their collaboration in a mutually beneficial manner. In fact, Pakistan (32%) and Singapore (43%) have by far the largest percentage of their international collaboration with China for nations with >10,000 collaborative papers with China.

China's collaborative focus

A more granular analysis is required to understand and interpret the intricacies of these relationship dynamics. The data clearly show that many countries/regions are increasingly engaging with China as a research partner. Its growing ties to emerging research economies in the Middle East is likely to be of widespread interest and its relationship with many countries/regions along the broad track of its belt-and-road initiative shows the importance of research investment as an aid to cultural diplomacy.

A question of wide interest is where China's research is concentrated. We provided a high-level view in the Research Footprints **(Figure 1.3)** and showed where the balance of its collaboration is focused.

To accomplish this, we specifically examined how China's collaborations are unfolding with the U.S. and the E.U. as comparable global regions.

China evidently has an exceptional share of the world's research publications in technology areas. In fact, this exceeds 40% of all articles and reviews published between 2017 and 2021 in areas such as automation control, telecommunications and nanotechnology. It also maintains a close partnership with the U.S. in those areas, with as many as one-third of U.S. papers in telecommunications and over one-quarter in a spread of other areas featuring a co-author affiliated with China institutions. China's share of the E.U.'s papers is notably less, usually just over 10% of the region's total.

As we noted earlier, China is progressively expanding its research base in biochemistry and molecular biology and in medical areas. However, the share of U.S. output co-authored with China is much lower in those subjects, although the U.S. should be able to support the development of such research since it has been a long-time research strength of the U.S. National Institutes of Health. China's share in the E.U.'s publications is even smaller again, despite the E.U.'s research strengths and their considerable contribution to global output. **(Table 3.1)**

These analyses suggest that China is relatively selective in its research collaborations. It collaborates much more broadly with some countries/regions, as diverse as the U.S. and Pakistan, and has more limited collaborations with others. It collaborates much more intensively in areas of existing strength, such as technology, rather than biomedical areas that it now seeks to develop. The evolution of China's research portfolio will be a continuing topic of interest for policymakers elsewhere.

Internationally collaborative research is impactful and often highly innovative. The potential for research in emerging green energy technologies could prove to be a major benefit stemming from China's engagement in the Middle East, where funding for such initiatives is growing. In the upcoming section, we discuss innovative methodologies for examining not only what China has already undertaken, but also shed light on the direction its research is now heading, through the medium of 'Research Fronts'.

"Internationally collaborative research is impactful and often highly innovative. The potential for research in emerging green energy technologies could prove to be a major benefit stemming from China's engagement in the Middle East."

Table 3.1: Share of global papers (articles and reviews) published in journals indexed in subject categories in the Web of Science (2017 – 2021) for China, the U.S. and the E.U., and the percentage of their output on which the U.S. and the E.U. collaborate with China.

Subject category	Share (%) of global output			Share (%) with China	
	China	U.S.	E.U.	U.S.	E.U.
Automation control systems	46.3	13.6	41.3	28.4	11.9
Imaging science	44.9	20.3	48.9	29.3	11.4
Ceramics	44.6	7.6	27.8	24.4	9.8
Telecommunications	44.5	13.5	33.7	33.4	13.2
Optics	43.5	14.3	38.0	18.4	7.9
Nanoscience and technology	43.0	19.9	36.6	27.6	9.6
Remote sensing	41.7	19.6	51.8	28.6	10.8
Geological engineering	41.6	12.9	37.2	24.1	9.8
Integrative complementary medicine	41.3	10.3	20.3	17.3	6.0
Applied chemistry	39.6	8.6	38.6	29.4	4.9
Cell biology	32.6	29.9	50.7	15.7	3.5
Oncology	30.9	29.6	48.7	10.6	2.6

04. Research Fronts in China

In Section 1 of this report, we delved into China's research landscape, observing trends that underscore its increasing productivity in fields such as Materials Science, Engineering, Computer Science and Chemistry. In Section 3, we looked in more detail at China's output and collaboration in specific subject categories. A further question, given this high-level information, is what the topical focus of that research might be?

