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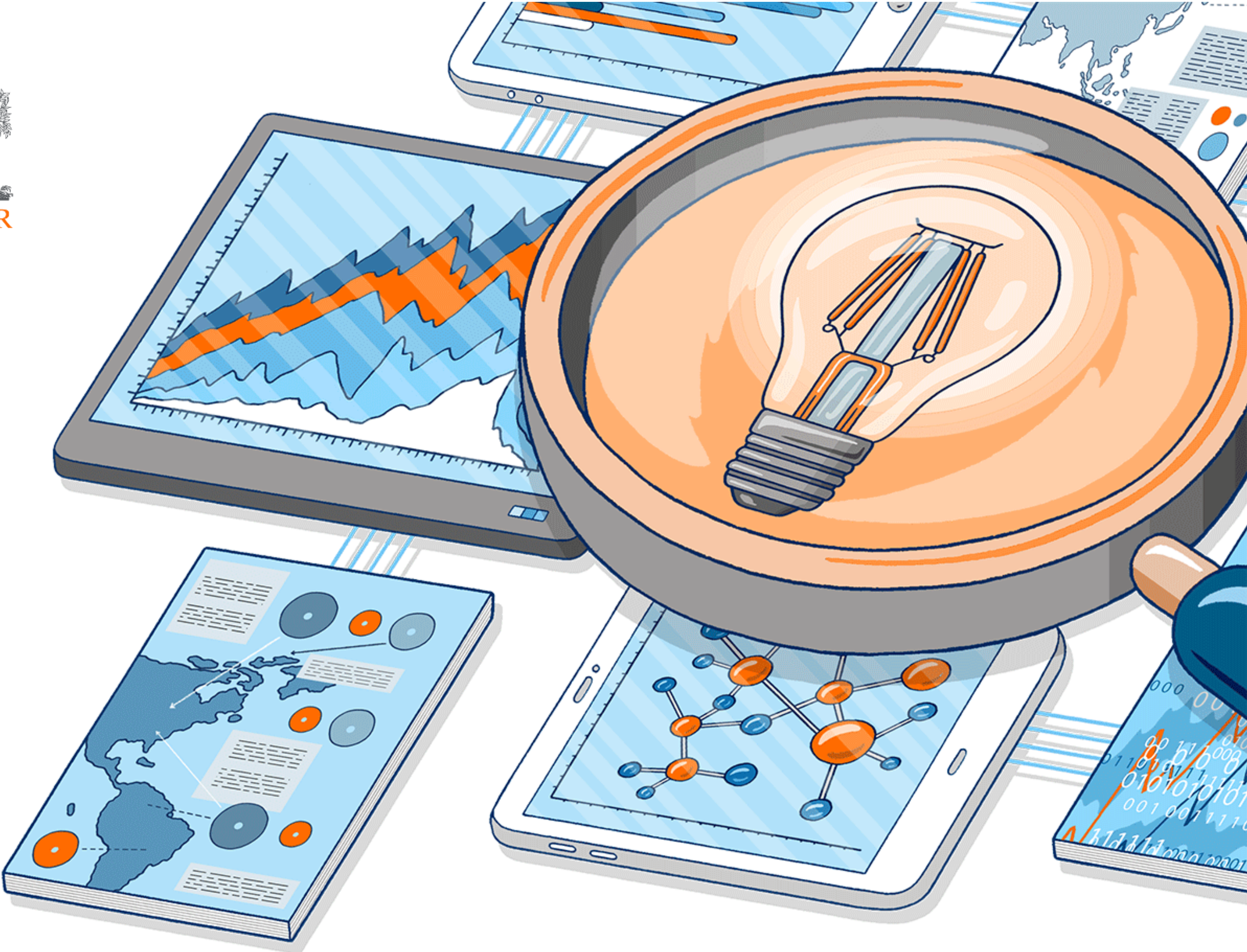

Landscape and Development Trends of Energy Research

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Introduction

Energy is fundamental to the survival and development of human society, and it is an important factor constraining human economic and social development. Energy has undergone two major transformations in human history, which have brought about tremendous productivity gains and social changes: first, the transformation from a reliance on wood to coal, and then from coal to oil and gas. However, with the advent of industrial civilization, serious environmental issues, climate problems and unsustainable resources have brought new energy challenges to mankind: the global energy structure is facing a new round of transformation. Energy has become a global issue of strategic importance relevant to national socio-economic development, and the reform of energy structure has become an important issue and agenda item for modern energy governance. The series of development and policy changes, including the gradual transition from the use of traditional fossil-based energy sources to the exploration and utilization of new energy sources, and from a national energy security and governance policy purely driven by traditional energy to one focusing on the governance and guidance of new energy sources, are also changing the world energy landscape.

For China, the transformation of its energy structure is characterized by the features of its own energy mix:

- As the world's second largest energy producer and consumer, China is relatively rich in total energy resources: China has relatively abundant fossil fuel energy resources, with coal playing a dominant role. Its proven oil and natural gas reserves are relatively insufficient, but the potential of unconventional fossil energy reserves, such as oil shale and coal-bed methane, is large;
- Relatively low energy resources per capita: With its large population, China has a low level of energy resources per capita in the world;
- Uneven distribution of energy resources: Large-scale and long-distance transportation of coal and oil from the north to the south, and of gas and electricity from the west to the east, are distinctive features of China's energy flow and the basic pattern of its energy transportation;
- Difficulty in energy resource exploitation: Compared with the rest of the world, China has relatively poor geological conditions for coal extraction, as most of China's coal reserves require underground mining rather than surface mining. Its oil and gas reservoirs are buried deep underground, requiring advanced technologies for prospecting and extraction. Furthermore, China's undeveloped water resources are mostly located in its Southwest deep valleys, far from places most in need of water, adding to the difficulty and cost of exploiting water resources[1].

[1] The State Council Information Office of the People's Republic of China: China's Energy Situation and Policy (www.gov.cn) (Chinese)

To this end, the Chinese government has applied a scientific development approach to guide the tackling of its energy issues, accelerating the development of modern energy industries, adhering to the basic national policy of saving resources and protecting the environment, and putting the construction of a resource-saving and environment-friendly society in a prominent position in its development strategy of industrialization and modernization. To achieve comprehensive, coordinated and sustainable development of energy to the greatest extent, China's energy development has been taking a path featuring high technological content, low resource consumption, low environmental pollution, good economic efficiency and guaranteed safety.

In December 2020, China proposed that by 2030, it will cut its carbon dioxide emissions per unit of GDP by more than 65% from 2005 levels, increase the share of non-fossil fuels in primary energy consumption to about 25%, increase forest accumulation by 6 billion cubic meters from 2005, and reach more than 1.2 billion kilowatts for the total installed capacity of wind and solar power. To this end, China will adopt stronger policies and measures so that CO_2 emissions peak by 2030 and will achieve carbon neutrality by 2060[2].

Achieving the carbon peak and carbon neutrality goals requires vigorously promoting the transition to green and low-carbon energy, to ensure energy supply security. This means advancing the energy industry overall and improving modernization of the industrial chain, driven and supported by science and technology innovation, while accelerating the energy system's adaptation to new, greener forms of energy. On one hand, China will take stricter measures to save energy, reduce carbon emissions and reduce its carbon footprint. This may include decreasing carbon in the exploitation, production, processing, storage, and transportation of fossil fuels; advancing revolutionary chemical engineering technologies to enable clean and efficient use of energy; developing carbon capture, utilization and storage technologies; and promoting low-carbon emissions for the energy end-use sector. On the other hand, China will make greater efforts to promote the development of non-fossil energy, including accelerating the development of wind and solar power, exploiting hydropower in line with local conditions, developing nuclear power in an active, safe and orderly manner, and diversifying biomass energy exploitation and use. Achieving these goals also entails promoting the construction of a novel power system primarily based on new energy, continuously increasing the share of new energy in use, and speeding up large-scale applications of novel, safe, and efficient energy storage and hydrogen power technologies[3].

Globally, both developed and developing countries are working hard to realize the transformation of the economic development model to a low carbon economy. The transformation of energy systems is imperative and presents opportunities and challenges. The establishment of an energy science subject area in line with current energy system development trends will be of both practical and long-term importance to the transformation of China's energy system. The construction of energy science as a subject area can provide systematic and theoretical knowledge reserves for the energy industry, which in

[2] Notice by the State Council of the Action Plan for Carbon Dioxide Peaking Before 2030
[3] Notice by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) for the issuing of the "14th Five-Year Plan for a Modern Energy System"

turn, can drive and advance research in the field, support undertaking major national projects or tasks and training high-level talents, and moreover, promote high-quality industrial development and related technological innovation by integrating the development of academia and industry.

This report, based on energy experts' interpretation of energy technology and industry development trends, national energy security and utilization statuses, and the current set-up of energy-related academic programs at home and abroad, summarizes the topical content of energy research, using scientific papers published in the field worldwide (based on the full Scopus database[4]), and establishes the following four sub-fields of energy science: **Carbon Emission Reduction Technology**, **Renewable Energy**, **Energy Storage and Hydrogen Energy**, and **Energy Efficiency Management**.

These four sub-fields constitute the Energy Science subject area or discipline, which distinguishes itself from other energy-related subject areas and traditional energy fields, as it focuses more on the revolution and transformation of current energy systems and the development of new energy technologies. It exhibits many cross-connections between various subject areas such as engineering, chemistry (e.g., physical chemistry, inorganic chemistry, applied chemistry,), materials science (e.g., metallic materials, inorganic non-metallic materials, nanomaterials), chemical engineering, environmental science, physics, biology, and economics.

The scientific articles for each sub-field are collected and classified using query searches in the full Scopus database: Elsevier's research analytics team takes the keywords and journals provided by experts as the initial input data, and via many iterations and by identifying co-occurrence keywords, expands the keyword list, and adds some restriction keywords, so that keywords in the query are combined in a way that is highly relevant to the research content of the subject area. To ensure the accuracy and breadth of the resulting publication sets, the query is also tested and updated until it achieves pre-set recall and precision rates. In a word, the queries are formed based on objective data, supplemented by manual identification by experts in the research field. The resulting queries are used to search the text of publication titles, abstracts, and keywords (including index keywords and author keywords), forming a collection of scientific publications for each sub-field. The combination of publication sets of the four sub-fields eventually forms the collection of scholarly output for the Energy Science subject area.

The four sub-fields of the Energy Science subject area are defined as follows:

- **Carbon Emission Reduction Technology**: Centering on the utilization and conversion of traditional carbon-based fossil resources (e.g., coal, oil, natural gas) to energy-carrying molecules and chemicals, as well as processes of carbon dioxide capture, storage, and resource utilization, this sub-field is mainly about developing green, efficient, and economically-feasible new methods and technologies to promote optimal utilization of carbon resources and reduction of emissions. The key research areas included in this sub-field are the development, conversion and utilization of gaseous fuels (e.g., natural gas), liquid fuels (e.g., petroleum), solid fuels (e.g., coal, oil shale, oil sands), syngas, oxide-containing compounds

[4] Scopus is Elsevier's database of peer-reviewed article abstracts and citations, covering 77.3 million articles published in more than 39,000 journals, serials, and conference proceedings from 5,000 publishers in approximately 105 countries (in English and other languages). In addition, more than half of Scopus content comes from outside North America, representing many countries in Europe, Latin America, Africa, and the Asia-Pacific region.

(e.g., ethanol, ethers, esters), and so forth, as well as CO_2 emissions and carbon capture and storage technologies.

- **Renewable Energy**: This sub-field is mainly about the conversion and utilization of clean, renewable energy sources, such as solar energy, wind, biomass, and tidal energy, along with the transformation patterns for their carriers and products involved. It is also about applying technical means to find sustainable solutions for solving key, practical engineering problems, to promote low-carbon energy utilization and to achieve carbon neutrality. The sub-field encompasses key areas such as the development, utilization, conversion and storage of solar, wind, biomass, tidal, geothermal and other renewable and alternative energy sources.

- **Energy Storage and Hydrogen Energy**: This sub-field focuses on methods to transform renewable energy sources into a variety of clean energy, including hydrogen energy, through chemical and physical processes. The focus is on electrochemical energy storage, physical energy storage, clean hydrogen energy and other energy storage methods, along with major scientific and technological problems encountered in the processes of energy conversion, storage, transportation and utilization. It is an important bridge linking the production and utilization of low-carbon clean energy. The sub-field includes key elements such as ion batteries, fuel cells, liquid flow batteries, lead-acid batteries, electrochemical capacitors, and hydrogen energy (hydrogen production and storage) for chemical energy storage, and pumped storage, compressed air energy storage, molten salt energy storage, flywheel energy storage and other forms of physical energy storage.

- **Energy Efficiency Management**: This sub-field focuses on the optimal allocation and efficient use of energy resources, and integrates economic, policy, societal and environmental factors to provide comprehensive analysis, design, planning and management for efficient use of energy in construction, industry, transportation and other fields. This research is committed to providing the best overall solutions for energy conservation and efficiency improvement in all aspects of the national economy. The sub-field focuses on system-level technology development, integration, optimization, and comprehensive control, aiming to improve energy efficiency, intelligence, economy, reliability, safety, and environmental friendliness across the whole life cycle of energy delivery, and to achieve deep cross-fertilization between energy science and emerging fields, such as big data, artificial intelligence, and the internet of things. The key research areas included in this sub-field are efficient utilization, clean, low-carbon development and digital, intelligent transformation of energy systems; cross-fertilization of energy resources with economic, policy, social and environmental factors; application and development of energy efficiency utilization in architecture, transportation, industry and other fields; and comprehensive analysis, design, planning and management of energy issues.

Definitions of these four sub-fields are also closely related to the current goals and initiatives of China to achieve carbon peaking and carbon neutrality. In the "Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy"[5] officially announced by China's State Council in September 2021, it is proposed that in order to achieve the goals

[5] http://english.www.gov.cn/policies/latestreleases/202110/25/content_WS61760047c6d0df57f98e3c21.html

of carbon peaking and carbon neutrality, five principles should be adhered to: "exercising nationwide planning, prioritizing conservation, leveraging the strengths of the government and the market, coordinating efforts on the domestic and international fronts, and guarding against risks." Research objectives of the four sub-fields as defined above are directly in line with four of these principles:

- Prioritizing conservation. To give first priority to the conservation of energy resources, the introduction of a comprehensive conservation strategy is needed. The country will continue to reduce energy and resource consumption and carbon emissions per unit of output, improve resource input–output efficiency, advocate simple, moderate, green and low-carbon living patterns, and effectively control carbon emissions at their source and entry point. This principle directly coincides with the research content and objectives of the Carbon Emission Reduction Technology sub-field.

- Leveraging the strengths of the government and the market. The government and the market each have important roles to play. China needs to establish a new system for mobilizing the nation to boost technological and institutional innovation and accelerate the revolution in green and low-carbon technology. This will deepen reform in energy and related fields, give full play to the role of market mechanisms, and create effective incentive and restraint mechanisms. This principle is closely related to the research content of the Energy Efficiency Management sub-field.

- Coordinating efforts on the domestic and international fronts. Based on China’s national context, the country will coordinate planning for domestic and international energy resources and promote advanced green, low-carbon technologies and practices. In the international response to climate change, China is preparing to both stand its ground and engage in collaboration, continue to increase China’s influence level and its power of discourse on the world stage, and resolutely safeguard its development rights and interests. This principle, in a sense, corresponds to the application scenarios and development prospects of the Renewable Energy and Energy Storage and Hydrogen Energy sub-fields.

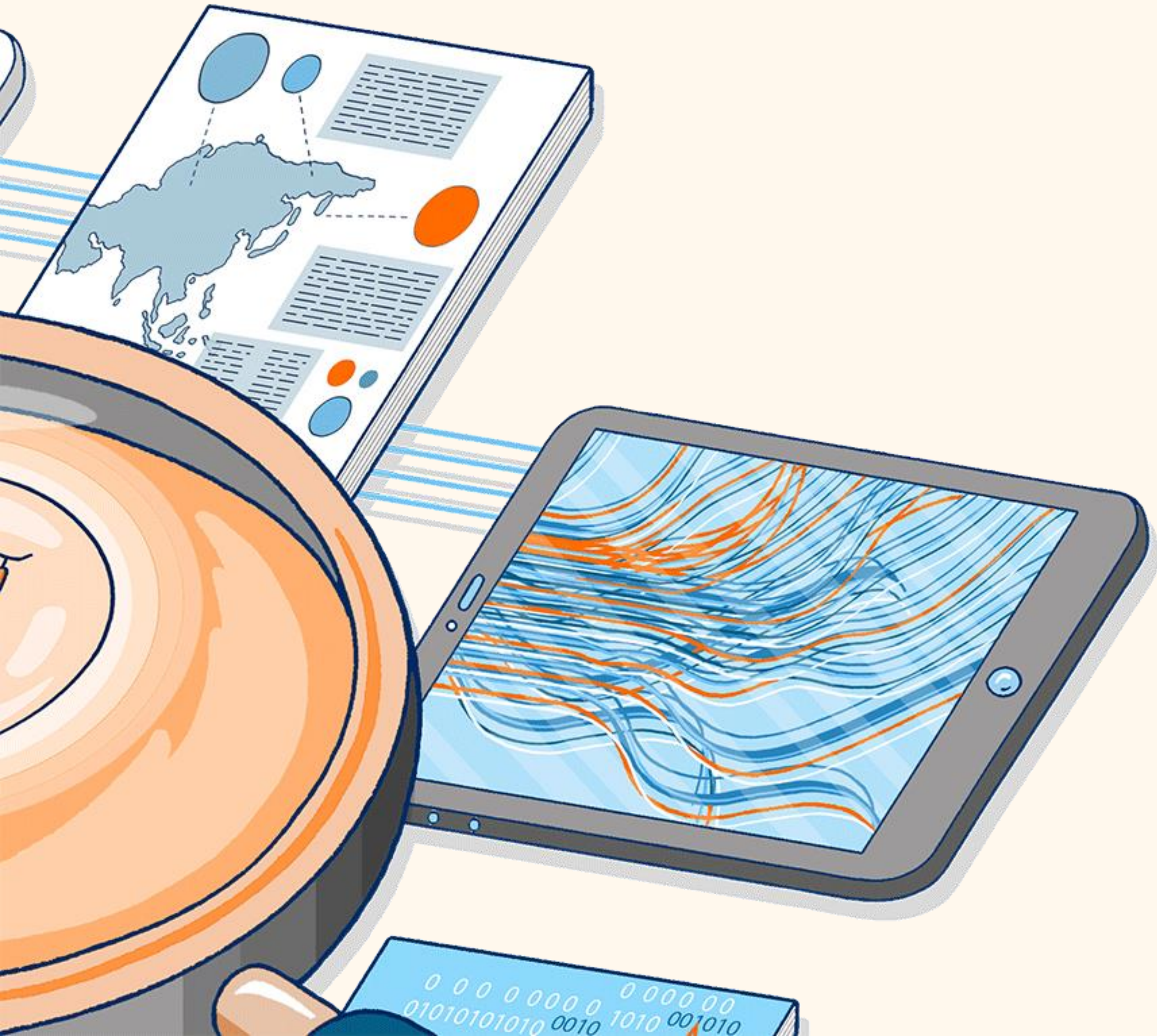
- Guarding against risks. Good management of the relationships between pollution, carbon reduction, and energy security, the security of the industrial chain and supply chain, food security and people’s quality of life is important for effectively addressing the economic, financial, and social risks that might accompany the green and low-carbon transformation. These are also essential for ensuring safety for carbon reduction. This principle is closely linked to the application and development of the Carbon Emission Reduction Technology and Energy Efficiency Management sub-fields.

In summary, the establishment of the Energy Science subject area is of far-reaching significance for promoting a rapid evolution of China's energy field and sustainable transformation of its energy industry strategies. Having a better understanding of the development status and the global development trends of the research field, based on the above definitions of the research fields, will be beneficial to promoting the construction and development of the Energy Science discipline.

Based on the analysis of scholarly output in Energy Science and its sub-fields, this report describes the overall research performance of the subject area, including scholarly output and impact, research collaboration and funding, and knowledge transfer, i.e., the integration of research and industry. The first three chapters of the report, using graphic visualization along with data and statistics, objectively analyze and show scholarly output performance, research development trends and research translation potential of the Energy Science subject area globally and for major countries in the most recent decade. The analyses aim to support decision-making for science and technology policymakers in strategic planning, construction of innovative science and technology platforms, talent training, and incentive policies for science and technology development. Chapter 4, by mapping out hot research topics, identified using big data text mining and natural language processing techniques, and their association with each sub-field, attempts to explore trending research directions of each sub-field and development trends, as well as how the research focuses of the sub-fields are related to key research topics of global importance. It aims to provide researchers with some insights that can guide their future research.

Chapter 1

Research Performance—Research Output and Scholarly Impact



Key Findings

- In the past decade, the absolute number of publications in Energy Science and its sub-fields has been increasing worldwide, reflecting the fact that Energy Science is a fast-growing subject area. At the same time, publications in Energy Science and its sub-fields are an increasing share of all publications. That this share is increasing indicates that the subject area is in an active development phase. The importance of Energy Science as a subject cannot be ignored.

- China is a world leader in number of publications in Energy Science and its sub-fields, making an outstanding contribution to scholarly output in the Asia-Pacific region and globally. Compared to its peers, China is the most active in this subject area and its sub-fields, and output continues to grow rapidly each year, reflecting the importance China places on the field of Energy Science.

- China's research impact in Energy Science has grown over the past decade, highlighting a simultaneous development in both "quality" and "quantity," while the research impact of other key comparators has declined to varying extents. However, there is still a gap between China and the United Kingdom and the United States in scholarly impact and average output per researcher, suggesting room for improvement for China.

- The Chinese Academy of Sciences has the highest scholarly output in Energy Science and each of its four sub-fields in China. Among higher education institutions, Tsinghua University, Peking University, University of Chinese Academy of Sciences, University of Science and Technology of China, and Zhejiang University are outstanding in terms of the number of publications or research impact (the above rankings are not in any particular order).

Overall Research Performance

This section will analyze the global scholarly output and research impact of the Energy Science discipline and its four sub-fields from 2010 to 2021, focusing on overall performance and trends for the entire discipline of Energy Science and the publication volume and research impact of the four sub-fields in key countries.

Scholarly output, i.e., the output of scientific publications, is defined as the number of all publications on the assessed subject in a specific research field during a fixed period of time. It encompasses journal articles, review papers, publications in conference proceedings, and books or other publication series. The scholarly output represents the volume of publications on the assessed subject during a fixed period of time, and to a certain extent represents the productivity of researchers in the research field.

To a certain extent, research impact can be evaluated by the quantitative indicators "citation count" and "Field Weighted Citation Impact (FWCI)." The citation count refers to the number of citations received by a publication on the subject in a fixed period of time, which can reflect the scholarly impact of the subject's publications. However, citation counts have several biases: publications more recently published may have a lower total number of citations due to less time to accumulate citations, compared with older publications; different publication types may attract different levels of citation, so that citation counts do not fairly reflect their scholarly impact; citation characteristics vary across different subject areas, which leads to biased assessment when comparing citation counts across subject areas. Therefore, this report mainly uses the normalized citation impact index FWCI in assessing research impact.

Despite some limitations, FWCI reflects the scholarly impact of the evaluated subject's publications. It is calculated by comparing the number of citations a publication receives with the number of citations expected for a publication of the same publication year, type, and same subject, and thus, can better circumvent the differences in the number of citations due to variations in publication size and citation characteristics by subject areas and by publication years. If the FWCI is 1, it means that the number of citations received by the evaluated subject's publication(s) is the same as what would be expected based on the global average for the same type of publications.

A. Overall Performance of Energy Science Subject Area

(A) Scholarly output in major countries and regions of the world

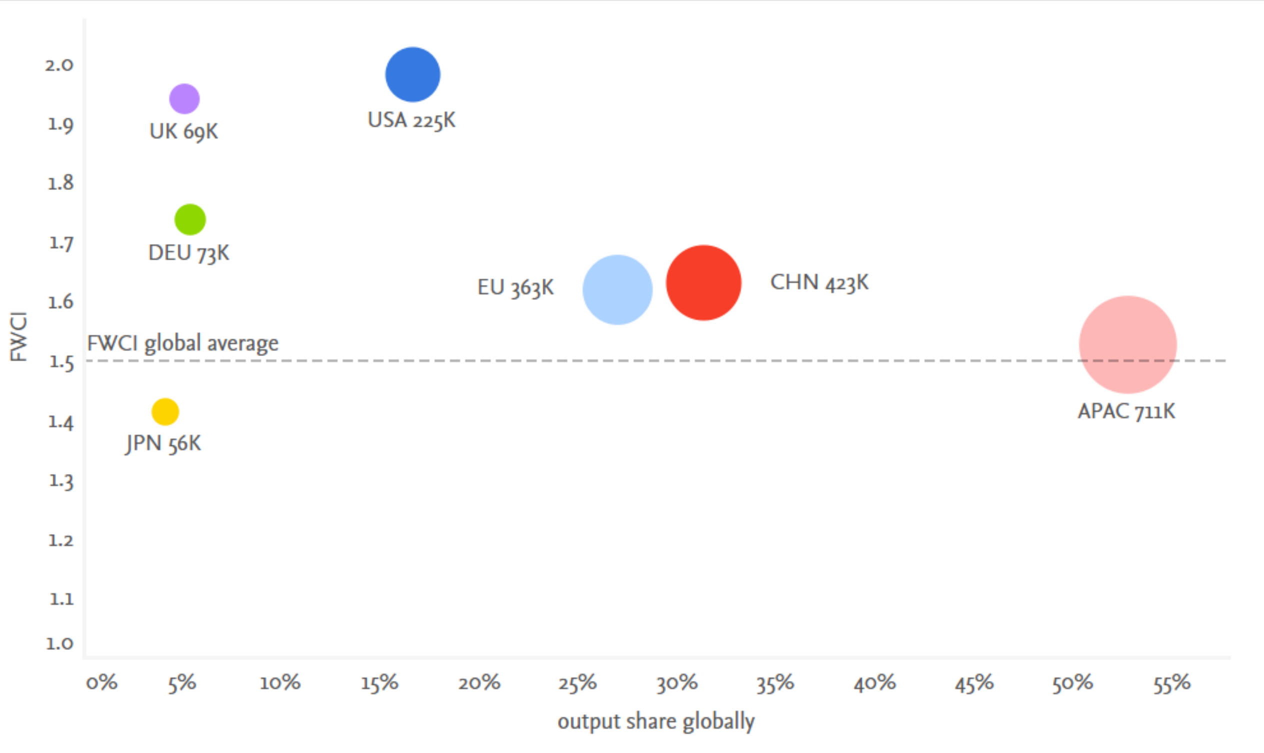


Figure 1.1.1.1 Output share in the world, and FWCI of Energy Science publications for comparators, 2010–2021 (codes: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, EU–Europe (aggregate region), APAC–Asia Pacific (aggregate region))

The scholarly output in Energy Science is considerable, with a total of about 1.346 million Energy Science-related articles published globally from 2010 to 2021. China is the country with the largest number of publications, with a total of 423,000 articles, more than the European Union combined. It accounts for more than 30% of global publications and nearly 60% of articles published in the Asia-Pacific region (see Figure 1.1.1.1). The United States (US) ranks second in the world in article volume, with a total of 225,000 articles. Among the comparators, Germany and the United Kingdom (UK) have similar volumes of publications, with 73,000 and 69,000 articles respectively, while Japan published the least, with 56,000 articles.

The Field-Weighted Citation Impact (FWCI[6]) reflects, to some extent, the scholarly impact of scientific publications. The FWCI of global Energy Science-related articles is 1.5, meaning that the scholarly impact of energy science publications is 50% above that of the global average of 1.0 for overall research. In the comparison of key countries, the US has the highest scholarly impact in this discipline. China's scholarly impact is higher than the global average in this discipline, but it is lower than that of the US, UK and

[6] FWCI is obtained by dividing the actual number of citations of an article by the average number of citations in the same subject area, in the same year, and of the same article type. The global average is set to 1. An FWCI equals to 1 indicates that the article's citation performance is comparable to the global average in the same field over the same time period. If the FWCI value is greater than 1, it means that the article has received more citations than the global average. As a normalized index, FWCI is widely used to show the quality of publications and to measure citation impact, overcoming the biases in citation analysis due to the cumulative effect of time and different citation practices in different subject areas.

Germany. Japan ranks last among all the comparators, and the scholarly impact of its publications is lower than the global average of the discipline.

(B) Development trends of scholarly output over the last decade

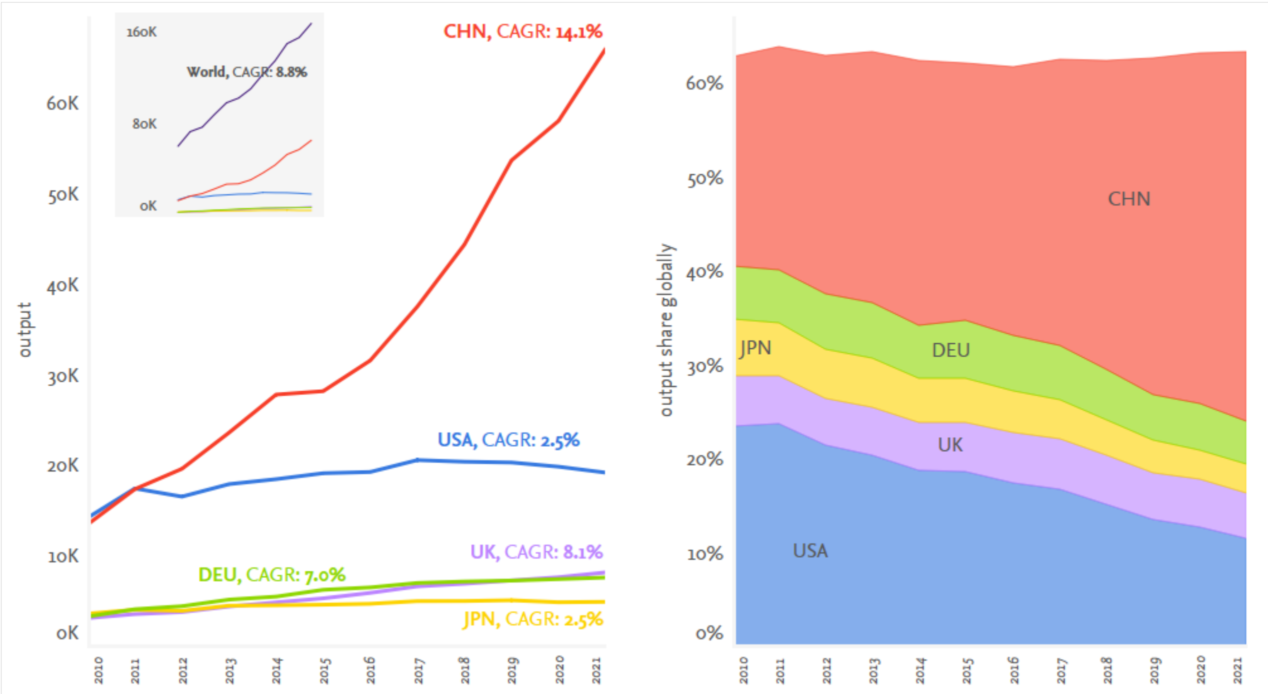


Figure 1.1.1.2 Global and benchmarking countries in Energy Science and compound annual growth rate (CAGR) (left) and the benchmarking country's proportion of Energy Science publication volume changes (right), 2010–2021 (code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, World–Global). CAGR indicates the average annual compound growth rate; for detailed calculations, see Appendix V.

Between 2010 and 2021, the global volume of Energy Science publications continued to grow, with a compound annual growth rate (CAGR) of 8.8% (see Figure 1.1.1.2, on the left). China's publication volume in this discipline has grown strongly, from 13,602 articles in 2010 to 66,105 articles in 2021, with a CAGR of 14.1%, 5 percentage points higher than the world level (8.8%). It is worth noting that China's publication volume has surpassed that of the US since 2011, and its lead has continued to increase since then. Although publications in this discipline by the other benchmarking countries continue to increase, their growth rate is lower than the global level.

Analysis of the change in the proportion of national publications (see Figure 1.1.1.2, on the right) shows that China and the US are the two countries in the world that contribute the most Energy Science articles. Over the past decade or so, due to China's rapid development in the discipline, the proportion of Energy Science articles published by Chinese researchers has increased from 22% in 2010 to 39% in 2021. The proportion of Energy Science articles published by researchers in the US has shown a clear downward trend since the US was strongly overtaken by China in 2011. The UK and Germany maintained a relatively stable contribution rate during this period. Japan, on the other hand, has gradually reduced its global share of publications, because its growth rate is much lower than the world level. It can be said that China's scholarly output growth in Energy Science has driven the growth of the Asia-Pacific region and even the world as a whole.

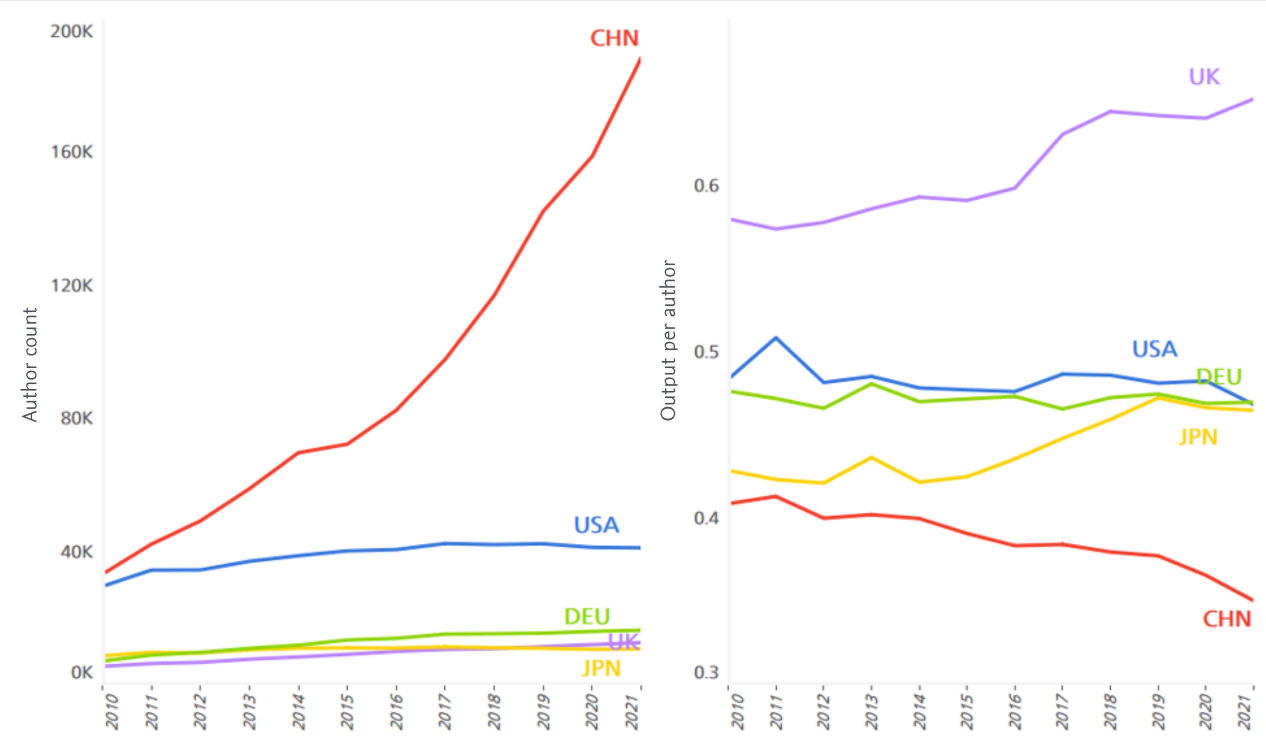


Figure 1.1.1.3 Changes in the number of authors in Energy Science and per capita output in the comparators, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

Similar to the scale of the increase in scholarly output, the number of Chinese authors having published in Energy Science discipline in the past 11 years has surpassed the number in all other benchmarking countries and maintained rapid growth[7]; the number of authors in the comparator countries has increased only slightly (see Figure 1.1.1.3, on the left). However, in terms of output per capita, the average output of Chinese researchers is at a low level and showing a downward trend, while the average output of UK researchers is the highest among the comparators and is still rising (see Figure 1.1.1.3, on the right). On one hand, this is due to the fact that China's Energy Science research is dominated by national collaboration, and the proportion of national collaboration has continued to increase in recent years, and the number of authors participating in the discipline has been increasing; in contrast, the UK is dominated by international collaboration, and the growth in the number of domestic authors is slower. On the other hand, because Energy Science is in a rapid development stage in China, new early-career researchers continue to join the field, which reduces the average output of all researchers. Improving the efficiency of per capita output is a problem that should be given attention while China continuously expands the scale of output in the development of its Energy Science discipline.

[7] Note that the number of researchers is based on the ID of the publication's authors, and there can be errors in the data in cases in which the same researcher has different author IDs.

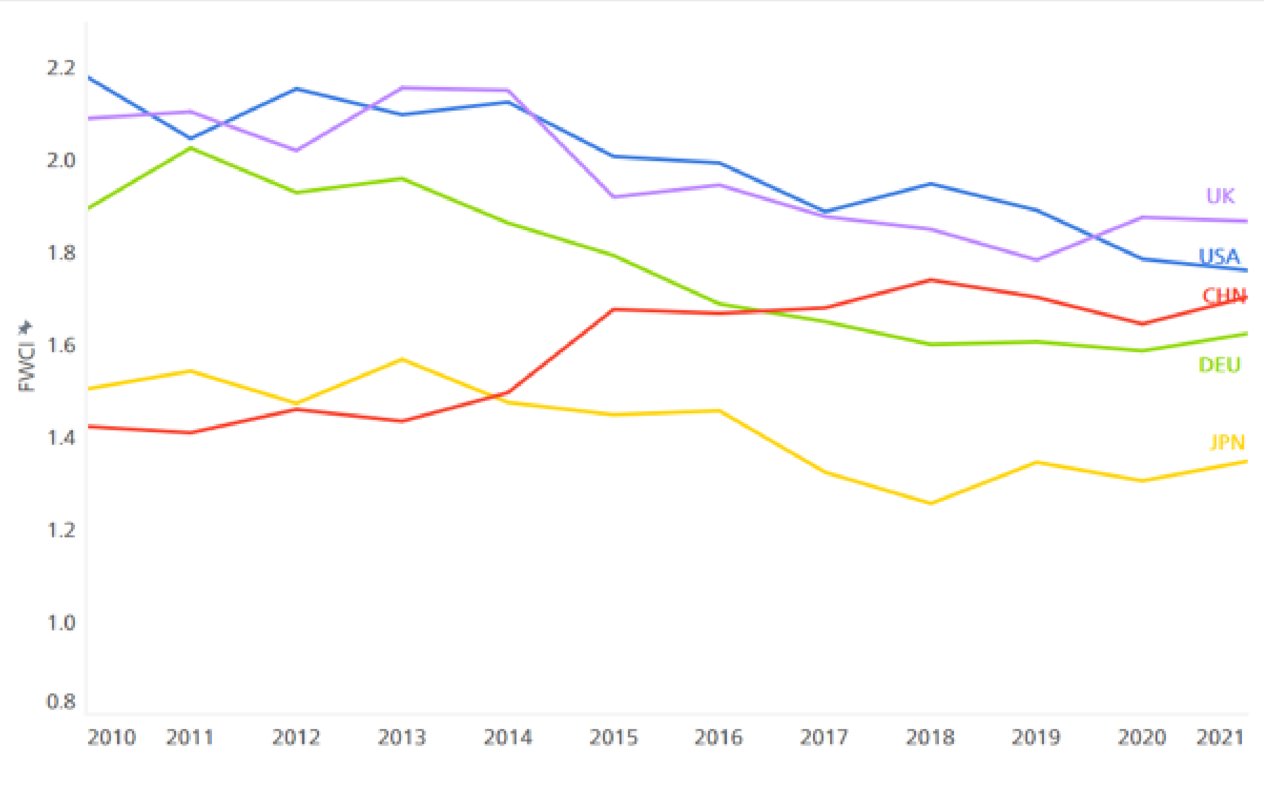


Figure 1.1.1.4 Changes in FWCI in Energy Science publications by benchmarking countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

It can be seen from the change in FWCI of each benchmarking country in the Energy Science discipline (Figure 1.1.1.4) that the scholarly impact of China's publications in Energy Science shows a steady growth trend in the past decade or so, and the FWCI has increased from 1.4 in 2010 to 1.7 in 2021. China is the only country among all the comparators to maintain positive growth in scholarly impact of publications, while the rest of the comparators have seen decline in FWCI to varying degrees. But although China's scholarly impact of Energy Science publications has grown over the past decade, catching up with Germany and Japan, there is still a gap in FWCI compared with the UK and the US.

(C) Classification of sub-fields under the Energy Science subject area

The Energy Science subject area was searched and classified in the full Scopus database using the keyword sequence method. It was divided into four sub-fields: Carbon Emission Reduction Technology, Energy Storage and Hydrogen Energy, Renewable Energy, and Energy Efficiency Management[8].

1. Carbon Emission Reduction Technology sub-field

The Carbon Emission Reduction Technology sub-field focuses on the conversion and utilization of traditional carbon-based fossil resources (e.g., coal, oil, natural gas) to energy-carrying molecules and chemicals, as well as the enrichment, storage and resource utilization of carbon dioxide, to develop new

[8] The keyword sequence methodology and search queries used for each sub-fields are detailed in Appendix I.

methods and technologies that are green, efficient and highly economical, and to promote the optimal utilization and emission reduction of carbon resources.

2. Renewable Energy sub-field

The Renewable Energy sub-fields describes the scientific connotations and transformation laws between the conversion and utilization of clean renewable energy sources such as solar, wind, biomass and tidal energy and the carriers, objects and products involved, and applies technical means to find sustainable solutions for solving key problems related to practical engineering, promoting low-carbon energy utilization and achieving carbon neutrality.

3. Energy Storage and Hydrogen Energy sub-field

Researchers in the Energy Storage and Hydrogen Energy sub-field mainly study the transformation of renewable energy into various clean energy methods, including hydrogen energy, through chemical and physical processes. They focus on the major scientific and technological issues in key aspects of energy conversion, storage, transportation and the utilization of electrochemical energy storage, physical energy storage, clean hydrogen energy and other energy storage methods. These are the key bridge from production to utilization of low-carbon clean energy.

4. Energy Efficiency Management sub-field

With the goal of optimal allocation and efficient utilization of energy resources, the Energy Efficiency Management sub-field integrates economic, policy, social and environmental factors to provide comprehensive analysis, design, planning and management of efficient utilization of energy in construction, industry, transportation and other fields. It is dedicated to providing optimal overall solutions for energy saving and efficiency enhancement in all aspects of the national economy. This sub-field focuses on system-level technology development, integration and optimization, and comprehensive control, aiming to improve energy efficiency, intelligence, economy, reliability, safety and environmental friendliness over the whole life cycle of energy delivery, and to realize the deep cross-fertilization of energy subject areas with emerging directions such as big data, artificial intelligence, and the internet of things.

Based on articles published between 2010 and 2021 and retrieved from Scopus using search queries, the sub-field of Carbon Emission Reduction Technology contains more than 330,000 publications, the Renewable Energy sub-field contains more than 641,000 publications, the Energy Storage and Hydrogen Energy sub-field contains more than 463,000 publications, and the Energy Efficiency Management sub-field contains more than 358,000 publications. Analysis of the various sub-fields will be carried out throughout the chapters of this report.

B. Overview of scholarly performance by sub-field

(A) Distribution of scholarly output in major countries and regions of the world

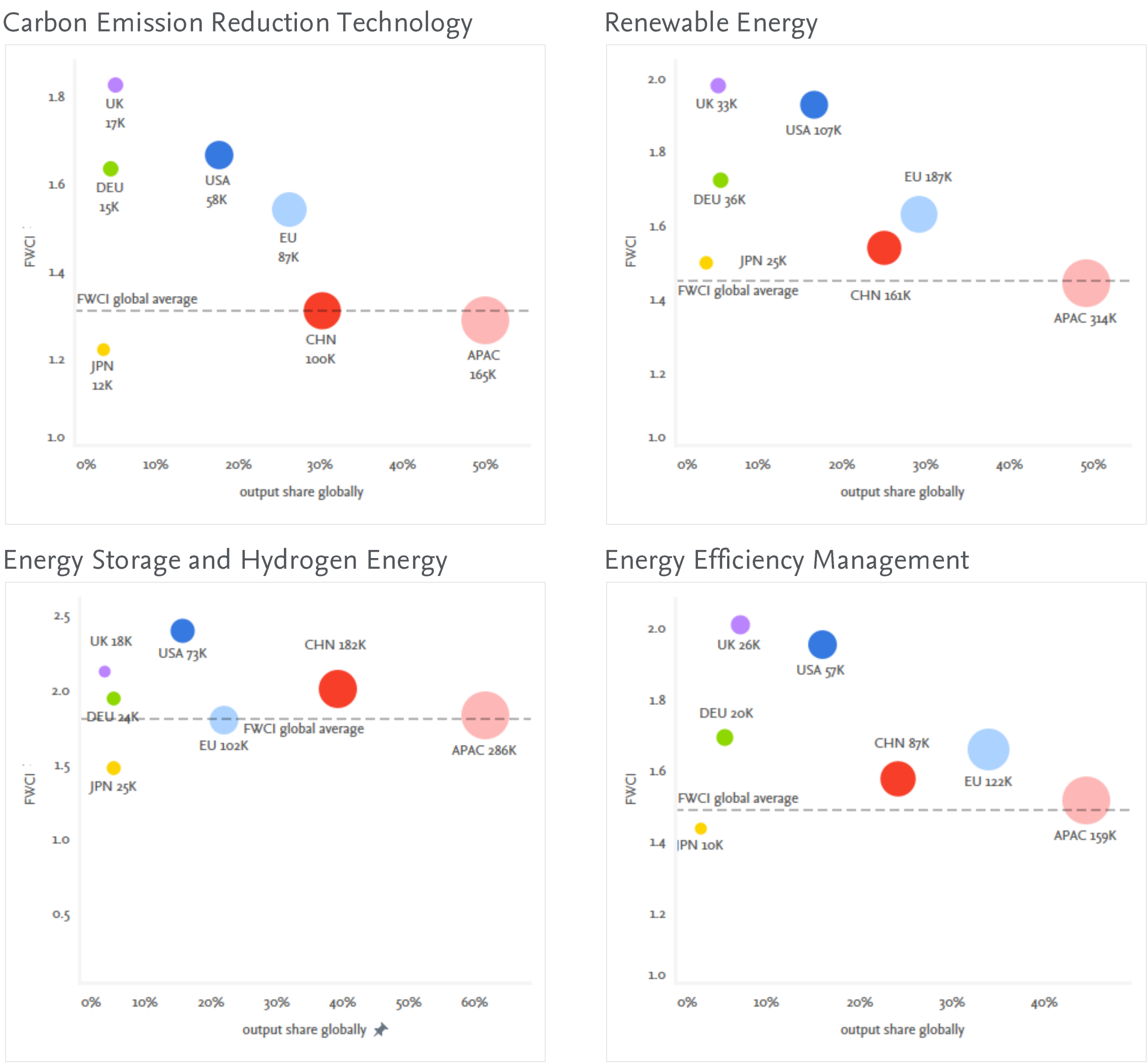


Figure 1.1.2.1 Number of articles in the benchmarking countries and regions, the proportion of the world and its FWCI, 2010–2021 (code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, EU–Europe Union, APAC–Asia Pacific)

Figure 1.1.2.1 compares the number and proportion of publications in four sub-fields from different benchmarking countries and regions. In terms of the number of articles published, China is the country with the highest output in all the four sub-fields, with a total output of 87,000 to 182,000 (Figure 1.1.2.1). In the sub-fields of Carbon Emission Reduction Technology and Energy Storage and Hydrogen Energy, China's publication volume even exceeds that of the EU. Among the key countries, the US ranked second in terms of output volume, the UK and Germany published approximately the same number of articles, and Japan published the fewest. In terms of the output share, China's publications in Energy Storage and

Hydrogen Energy accounts for about 40% of the global publications in this sub-field. For the other sub-fields, China's publications account for about 30% of the world's publications respectively.

In terms of scholarly impact, the FWCI of the four sub-fields ranged from 1.3 to 1.8, and the average FWCI of the sub-field of Energy Storage and Hydrogen Energy was the highest. This means that publications in this sub-field have, on average, higher citation impact. Except for being slightly lower in the sub-field of Carbon Emission Reduction Technology, China's scholarly impact is higher than the world average in the other sub-fields. In the comparison of other key countries, the UK and the US have the highest scholarly impact in the sub-fields, followed by Germany and Japan.

(B) Development trends in scholarly output over the last decade

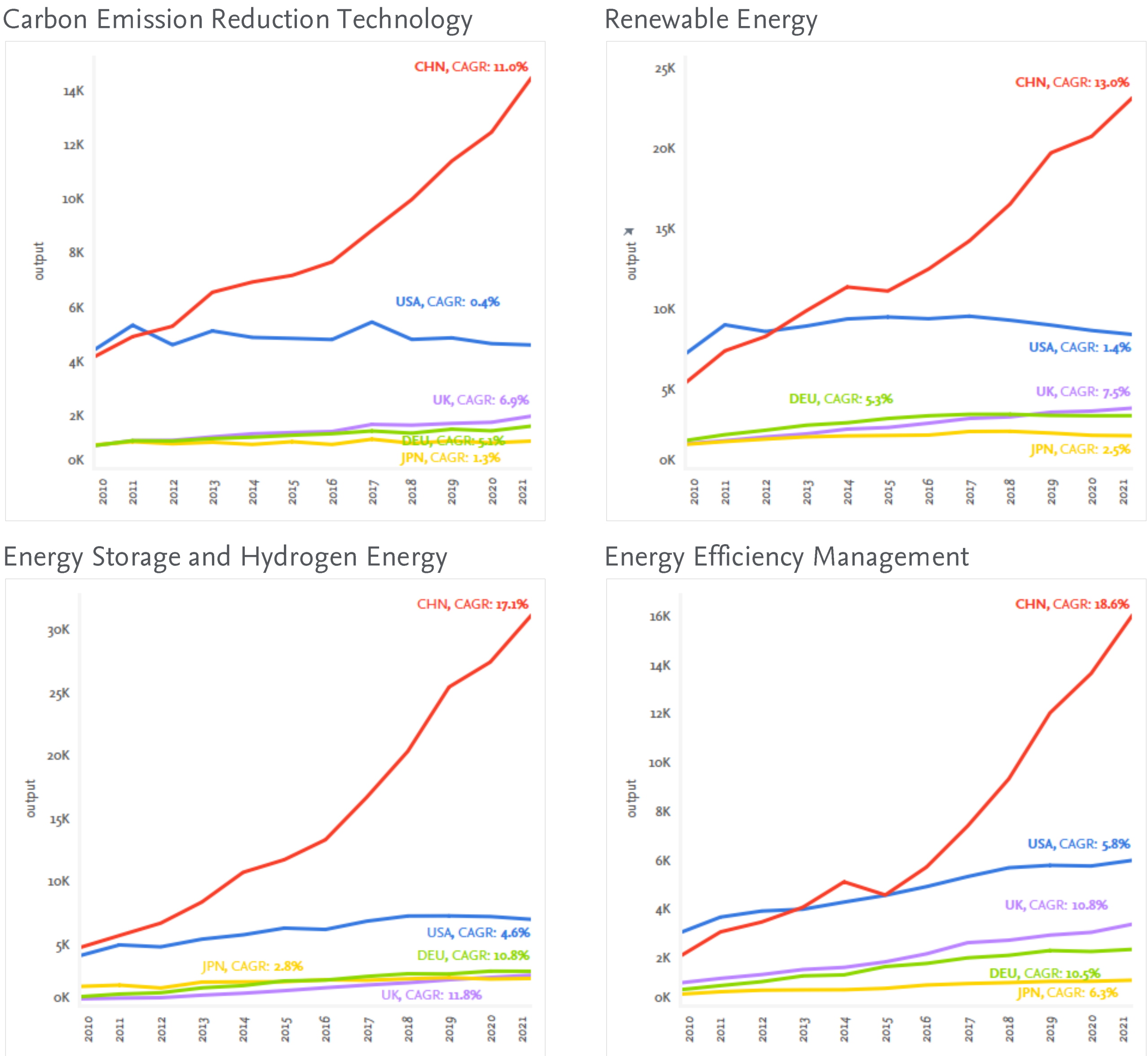
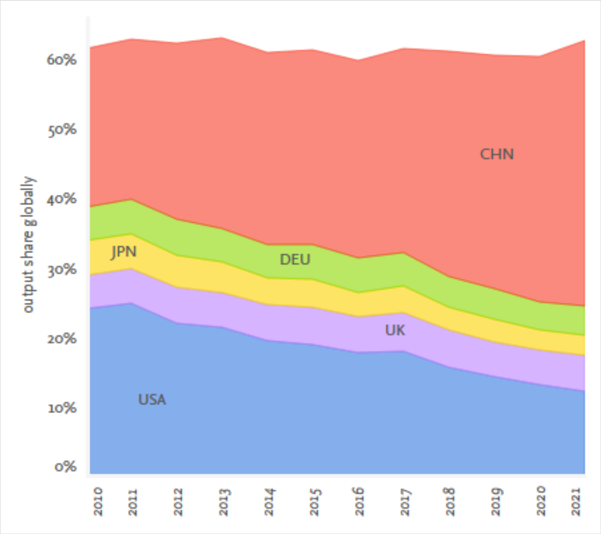


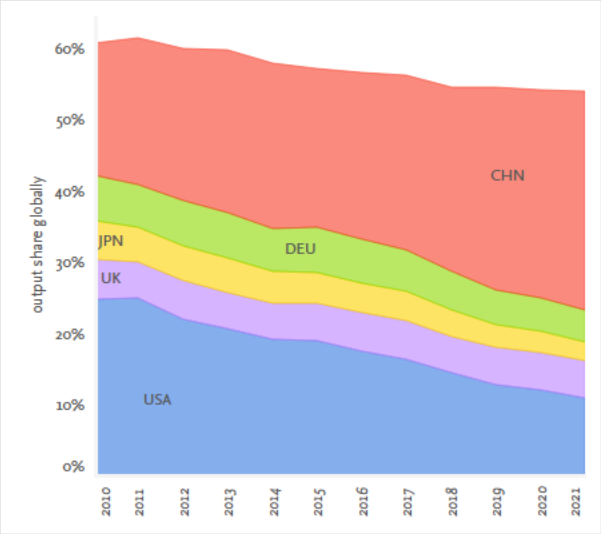
Figure 1.1.2.2 Trends and Compound Annual Compound Growth Rate (CAGR) of benchmarking countries in four sub-fields, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States), CAGR indicates Compound Annual Growth Rate, see Appendix for detailed calculation methods.

For the period from 2010 to 2021, when compared with other comparator countries, the growth trend of China's publications in the four sub-fields is very strong, with an CAGR exceeding 10%. In the sub-fields of Energy Storage and Hydrogen Energy and Energy Efficiency Management, China's CAGR exceeds 15%. Most of the other countries have CAGRs below 10%: the UK's growth rate is basically the same as the global average; Germany's publication growth rate is slow, below the global average, while the US and Japan are growing at a slower rate (Figure 1.1.2.2). It is worth noting that in the four sub-fields, China's publication volume began to surpass that of the US from 2012 to 2015, and the momentum of its lead has continued to increase since then. As with the scholarly output of the entire field of Energy Science, it can be said that China's growth has largely driven the academic growth of the Asia-Pacific region and even the world in all the four sub-fields of Energy Science.

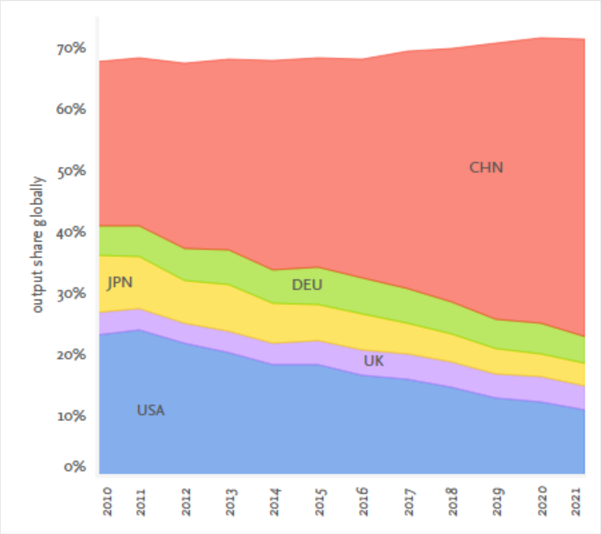
Carbon Emission Reduction Technology



Renewable Energy



Energy Storage and Hydrogen Energy



Energy Efficiency Management

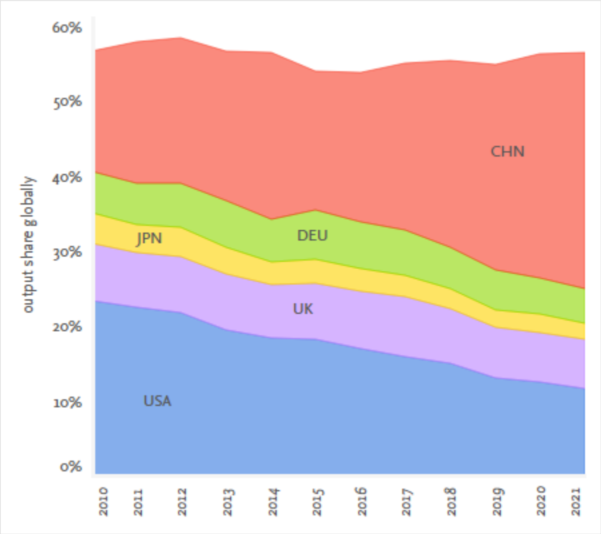


Figure 1.1.2.3 Changes in the proportion of article published in four sub-fields by comparators, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

Figure 1.1.2.3 shows that China and the US are the two countries in the world that contribute the most articles related to the various Energy Science sub-fields. In the past decade, because of the rapid development in China of this discipline, the proportion of Chinese publications has also increased to varying degrees across the sub-fields. The proportion by sub-field varies slightly, but the proportion of Chinese publications in recent years has reached more than 20%. The US share and Japan's share are declining due to their lower output growth rates. Both the UK and Germany maintained low but relatively stable contribution rates during the period.

(C) Development trend of the scholarly impact of the publications over the last decade

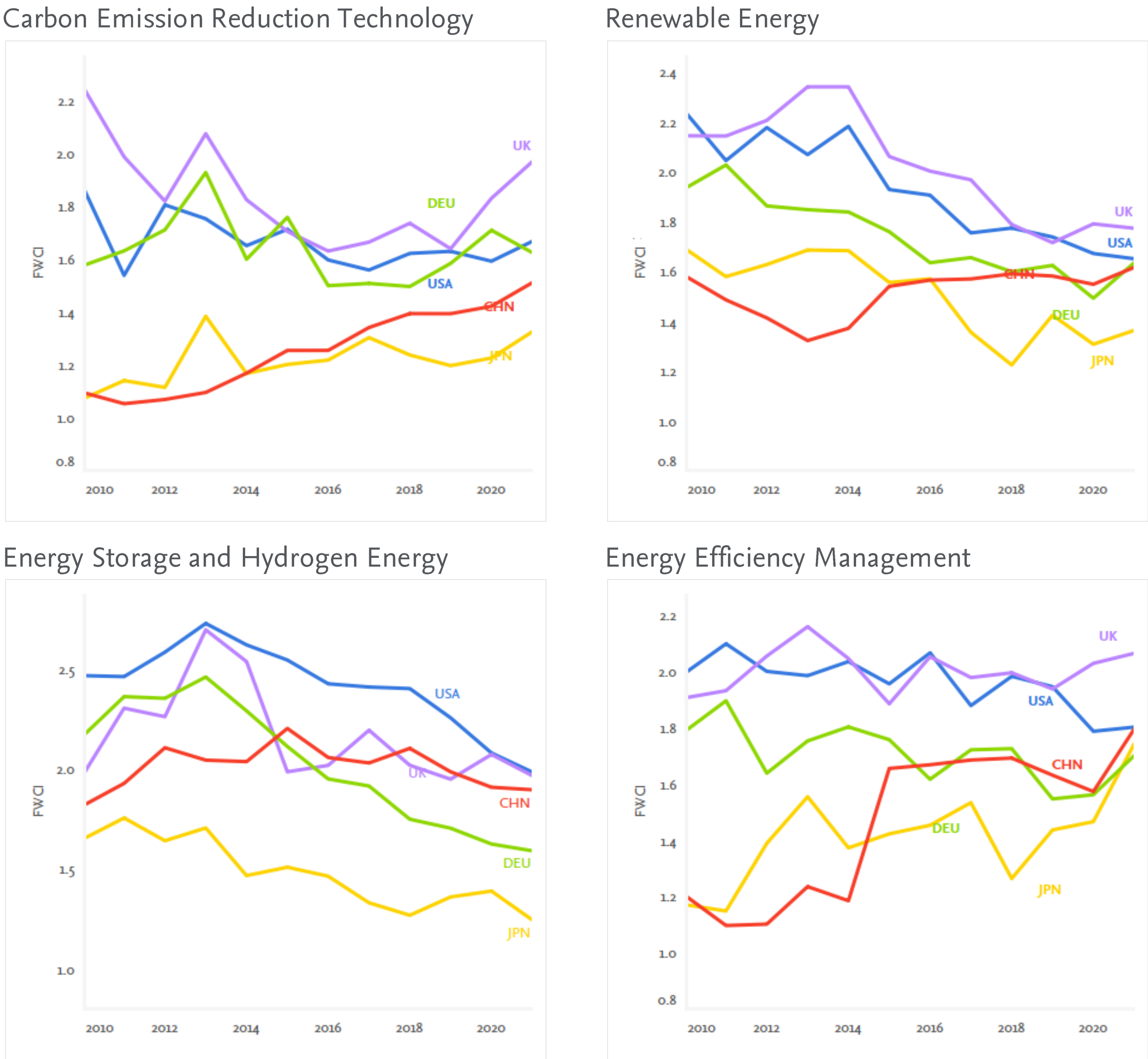


Figure 1.1.2.4 FWCI of the benchmarking countries in four sub-fields, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, World–Global), CAGR indicates Compound Annual Growth Rate, see Appendix for detailed calculations.

Figure 1.1.2.4 compares the change in the FWCI for the key contributing countries over time for the four sub-fields. Most of the comparators have a slight downward trend in FWCI, which is partly attributable to the fact that some early publications have a foundational and original role in their field, and present a greater influence on subsequent publications, while in recent years, the FWCI has gradually decreased and returned to the average value. Considering that China's publications started from a low level compared with other countries, and its FWCI has grown significantly in the past decade, it is possible to infer that China has been catching up with the pace of developed countries and showing a gradual improvement in scholarly impact of its Energy Science research.

Research Activity

The development of a subject area is not only reflected in the growth of the absolute number of publications in that subject area, but also in the growth of the output volume in the subject area relative to the number of publications in all subject areas, i.e., whether the subject area is more active in publication compared to all subject areas. A continuous increase in the publication activity of the subject area indicates that the subject area is in a positive stage of development, that the research focus on the subject area is increasing, and that investment in the relevant research area is also increasing. All these positive signals mean that the subject area is a field with potential and developing attractiveness to researchers.

This section assesses the research activity of Energy Science and its four sub-fields in terms of their share of all subject area publications and trends, and it focuses on the performance of this activity in key countries.