There are various ways we could address this question. The Web of Science journal-based categories **(Table 3.1)** are more focused than the ESI fields of, for example, Materials Science and Engineering **(Figure 1.3)** and provide a useful starting point. Nonetheless, Telecommunications, Artificial Intelligence and Ceramics remain somewhat ambiguous. We can use the citation links between papers to increase the resolution of the categorization by clustering from the individual document level upwards. This guides us to Macro (coarse grained) and Micro (fine grained) Citation Topics. Using this method, we can identify the leading micro topics for China's research in Supercapacitors, Deep Learning and Long non-coding RNA.

While these citation-based categories help to give an overview of research by general themes, they fall short of capturing an understanding of the current hot topics that are drawing on this research in a holistic manner. How, for example, is Deep Learning being studied or applied?

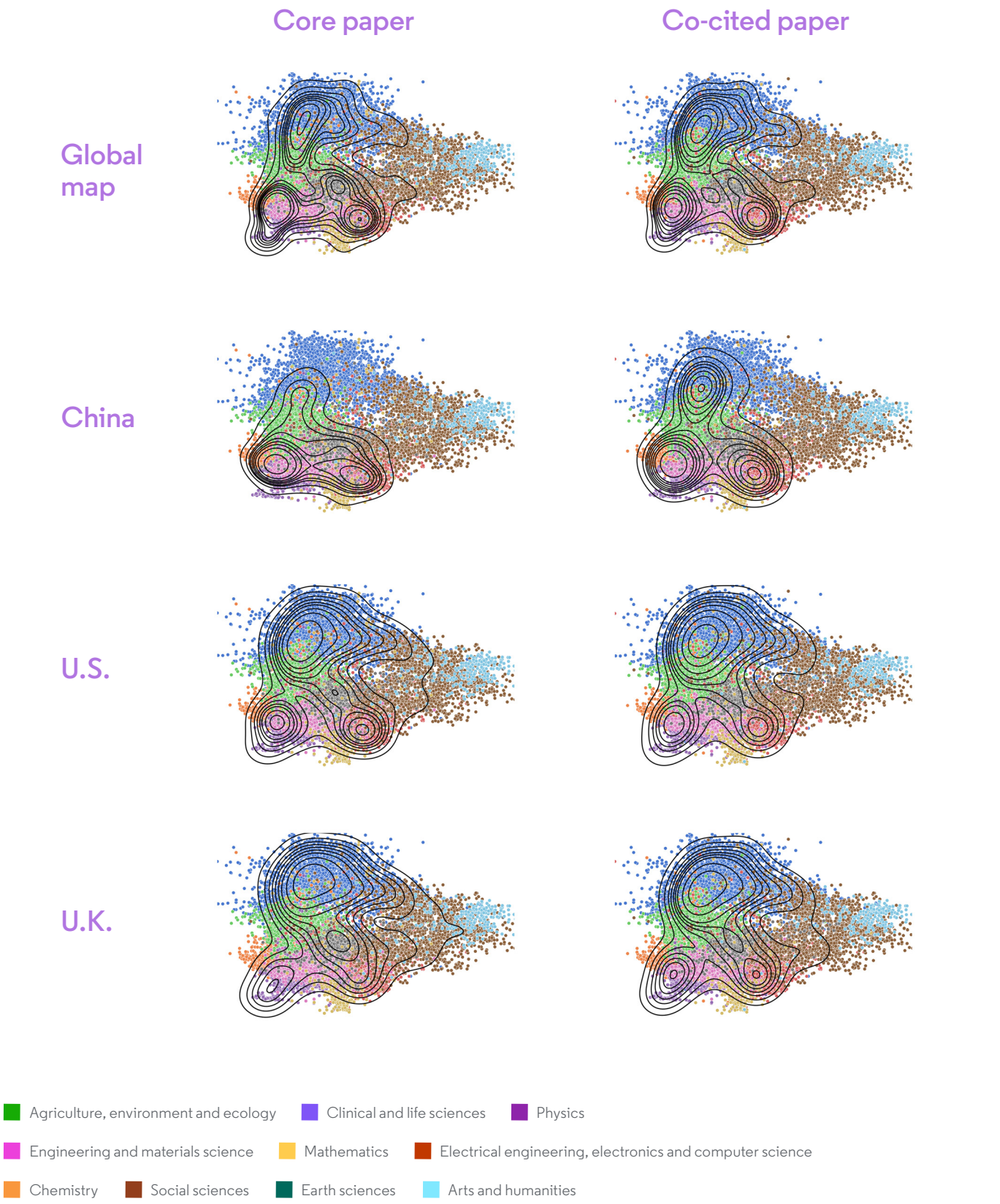
To address this gap, we turn to the idea of a Research Front: an emerging field or growth area in research, as explored in our Global Research Report: **Identifying Research Fronts in the Web of Science** (Szomszor, Pendlebury and Rogers, 2020). Our methodology to identify Research Fronts involves clustering recently published, Highly Cited Papers based on the even more recent papers that cite them.