A. Activity of Energy Science Subject Area

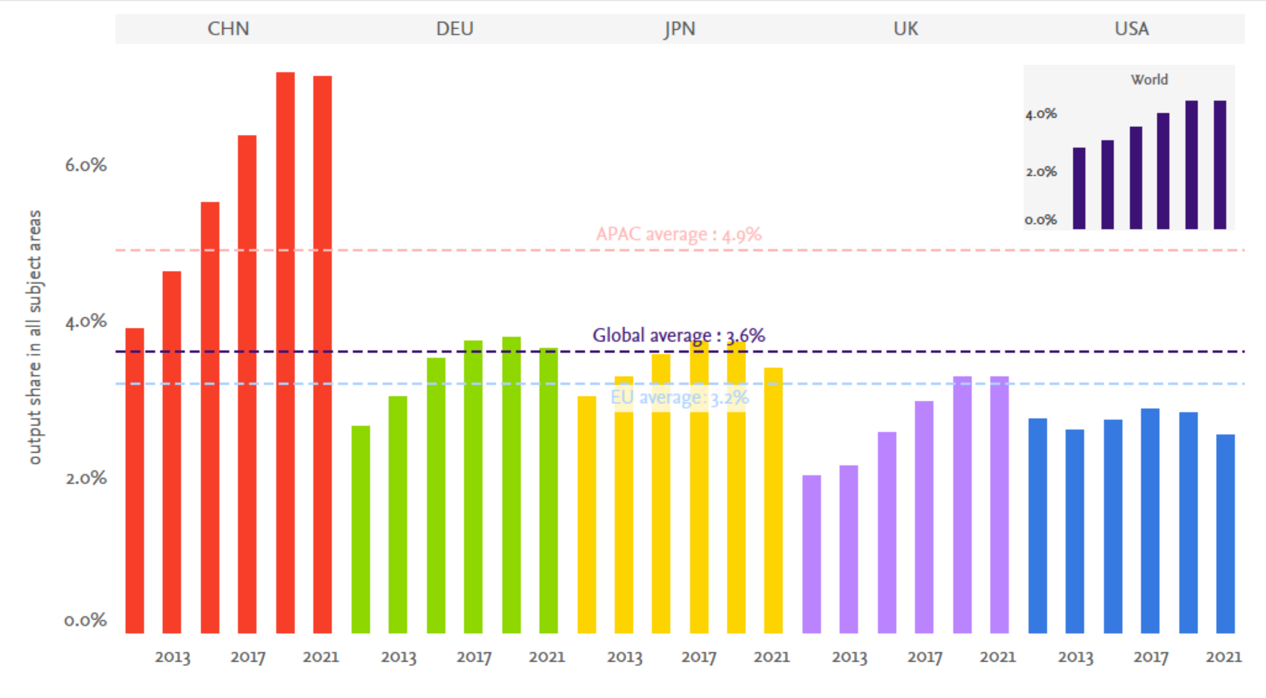


Figure 1.2.1 Changes in the proportion of Energy Science publications as a share of all articles in the benchmarking countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, World–Global)

As can be seen from Figure 1.2.1, the proportion of Energy Science publications (as a share of publications from all subject areas), globally, increased from 2010 to 2021, indicating that the discipline is currently in a stage of active growth. Among the key countries, China's Energy Science publications as a proportion of its own all-discipline publications is increasing, accounting for an increase from 3.4% in 2010 to nearly 7% in 2021. The proportion and growth rate are higher than other benchmarking countries and the world average, which shows that the activity level of Energy Science in China is higher. In contrast, the proportion of Energy Science publications of the comparators is generally lower than the global average (3.6%). The proportion of Germany and the UK in this discipline is relatively in a good growth mode, exceeding the European average (3.2%) in recent years, indicating that Energy Science is relatively active in Germany and the UK and maintains growth. The proportion of publications in Energy Science in the US and Japan has shown a slow downward trend in recent years, indicating that the activity of Energy Science in the US and Japan is relatively weak.

B. Sub-field activity

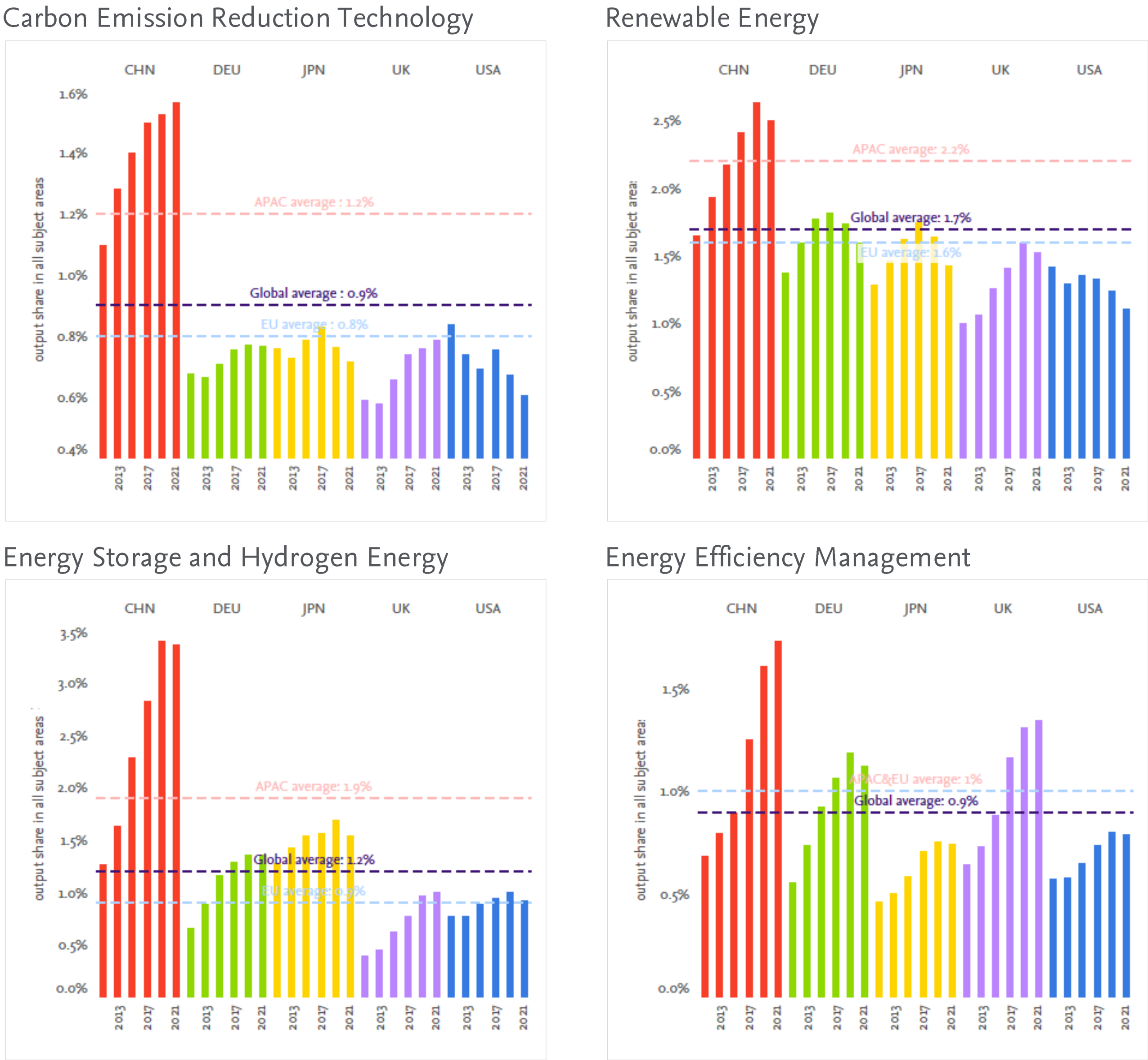


Figure 1.2.2 Changes in the proportion of publications in four sub-fields out of all articles in the benchmarking countries 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

It can be seen from the change in the share of articles published in the sub-fields as a proportion of articles published in all subjects (see Figure 1.2.2), that among the key countries, the proportion of publications in the Energy Science sub-fields in China is not only far higher than in the benchmarking countries, but also higher than the global average (ranging from 0.9% to 1.7%). Energy Storage and Hydrogen Energy is the sub-field representing the highest share of publications in China, and its lead is also the most prominent compared with other benchmarking countries. In terms of growth in the proportion of publications in the sub-fields, China has continued to increase over the past decade. Although the proportion of publications in Renewable Energy, as well as in Energy Storage and Hydrogen Energy has stabilized or declined in recent years, the overall growth rate is much higher than the average level of all comparators and the world, indicating that China has maintained a high degree of activity in various sub-fields of Energy Science, and its attention to this sub-field is also increasing. In contrast, the proportion of publications in the US on various sub-fields does not have an advantage over the benchmarking countries, and some sub-fields have small fluctuations or even downward trends (Carbon Emission Reduction Technology and Renewable Energy). Although the activity of sub-fields in the UK is not as high as in China, the proportion of its articles published in the four sub-fields is increasing year by year. Germany's activity in the Energy Storage and Hydrogen Energy and Energy Efficiency Management sub-fields is also increasing year by year. Japan has the most prominent advantage in the publication of Energy Storage and Hydrogen Energy, and although its proportion of articles published in the sub-field of Energy Efficiency Management is low, the activity has increased year by year. These characteristics are closely related to national energy conditions and the related scientific and technological structures of various countries.

Leading Research Institutions

Scientific research institutions are the most important engines of research output and usually consist of colleges, universities, and research institutes. These are the concentrated embodiment of a country's strategic scientific and technological strength and national competitiveness and play a leading role in the national innovation system. In China, scientific research institutions not only undertake the task of carrying out major cutting-edge research and even carrying out technology transfer and technical services, but they are also responsible for cultivating talent and building innovation platforms. These scientific research institutions are important to long-term development and overall science and technology strategy in China, and they play a fundamental, core role in the national scientific and technological ecosystem. Therefore, the identification and evaluation of leading research institutions in the field will help guide scientific research institutions to serve national goals, enhance core competitiveness, establish a sound research incentive mechanism, and improve management systems, as well as research fund allocation and talent development programs, so as to further develop disciplines.

This subsection focuses on China's leading research institutions in Energy Science and conducts a comparative analysis from the perspectives of research output and scholarly impact. In addition, this section briefly focuses on national and international institutions that have a high volume of publications in high-impact journals in each of the four sub-fields of Energy Science.

A. Leading Research Institutions of Energy Science

From 2010 to 2021, the top-ranking domestic research institution (in terms of the total number of publications in Energy Science) was the Chinese Academy of Sciences (CAS), with a total of more than 45,000 articles. The scholarly impact of its publications in Energy Science is also strong, with an FWCI of 2.3. Due to the difficulty in separating out publications by individual institutes within CAS given the current data sources, this report only counts in the University of Chinese Academy of Sciences when analyzing leading universities in China, and includes CAS as a whole in the analysis of leading research institutions globally.

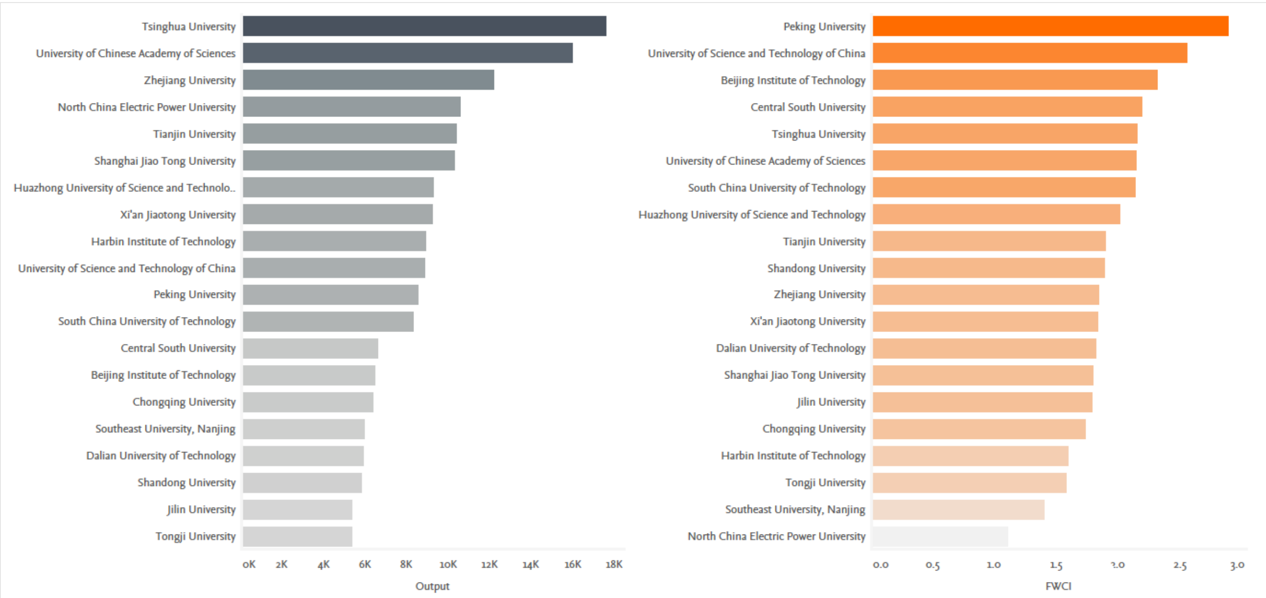


Figure 1.3.1 Top 20 Chinese universities in terms of scholarly output in Energy Science, and their FWCI, 2010–2021

As shown in Figure 1.3.1, among the top 20 Chinese universities by research output in Energy Science, Tsinghua University (17,000), the University of Chinese Academy of Sciences (16,000) and Zhejiang University (12,000) have published more than 10,000 articles. In terms of scholarly impact as measured by FWCI, Peking University (2.9) and the University of Science and Technology of China (2.6) are clearly ahead of other universities.

B. Leading Research Institutions of sub-fields

Publications in the top 10% high-impact journals refer to the articles published in journals among the top 10% based on CiteScore in a given year or period. Since such articles are accepted for publication by high-impact journals, it means that they have been recognized by peer reviewers as important and evaluated as excellent, and thus, can be treated as indicative of excellent research.

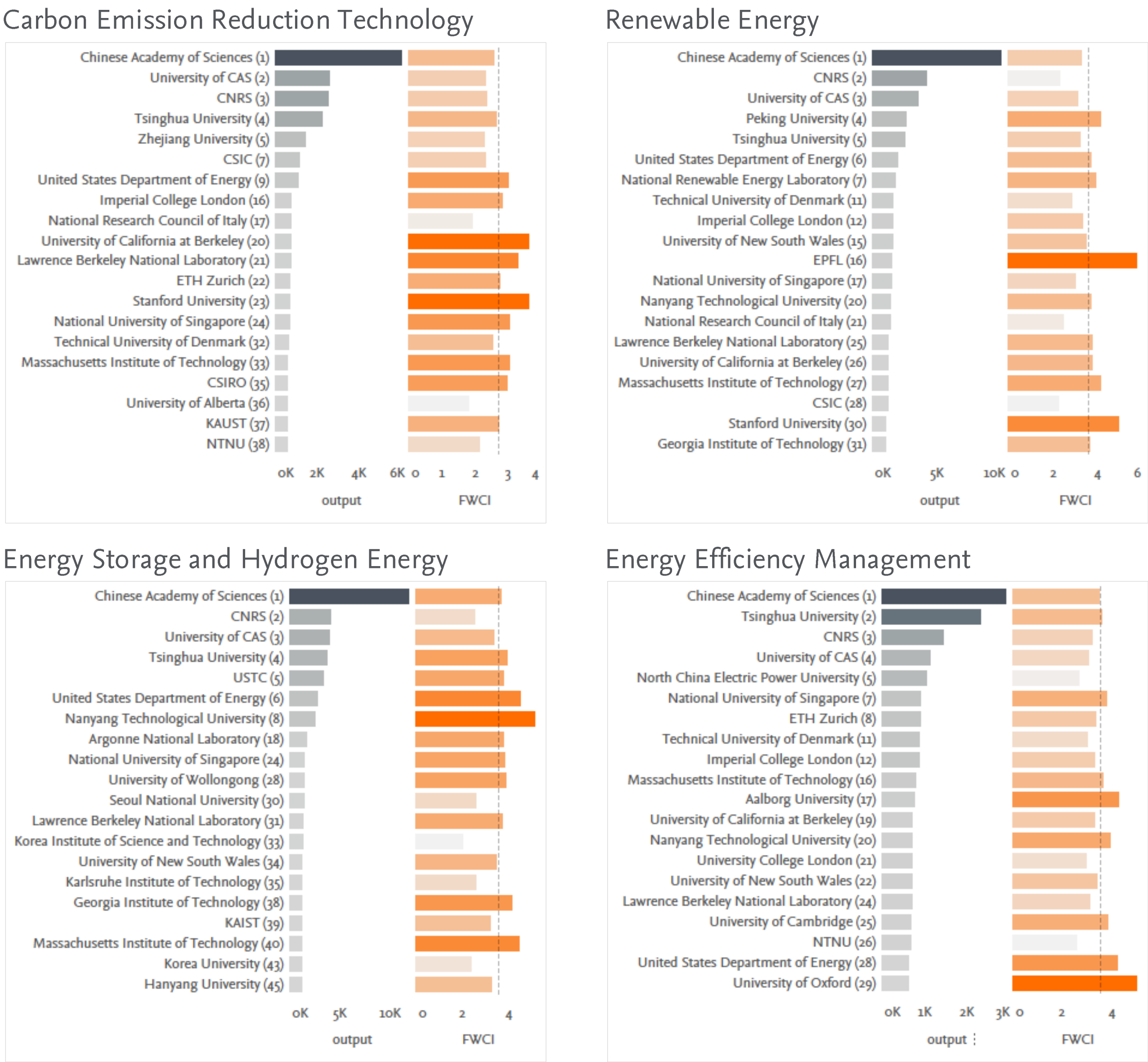
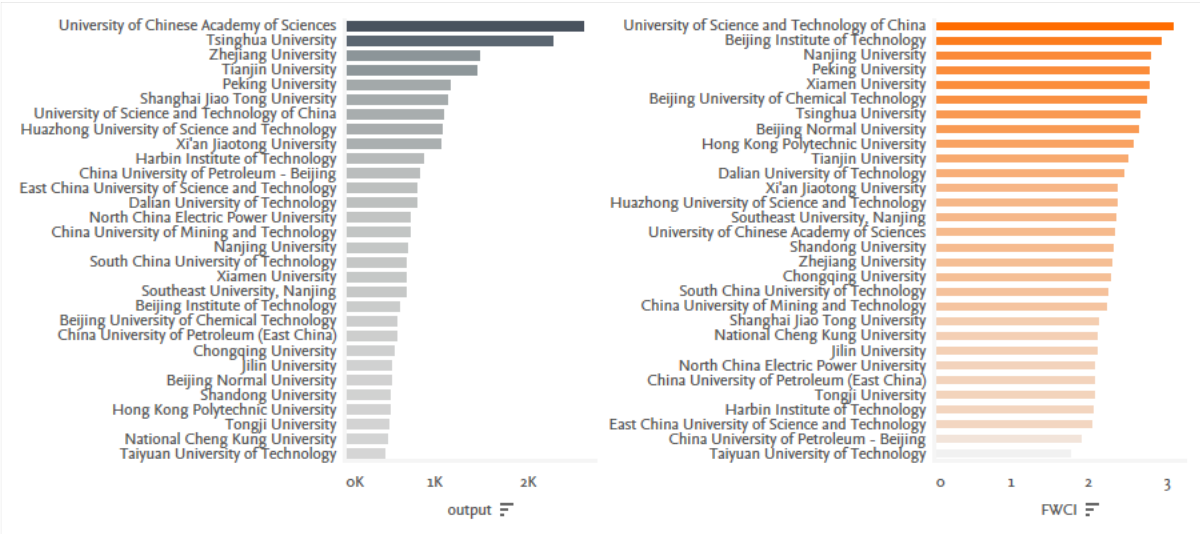


Figure 1.3.2.1 Leading research institutions globally by the number of publications in the top 10% journals for each of the sub-fields and their FWCI, 2010–2021 (Due to the high output volume of Chinese research institutions, for institutions ranked below the top 5, only international institutions other than the Chinese ones are displayed, and their global rankings by output volume are shown in parentheses)

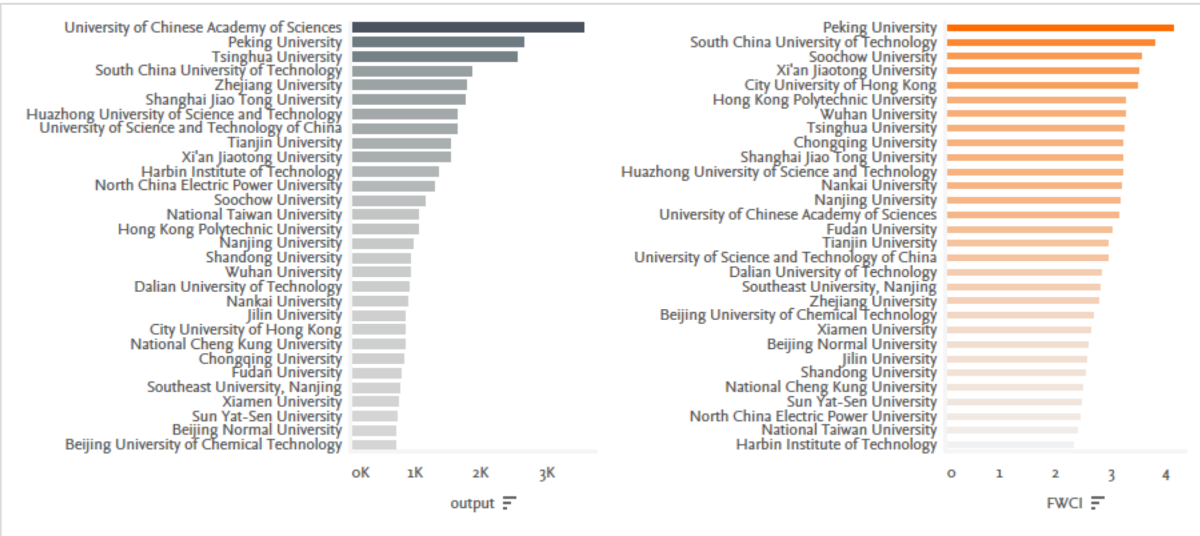
Institutional abbreviation: University of CAS–University of Chinese Academy of Sciences; ETH Zurich–Swiss Federal Institute of Technology Zurich; KAUST–King Abdullah University of Science and Technology; NTNU–Norwegian University of Science and Technology; USTC–University of Science and Technology of China; KAIST–Korea Advanced Institute of Science and Technology; EPFL–Swiss Federal Institute of Technology Lausanne.

Due to the high volume of articles published by China's research institutions, and in order to show more international institutions with the similar publishing strength, Figure 1.3.2.1 presents the top five global research institutions with the most publications in the top 10% of high-impact journals in each sub-field, and for institutions ranked below the top five, only displays international institutions that have published considerably in the relative sub-field. Globally, in all the four sub-fields, the institution that publishes the most is the Chinese Academy of Sciences. Among international institutions, the French National Center for Scientific Research (CNRS), and the US Department of Energy have published substantially in all the sub-fields. In terms of scholarly impact, institutions in the UK and the US, such as Stanford University (US), the University of California, Berkeley (US) and the University of Cambridge (UK), tend to have higher FWCI of their publications.

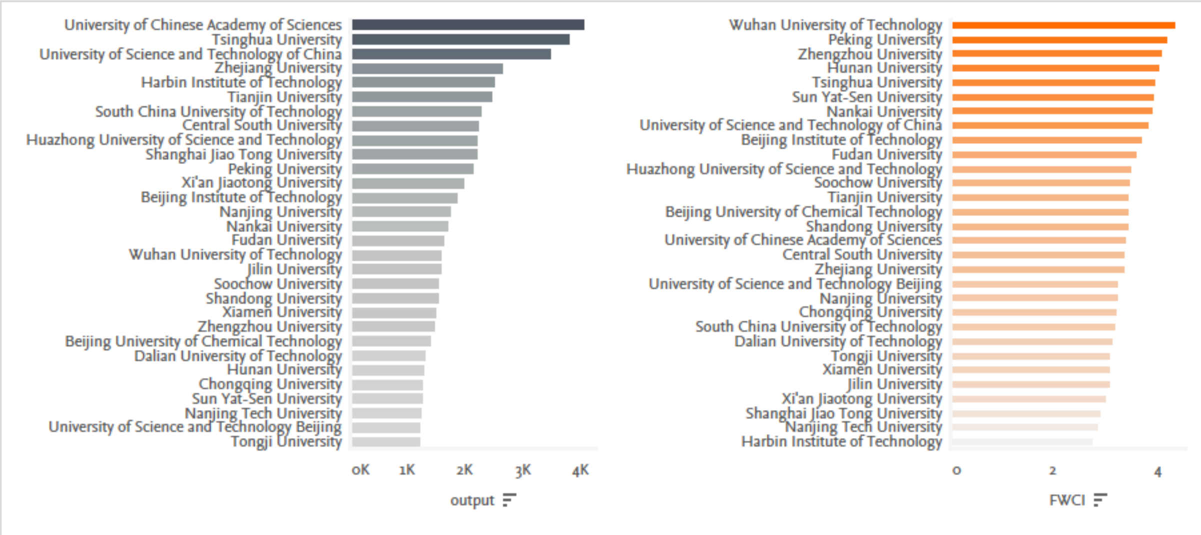
Carbon Emission Reduction Technology



Renewable Energy



Energy Storage and Hydrogen Energy



Energy Efficiency Management

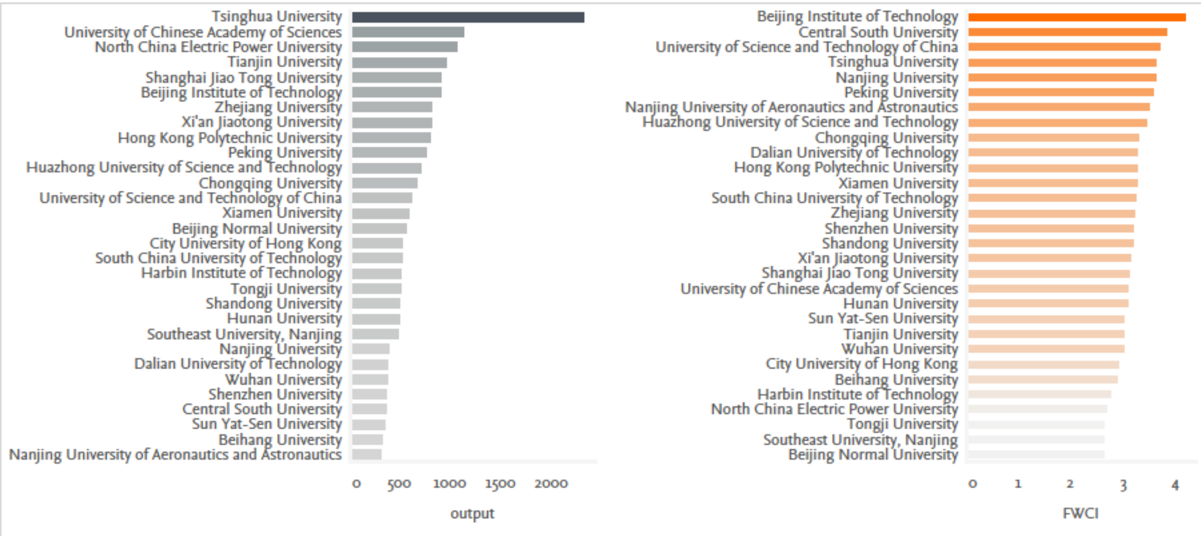


Figure 1.3.2.2 Top 30 Chinese universities by top 10% journal publications and their FWCI, 2010–2021

Figure 1.3.2.2 lists the top 30 Chinese universities that have published the most in the top 10% journals in each of the four sub-fields, as well as the FWCIs of their publications. Given the variation in research resources, faculty, and school policies, each university has different emphases in various sub-fields of energy. In general, universities with a high volume of publications include: University of Chinese Academy of Sciences, Tsinghua University, Peking University, Zhejiang University, University of Science and Technology of China, North China Electric Power University, Tianjin University, and South China University of Technology. Universities with high scholarly impact as measured by FWCI are the University of Science and Technology of China, Peking University, Beijing Institute of Technology, Nanjing University, Zhengzhou University, South China University of Technology, Wuhan University of Technology, Central South University, and Tsinghua University. (The universities are listed in no particular order).

Chapter 2

Driving Forces for Research Development—Research Collaboration and Funding

Key Findings

- Globally, most publications in the subject area of Energy Science and its four sub-fields result from national collaboration, supplemented by international collaboration. The Asia–Pacific region is dominated by national collaboration, while the European region is dominated by international collaboration. Among the key countries, China's research output is mainly based on institutional collaboration and national collaboration, and the proportion of its output that is internationally collaborative is the lowest among the comparators, while the United Kingdom (UK) has the highest share of internationally-collaborative output among the comparators[9].

- The scholarly impact of internationally collaborative output, either for Energy Science or its four sub-fields, is higher than that of nationally or institutionally collaborative output. Among the key countries studied, the United States (US) and the UK have a high scholarly impact for their nationally, institutionally or internationally collaborative research output. China has the highest scholarly impact for internationally collaborative output among all comparators, which is also the highest for all forms of research collaboration, but the scholarly impact of its output for the other two forms of collaboration is relatively low.

- In the past ten years or so, Europe and the US had a high starting point for their share of internationally collaborative output in Energy Science, and their internationally collaborative research developed rapidly, contributing 50% or more to overall research in Energy Science. However, China's Energy Science lags behind in terms of the share of international collaboration and its growth rate, suggesting room for improving its share of international collaboration. In view of the fact that the scholarly impact of China's internationally-collaborative Energy Science output is relatively high globally, improving the share of output that is international collaborative will help to enhance the scholarly impact of the overall Energy Science output for China and can be a future development direction for China's Energy Science discipline.

[9] Differences in the form of scientific collaboration are also affected by political and geopolitical factors in regions and countries.

- The cross-border collaboration network for Energy Science is characterized by a wide distribution of participating countries, and close collaboration between regions, with a few countries playing a centralized role. The collaboration network is not limited to economically developed regions, but also covers many African and Latin American countries, reflecting the globalization of the subject area, and highlighting Energy Science as a scientific research field with substantial global participation and attention. China and the US are the most active countries in the global collaboration network, with not only the widest distribution of collaborators, but also the highest frequency of collaboration. China and the US also collaborate most closely with each other. Given that only a relatively low proportion of research output comes from international collaboration in China, the country still has a lot of room to grow its international collaboration, and it can continue to play an important role in promoting global collaboration in Energy Science in future.

- Given the data availability limitations, the analysis of funding data shows that funded projects in Energy Science are mostly located in the European Union (EU) region, which also receives a higher amount of funding than the Asia–Pacific region. Among the major funding organizations in the comparators, although the EU's Horizon 2020 Plan provides the highest amount of funding, the National Natural Science Foundation of China (NSFC) has funded the largest number of research projects. Moreover, compared to other global funding institutions, China's NSFC has funded the largest number of research publications between 2010 and 2021 in absolute volume, showing the strong support it gives to basic research in the field of Energy Science.

Research Collaboration Performance

Solving increasingly complex global problems often requires knowledge-sharing and resource-sharing between scientists in different regions or fields. Various forms of research collaboration not only effectively promote the flow and sharing of knowledge, but also stimulate innovation and provide new perspectives for scientific research. Moreover, research collaboration between different regions and countries often creates a wider scholarly and social impact than independent research. How collaborative research performs is an important dimension to focus on for developing a subject area.

This section focuses on collaborative publications in Energy Science literature from 2010 to 2021, starting with three types of research collaboration: international collaboration, national collaboration, and institutional collaboration. It analyzes the research impact of the various forms of collaboration and their collaboration trends. Moreover, this subsection also compares and analyzes research collaboration performance in the overall Energy Science subject and its four sub-fields for key countries.

A. The performance of research collaborations in Energy Science

(A) Output share by research collaboration type

This report classifies scientific publications into the following four types according to the number of authors of a publication and the type of institution with which they are affiliated:

Internationally collaborative publications: An internationally collaborative publication is a paper that is published with multiple authors, where the affiliations listed by the authors include institutions from two or more countries.

Nationally collaborative publication: A nationally collaborative publication is published by multiple authors, and none of the authors is affiliated with a foreign research institution, but the affiliations listed by authors include at least two different institutions (all institutions are from the same country). Institutionally collaborative publication: An institutionally collaborative publication is published by multiple authors, and all authors are affiliated with the same institution.

Independent research: This refers to publications by a single author, and as the number of this type is very small, these are only presented as a comparison item.

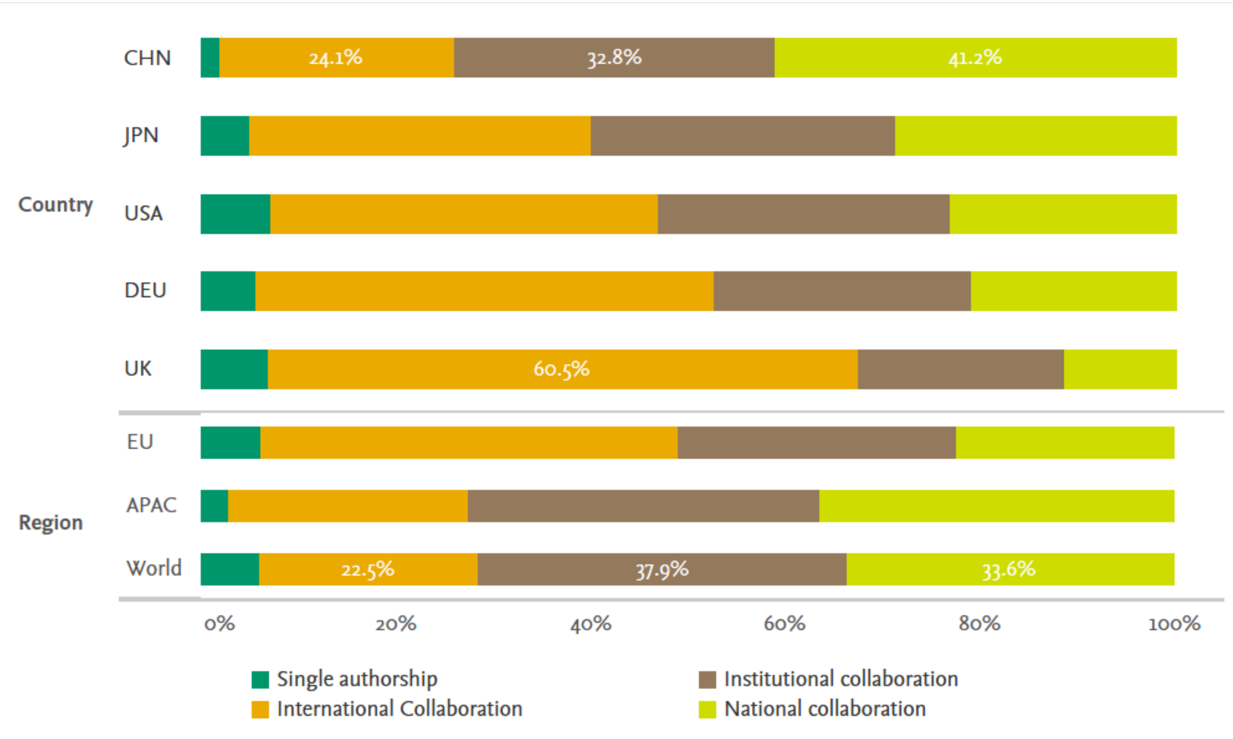


Figure 2.1.1.1 Proportion of Energy Science publications by the types of scientific collaboration in the comparators and regions, 2010–2021 (code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, EU–Europe Union, APAC–Asia Pacific, World–Global)

For the types of Energy Science-related articles published between 2010 and 2021 (Figure 2.1.1.1), among the key countries, China has the highest share of national collaboration in Energy Science publications, reaching 41.2%, and the smallest share of international collaboration, at 24.1%, indicating that China's

Energy Science research mainly relies on collaboration within the territory of the country. In contrast, other comparators are dominated by international collaboration, with their share exceeding that of national collaboration or institutional collaboration, indicating that international collaboration in Energy Science is quite frequent in developed countries such as the US and major European countries. Among them, the UK has the highest share of international collaboration, with 60.5% of research results coming from international collaboration. It is worth mentioning that the research collaboration pattern is also influenced by national geopolitics, and the UK's high rate of international collaboration may be related to its special geographical location and national historical evolution.

As for publications by region, because China's Energy Science-related publications contribute more than 50% of output in the Asia–Pacific region, the distribution of publication types in the Asia–Pacific region is affected by China, and the publication pattern is similar to that of China, with more frequent national or institutional collaboration, and only 24.5% of the publications are an international collaboration. In contrast, the European region is dominated by international collaboration, which accounts for 42.8% of the publications. Globally, Energy Science publications are dominated by institutional (37.9%) and national collaboration (33.6%), and supplemented by international collaboration (22.5%), which is similar to the shares of various types of scientific collaboration in overall research.

(B) Scholarly impact of research collaboration

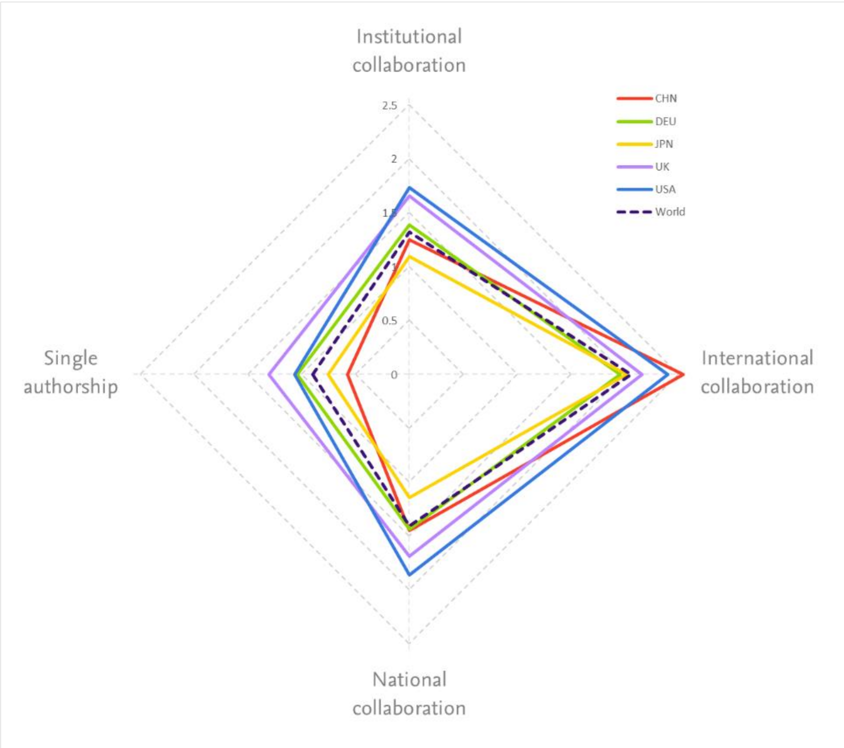


Figure 2.1.1.2 FWCI by collaboration type for publications in Energy Science globally and in benchmarking countries, 2010–2021 (code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, World–Global)

As shown in Figure 2.1.1.2, among all types of Energy Science publications, the FWCI of independently authored publications is lower than those of other forms of collaboration, and the research impact increases as collaboration broadens, meaning that collaboratively published articles have a higher scholarly impact. For all the comparators, international collaboration has the highest FWCI among the four types of collaboration, indicating that internationally collaborative publications in Energy Science generally have a high scholarly impact. This suggests that in academic development and planning, strong support for cross-border research collaboration will likely improve the research impact of the Energy Science subject.

In terms of national performance, the US has a higher scholarly impact than other countries in both national and institutional collaboration in Energy Science, which is another indication of the overall strength of the research output of research institutions in the US. The scholarly impact of the UK's nationally and institutionally collaborative publications is also at a high level, higher than the global average. China has the highest scholarly impact for international collaboration in Energy Science, leading among the comparators. Given that China's share of international collaborative publications in Energy Science is much lower than that of the comparators, encouraging large-scale international collaborative research will help enhance China's overall research impact in Energy Science.

(C) Trends in the output share of international collaboration

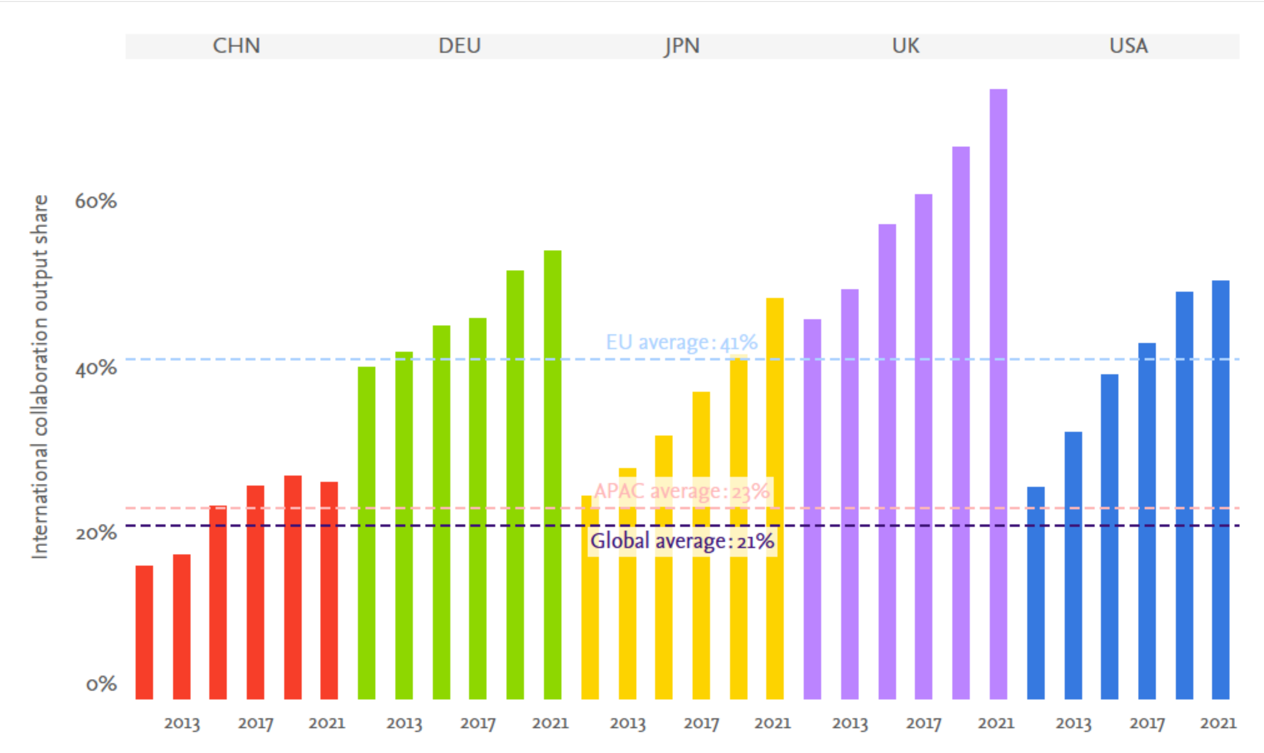


Figure 2.1.1.3 Trends in the share of international collaboration in Energy Science in comparator countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

As shown in Figure 2.1.1.3, in the past decade or so, the share of international collaboration in Energy Science has continued to grow in key countries, and the internationally collaborative publications of the comparators, except China, have all exceeded or approached half of their total Energy Science publications in recent years, indicating that international collaboration is a mainstay of development in Energy Science in these countries. Among them, the UK leads in international collaboration, with not only the highest share as the base value, but also rapid growth of the share, with an international collaboration rate exceeding 50% since 2014, and reaching 73% in 2021. Although China's international collaboration rate began to reach the global average (21%) in 2016, the overall share and growth rate still lag behind other comparators, indicating that its international collaboration still has much room for improvement, and is one of the future development directions of Energy Science in China. China's international collaboration rate declined a bit after 2019, which may be related to the emergence of the COVID-19 pandemic.

(D) Trends in the output share of national collaboration

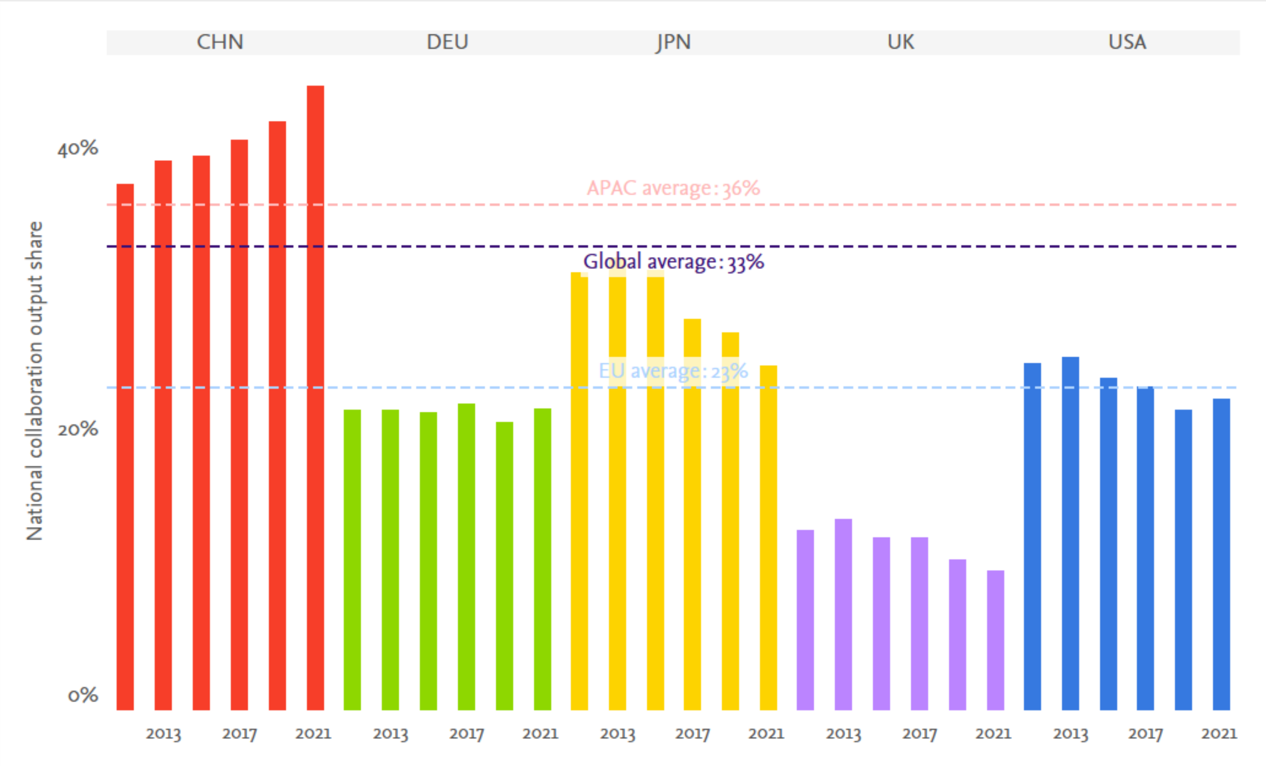


Figure 2.1.1.4 Trends in the share of national collaboration In Energy Science in benchmarking countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

Figure 2.1.1.4 shows that over the past decade or so, China's national collaboration has been higher than the world, Asia–Pacific, and European averages, and has been growing steadily. The share of national collaboration in other comparator countries has barely changed or shows a declining trend. In absolute terms, the UK has the smallest share of national collaboration. The different collaboration patterns presented by each comparator are related to the geopolitical differences of each country.

B. Research collaboration performance of sub-fields

(A) Share of output by type of research collaboration

Figure 2.1.2.1 Share of publications by type of research collaboration in the benchmarking countries and regions for the four sub-fields, 2010–2021 (code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA –United States, EU–Europe Union, APAC–Asia–Pacific, World–Global)

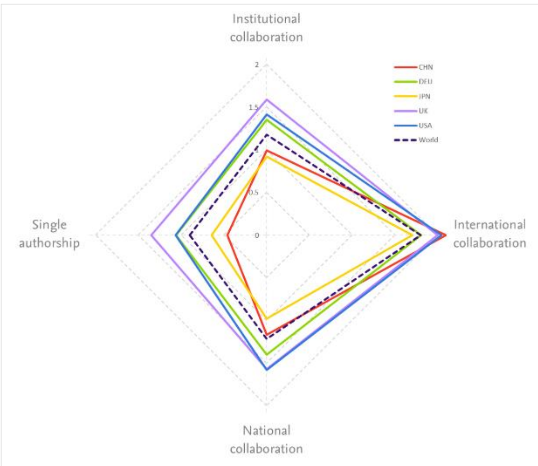
Analysis of the collaboration of research output in the four sub-fields of Energy Science between 2010 and 2021 shows that across the four sub-fields, China is dominated by national collaboration, which accounts for 35% to 45% of its research output; institutional collaboration is the second-most dominant collaboration form, while international collaboration accounts for a relatively small proportion of publications (less than 30%). Among the comparator countries, China has the highest share of national collaboration and the lowest international collaboration rate, suggesting that for all the sub-fields of Energy Science, China's research output mainly relies on research collaboration within the country.

In contrast, in the comparator countries, international collaboration dominates for each sub-field, with the share exceeding that of national or institutional collaboration. Among them, as with the entire Energy Science subject, the UK has the highest international collaboration rate, with more than 55% of its research output resulting from international collaboration, indicating its frequent collaboration with other developed countries in Europe and the US in all the sub-fields.

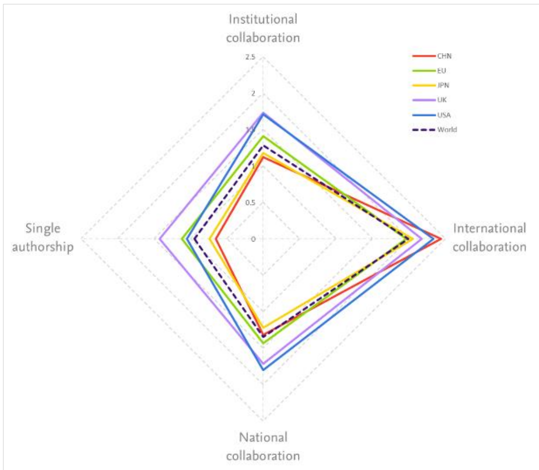
As for regional publications, given China's high contribution rate to publications in the Asia–Pacific region, the collaboration pattern in the Asia–Pacific region is greatly affected by China, and its distribution of publications by collaboration type has a similar pattern to that of China. That is, its publications are dominated by national or institutional collaboration, while the share of international collaboration is under 30%. In contrast, international collaboration is more frequent in the European region, accounting for about 40% of publications. Globally, the research collaboration pattern of the sub-fields is similar to that of the overall Energy Science subject. That is, research output is mainly in the form of institutional or national collaboration, supplemented by international collaboration, which may also be related to the high research output by China in all the four sub-fields.

(B) Scholarly impact of collaborative publications

Carbon Emission Reduction Technology



Renewable Energy



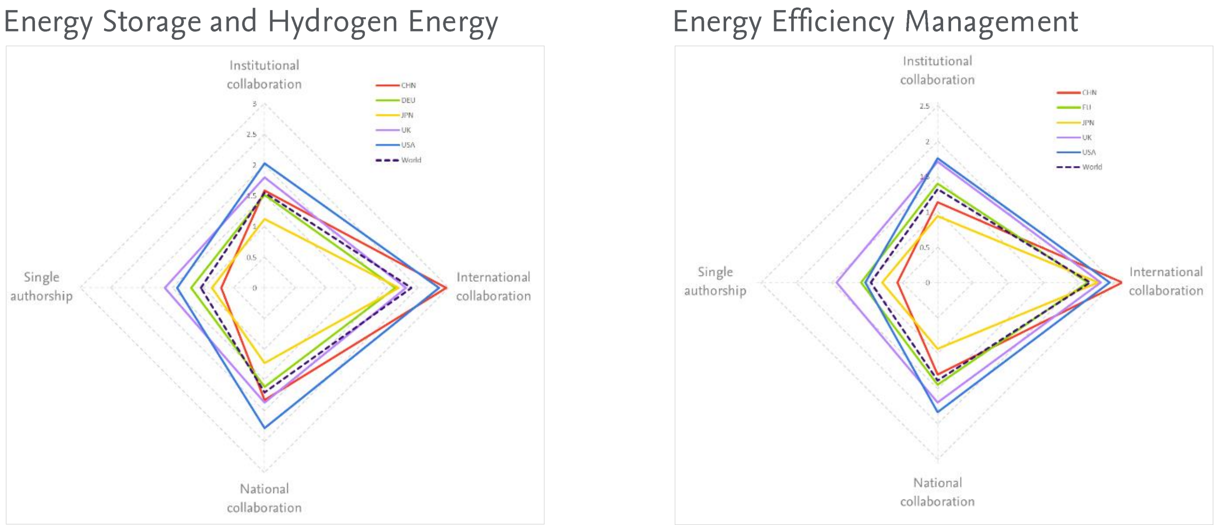


Figure 2.1.2.2 Comparison of global and benchmarking countries' scholarly impact (FWCI) by collaboration type for the four sub-fields, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States, World–Global)

Figure 2.1.2.2 shows that in the four sub-fields, among all types of collaboration, the FWCI of international collaboration is higher than that of national collaboration and institutional collaboration, indicating that, in all the four sub-fields, the research results of international collaboration have the highest scholarly impact. This also suggests that international collaboration helps to enhance the research impact of various sub-fields.

In terms of performance in benchmarking countries, the scholarly impact of the UK and the US is generally ahead of other benchmarking countries in each of the sub-fields. This shows that research institutions in the UK and the US have strong research performance in various sub-fields of Energy Science. In terms of the scholarly impact of its international collaboration, China is the highest among the comparators in the four sub-fields; the FWCI of international collaborations in the US and the UK is also at the leading level; Japan is the lowest, and its FWCI of international collaboration is slightly lower than or close to the global level. As with the discipline overall, given that China's international collaboration accounts for a relatively low proportion of its research but has the highest scholarly impact, encouraging international collaboration in research will help enhance China's overall research impact in various Energy Science sub-fields.

(C) Trends in the share of output resulting from international collaboration

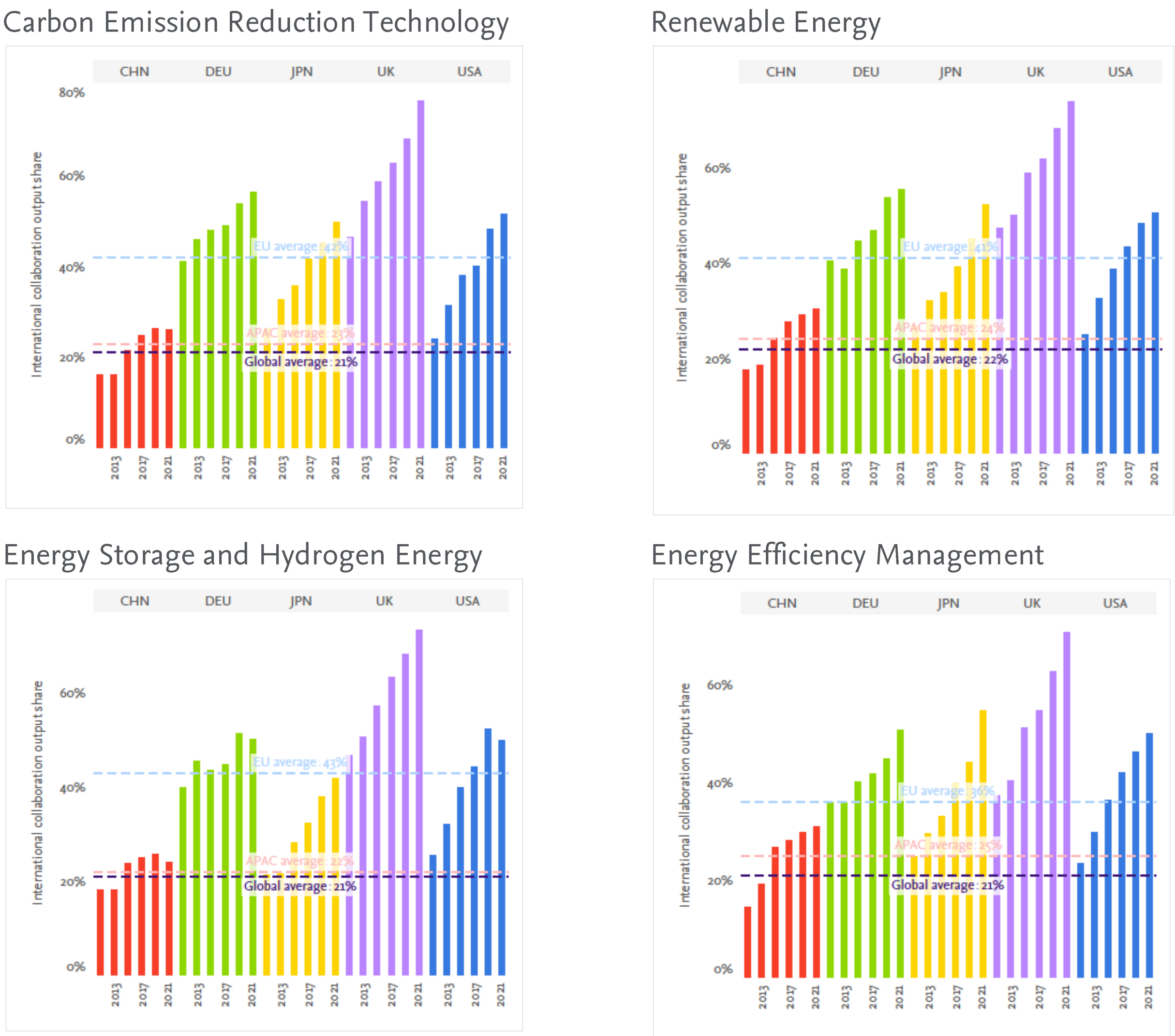


Figure 2.1.2.3 Trends in the proportion of international collaboration in publications by each sub-field in benchmarking countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

As shown in Figure 2.1.2.3, over the past decade, the proportion of international collaboration in various sub-fields has trended upward in all key countries, and in recent years, except for China and Japan, the internationally collaborative publications from each benchmarking country have reached nearly half of the total publications on the sub-fields in their own countries, indicating that international collaboration is a general trend. In a pattern that mirrors that of the entire discipline, the greatest development of international collaboration is in the UK, where not only is the international collaboration rate much higher than the world and even the EU average, but the proportion of international collaboration in each sub-field since 2010 has exceeded 40%, and in 2021 reached nearly 70%. Although the international collaboration in China reached the global average around 2016, both the proportion and the growth rate lagged behind those of other benchmarking countries, indicating that there is still substantial room for improvement in international collaboration and it could be a direction for future efforts.

(D) Trends in the share of output resulting from national collaboration

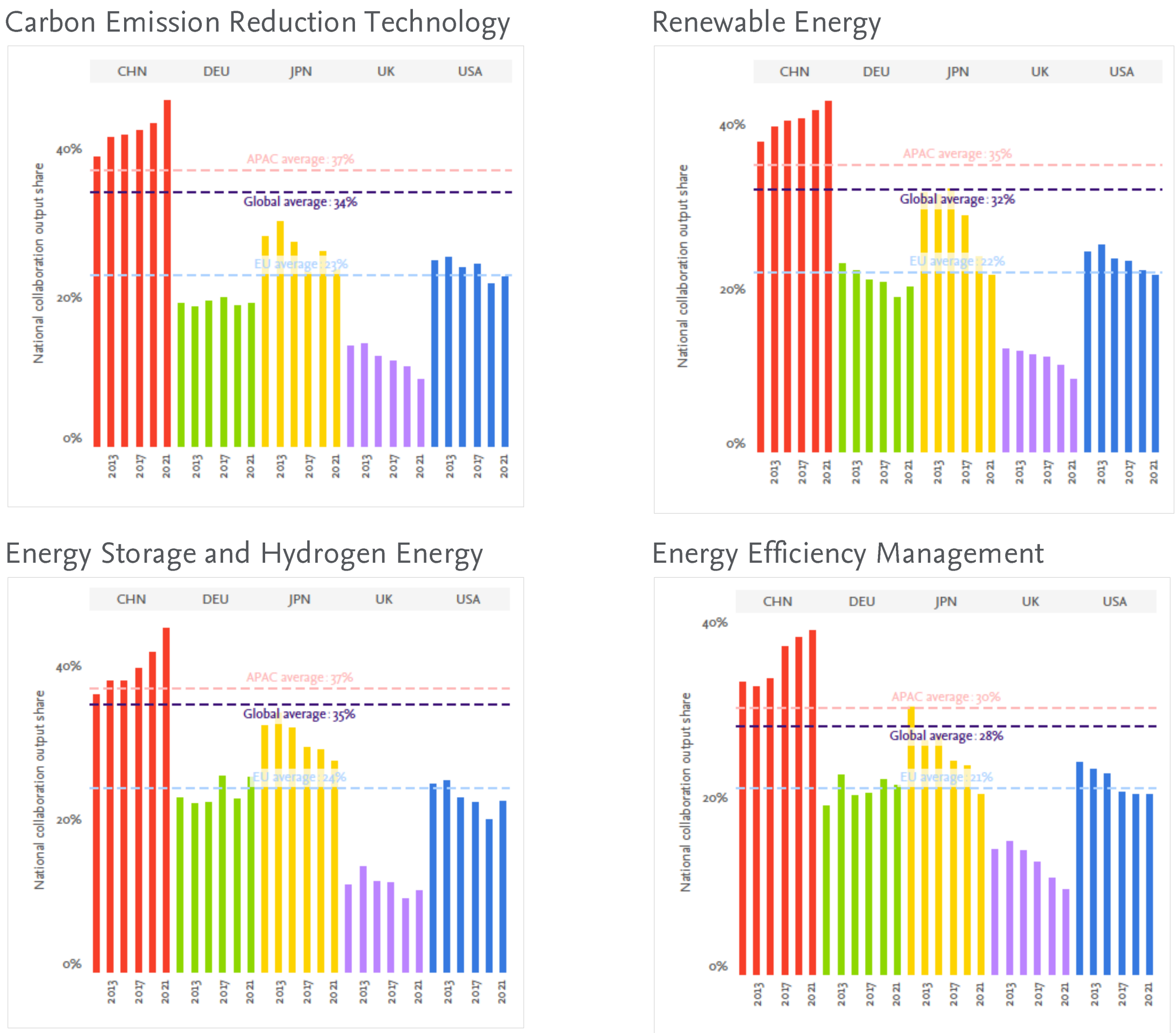


Figure 2.1.2.4 Trends in the proportion of nationally collaborative publications in sub-fields for benchmarking countries, 2010–2021 (Code: CHN–China, DEU–Germany, JPN–Japan, UK–United Kingdom, USA–United States)

As shown in Figure 2.1.2.4, over the past decade or so, the proportion of nationally collaborative publications in China has been increasing in all sub-fields. In contrast, the share of national collaboration among the benchmarking countries has either remained stable (Germany) or declined (US, UK, and Japan). In absolute terms, China's national collaboration accounted for the highest proportion of publications, exceeding the average level of the Asia–Pacific region, while the UK is the country with the lowest proportion of national collaboration, and its proportion has always been lower than the European average. Because it is affected by China, the proportion of national collaboration in the Asia–Pacific region is higher than the world average, while the proportion of national collaboration in the European region is lower than the world average, which has much to do with geopolitical factors in the two regions.

An Overview of the International Collaboration Networks

Because international collaboration often involves multiple research institutions, diverse researchers, and larger financial investment, it often results in greater academic and social impact. Globalization has made cross-border collaboration more convenient than in the past, and more frequent. The growing international collaboration helps promote the flow of inter-regional research knowledge, funds, and resources and can increase the research impact of a country in the world.

To understand the current situation in Energy Science research collaboration around the world, this subsection analyzes two aspects: the global collaboration network and the leading countries in international collaboration. Together, these factors reflect the importance of the field of Energy Science from a global perspective and the extent of activity within the discipline.