The emphasis on papers that are both recent (published within the last five years) and highly cited (those in the top 1% by citation count by field, document type and publication year) ensures a focus on cognate papers in hot research topics. These clusters provide two key things: the highly cited core papers that form the source platform of innovative knowledge in each Research Front; and the papers that co-cite at least two of the core papers and show how the innovative knowledge in the core papers can be applied.

With an appropriate choice of clustering resolution, we have identified around 13,000 Research Fronts. By filtering these clusters based on the countries/regions involved in either the core or co-citing papers, we can begin to understand the hot topics in China's research focus.

Starting with the methodology used to create a heat map of research generally (Global Research Report: **Unpacking research profiles: moving beyond metrics**, Figure 6; Adams, Pendlebury, Potter and Rogers, 2023), we can calculate a weighted average location for each Research Front and plot them as a scatterplot across the map. The research focus taken by different countries/regions can then be revealed if we overlay a set of contours on this map (using what is known as a kernel density estimate). This is readily applied to research data for the world research network as a whole and then separately for China, and — for comparison — the U.S. and the U.K. We can compare the distribution of core and co-citing papers, with Research Fronts colored by their most common Macro Citation Topic **(Figure 4.1)**.

Figure 4.1: The distribution of Research Fronts, by Macro Citation Topic for core (left) and co-citing (right) papers: globally; in China; the U.S.; and the U.K.



The resulting plots are a visual indication of the differing hot-topic research priorities in the three most productive research economies. Globally, the core papers exhibit peaks in the overlap between Chemistry and Engineering & Materials Science, as well as in Electrical Engineering, Electronics & Computer Science, and in Clinical & Life Sciences, with some additional activity in Earth Sciences. Conversely, in China the Research Fronts driven by 'core papers' are primarily focused on Chemistry and Engineering & Materials Science and in Electrical Engineering, Electronics & Computer Science. This aligns with the points made earlier in this report regarding areas of increasing productivity. However, for co-citing papers, China has markedly more activity in Clinical & Life Sciences. This is also in line with our findings on China's future directions and growing fields, where activity in other leading research economies is already strong.

Table 4.1 highlights the Micro Citation Topics associated with the Research Fronts in each of the five leading peaks for which China contributes the most core or co-citing papers (as applicable): core and co-citing papers for Chemistry; core and co-citing papers for Electrical Engineering, Electronics & Computer Science; and co-citing papers for Clinical & Life Sciences.

Some noteworthy trends stand out. In many of these Research Fronts, China emerges as the lead contributor for both core and co-citing papers. Many of the leading Chemistry and Materials Science Research Fronts relate to the advancement of green technologies, such as solar cells and fuel cells e.g., Oxygen Reduction Reactions being commonly associated with the chemistry involved with fuel cells. However, they contribute the most core papers to a Research Front on the absorption of microwaves and other electromagnetic radiation. This involves a wide range of materials, including graphene and MXenes, and has a variety of both civilian and military applications — from shielding electronic components to stealth technologies.

"Some noteworthy trends stand out. In many Research Fronts, China emerges as the lead contributor for both core and co-citing papers. Many of the leading Chemistry and Materials Science Research Fronts relate to the advancement of green technologies, such as solar cells and fuel cells e.g., Oxygen Reduction Reactions being commonly associated with the chemistry involved with fuel cells."

"In China the Research Fronts driven by 'core papers' are primarily focused on Chemistry and Engineering & Materials Science and in Electrical Engineering, Electronics & Computer Science."