A. Global collaboration network

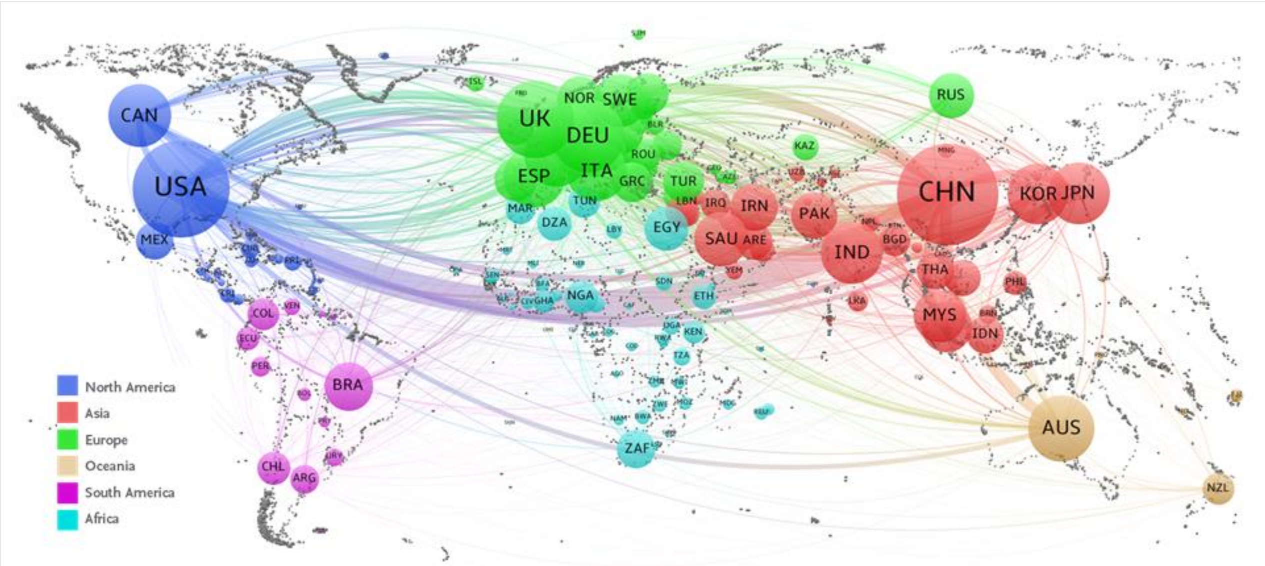


Figure 2.2.1.1 International collaboration network diagram of Energy Science, 2010–2021. (The size of the nodes in the network diagram represents the size of the total volume of international collaboration in Energy Science, the thickness of the lines between the nodes represents the frequency of collaboration between the two countries, and the color classification of the nodes indicates the geographical regional classification of the country.)

Based on internationally-collaborative publications in Energy Science from 2010 to 2021, this report draws a map of the global collaboration network. As shown in Figure 2.2.1.1, the countries involved in international collaboration in Energy Science are widely distributed, and collaboration and exchanges between regions are frequent. Judging from the number and frequency of international collaborations, China, the US and major European countries (such as the UK and Germany) have performed prominently, not only with the highest output of international collaboration, but also with close collaboration with many countries. Among them, China's main countries of collaboration include the US, Japan, South Korea, Australia and major European countries. It is worth noting that many African countries and Latin American countries have also participated in collaborative research in Energy Science. Brazil, for example, has a notable volume of international collaboration among countries in South America, and has frequent collaborations with the US and major European countries. This shows that Energy Science has become a research field widely participated in by and of importance to countries around the world.

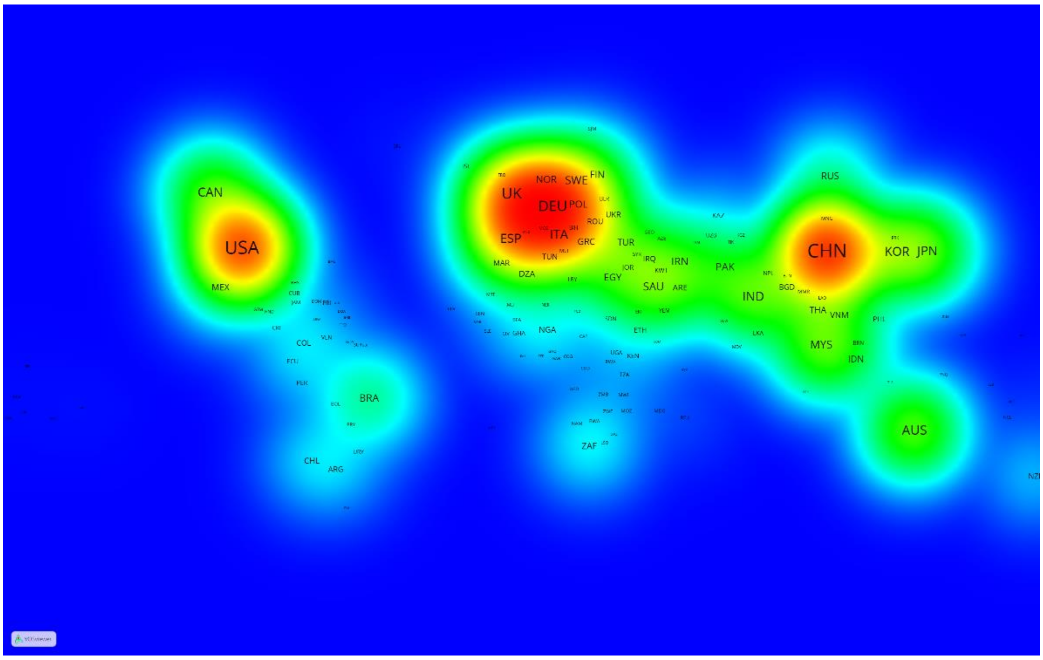


Figure 2.2.1.2 Heat map of international collaboration in Energy Science, 2010–2021 (Heat map color represents the density of collaborative networks around the country: the greater the density of collaborative networks, the closer the color is to red, the smaller the density, the closer the color is to blue.)

To better understand the intensity of the global collaboration network and to explore which regions or countries are central to the global collaboration network, the report also draws a heat map of the international collaboration network for Energy Science (Figure 2.2.1.2). In this map, with the country as the node, the closer the node color is to red, the greater the density of the collaborative network. This enables the viewer to quickly and intuitively identify the country or region with the highest density in the international collaboration network.

As shown in Figure 2.2.1.2, from a global perspective, the collaboration network of European countries is the densest, and its collaboration network is mainly concentrated in Germany, the UK, France, Italy, Spain and other countries. China's international collaboration network is the densest in Asia, indicating that China is the country in Asia with the most collaboration with other countries and the highest frequency of collaboration in Energy Science research. North America is centered on the US, and its collaboration network is as dense as China's. International collaboration networks in Oceania, South America and Africa are less dense than those in North America and Eurasia, but they also present networks of collaboration centered on individual core countries. Among them, Brazil, Australia and South Africa are the predominant countries of the collaboration networks in South America, Oceania and Africa, respectively.

B. Top countries in international collaboration

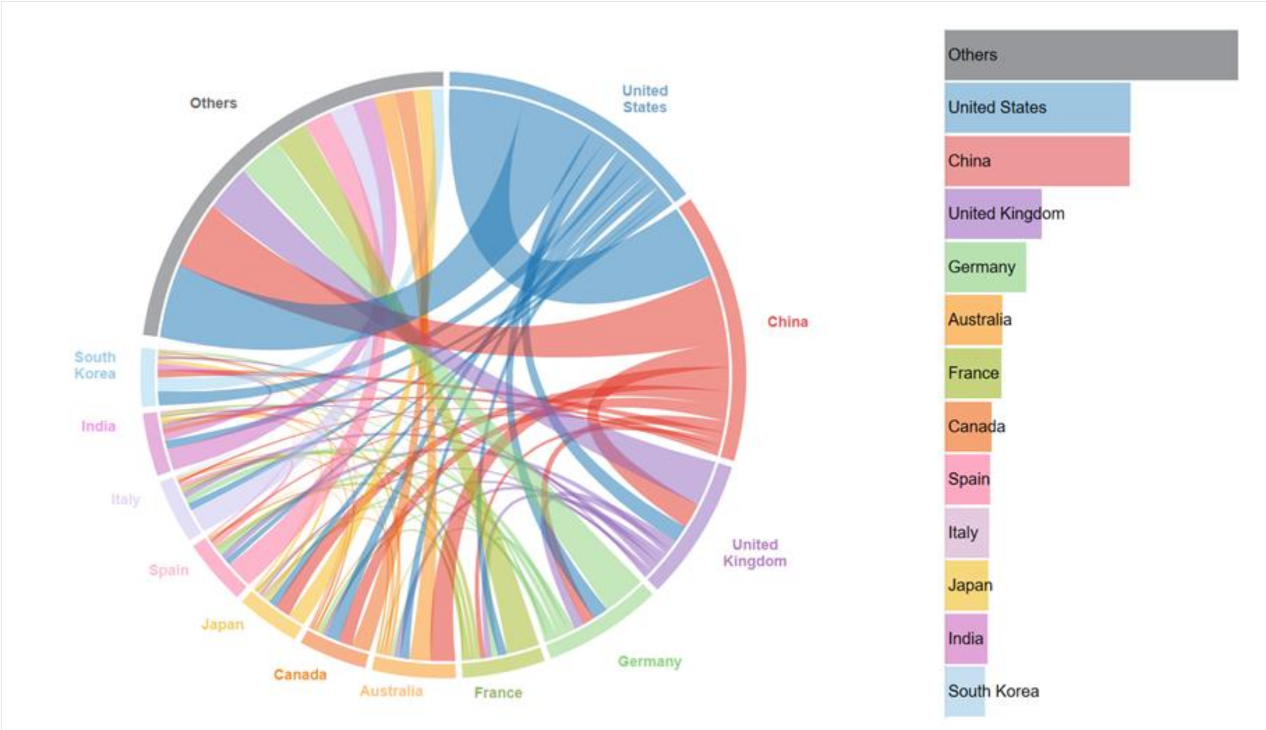


Figure 2.2.2.1 Top 12 countries by internationally collaborative publication output in Energy Science discipline (right) and the number of collaborations between countries (left), 2010–2021. (On the inter-country collaboration map (left), the ties between countries represent the relationship between Energy Science collaboration publications, the width of the ties represent the number of collaborative publications. The more collaborative publications, the thicker the tie.)

As shown in Figure 2.2.2.1, between 2010 and 2021, the countries with the largest number of internationally collaborative publications in Energy Science are the US and China, and these two countries are also the most important partners in international collaboration, and the amount of collaboration is the highest among their respective collaborating countries. Among the remaining countries with active international collaboration, the top two partners of most countries are also China and the US, indicating that China and the US are active in Energy Science research collaboration with many countries, and that the research strength of the two countries in this field is prominent. In addition, Germany is the most important partner of France and Italy after the US; the UK is Spain's main collaborative country partner in addition to the US, which shows that in addition to frequent collaboration with the US, the major European countries have also established important cooperative partnerships with each other. In addition, it is worth noting that South Korea is the most frequent collaborative country of India after the US.

Research Funding

Scientific research funding is used to support researchers to carry out basic research and cutting-edge explorations, or to invest in developing new research talent and team building. Investment in scientific research is also one of the main factors driving the development of a discipline. This analysis of research funding, examining funded projects and funding organizations, will help research managers understand the current funding landscape. It will also provide information to support government in making major scientific research decisions, guiding government or research administrators to invest resources on excellent talents and teams, and improving the efficiency of the use of research funds.

This subsection provides an overview analysis of the performance of major funding organizations and research institutions in major regions of the world and in benchmarking countries in terms of the amount of funding, the number of funded research projects and the number of funded publications. It is expected to show the importance that countries attach to the field of Energy Science in terms of financial investment.

A. Global and regional funding support

Elsevier's Funding Institutional[10] is an analytics tool focused on funding organizations and funding data, using a comprehensive solution to help research managers gain a competitive advantage by providing a comprehensive view of research funding. The analytics tool collects data from more than 18,000 active funding programs and more than 7 million funded research projects from funding organizations around the world, covering more than 4,300 government and private funding organizations. The analysis of funding programs and funding amounts in this section is based primarily on funding data from Funding Institutional for the period 2010 to 2021[11].

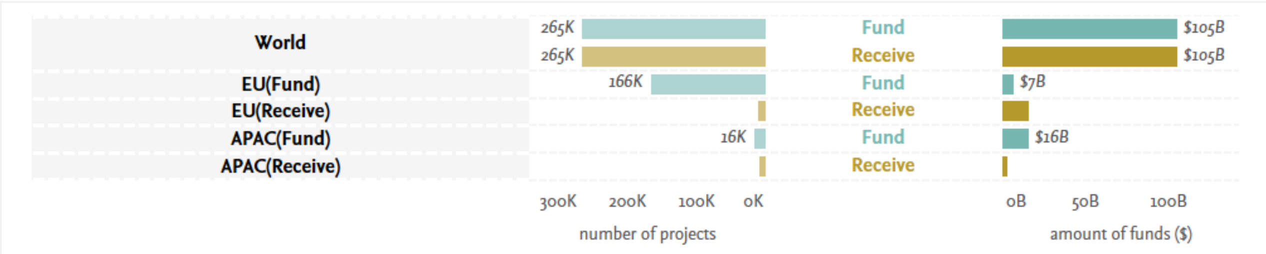


Figure 2.3.1 Funding paid out and received in the discipline of Energy Science in the global and benchmarking regions, 2010–2021. (Fund: number of projects or amount of funds by a country or a region. Receive: number of projects or amount of funds received by a country or a region).

Figure 2.3.1 shows that in the field of Energy Science, the global funding amount reached nearly US$105 billion between 2010 and 2021, and more than 265,000 projects have been funded. The amount of funding from the European Union's research funding organization is about US$7 billion, and the amount of funding received by research institutions in the region is about US$16 billion from around the world, which shows that the EU region has undertaken many funding projects from outside the region, and also echoes the generally high international collaboration rate of the European countries mentioned above.

Research grants in the Asia–Pacific region amount to about US$16 billion, but research institutions in the region receive about US$3 billion. The difference between the amount of funding received and the amount of funding released shows that more energy science projects are likely to be distributed in the EU region. On the other hand, however, the above results are limited by the data coverage of the database for funding organizations in the Asia–Pacific region, so the data is for reference only.

[10] https://www.elsevier.com/solutions/funding-institutional

[11] Since the data set includes data from the National Natural Science Foundation of China (NSFC) only until 2019, the inclusion of China's funding data is small at the country level, and the amount of funding and number of projects received from China by institutions covered in the report are limited to data from NSFC only.

B. Funding support of the comparators

For the comparators, this report provides a comparative analysis at the institutional level. For each country, representative funding organizations and research institutions were selected, to enable comparison of the amount of funds and the number of scientific research projects.

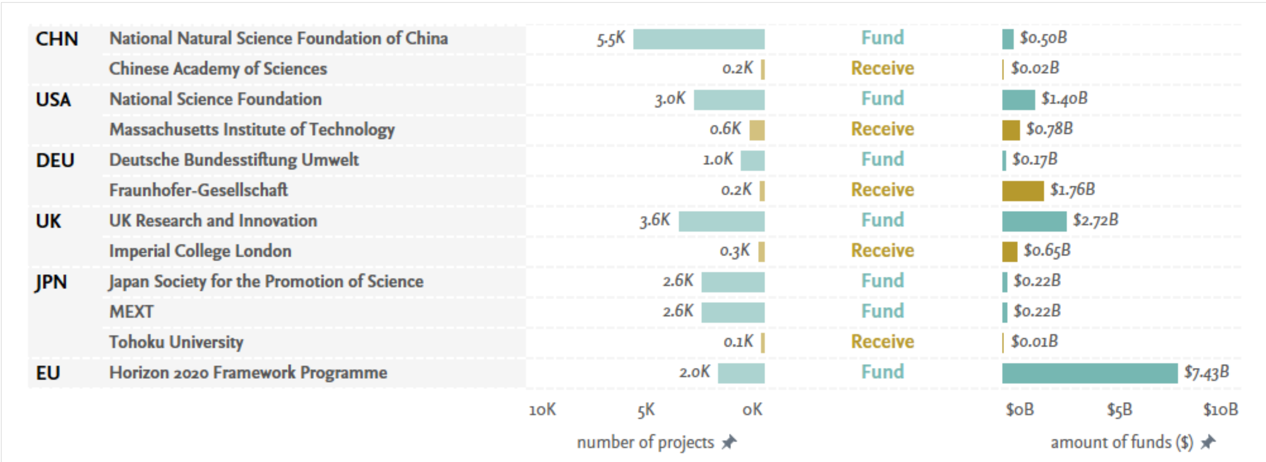


Figure 2.3.2.1 Benchmarking countries and regions' funding organizations and research institutions receiving funds in Energy Science, 2010–2021. (Fund: number of projects or amount of funds by a country or a region. Receive: number of projects or amount of funds received by a country or a region. MEXT: Ministry of Education, Culture, Sports, Science and Technology).

For the representative funding organizations of each benchmarking country, Figure 2.3.2.1 lists the funding for the Energy Science discipline of the National Natural Science Foundation of China (NSFC), the National Science Foundation (NSF) of the US, the Federal Environment Foundation of Germany, the UK Research and Innovation (UKRI) sponsored by the Department for Business, Energy and Industrial Strategy (BEIS) of the UK, the Japan Society for the Promotion of Science and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, and the Horizon 2020 Framework Program of the European Union. Among them, the EU's Horizon 2020 Plan provides the highest amount of funding in Energy Science, reaching US$7.43 billion between 2010 and 2021; UKRI has the second largest amount of funding, reaching US$2.72 billion. The NSF in the US is close behind, with the funding amount of US$1.40 billion. In terms of funded projects, China's NSFC funds the largest number of research projects in Energy Science, reaching more than 5,000 in the analytical period, but the overall amount of funding is not high.

In terms of research institutions receiving funds, Figure 2.3.2.1 lists the Chinese Academy of Sciences in China, Massachusetts Institute of Technology in the US, the Fraunhofer Society for the Advancement of Applied Research in Germany, Imperial College London in the UK, and Tohoku University in Japan. Of these institutions, the Fraunhofer Society for the Advancement of Applied Research received the largest amount of funding with US$1.75 billion, followed by Massachusetts Institute of Technology in the US with US$770 million, followed by Imperial College London in the UK with US$650 million. Since in the database, the Chinese Academy of Sciences only counts financial support from NSFC, the number of received funding reported here is very small, and is not appropriate to be included for comparison here.

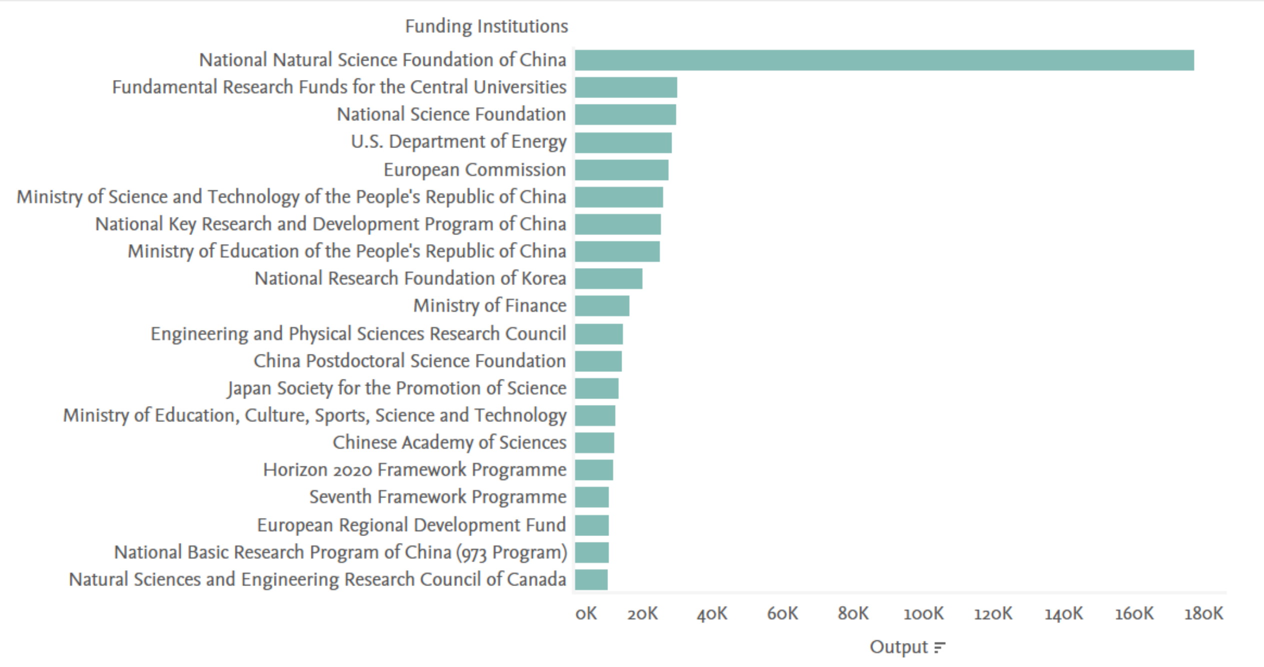


Figure 2.3.2.2 Number of funded Energy Science publications by funding organizations, 2010–2021

Quantifying funded research output in the form of scientific publications is an important aspect of evaluating funding for research development. According to the reported funding agency information for publications in Energy Science from 2010 to 2021, China's NSFC has funded the most publications in the field, with more than 177,000 articles funded, taking a prominent leading position (Figure 2.3.2.2). This may be related to the large volume of China's publications in this field. It also reflects China's emphasis on the field of Energy Science, especially, as represented by the capital investment of NSFC, which has provided strong support for basic research in Energy Science. NSFC is followed by the Fundamental Research Funds for the Central Universities[12] in China, the NSF in the US, the US Department of Energy (USDOE), the European Commission, and the Ministry of Science and Technology of China, all of which have funded fewer than 40,000 publications each in the analytical period. It is worth noting that the relatively smaller number of publications funded by other funding institutions (as compared to NSFC) may be due to the fact that the research projects funded by these funding organizations do not necessarily focus on scholarly output, or their research results are not necessarily presented in the form of paper publications.

[12] Since 2008, China's Ministry of Finance and the Ministry of Education have set up "Fundamental Research Funds for the Central Universities" to provide stable financial support for the scientific and technological work of universities. http://www.gov.cn/xinwen/2016-11/02/content_5127518.htm

Chapter 3

Integration between Research and Industry—Knowledge Transfer

Key Findings

- In recent years, the scale of academic–corporate collaboration in the field of Energy Science in China has increased at a relatively fast rate, and China has taken a leading position among the benchmarking countries, showing that academic–corporate collaboration is one of the directions in which the discipline is actively developing. However, there is still a big gap between China and the other benchmarking countries in the research output of academic–corporate collaboration and the scholarly impact of these collaborative publications, which shows that China still has a lot of capacity to develop its academic–corporate collaborations.

- Worldwide, among the comparators, enterprises with high participation in academic – corporate collaboration belong to different industries. Chinese companies are concentrated in large state-owned enterprises in the traditional energy sector. Enterprises involved in the field of Energy Science in the US, UK, Germany, Japan and other countries are not limited to the traditional energy sector, but cover a range of industries such as machinery, manufacturing, and engineering. Given the fact that the scholarly impact of Chinese enterprises in academic–corporate collaboration lags behind enterprises in Europe, the US and Japan, Chinese enterprises in Energy Science should also pivot in these directions in future, and, indeed, already these types of energy companies are emerging.

- When evaluating the citation of scientific publications by patents, the countries with a high degree of patent uptake in the field of Energy Science are also those with a high degree of academic–corporate collaboration[13]. China has a substantial number of publications cited by patents in the field of Energy Science, but in terms of the average patent uptake per publication, China still needs to improve its performance.

[13] Since there are many different definitions of patent conversion or research conversion and its degree of conversion, this analysis will be conducted only from the perspective of scientific articles cited by patents

Academic–Corporate Collaboration

Academic–corporate collaboration refers to collaboration between industry and academia in scientific research. Here, "corporate" refers to enterprises or companies, and "academic" refers to academia, including universities and research institutions. For enterprises, academic–corporate collaboration injects fresh ideas into enterprise research and innovation, reduces research costs and increases the potential of capital development. For universities and research institutions, academic–corporate collaboration reduces the burden of research funding, helps universities cultivate high-quality practical research talents, and helps researchers realize the transfer of their research results, so that research findings can truly bring social and economic benefits. Given the highly interdisciplinary nature and industrial applications of the Energy Science, an analysis of the performance of academic–corporate collaborations in this field will help build better understanding of the importance of this research field to the national economy and industrial development, and additionally will provide guidance and reference for further academic–corporate development in this subject area.

The analysis in this section examines the share and scholarly impact of publications that are academic–corporate collaborations in the Energy Science subject area and its sub-fields for each comparator country or region. It attempts to explore the prospect of research transfer for the field of Energy Science.

A. Academic–corporate collaboration in Energy Science

(A) Trends in the output of academic–corporate collaborative publications

Using the Scopus database, this report explores the scale of academic–corporate collaboration by analyzing the output of academic–corporate collaborative publications in a country or region. In this case, the term "academic–corporate collaboration" refers to a publication by multiple authors, with at least one of the authors belonging to an academic institution and at least one of the authors belonging to industry.

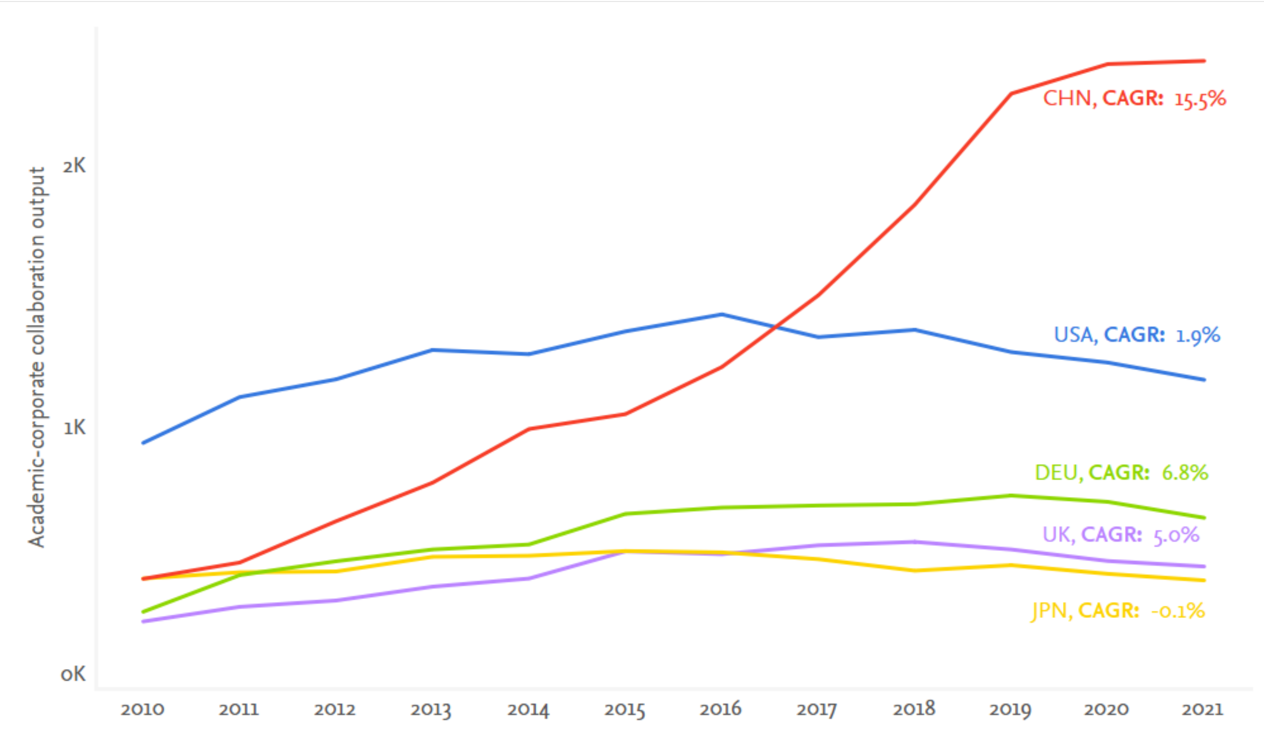


Figure 3.1.1.1 Trends in academic–corporate collaborations in Energy Science in benchmarking countries, 2010–2021

Figure 3.1.1.1 shows that China's academic–corporate collaboration has shown high-speed growth momentum in the past decade or so, with a compound annual growth rate (CAGR) of more than 15%; and after 2017, China's number of academic–corporate collaborative publications exceeds that of all comparators. The growth trend of China's academic–corporate collaboration is related to the overall trend of publications in the entire Energy Science discipline. The rapid growth in the overall Energy Science research output has also driven the research output of academic–corporate collaboration, so there has been no big change in the proportion of academic–corporate collaboration in the field for China, which shows that the growth of academic–corporate collaboration is basically in line with the growth rate of scholarly output of the entire discipline. Among the comparators, the CAGR of academic–corporate collaboration in Germany and the UK has reached more than 5%. Japan and the US have a higher starting point, but the growth rate is slower, and there has been a downward trend in recent years.

(B) Scholarly impact of academic–corporate collaboration

By analyzing the publication share and scholarly impact of academic–corporate collaboration in a country or region, we can partly understand the deepening degree and research quality of academic–corporate collaboration.

The publication share of academic–corporate collaboration refers to the publication output of academic–corporate collaboration in a country (region) as a share of the publication output of the whole country (region). The FWCI is a normalized index of the number of citations of publications, which can be used as a measure of scholarly impact, to some extent, and to partly reflect the research impact of academic–corporate collaboration.

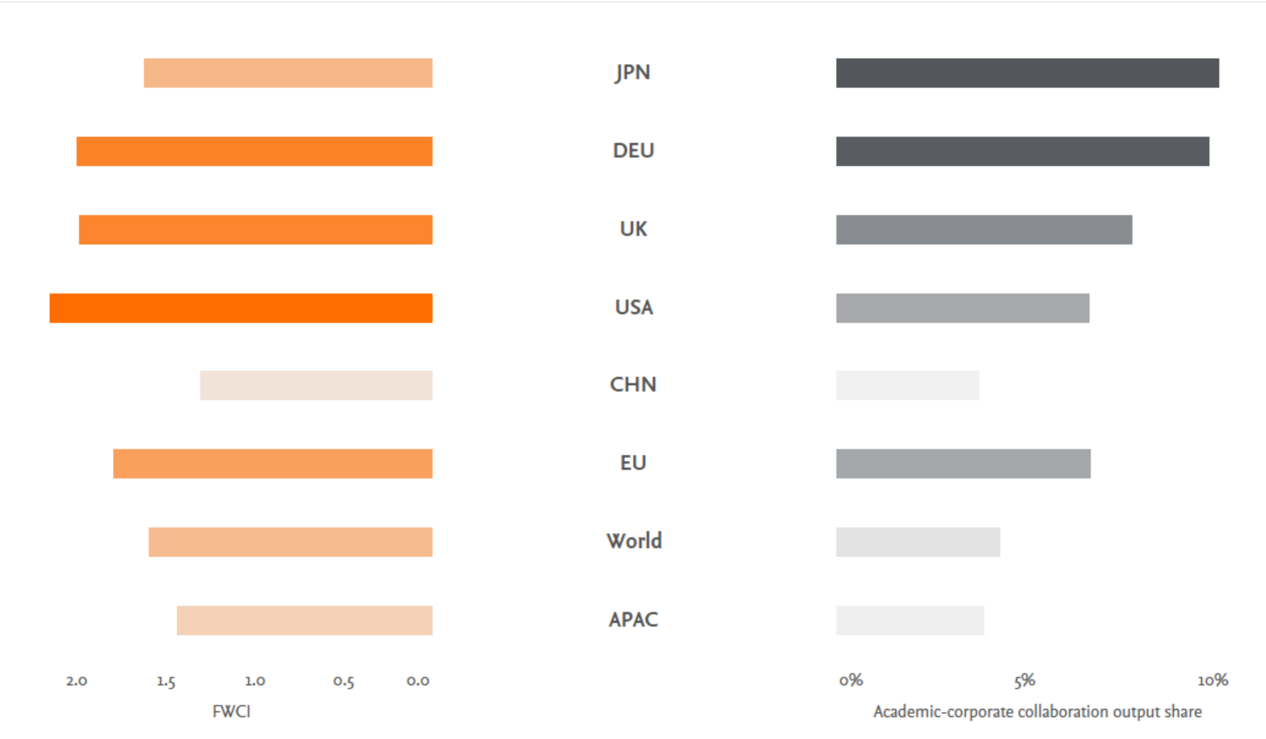


Figure 3.1.1.2 FWCI and proportion of academic–corporate collaborations in Energy Science discipline in benchmarking countries, 2010–2021

The proportion of academic–corporate collaboration in Energy Science discipline is higher than the proportion for all subject areas (2.7%), suggesting that Energy Science is a research field with a high degree of academic–corporate collaboration. At the country level, Figure 3.1.1.2 shows the proportion of academic–corporate collaboration in Energy Science discipline in the benchmarking countries, along with their FWCI values. Although China has the highest output volume of academic–corporate collaboration, which is still growing rapidly, due to the large volume of China's overall scholarly output, the proportion of its academic–corporate collaboration is relatively low. China’s proportion of academic–corporate collaboration is the lowest among all the comparators and is lower than the world and Asia–Pacific averages. At the same time, the scholarly impact of China's academic–corporate collaboration output, as reflected in FWCI, is also the lowest among all the comparators, and is lower than the FWCI of China's overall output in the discipline. This shows that there is still room for improvement in the scale and scholarly impact of China's academic–corporate collaboration output, and academic–corporate collaboration is a direction that can be vigorously developed in future for the field of Energy Science in China.

Japan's academic–corporate collaboration accounted for a slightly higher proportion than Germany's, ranking first among the comparators. Although this might be related to the small number of articles published in Japan overall, still, it suggests a high degree of academic–corporate collaboration in Japan. Moreover, the scholarly impact of Japan's academic–corporate collaboration is slightly higher than that of its entire discipline output, indicating the driving effect of academic–corporate collaboration on its research output. The country with the highest scholarly impact of academic–corporate collaboration output is the US, with FWCI above 2.0, followed by Germany and the UK. This also confirms from another aspect that the overall research output of Energy Science in these three countries has a high scholarly impact.

At the regional level, the level of academic–corporate collaboration in the Asia–Pacific region, whether evaluated in terms of proportion or scholarly impact, is lower than the global average, which is also partially affected by the performance of China's academic–corporate collaboration. The proportion and scholarly impact of academic–corporate collaborative output in the European region are higher than the world average.

B. Academic–corporate collaboration by sub-fields

(A) Trends in the output of academic–corporate collaboration

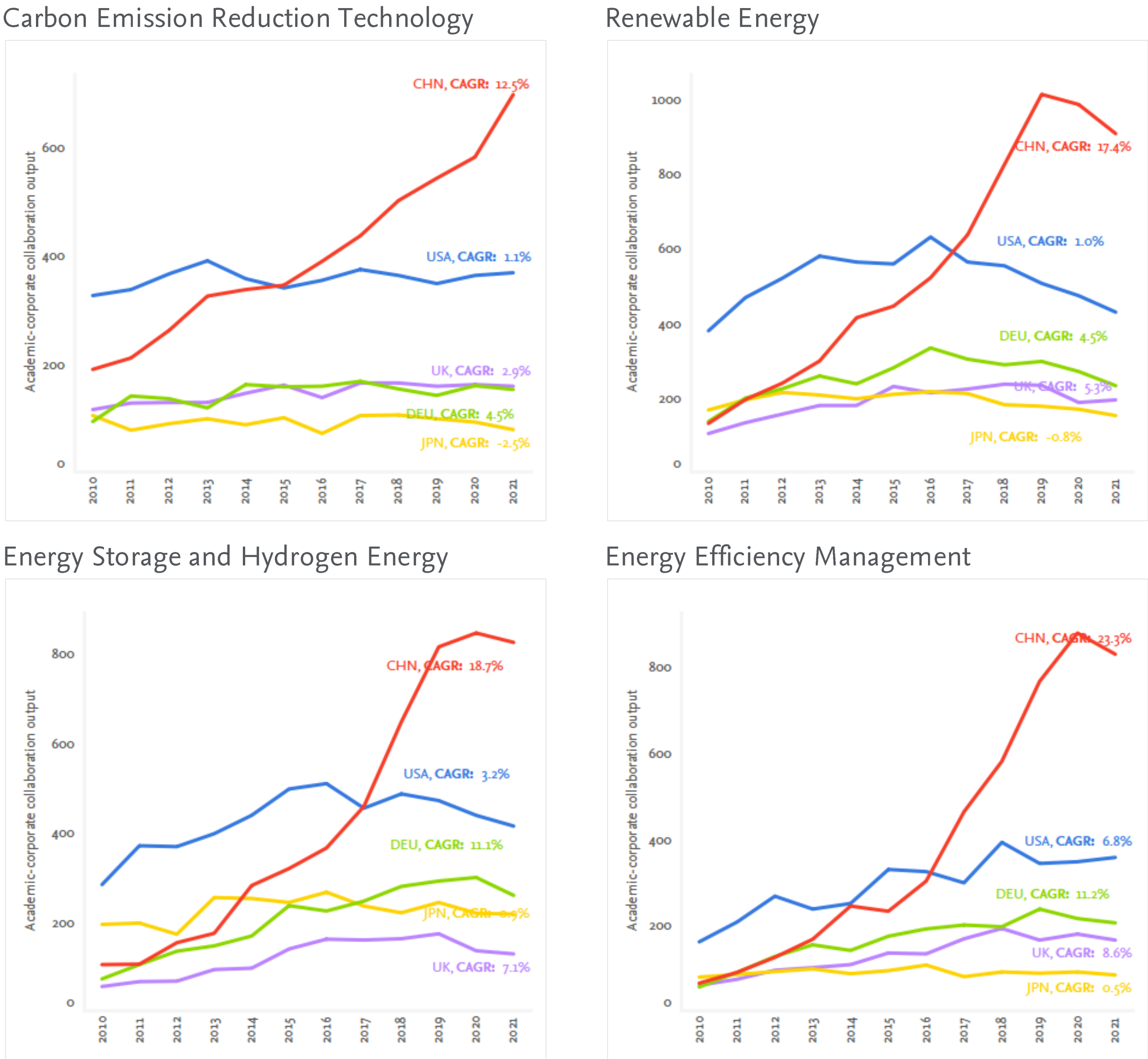


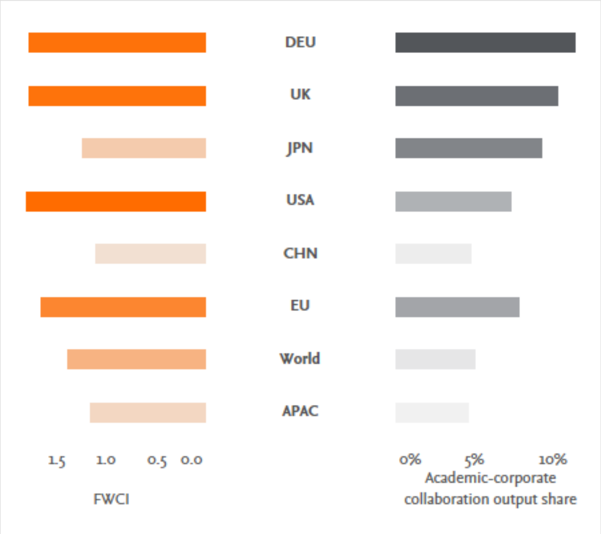
Figure 3.1.2.1 Trends in academic–corporate collaborations by sub-fields in the benchmarking countries, 2010–2021

Figure 3.1.2.1 shows that for the various Energy Science sub-fields, the volume of academic–corporate collaboration in China is similar to the development trend of the overall discipline, showing momentum and rapid development in the past ten years or so, with a CAGR of more than 10%. The average CAGR of academic–corporate collaboration in the sub-field of Energy Efficiency Management is more than 20%. In absolute terms, although there are slight differences across sub-fields, China's number of academic–corporate collaborative publications, in each sub-field, has exceeded that of other comparators after 2018.

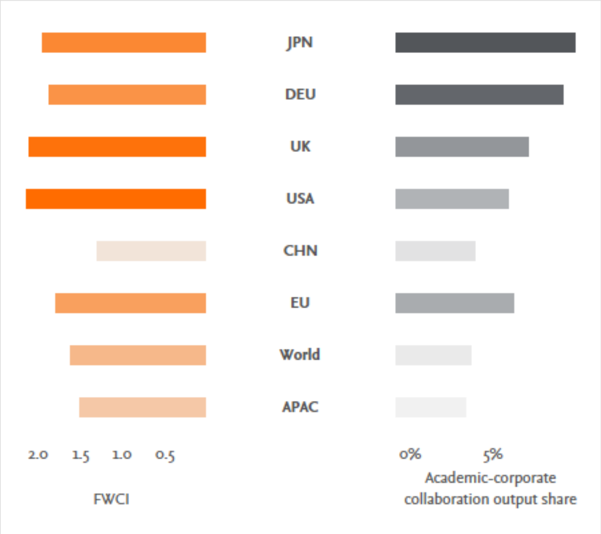
In contrast, the volume of academic–corporate collaboration output in other benchmarking countries has only fluctuated slightly or has not changed significantly. The volume of academic – corporate collaborations in the US has not changed much in the past 12 years, and there is even a downward trend in Renewable Energy and Energy Storage and Hydrogen Energy. Although the growth rates of the UK and Germany are slightly higher, their base values of academic–corporate collaborative publications have been small. Not only is the output volume of academic–corporate collaboration in Japan the lowest among the comparators (except for the Energy Storage and Hydrogen Energy sub-field), but also its CAGR is almost zero or even negative. It is worth mentioning that in the benchmarking countries, the growth rate of academic–corporate collaboration in the sub-field of Energy Efficiency Management is relatively high compared with other sub-fields, which also shows from another perspective that this sub-field is an emerging cross-cutting field and is in a stage of rapid development.

(B) Scholarly impact of academic–corporate collaboration

Carbon Emission Reduction Technology



Renewable Energy



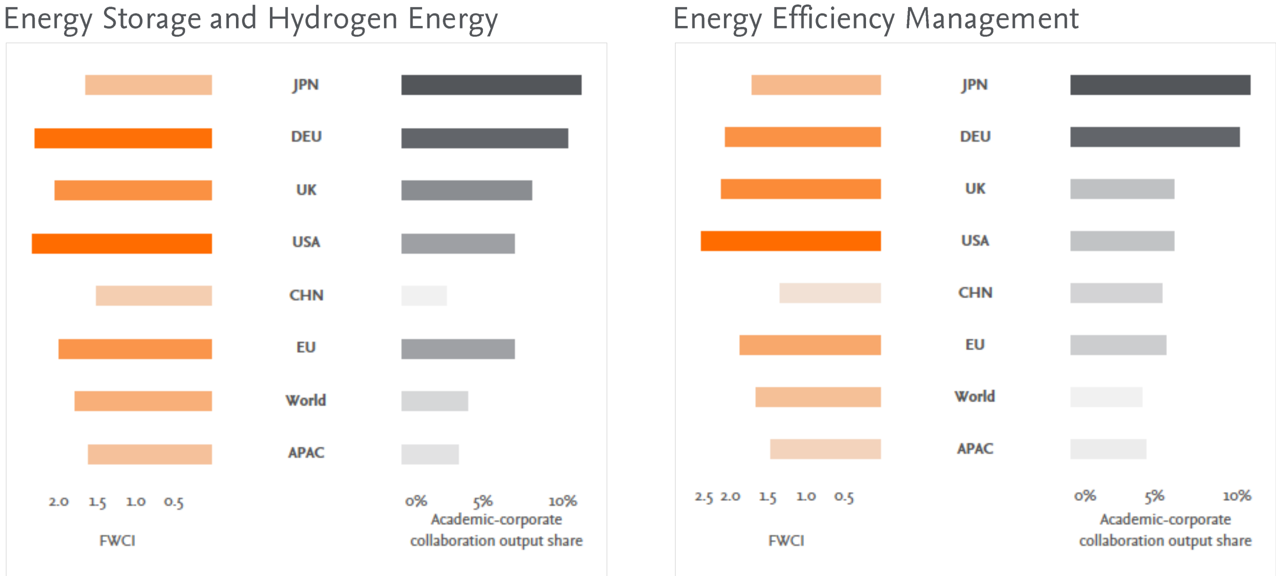


Figure 3.1.2.2 FWCI and proportion of academic–corporate collaborations by sub-fields in the benchmarking countries, 2010–2021

Figure 3.1.2.2 shows the proportion of academic–corporate collaborations in the four sub-fields of Energy Science in the benchmarking countries and their FWCI values. The proportion of academic–corporate collaborations in China is the same as the Asia–Pacific average, but lower than the world average. Moreover, in all the sub-fields, the FWCI value of China's academic–corporate collaboration is also the lowest among all the comparators, indicating that in various sub-fields of Energy Science, China's scholarly impact of academic–corporate collaboration needs to be improved.

Among the comparators, in a pattern that is similar to that of the entire Energy Science discipline, Germany and Japan have the highest proportion of academic–corporate collaboration. The countries with the highest scholarly impact of academic–corporate collaboration output are all Western developed countries (the US, the UK and Germany).

Leading Corporate Partners

Academic–corporate collaboration is based on the complementary resources of industry and academia to promote the transformation of research results into productivity and economic gains. In contrast with academia, enterprises and industrial groups have a stronger sense of competition and more urgently pursue technological innovation given their market attributes, so the active collaboration of academia with industry is conducive to improving the speed and degree of scientific and technological innovation, as well as the dissemination of knowledge and technology. On the other hand, as it becomes more difficult for enterprises to carry out technological innovation alone, the strong R&D power of higher education institutions and research institutes is conducive to improving the transfer of scientific and technological achievements and enhancing industrial competitiveness. Therefore, in addition to locating the main research institutions in the subject area (see Chapter 1 for details), finding the leading enterprises in the research field that actively participate in academic–corporate collaboration will assist further development of research and knowledge transfer of the subject area, and improve the influence of the subject area on the social economy.

After analyzing academic–corporate collaboration at the regional or country level, this section investigates corporations that are highly involved in academic–corporate collaboration, both in the world and in China, to identify differences and common grounds for future collaboration.

A. Top 20 corporations by academic–corporate collaborative output

To get a glimpse of the major global participants in academic–corporate collaboration, the following analysis explores the companies that are leading the world in terms of output of publications as a result of academic–corporate collaboration in the Energy Science subject area.

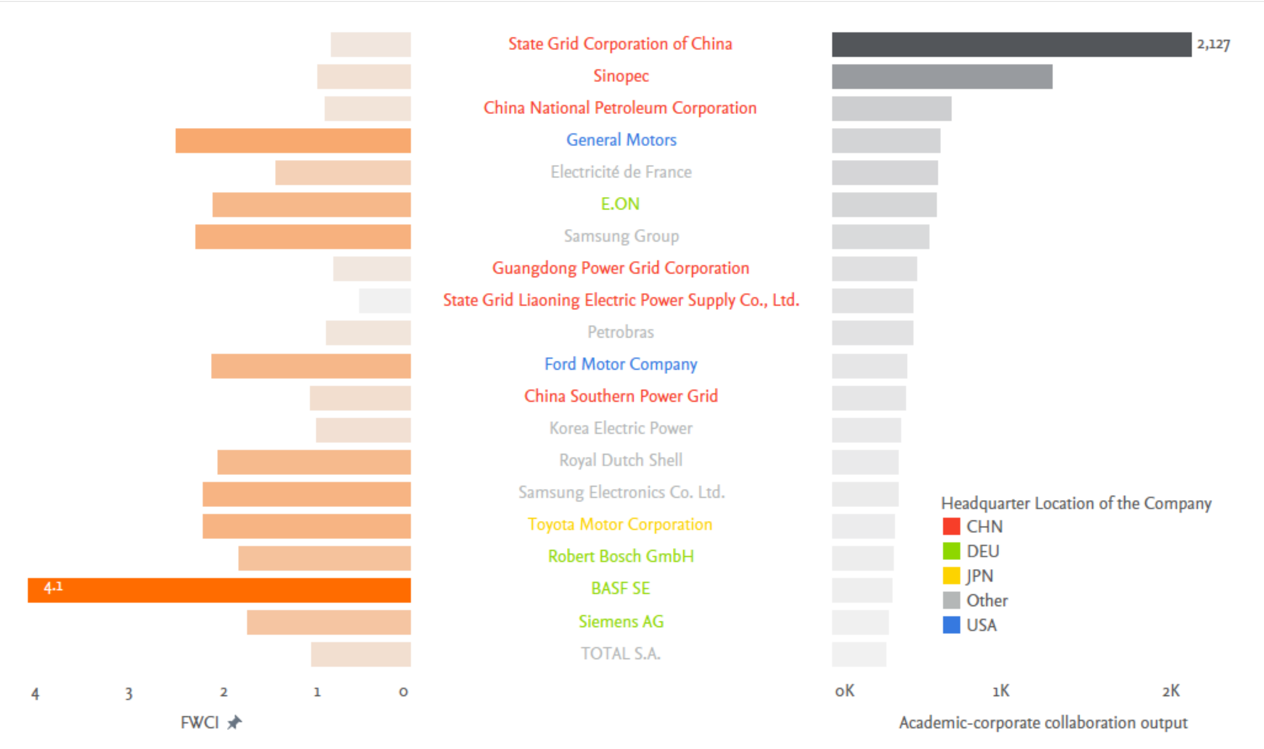


Figure 3.2.1 Output of publications of the top 20 academic–corporate collaborative corporations in the world in Energy Science and their FWCI, 2010–2021

Figure 3.2.1 shows the FWCI and output volume of the leading enterprises in the field of energy science by the number of academic–corporate collaborative publications. Of the top 20 companies, five are headquartered in China, most of which are in the traditional energy industry of oil and electricity. The top enterprise by output volume of academic–corporate collaboration in the world is China's State Grid Corporation, and its research output exceeds that of Sinopec, in second place, by nearly 70%. State Grid and Sinopec have been ranked in the top 10 of the Fortune Global 500 for many years. State Grid Corporation is a wholly state-owned company directly managed by the central government, with the investment, construction and operation of power grids as its core business. It undertakes the basic mission of ensuring a safe, economical, clean and sustainable power supply. China Petroleum & Chemical Corporation Limited is also a central state-owned enterprise, China's largest supplier of refined oil and petrochemical products, and the world's largest refining company. The scale of the academic–corporate collaboration in the field of energy science for the two state-owned enterprises can show the importance that large state-owned enterprises in traditional energy attach to energy transformation and new energy research.

The company with the academic–corporate collaborative output resulting in the highest scholarly impact in Energy Science is BASF SE from Germany. BASF Europe's five major business segments are chemicals, performance products, functional materials and solutions, agricultural solutions, and oil- and gas-related products. In addition to the chemical industry, German companies included in the top 20 list also come from the power and engineering technology industries. Among them, E.ON Group is a world-leading European energy company, with its business mainly in Europe, and primarily in natural gas and electricity. Another German company, Robert Bosch GmbH, has its core products covering automotive components, industrial products and construction products.

Most of the companies with active academic–corporate collaboration in Energy Science in the US and Japan are car companies. General Motors and Ford Motor Company are the first and second largest automakers in the US, respectively. Toyota Motor Corporation, based in Japan, is also one of the world's largest automakers. The scholarly impact of the scientific publications produced by the academic–corporate collaboration of these car companies is also notable.

Similar to the characteristics of the academic–corporate collaborative publications in China's Energy Science discipline as a whole, academic–corporate collaborations by Chinese enterprises are more significant in terms of the output volume, but the scholarly impact of their research output needs to be improved. Moreover, it should be noted that enterprises involved in the field of Energy Science in Europe, the US and Japan are not limited to the traditional energy industry, but also involve high-tech areas such as machinery, manufacturing, and engineering, which are also the embodiment of the transformation of the world's energy structure in the industrial sector. Therefore, it is expected that in future, China's enterprises in the field of Energy Science should also, and will soon change in these directions, that is, expanding the scope of industries involved.

B. Top 20 corporations by academic–corporate collaborative output in China

The following analysis explores the corporations that are leaders in the output of academic–corporate collaborative publications in the Energy Science subject area within China. In addition to the output volume, share of academic–corporate collaborations that are Energy Science publications is also examined, that is, an enterprise' publications in Energy Science as a proportion of its total academic–corporate collaborative publications in all subject areas. This proportion reflects the overlap between a company's core business and Energy Science in one respect, and the importance that the company attaches to Energy Science research and development in another respect.

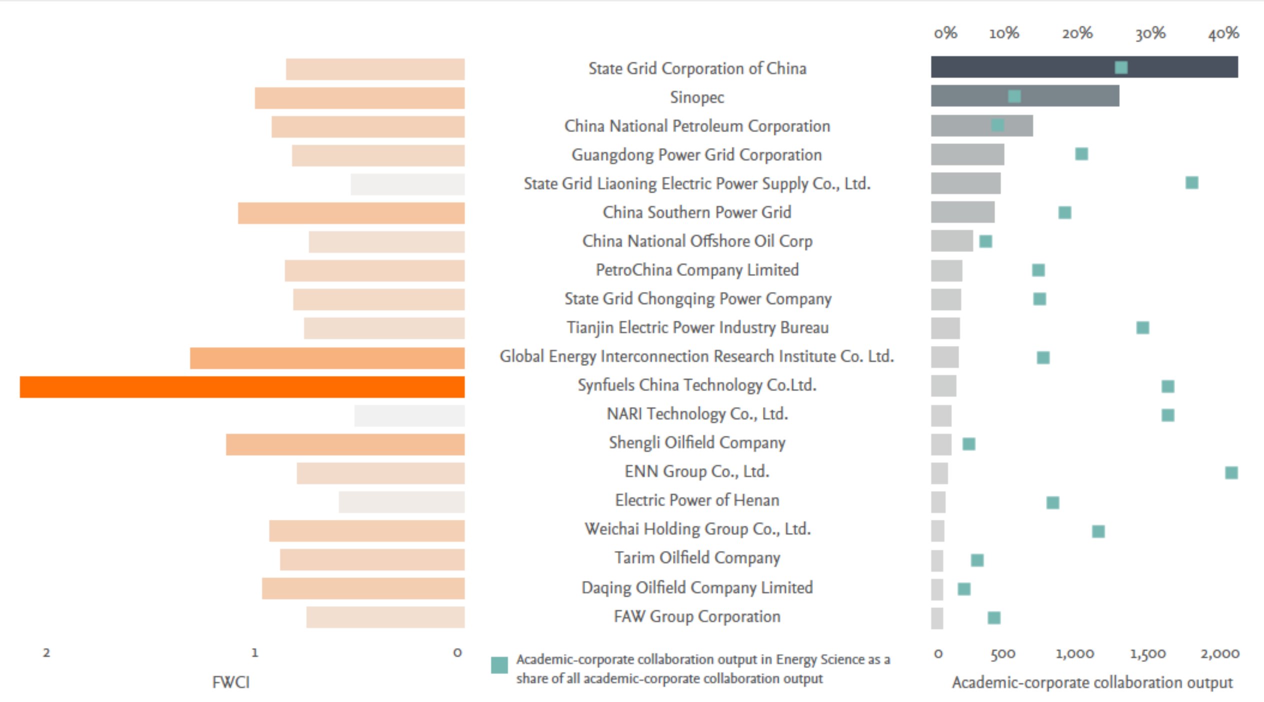


Figure 3.2.2 The top 20 Chinese corporations by academic–corporate collaboration in Energy Science, their output volume, share and FWCI of Energy Science academic–corporate collaborative publications, 2010–2021

Figure 3.2.2 shows that in China, most of the enterprises that contribute the most to the output of academic–corporate collaboration in Energy Science are large state-owned enterprises in the power and petroleum industries. As shown in the analysis in the previous section, the top-ranking enterprise in output of academic–corporate collaboration is the State Grid, and its Energy Science publications account for more than 20% of the total volume of academic–corporate collaboration output from the enterprise. Although at present, China's leading academic–corporate collaborative enterprises in Energy Science are mainly in the traditional energy industry, some high-tech enterprises and new energy enterprises are actively responding to the reform of the energy structure as described below.

For instance, the Chinese company with the highest scholarly impact of its academic–corporate collaborative output in Energy Science, Synfuels China Technology Co. Ltd., is such a high-tech enterprise based on research and development (R&D). Its engineering design and scientific research personnel account for more than 80% of the company's employees[14]. Its main business covers R&D for national special projects, coal-to-oil technology R&D, industrialization technology transfer, etc. Although the output of its academic–corporate collaboration is not high, its energy science publications account for 30%, indicating that the company attaches great importance to energy science research and technology development.

The enterprise in China with the highest proportion of publications in Energy Science out of total academic–corporate collaborative output is ENN Group. Although ENN Group is China's largest private urban pipeline gas company, it has launched a new business segment in the face of energy structure reform, namely "integrated energy services," to help customers manage and optimize energy utilization efficiency, and ultimately strive to build itself as an intelligent ecological operator in the energy industry.

In the face of China's carbon-peaking and carbon-neutrality goals, the industry has also launched corresponding initiatives, such as the development of wind power and photovoltaic new energy, research on energy storage technology, and assistance to energy-consuming enterprises in designing energy-saving and emission-reducing solutions. These new solutions are inseparable from the support of academic–corporate collaboration, and academic–corporate collaboration will be one of the directions of future vigorous development in the field of Energy Science for China.

[14] http://www.synfuelschina.com.cn/

Patent Citations

The purpose of scientific research is not only purely academic, but also to transform knowledge into production materials, which can truly bring innovation to the marketplace and drive industrial development; only when science and technology are deeply integrated with the economy, it is possible to achieve high-quality economic development. Therefore, the degree of scientific and technological innovation and transfer of research results is an important aspect to assess the economic benefits and societal impact generated by research findings. On the other hand, universities and research institutes are an important driving force in the output and transfer of intellectual property. Knowing how often the publications of research institutions in specific research fields are cited by patents is an important reference for objectively understanding the issue of transfer of research results, making the next decision on scientific and technological innovation, and for pointing out the direction for improving the efficiency of transferring and transforming scientific and technological achievements.

This section will explore the transfer of research results[15] in the field of Energy Science by analyzing the citation of scientific publications by patents from different perspectives.

[15] Given that there are many different definitions of the transfer of research results and their degree of transfer, this section will only be analyzed from the perspective of scientific articles being cited by patents.

A. The scale of patent citations for articles in Energy Science

The analysis of the patent citation of articles mainly focuses on the two indicators of "number of patents citing publications" and "number of publications cited by patents." The former refers to the number of patents that have cited scientific research articles published in a certain field, which helps to understand the impact of scientific research on product R&D and patent creation, and also reflects the influence of research in terms of economic benefits, to a certain extent. The latter refers to the number of scientific research articles published in a field that are cited in patents, which can help understand the extent to which scientific research is used in product research and patent creation, and can also reflect the industrial application prospects of research results.

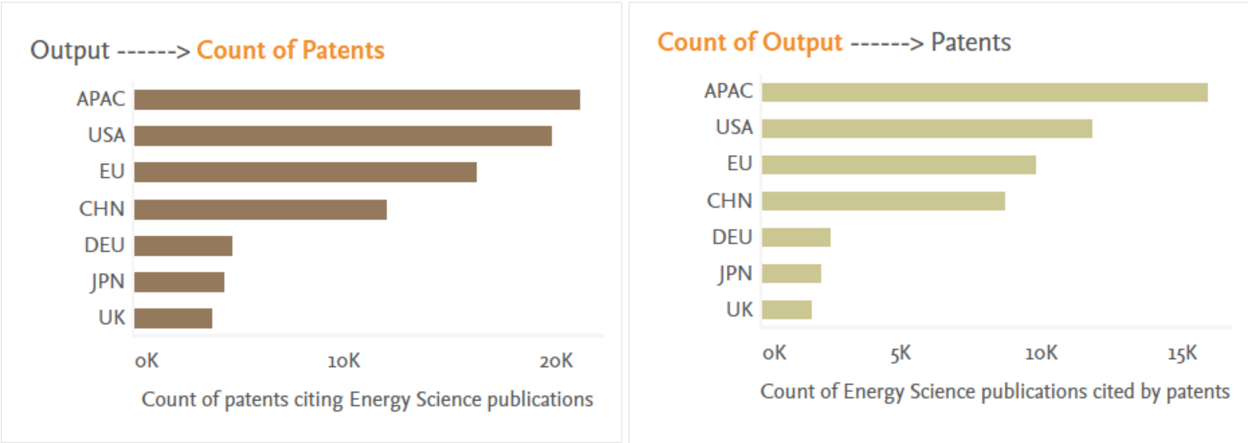


Figure 3.3.1 Count of patents citing Energy Science publications in comparators (left) and count of Energy Science publications cited by patents in comparators (right), 2010–2021.

Figure 3.3.1 on the left shows that from 2010 to 2021, nearly 20,000 patents have cited scientific research published in the field of Energy Science in the US, ranking it first among the benchmarking countries. The number of patents citing articles on energy science in the European region is smaller than in the US and slightly more than in the Asia–Pacific region. China has the second-largest number of patents citing Energy Science publications among the comparators.

Figure 3.3.1 on the right shows that in the study period, the US has more than 11,000 Energy Science articles being cited by patents, ranking first among the benchmarking countries, which is less than the number of articles cited by patents in the entire Asia–Pacific region, but more than the number in Europe. The number of articles cited by patents in China exceeds that of Germany and Japan, ranking second among the comparators.

B. Average number of articles in Energy Science cited by patents

The number of patents citing publications and the number of publications cited by patents are easily affected by the scale of scholarly output in a country or region, while the average number of patent citations per thousand publications and the proportion of publications cited by patents help to understand the average degree of scientific research used for patent creation, and can also partially reflect the influence of scientific research in terms of economic benefits.

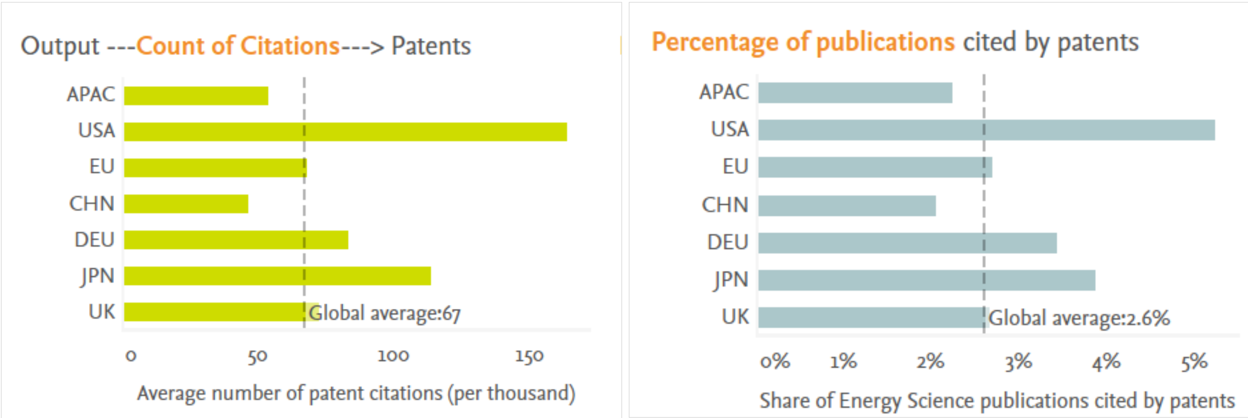


Figure 3.3.3 Average number of patent citations for Energy Science publications (per thousand) in the comparators (left) and share of Energy Science publications cited by patents in the comparators (right), 2010–2021

Figure 3.3.3 on the left shows that count of patent citations per thousand publications in China is below the world average and is the lowest among the benchmarking countries. This may be because China's research output in the field of Energy Science is very large, and the number of publications as a denominator is large. It can also be due to the fact that the data of the Chinese Patent Office is not included in the statistics, and that the number of patent citations may be lower than the actual situation. The US has the highest number of patent citations per thousand publications among the benchmarking countries. Both the UK and Japan have also exceeded the world average (67 times/1,000 articles).

Figure 3.3.3 on the right shows that for the proportion of publications cited by patents, the highest proportion among the benchmarking countries is the US; more than 5% of Energy Science publications from the US have been cited by patents. In addition to the US, Japan and Germany also have a relatively high proportion of publications cited by patents. This may be due to the low amount of Energy Science research in Japan and Germany, and the small base number of publications, but it may also show how entwined scientific research output and patents in this field are in these countries. With the exception of China and the Asia–Pacific region, the comparator countries and regions exceeded the world average of 2.6%.

In general, the US performs best in patent uptake in terms of scientific publications being cited by patents among the benchmarking countries, and Japan is the country performing the best in the Asia–Pacific region. These two countries are also those with a high share of academic–corporate collaboration and high scholarly impact of academic–corporate collaborative publications as mentioned in the previous analysis. China's patent uptake performance is still largely shaped by its high output volume of publications, but in terms of average number of patent citations received or share of publications cited by patents, its performance still needs to be improved.

In addition, possible reasons for the low patent uptake for China's Energy Science research could be due to: 1) China's Energy Science is still in a stage of rapid development, and the links between industry and academia are weak, affecting the frequency of China's basic research results being cited by the industry, 2) The patent citation data only includes patents from the world's five major patent offices[16], and the patent citation data of the Chinese patent office is not included, which reduces the number of Chinese publications being cited by patents and affects the assessment of the patent uptake of Chinese Energy Science research output.