Table 4.1: The leading Research Fronts in which China contributes the most papers (articles and reviews) in their leading fields. The columns listing 'papers' and '% of total' are with respect to the core or co-citing papers as appropriate.

Leading Micro Citation Topics	Papers	% of total
Core: chemistry/materials science		
Microwave absorption	462	91.8%
Supercapacitor	432	78.8%
Oxygen reduction reaction; CO2 reduction; co oxidation; photocatalysis	364	79.5%
Organic solar cells	304	86.4%
Perovskite solar cells	251	51.3%
Co-citing: chemistry/materials science		
Oxygen reduction reaction; CO2 reduction; co oxidation; photocatalysis	12,288	77.4%
Oxygen reduction reaction	9,204	77.2%
Perovskite solar cells	8,385	50.3%
Oxygen reduction reaction	6,087	72.0%
Magnetic nanoparticles; gene delivery; warburg effect; metal-organic frameworks; photodynamic therapy	5,878	84.3%

Cont'd ▼

Leading Micro Citation Topics	Papers	% of total
Core: electrical engineering, electronics and computer science		
Particle swarm optimization; MPPT; deep learning; fault diagnosis; unit commitment	208	87.4%
Adaptive control; linear matrix inequalities; multi agent systems	152	90.5%
Visual search; deep learning; object tracking	124	86.7%
Object tracking	116	68.6%
MIMO; network coding; unmanned aerial vehicles; metamaterials; indoor localization	113	44.7%
Co-citing: electrical engineering, electronics and computer science	7	17
Deep learning; object tracking; super-resolution; NDVI; defect detection	11,138	70.0%
Deep learning; object tracking; defect detection; OCR; harvesting robot	5,559	62.4%
Adaptive control; linear matrix inequalities; multi agent systems	3,802	82.9%
Deep learning; defect detection; face recognition; super-resolution; object tracking	2,996	48.4%
Internet Of Things; Unmanned Aerial Vehicles	2,800	65.3%
Co-citing: Clinical & Life Sciences		
lncRNA; PD-1; MicroRNAs; Pancreatic Cancer; NSCLC	36,878	43.1%
lncRNA	5,841	86.7%
Coronavirus; erysipelothrix rhizopathies; competing risks; Fc receptor; mass cytometry	4,833	68.6%
Warburg effect; iron overload; apoptosis; autophagy; lncRNA	4,784	44.7%
Coronavirus	4,631	18.0%

As we have suggested in previous reports, the Web of Science data on global research publications tell us very clearly that the impact of China's emerging capacity and likely excellence in all these Research Fronts will be of profound significance for and benefit to many research advancements globally.

Another interesting exception to the focus on green technology is China's fifth Research Front for co-citing papers in this field. While the core of this front centers on magnetic nanoparticles, many co-citing papers delve into areas like gene delivery, the Warburg effect — which has relevance to cancer treatments — and the synthesis of metal-organic frameworks, which have a variety of applications, including hydrogen storage.

As noted earlier, Deep Learning emerges as a leading Micro Citation Topic across all of China's papers. The Electrical Engineering & Computer Science Research Front that China's researchers contribute the most core papers to relates to technologies aimed at optimizing electrical power networks. Many of their other leading Computer Science Research Fronts, however, relate to technologies involving image recognition for various applications. These include tracking individual objects, vegetation detection (NDVI), drones and facial recognition. This sheds light on our earlier question and highlights the diverse ways in which Deep Learning is being studied or applied.

It should be no surprise that some of the leading Clinical & Life Sciences Research Fronts relate to the study of coronaviruses. Although Chinese researchers contribute many co-citing papers to the field, these form a modest part of the total volume of research on this topic. Their contributions to research on the applications of long non-coding RNA (lncRNA) are more significant: these include studying cancer and its treatment; and the immune system in general.

As we have suggested in previous reports, the Web of Science data on global research publications tell us very clearly that the impact of China's emerging capacity and likely excellence in all these Research Fronts will be of profound significance for and benefit to many research advancements globally. That was evident a decade ago, has been reinforced by developments since, and is poised to shape future research and innovation not only in Asia-Pacific but across all leading research economies.

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