[16] Patent citations are based on patent data from: European Patent Office, UK Intellectual Property Office, Japan Patent Office, United States Patent and Trademark Office, World Intellectual Property Organization Trademark Office, World Intellectual Property Organization

Chapter 4

A preliminary look at the content of the Energy Science research

Key Findings

- Energy Science research is highly interdisciplinary, reflected by the wide variety of subject areas covered by articles referenced by Energy Science publications, as well as the wide variety of those which cite Energy Science publications. In addition to the physical sciences (such as chemistry, materials science, physics and astronomy) and engineering, all subject areas closely related to Energy Science, publications that cite or cited by Energy Science research cut across subject areas as diverse as biology, social sciences, economics and finance, and business and management.

- Looking at the leve of maturity of the research field, most Energy Science publications fall within the category of applied technology. Meanwhile, the overall discipline continues to contribute rapidly and prolifically to research that is closely related to China's "double carbon" goal.

- Among the four sub-fields, Carbon Emission Reduction Technology and Energy Efficiency Management show a keyword network centered on one core keyword of the sub-field; in contrast, Renewable Energy and Energy Storage and Hydrogen Energy show a keyword network map featuring several interconnected clusters of keywords, suggesting linked research content.

- For the four sub-fields, most of the high-frequency keywords in Carbon Emission Reduction Technology and Renewable Energy come from articles published in 2014–2015, while most of the high-frequency keywords in Energy Storage and Hydrogen Energy and Energy Efficiency Management were from publications after 2017, indicating that these two sub-fields are relatively new, emerging research fields.

- For the topic clusters related to the discipline of Energy Science, China's contribution is leading, but its scholarly impact is still lagging behind that of the United States. An analysis of the global hotspot topic clusters covered by Energy Science research helps to identify areas that have yet to be explored in the discipline, and researchers can use keyword graphs in the topic clusters and highly cited articles to make decisions regarding the direction of future research.

Interdisciplinarity and interdisciplinary extensibility

As a field of study broadens and deepens to encompass more areas and subtopics, a subject area classification of that field becomes particularly important. The classification of subject areas provides a knowledge framework for stable development of scientific knowledge, as well as a basis for the open, innovative, and comprehensive development of the field. As science and technology develop rapidly, dynamic subject area construction and classification can help accurately reflect the current status of the field. There are several established subject area classification systems used within China and internationally, but they cannot accurately model the new and fast-developing field of Energy Science. This report, combining big data and manual checks, has managed to classify and define sub-fields of Energy Science. This newly defined discipline of Energy Science is highly interdisciplinary and extensible. This section will illustrate the characteristics of the discipline using several approaches.

First, this section shows the mapping of the discipline to the ASJC (All Science Journal Classification)[17] classification. ASJC subject classification is defined at the journal level. Elsevier experts classify journals into 27 broad categories and 334 subcategories based on the objectives, scope and content of the journals. Because the classification of ASJC disciplines is detailed, by looking at the distribution of articles cited by or citing Energy Science publications across ASJC subject areas, it is possible to gain insights into which subject areas have contributed to or received contributions from Energy Science research.

In addition, this section will also classify the research output of Energy Science according to the level of maturity of research. From basic scientific research to applied technology, scientific publications can be classified into four research levels, which help to show the development trend of research output of the discipline in terms of the research maturity.

In view of the closeness of Energy Science to the "double carbon" goal, this subsection also adds an analysis of the intersection of Energy Science and "Net Zero" research. Moreover, the intersection of Energy Science and nuclear energy and traditional fuel research are respectively examined, along with their current development trends. All these are expected to help present the disciplinary characteristics of Energy Science more comprehensively.

[17] https://service.elsevier.com/app/answers/detail/a_id/21525/supporthub/scival/ Check the detail of ASJC description in Appendix VII

A. Cross-disciplinarity of Energy Science

This section of the report draws on the subject area distribution of referenced and citing articles of Energy Science publications to provide a macro-level understanding of the impact and contribution of Energy Science to various scientific fields. Exploring the subject area distribution of articles cited by Energy Science publications helps to understand which research fields have contributed to Energy Science research. Exploring the subject area distribution of articles that have cited Energy Science publications, on the other hand, enables understanding of which research fields Energy Science has contributed to.

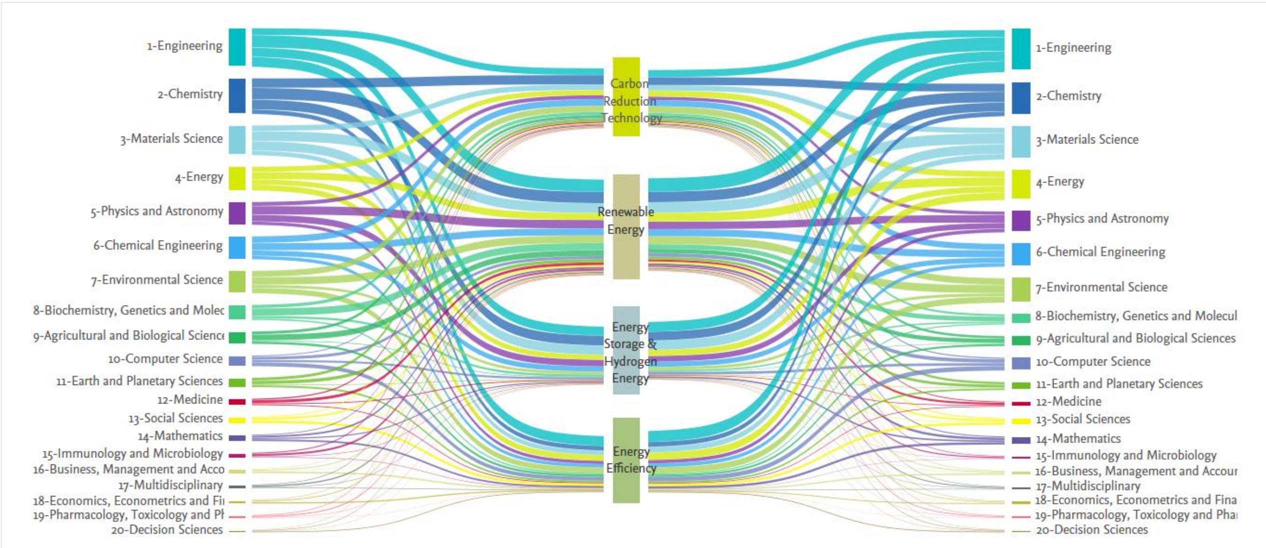


Figure 4.1.1.1 Citing (left) and cited (right) relationships between the four sub-fields of Energy Science and ASJC subject areas, 2010–2021

Figure 4.1.1.1 shows the citing and cited relationships of Energy Science by ASJC subject areas. Energy Science is highly cross-cutting, with a wide range of subject areas covered by its citing and cited articles. In addition to the physical sciences fields (chemistry, materials science, energy, physics and astronomy, etc.) that are closely related to Energy Science, it also covers biology, social sciences, economics and finance, and business and management.

The top five most cited subject areas for Energy Science are engineering, chemistry, materials science, energy, and chemical and engineering (as defined by ASJC subject classifications). As for articles that have cited Energy Science publications, namely, its citing articles, subject area distribution is similar, with the top five ASJC subject areas being engineering, chemistry, materials science, energy, and environmental science.

Output of the Carbon Emission Reduction Technology sub-field cited chemistry articles the most, followed by engineering articles. In addition to engineering and chemistry, the Renewable Energy sub-field publications also cited more materials science publications. The Energy Storage and Hydrogen Energy sub-field cited more articles from chemistry and materials science. As for the Energy Efficiency Management sub-field, it cited energy and engineering articles most, rather than chemistry, materials science, and physics and astronomy, indicating the breadth of cross-disciplinary articles cited by this sub-field.

Articles that have cited Carbon Emission Reduction Technology publications are mainly in chemistry and engineering subject areas. The Renewable Energy and Energy Storage and Hydrogen Energy sub-fields are more frequently cited by engineering and materials science publications. The Energy Efficiency Management sub-field is mainly cited by engineering and energy publications.

B. Classification by research levels

Based on the title, abstract, and cited reference of the publication, Scopus categorizes the publication into four different research levels[18]: basic scientific research, applied research, engineering technological mix and applied technology. This is done through algorithm iterations of machine learning, combined with expert identification. Each stage of research is mutually exclusive, meaning that each publication has one and only one research level classification.

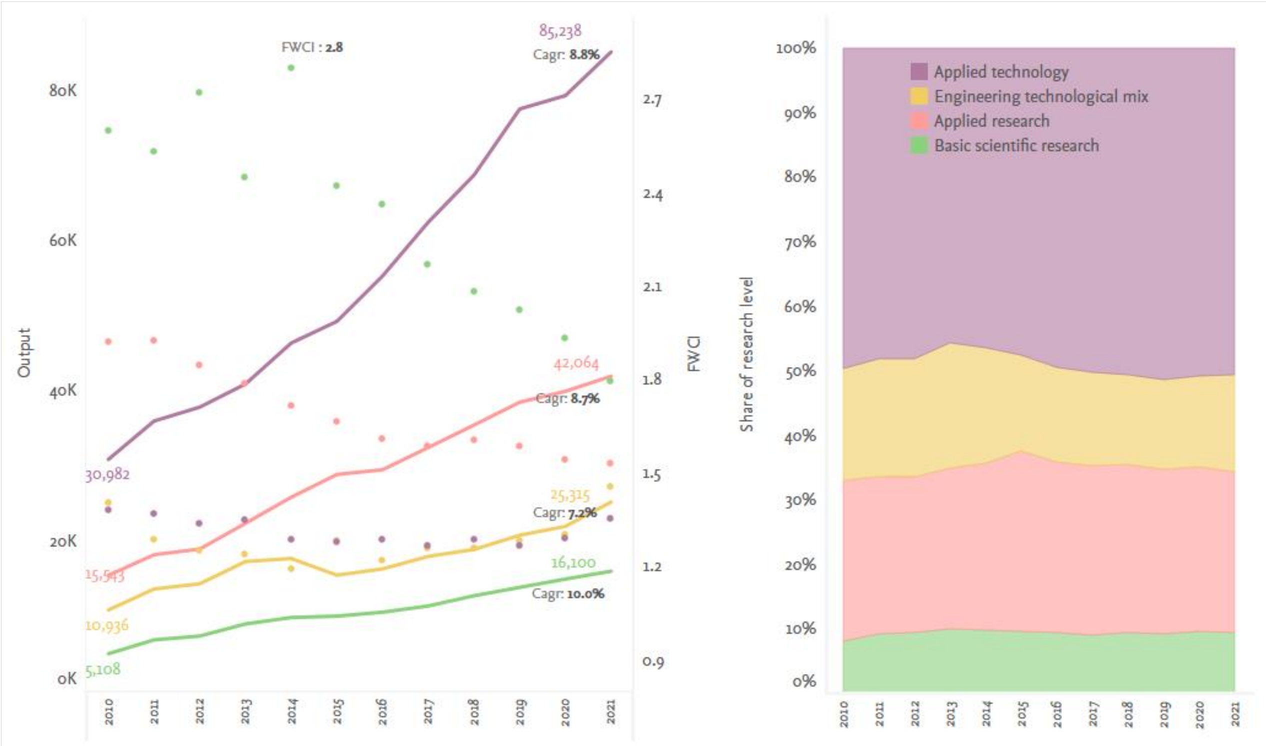


Figure 4.1.2.1 Four research levels of Energy Science publications, the volume of papers published and the FWCI (left) and the proportion (right) over time, 2010–2021

As shown in Figure 4.1.2.1, the number of articles published in all stages of global Energy Science research has maintained a high-speed growth trend in the past 10 years: the compound annual growth rate (CAGR) of basic scientific research has reached 10% from 2010 to 2021, which is nearly three percentage points higher than that of engineering technological mix research (7.2%); applied research and applied technology studies have similar CAGRs of 8.7% and 8.8%, respectively. The applied technology stage saw the highest increase in publications, from 30,982 in 2010 to 85,238 in 2021. In terms of the proportion of articles at each research level, the publications of Energy Science mainly fall within the category of applied technology, with its proportion out of the total Energy Science research output maintaining at about 50%, which shows that Energy Science is a discipline with high technological maturity and strong applications. The next most common research level is applied research, followed by engineering technological mix

[18] Boyack, K. W., Patek, M., Ungar, L. H., Yoon, P., & Klavans, R. (2014). Classification of individual articles from all of science by research level. Journal of Informetrics, 8(1), 1---12 https://doi.org/10.1016/j.joi.2013.10.005,

research and basic scientific research, and these proportions are also relatively stable, at about 25%, 15%, and 10% respectively.

In terms of research impact, the FWCI of basic scientific research is the highest, and it reached a peak of 2.8 in 2014, which also shows that basic research is an important engine of output for the other three research levels. The FWCI of research findings later in the research stage, such as the engineering technological mix category and applied technology output, is low. Except for the engineering technological mix category, the FWCI of output in other research levels has declined. This shows that some original research findings in the early research stage may have far-reaching scholarly impact, while a certain amount of time may need to pass before the impact of such achievements is apparent.

C. Connection between Energy Science research and Net Zero and traditional energy research

In October 2021, Elsevier released a report titled "Pathways to Net Zero: The Impact of Clean Energy Research"[19] which gives a panorama view of the development of global clean energy research over the past 20 years. The report shows that the field of clean energy has become a global research hotspot, and that China has taken a world-leading position in research in this field. Analyzing academic performance at the intersection of Energy Science and Net Zero research (namely, the publication set analyzed in the "Net Zero" report) helps us to gain a better understanding of the disciplinary characteristics of Energy Science.

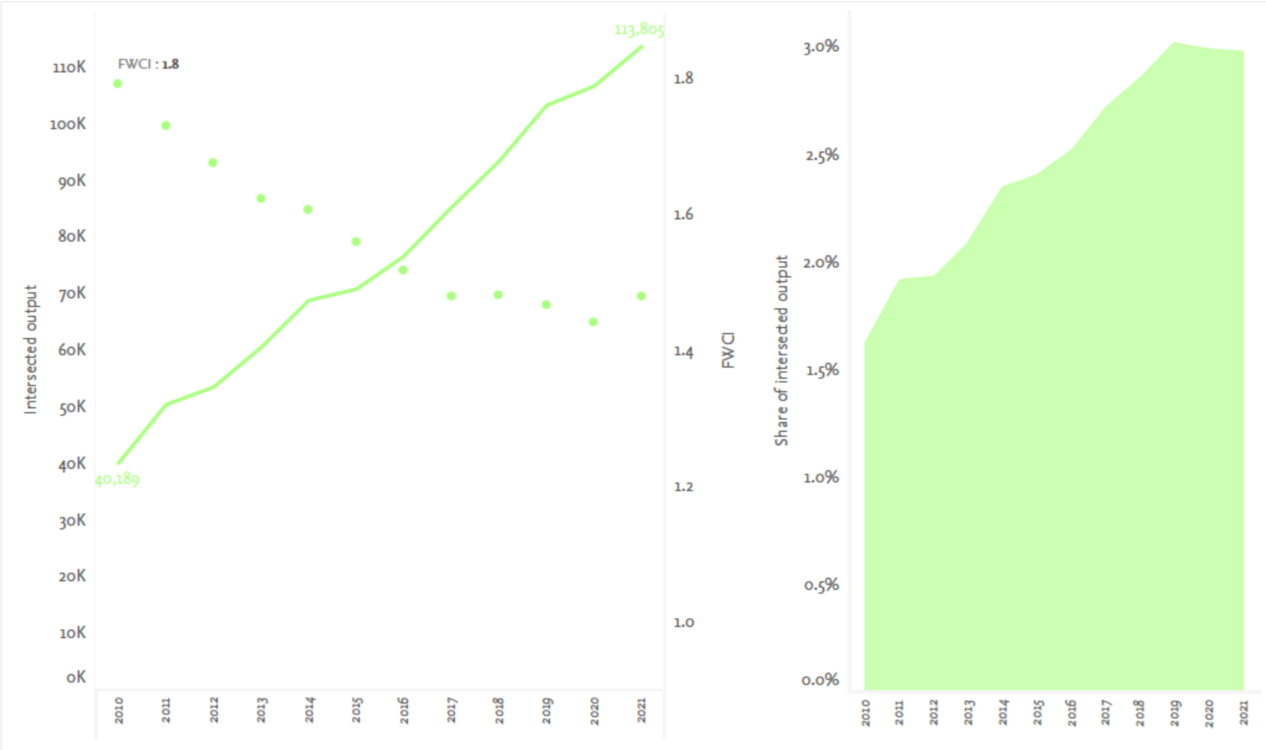


Figure 4.1.3.1 Intersecting-publication volume and FWCI (left) and proportion of global publications (right) of the Energy Science discipline and Net Zero over time, 2010–2021

In the past decade, the number of cross-publications in Energy Science and Net Zero has maintained a high-speed growth trend, from about 40,000 articles in 2010 to around 113,000 articles in 2021. The proportion of intersecting papers in Energy Science and Net Zero out of the total global research output is also increasing year by year, from 1.6% in 2010 to 3.0% in 2021. The rapid growth of the intersection of Energy Science and Net Zero directly reflects the importance of the Energy Science discipline to China's "double carbon" goal.

[19] https://www.elsevier.com/connect/net-zero-report#:~:text=Pathways%20to%20Net%20Zero%3A%20The%20Impact%20of%20Clean,research%20can%20accelerate%20efforts%20to%20mitigate%20climate%20change.

The scholarly impact of the interdisciplinary collection of Energy Science and Net Zero publications declined slightly though, with the highest FWCI of 1.8 in 2010. The decline of the FWCI in recent years might be due to the rapid increase of output volume, and that the most influential original research in this cross-field were published in early years around 2010. Compared with the average FWCI of 1.5 for the field of Energy Science, the average FWCI of publications in the intersection of Energy Science and Net Zero is 1.6, indicating that the scholarly impact of the cross-field research is higher.

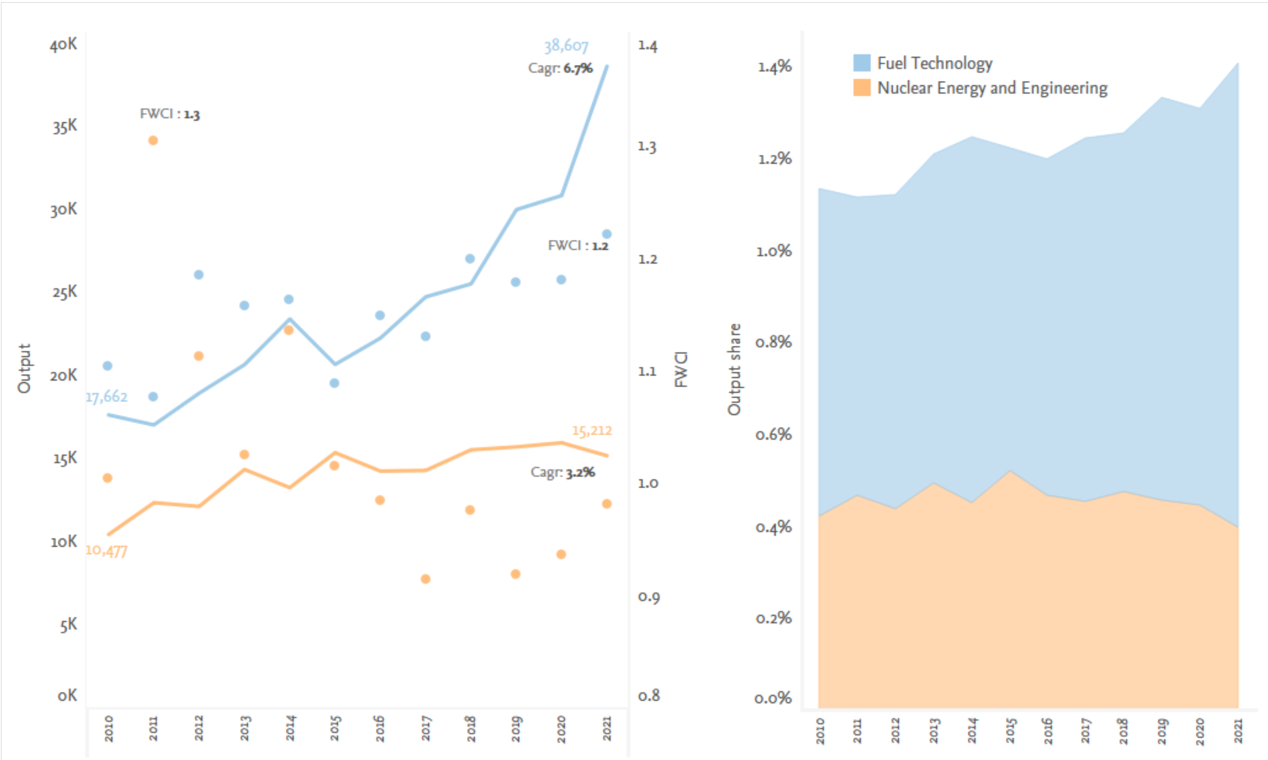


Figure 4.1.3.2 Intersecting publication volume of Energy Science and nuclear energy and fuel technology publication volume and FWCI (left) and proportion out of global publications (right) over time, 2010-2021

The 334 journal-level ASJC sub-categories defined by Elsevier include "nuclear energy" and "fuel technology," which embody the traditional components of the energy system. As shown in Figure 4.1.3.2, in the past 11 years, the global output volume of Energy Science publications that are also categorized into fuel technology has maintained a high-speed growth trend, with a CAGR of 6.7%, more than three percentage points higher than that of the cross-field with nuclear energy (3.2%), and the number of articles published has increased from around 17,700 in 2010 to about 38,600 in 2021. Publications in the cross-field of Energy Science and nuclear energy are also increasing, but their growth rate is slower. In terms of contribution to global research overall, Energy Science publications on fuel technology have always accounted for a larger proportion out of the total output in all subject areas globally (more than 0.7%) than those on nuclear energy, and this proportion is still increasing year by year, reaching 1.0% in 2021. In contrast, the proportion of Energy Science publications on nuclear energy is decreasing year by year. At the same time, the scholarly impact of the intersecting fuel technology research continues to grow, while the FWCI of intersecting publications on nuclear energy is lower than that for fuel technology, and it is on a downward trend. All this shows that the fuel technology in traditional energy is still an important research area in the energy field, and the energy transition is still in the development stage, but research and development on nuclear energy have stabilized.

Overview of the research content and trends of the four sub-fields of Energy Science

This section will further demonstrate the characteristics of the four sub-fields under Energy Science: first, based on the analysis of index keywords, the structure of the four sub-fields is macroscopically displayed; then, the trend changes of the sub-fields are shown from the change of the keywords and their related words; and finally, the changes in the research content of each sub-field from the perspective of researchers are reflected through the changes of author keywords over time.

The index keywords used in this analysis come from standardized thesauri and are a helpful approach for non-specialists or interdisciplinary researchers seeking to understand the discipline. Here, similar index keywords may be repeated in different forms, and their recurrence indicates that such research content is quite representative of a research field.

The author keywords are provided by the author. The keywords assigned by the author are subjectively selected by researchers themselves to represent the main research content, and are what researchers typically use to describe their research. Given that the analysis of indexed keywords and topic clusters is mainly generated by specific algorithms, and there is less manual evaluation, the analysis of author keywords is added to this report to adjust and neutralize the limitations of indexed keywords.

A. Index keyword networks

To facilitate the collection, collation, retrieval and dissemination of articles, Indexed Keywords[20] are widely used in bibliometrics. The content reflected by the indexed keywords is generally broader and macroscopic, suitable for non-scientific and technological workers and cross-field scientific and technological workers to understand the main content of a research field. Unless explicitly stated, all keywords below refer to indexed keywords.

The keyword network of each sub-field can be depicted based on the frequency of indexed keyword occurrence for each sub-field and the frequency of each pair of keywords appearing together. The larger the node in the network diagram, the higher the frequency of occurrence of the keyword, and the thicker the tie between nodes, the higher the frequency of each pair of keywords appearing together. Keyword networks can help to show research content and interrelationships.

Figures 4.2.2.1 and 4.2.2.4 below show that in the two sub-fields of Carbon Emission Reduction Technology and Energy Efficiency Management, the central keywords are "carbon dioxide" and "energy efficiency", which not only appear most frequently, but are also closely related to other keywords. This shows that research in these two sub-fields mainly revolves around carbon dioxide and energy efficiency, respectively. In the two sub-fields of Renewable Energy and Energy Storage and Hydrogen Energy, the keywords form clusters around several major keywords (Figures 4.2.2.2 and 4.2.2.3). The former mainly focuses on solar energy-related keywords and biomass energy, wind energy and other keywords; Energy Storage and Hydrogen Energy mainly revolves around keywords such as "energy storage," "photovoltaic cells," "hydrogen production," "fuel cells," "batteries," "electrodes" and so on.

(A) Carbon Emission Reduction Technology sub-field

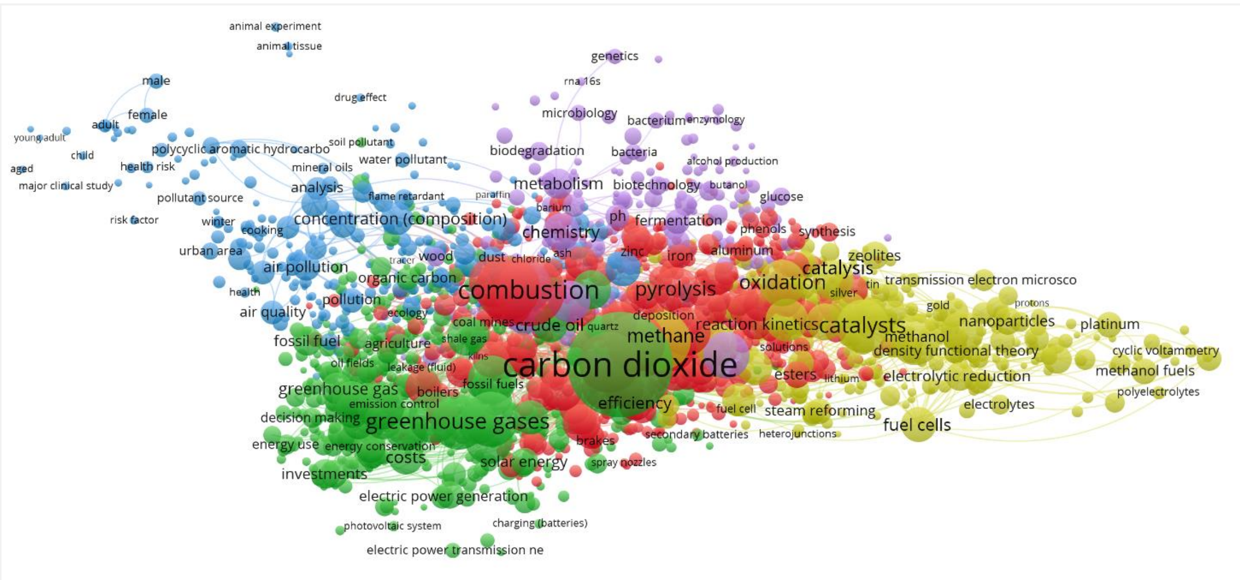


Figure 4.2.2.1 Carbon Emission Reduction Technology sub-field index keyword network, 2010–2021

[20] Journal publishers or databases select matching index keywords from the published standardized vocabulary based on article content and certain algorithms. https://service.elsevier.com/app/answers/detail/a_id/21730/kw/indexed+keywords/supporthub/scopus/

Figure 4.2.2.1 shows that the network of indexed keywords in Carbon Emission Reduction Technology has a clear central keyword: "carbon dioxide." Other keywords are interrelated to form five clusters based on the following groups of keywords:

1. combustion, coal, fuels, carbon, coal combustion;

2. carbon dioxide, greenhouse gases, energy utilization, gas emissions, fossil fuels;

3. particle size, concentration (composition), air pollution, particulate matter, environmental monitoring;

4. methane, catalysts, methanol, oxidation, catalyst activity;

5. biomass, ethanol, biofuel, metabolism, biogas.

(B) Renewable Energy sub-field

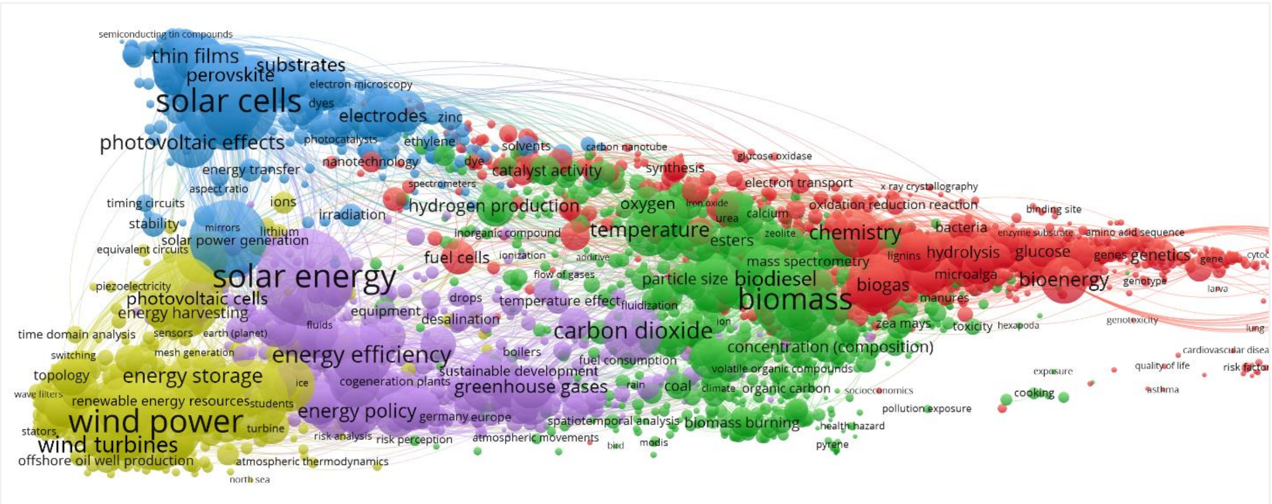


Figure 4.2.2.2 Renewable Energy sub-field index keyword network, 2010-2021

Figure 4.2.2.2 shows that unlike the Carbon Emission Reduction Technology publication collection, there is no obvious central word in the keyword network for Renewable Energy, and each keyword is mainly based on different energy categories to form clusters. "Wind power," "biomass" and "solar cells" form the central keyword of the discipline through close association with other keywords. The keyword network mainly has the following five clusters:

1. biofuel, bioenergy, ethanol, cellulose, fermentation;

2. biomass, biodiesel, carbon, temperature, combustion;

3. solar cells, solar power generation, perovskite, conversion efficiency, thin films;

4. wind power, photovoltaic cells, renewable energy resources, electric power transmission networks, optimization;

5. solar energy, energy efficiency, carbon dioxide, sustainable development, energy utilization.

It should be noted that solar energy, energy efficiency, and carbon dioxide in the fifth cluster are highly cross-cutting with other sub-fields.

It is worth mentioning that "biomass" is one of the five hotspots in Figure 4.2.2.2. In China, the biomass energy industry has undergone about 15 years of development and has made great achievements, but the biomass energy industry also has problems such as unbalanced and insufficient development[21]. For example, China's investment in biomass power plants is mainly concentrated in the middle and lower reaches of the Yangtze River, while the three northeastern provinces with rich biomass resources and important grain and cotton production bases, such as Xinjiang, have insufficient investment. Compared with the wind power and photovoltaic industries, biomass energy is not only underinvested, but also has weak market development and small industrial scale. Compared with Western developed countries, China's biomass energy accounted for a significantly lower proportion of Renewable Energy. At present, China is actively adjusting fiscal policy subsidies and promoting biomass power generation. The development of the sub-field of Renewable Energy, which includes biomass energy research, will provide strong scientific research support for achieving this national objective.

(C) Energy Storage and Hydrogen Energy sub-field

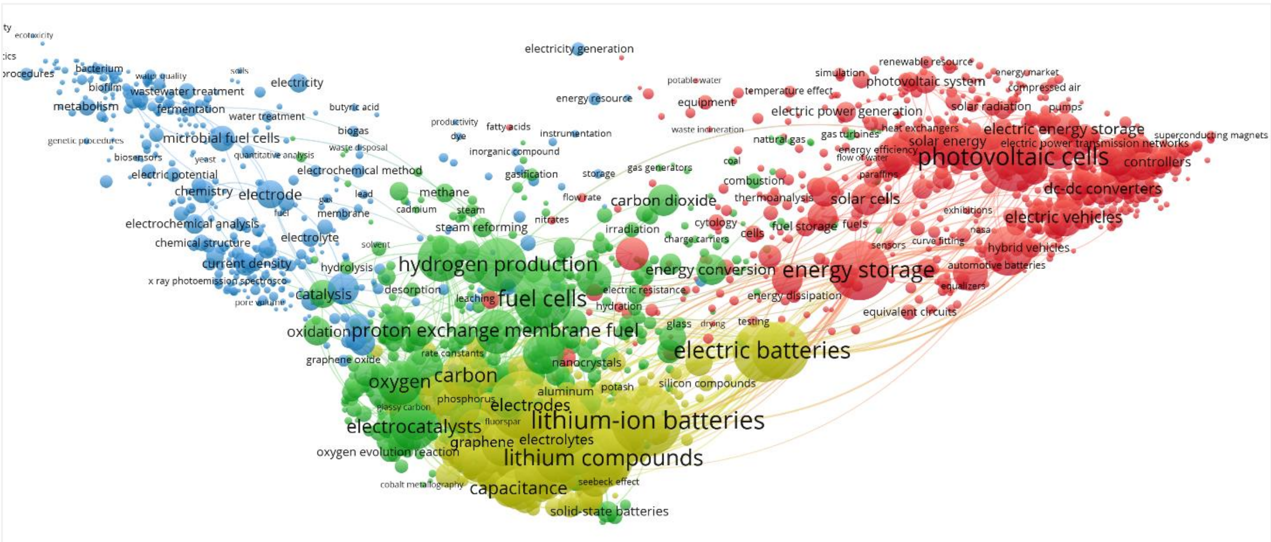


Figure 4.2.2.3 Energy Storage and Hydrogen Energy sub-field index keyword network, 2010–2021

Figure 4.2.2.3 shows that the keywords in Energy Storage and Hydrogen Energy mainly form two clusters: (1) energy storage, represented by the keywords "energy storage" and "electric batteries" and, (2) generation, storage, transportation and utilization of hydrogen energy, represented by the keyword "hydrogen production." At the same time, centering around the three central keywords of "photovoltaic cells," "lithium-ion batteries" and "fuel cells”, the sub-field forms clusters based on the following keywords as the main content:

1. photovoltaic cells, energy storage, charging (batteries), solar power generation, solar energy;

[21] http://www.xinhuanet.com/finance/2021-09/13/c_1127858151.html

2. fuel cells, hydrogen production, hydrogen, electrocatalysts, proton exchange membrane fuel cells (pemfc);
3. electrochemistry, electrode, microbial fuel cells, particle size, electric conductivity;
4. lithium-ion batteries, electrodes, electric batteries, electrolytes, anodes.

The discipline of Energy Storage and Hydrogen Energy also shows strong interdisciplinarity; for example, the research area of photovoltaic cells has substantial intersection with other sub-fields.

It is worth mentioning that hydrogen, as an energy carrier, has important applications in the energy supply of various fields such as transportation, industry and construction. Hydrogen energy has the advantages of being clean and low-carbon, convenient for storage, and having a wide range of applications. According to the "China Hydrogen Energy and Fuel Cell Industry White Paper"[22] it is estimated that by 2050, hydrogen energy will account for about 10% of China's energy system, hydrogen demand will reach close to 60 million tons, the annual economic output value will exceed 10 trillion *yuan*, and hydrogen energy will be widely used in transportation, industry and other fields. However, at present, China still has a long way to go in the utilization of hydrogen energy and the construction of industrial chains. Currently, China's hydrogen energy production mainly relies on fossil fuel energy, and hydrogen energy consumption is concentrated in chemical raw materials. From the perspective of the four links of hydrogen energy utilization, there are still obstacles to storage and transportation. The development of Energy Storage and Hydrogen Energy sub-field will play an important role in the popularization and utilization of hydrogen energy.

In 2021, the hydrogen energy industry was written into China’s "14th Five-Year Plan and the 2035 Long-term Goal Outline" and became one of the six major future industries. In the field of transportation, hydrogen fuel cell vehicles will become an important carrier for the landing of the hydrogen energy industry. Since 2019, 13 provinces or cities including Beijing, Shanghai, Guangzhou, and Zhejiang have successively formulated policies and plans related to the hydrogen fuel cell vehicle industry and have made detailed arrangements for the planning and construction of hydrogen refueling stations, the promotion and application of hydrogen fuel cell vehicles, and the layout of the core industrial chain[23]. Among them, the "Beijing Hydrogen Fuel Cell Vehicle Industry Development Plan (2020–2025)" issued in 2020 has made a clear deployment of the layout and development goals of the hydrogen fuel cell vehicle industry in Beijing, including cultivating leading enterprises with international influence in the

[22] https://www.ceic.com/gjnyjtww/chnjtyw/202103/ab2b674a8fc94b88bb3916f42169e0e9.shtml

[23] Provincial and municipal policy documents: "Beijing Hydrogen Fuel Cell Vehicle Industry Development Plan (2020-2025)", "Shanghai Fuel Cell Vehicle Industry Innovation and Development Implementation Plan", "Guangdong Province Accelerates the Development of Hydrogen Fuel Cell Vehicle Industry Implementation Plan", "Zhejiang Province Accelerates the Cultivation of Hydrogen Fuel Cell Vehicle Industry Development Implementation Plan", "Tianjin Hydrogen Energy Industry Development Action Plan (2020-2022)", "Guangdong Province Accelerates the Cultivation of Hydrogen Fuel Cell Vehicle Industry Development Implementation Plan", "Tianjin Hydrogen Energy Industry Development Action Plan (2020-2022)", " Medium- and long-term development plan of hydrogen energy industry in Shandong Province (2020-2030)", "Development Plan for New Energy Vehicle Industry in Jiangsu Province", "Hydrogen Energy Industry Development Plan of Sichuan Province (2021-2025)", "Guidance Plan for the Development of Hydrogen Fuel Cell Vehicle Industry in Chongqing", "Action Plan for the Development of Hydrogen Fuel Cell Vehicle Industry in Henan Province", "14th Five-Year Plan for the Development of Hydrogen Energy Industry in Hebei Province", "Several Opinions on Promoting the Development of Hydrogen Energy Industry in Inner Mongolia Autonomous Region (Trial)". (Draft for Comments), Ningxia's Guiding Opinions on Accelerating the Development of the Hydrogen Energy Industry, etc.

hydrogen fuel cell vehicle industrial chain, striving to achieve a cumulative promotion of hydrogen fuel cell vehicles exceeding 10,000 units, and building new hydrogen refueling stations, so as to achieve the cumulative output value of the whole industrial chain of hydrogen fuel cell vehicles exceeding 24 billion *yuan*. Hydrogen fuel is facing an unprecedented development opportunity, and its industrial application prospects have also promoted the development of related research.

(D) Energy Efficiency Management sub-field

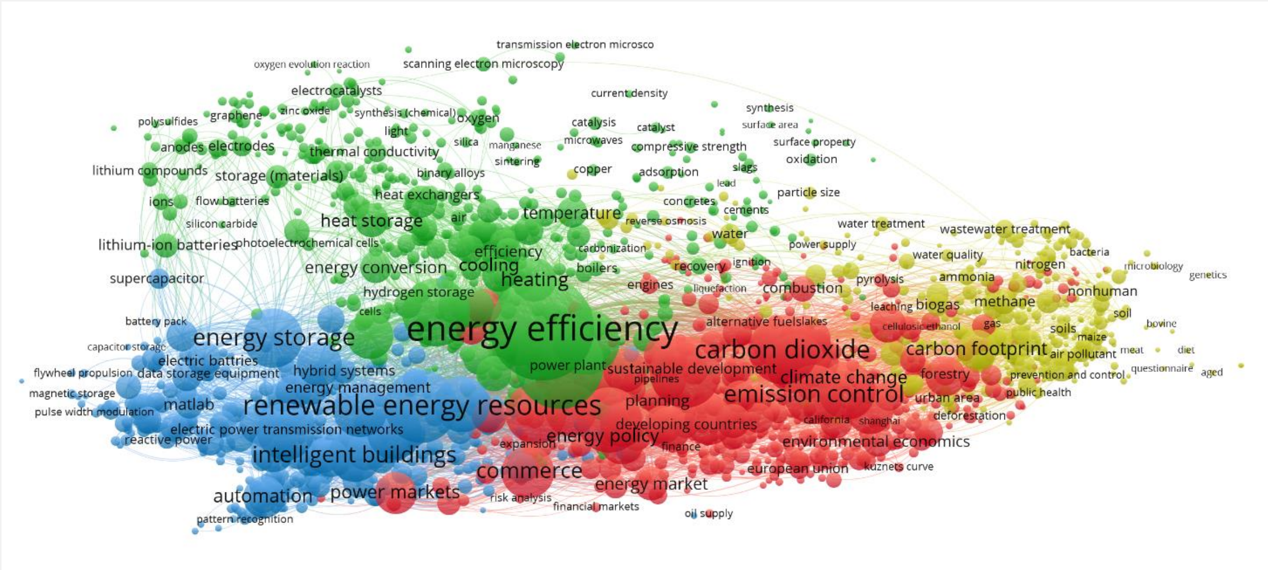


Figure 4.2.2.4 Energy Efficiency Management sub-field index keyword network, 2010-2021

Figure 4.2.2.4 shows that, similar to the sub-field of Carbon Emission Reduction Technology, the Energy Efficiency Management keyword network also has a relatively central keyword: "energy efficiency." Other keywords are interrelated to form clusters based on the following groups of keywords:

1. sustainable development, carbon dioxide, energy policy, emission control, greenhouse gases;
2. energy efficiency, energy utilization, solar energy, energy conservation, solar power generation;
3. renewable energy resources, energy storage, electric power transmission networks, optimization, energy management;
4. carbon footprint, agriculture, air quality, methane, biogas.

The concept of "energy efficiency" has become a global topic. In November 2021, the International Energy Agency released its Energy Efficiency 2021 report[24], which notes that the pace of global energy efficiency improvements had returned to pre-COVID-19 levels by 2021, but this is far from enough to meet the climate target of net zero emissions on time. The report projects that under a net-zero emissions scenario, global energy intensity will need to decline by 4% per year between 2020 and 2030. At the 26th United Nations Climate Change Conference (COP26) [25] in November 2021, Danfoss, the world's leading provider

[24] Energy Efficiency 2021 – Analysis - IEA

[25] Danfoss calls attention to "improving energy efficiency" at UN Climate Change Conference| Energy_NetEase Subscribe (163.com)

of green transition solutions, said that energy efficiency will make a significant contribution to achieving global climate and energy targets, helping energy-related sectors to reduce emissions by more than 40%. At present, the research topic of energy efficiency has become an area of increasing concern for government, industry and science.

B. Subject content changes (index keyword changes)

By introducing the dimension of time into the analysis of index keywords, the relative activity of a research area in a specific year or period of years becomes apparent. In the index keyword change chart below, the red or orange color blocks represent keywords with more frequent occurrences from 2017 to 2021, and the blue and green color blocks represent keywords that appear more frequently before 2015. The analysis only considers keywords with a frequency of more than 500 occurrences per year in the data selection in order to reflect changes over time.

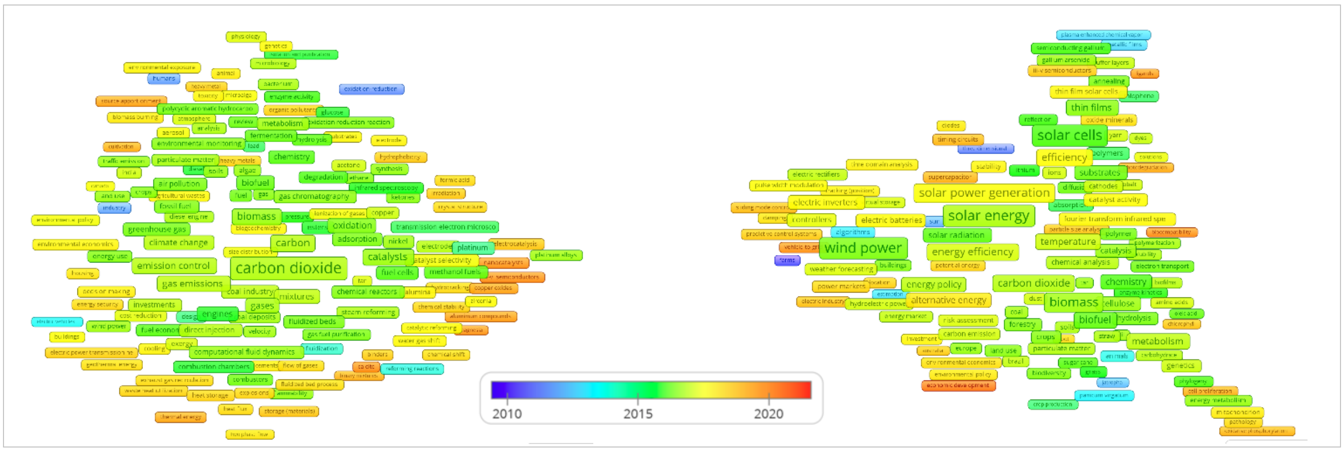


Figure 4.2.3.1 Keyword content change – Carbon Emission Reduction Technology sub-field (left), Renewable Energy sub-field (right), 2010–2021

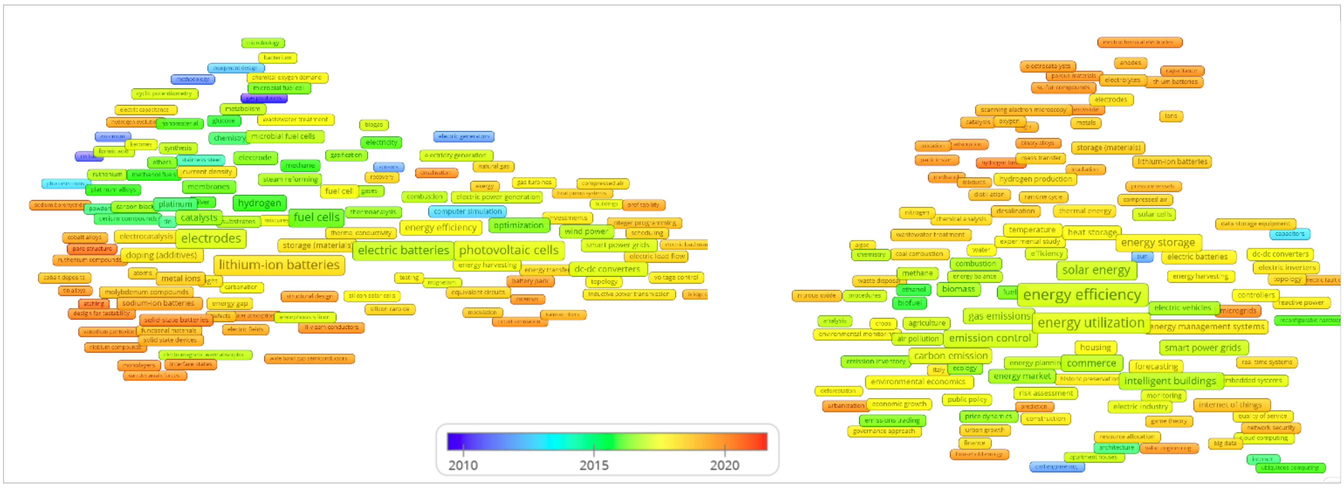


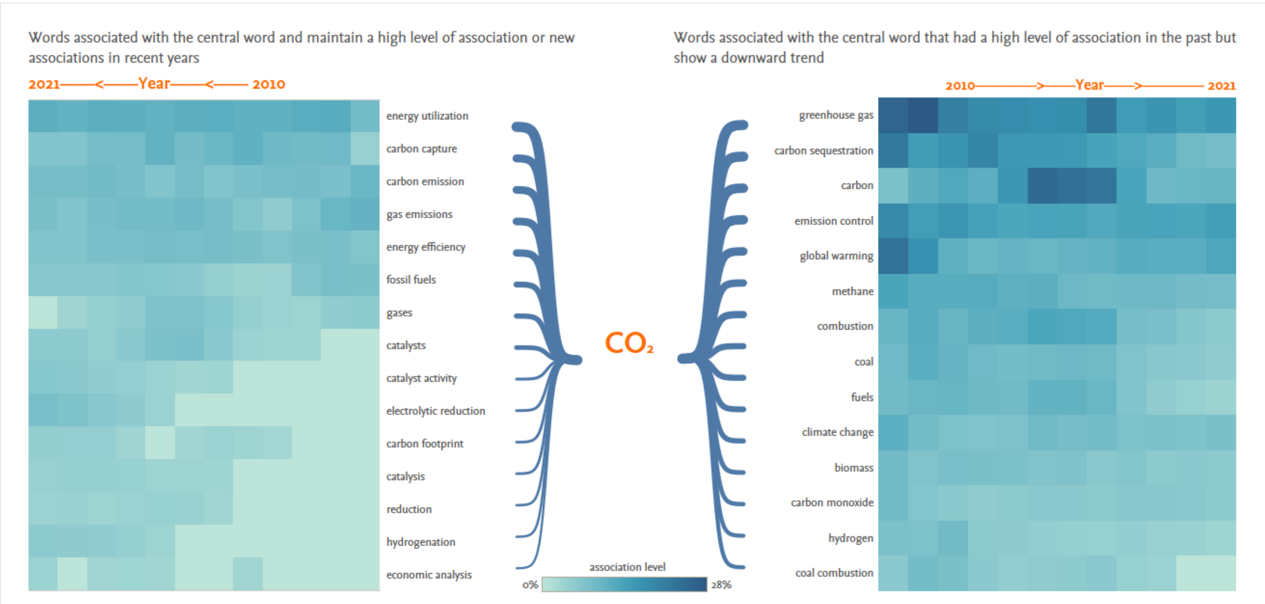
Figure 4.2.3.2 Keyword content change – Energy Storage and Hydrogen Energy sub-field (left), Energy Efficiency Management sub-field (right), 2010–2021

The above sub-field index keyword content change chart (Figure 4.2.3.1-2) shows that most of the high-frequency keywords of the Carbon Emission Reduction Technology sub-field and the Renewable Energy sub-field are concentrated in 2014–2015, while in the Energy Efficiency Management and the Energy Storage and Hydrogen Energy sub-fields, most of the keywords emerged after 2017, which means that these two sub-fields are relatively new.

C. Change in the relevance of index keywords related to the central keywords

As mentioned above, the central keywords of the two sub-fields of Carbon Emission Reduction Technology and Energy Efficiency Management are "carbon dioxide" and "energy efficiency," which not only appear most frequently, but are also closely related to other keywords. In the sub-fields of Energy Storage and Hydrogen Energy and Renewable Energy, there are several major keywords that function as nodes connected to each other. Therefore, discussing the relationship between the central keyword of the sub-field or the main keywords and their closely related keywords can reflect the disciplinary characteristics and potential development directions of the sub-field, to a certain extent. The analysis in the following section examines the central keywords "carbon dioxide" and "energy efficiency" for Carbon Emission Reduction Technology and Energy Efficiency Management sub-fields, respectively, and the main keywords "lithium-ion battery" and "solar energy" are selected for analysis in the sub-fields of Energy Storage and Hydrogen Energy and Renewable Energy, respectively.

(A) Carbon Emission Reduction Technology sub-field



The shades of the heat map indicate the share of the frequency of the keywords co-appearing with the central keyword out of the occurrence frequency of the central keyword, which directly reflects the relevance of the keywords and the central keyword in that year.

Figure 4.2.4.1 Trends of keywords associated with the central keyword "carbon dioxide" in Carbon Emission Reduction Technology sub-field, 2010–2021

According to the keyword network, the central keyword in the sub-field of Carbon Emission Reduction Technology is "carbon dioxide." Among the keywords on the right side of Figure 4.2.4.1 that have a high association level with carbon dioxide but a downward association trend, many keywords related to traditional energy use are listed, such as "carbon," "coal," "coal combustion" and so on. Among them, the association level between "carbon" and “carbon dioxide” increased in 2015–2017 but decreased in recent years.

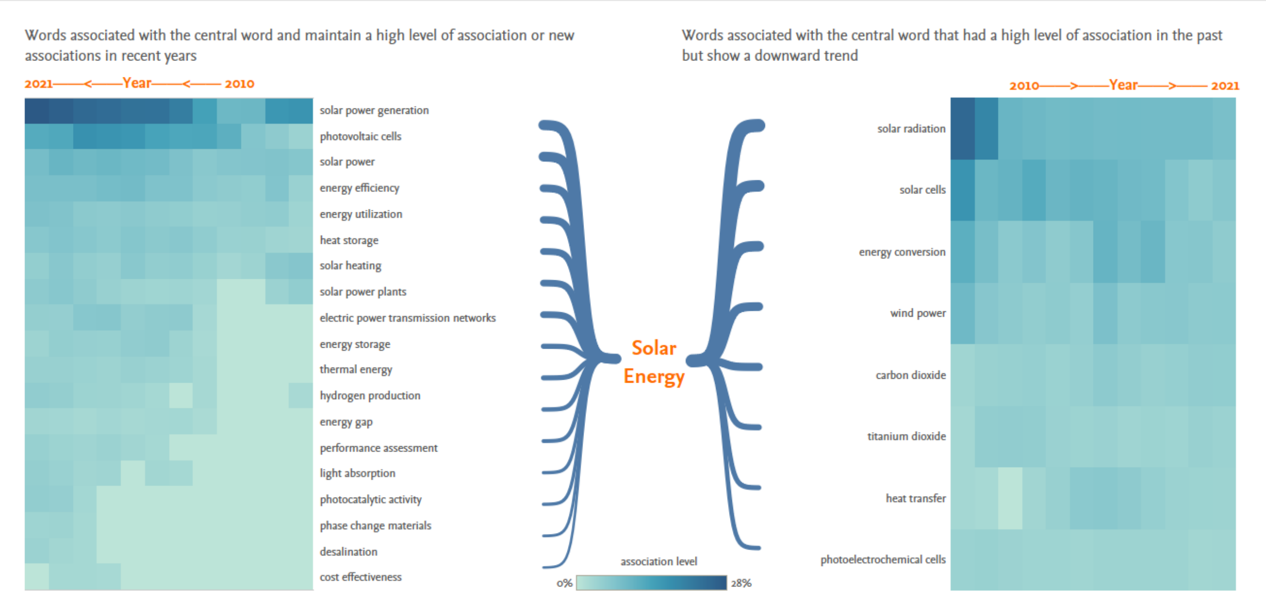
Among the keywords on the left that maintain a high association with carbon dioxide or have increased relevance in recent years, there are many related to low-carbon emission reduction technology issues, such as "carbon/gas emissions," "carbon capture," and "carbon footprint." These technologies are closely related to the research content and the energy structure transformation that China is currently facing.

China is the world's largest emitter of carbon dioxide. Slowing down and eventually effectively controlling carbon dioxide emissions in the process of energy production and utilization is an important task and goal of China in the next 10 years. Carbon Emission Reduction Technology processes can occur before, during, and after energy use. Specifically, before energy is used, the cleanliness of coal can be improved, equipment can be improved to improve the combustion efficiency of coal combustion, and cleaner alternative energy sources can be adopted; in the process of energy utilization, various technologies can be used to capture the generated carbon dioxide, such as post-ignition capture, pre-ignition capture and oxygen-enriched combustion. After the energy is used, the carbon dioxide can be buried. A representative approach is the carbon capture and sequestration with enhanced oil recovery (CCS-EOR) technology[26]. These research directions are important components of the sub-field of Carbon Emission Reduction Technology.

In addition to the research on the combustion process of traditional organic matter, research of some emerging technologies may also include the keyword "combustion". For example, oxygen-enriched combustion technology is a kind of carbon capture, utilization and storage (CCUS) technology used in combustion. Able to be fitted to existing conventional atmospheric boiler systems in power plants, it uses the mixture of oxygen and partial recirculation flue gases as oxidants to improve the CO_2 concentration in the tail flue gas, and thus, to achieve the purpose of CO_2 capture[27]. At present, the technology has developed rapidly in many developed countries, and has also received corresponding attention in China.

[26] Explore new paths for global carbon reduction technologies http://news.cnpc.com.cn/system/2019/11/05/001750449.shtml
[27] Ministry of Science and Technology "Carbon Capture, Utilization and Storage Technology in China" https://www.mfa.gov.cn/ce/cgla//chn/kjsw/news/P020101015043925841433.pdf

(B) Renewable Energy sub-field



The shades of the heat map indicate the share of the frequency of the keywords co-appearing with the central keyword out of the occurrence frequency of the central keyword, which directly reflects the relevance of the keywords and the central keyword in that year.

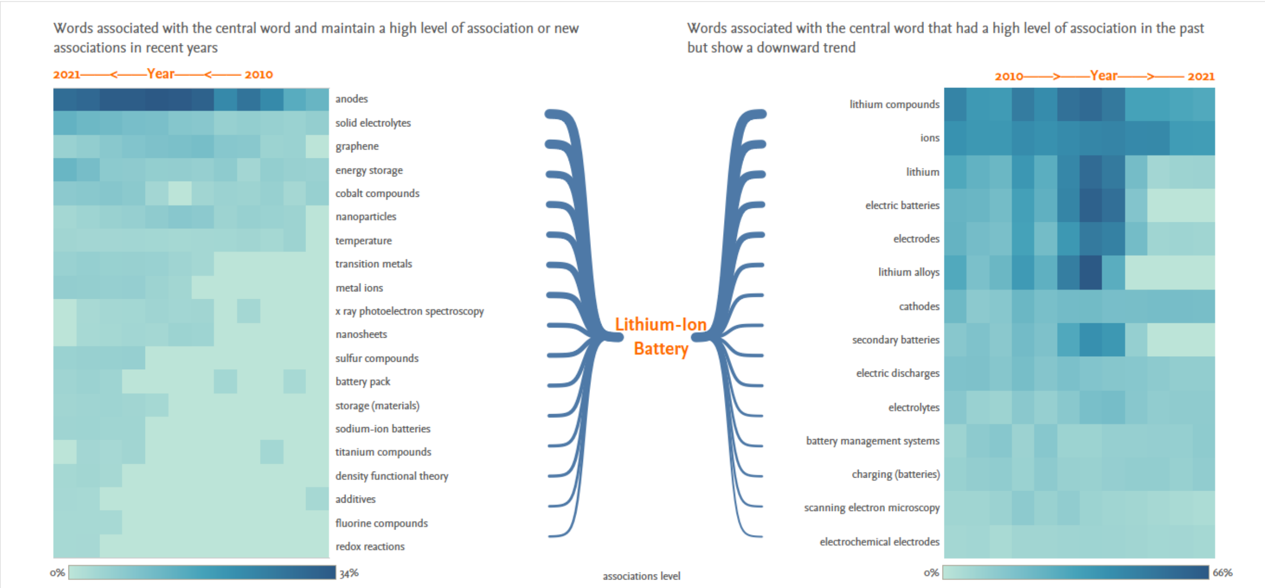
Figure 4.2.4.2 Trends of keywords associated with the central keyword "solar energy" in Renewable Energy sub-field, 2010–2021

The keyword "solar energy" has jumped to first place in frequency in the Renewable Energy sub-field in recent years. In Figure 4.2.4.2, the number of emerging associative keywords on the left is much higher than the keywords with declining relevance on the right, indicating that the research of solar energy has been more active in recent years, and new related keywords have emerged. The keyword "photovoltaic cells," which has the second highest average relevance on the left, has a higher relevance in the middle of 2010–2021, and a decrease in relevance in later years.

The trend towards active research on Renewable Energy sources in recent years also confirms the findings of some observations: the 70th edition of the "BP World Energy Statistics Yearbook," released in 2021,[28] mentions that renewable energy, as a share of global total power generation, achieved the fastest growth in history in 2020, and this increase is mainly due to the decline in the proportion of coal-based power generation. The trend towards the gradual replacement of coal by renewables is in line with the world's need to transition to net zero emissions.

[28] https://www.bp.com/zh_cn/china/home/news/reports/statistical-review-2021.html

(C) Energy Storage and Hydrogen Energy sub-field

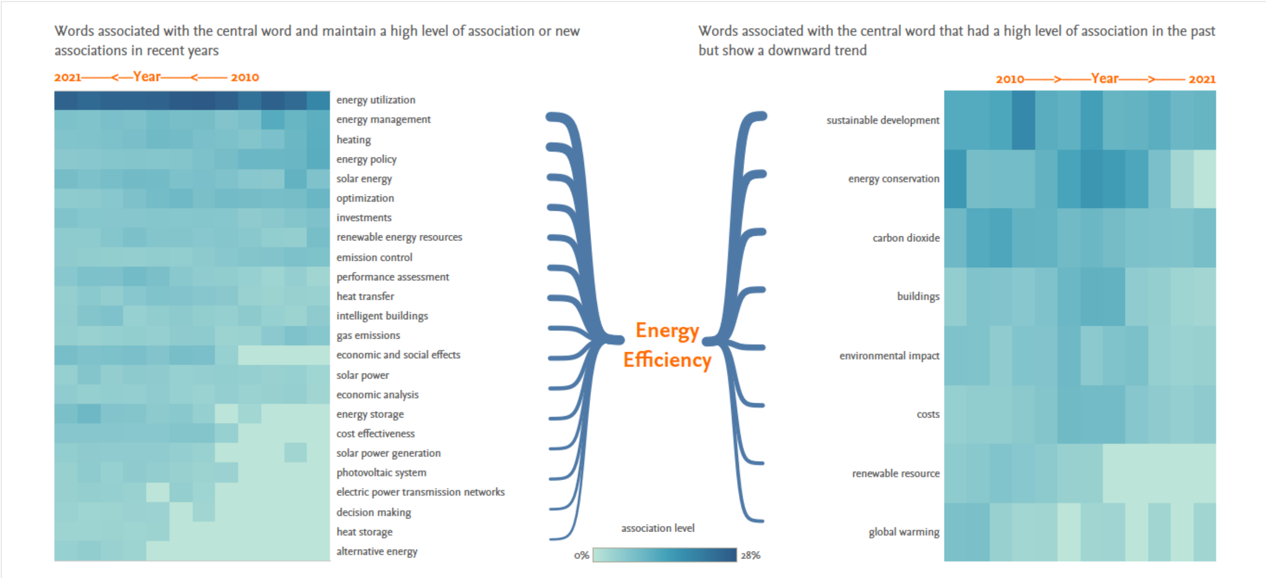


The shades of the heat map indicate the share of the frequency of the keywords co-appearing with the central keyword out of the occurrence frequency of the central keyword, which directly reflects the relevance of the keywords and the central keyword in that year.

Figure 4.2.4.3 Trends of keywords associated with the central word "lithium-ion battery " in Energy Storage and Hydrogen Energy sub-field, 2010 –2021

In the sub-field of Energy Storage and Hydrogen Energy, the index keyword "lithium-ion battery" has considerable frequency, which has grown rapidly in recent years. Figure 4.2.4.3 shows that the number of emerging relevant words on the left is more than the keywords with declining relevance on the right, indicating that the research on lithium-ion batteries has become more active in recent years, and new keywords have emerged. Particularly, some nanotechnology-related terms, such as "graphene" and "nanoparticles," have increased in recent years.

(D) Energy Efficiency Management sub-field



The shades of the heat map indicate the share of the frequency of the keywords co-appearing with the central keyword out of the occurrence frequency of the central keyword, which directly reflects the relevance of the keywords and the central keyword in that year.

Figure 4.2.4.4 Trends of words associated with the central word "energy efficiency " in Energy Efficiency Management sub-field, 2010 –2021

The keyword "energy efficiency" is the central keyword in the Energy Efficiency Management keyword network. In Figure 4.2.4.4, there are more emerging associative keywords on the left than those with declining association on the right, indicating that research on energy efficiency has been more active in recent years, with new keywords emerging. The first associative word on the left, "energy utilization," has maintained high relevance with the central keyword. New keywords have also emerged in recent years, including "energy buildings" and "cost effectiveness," which also point to some of the new focus of energy efficiency-related research.

D. Author keywords changes

Author keywords are provided by the author of each article and reflect the main content of the article as perceived by the author. However, author keywords are not standardized, and not every article has author keywords, so author keywords have a certain degree of irregularity. Because of these limitations, analysis of author keywords must be interpreted with caution and is included for the reference of researchers only.

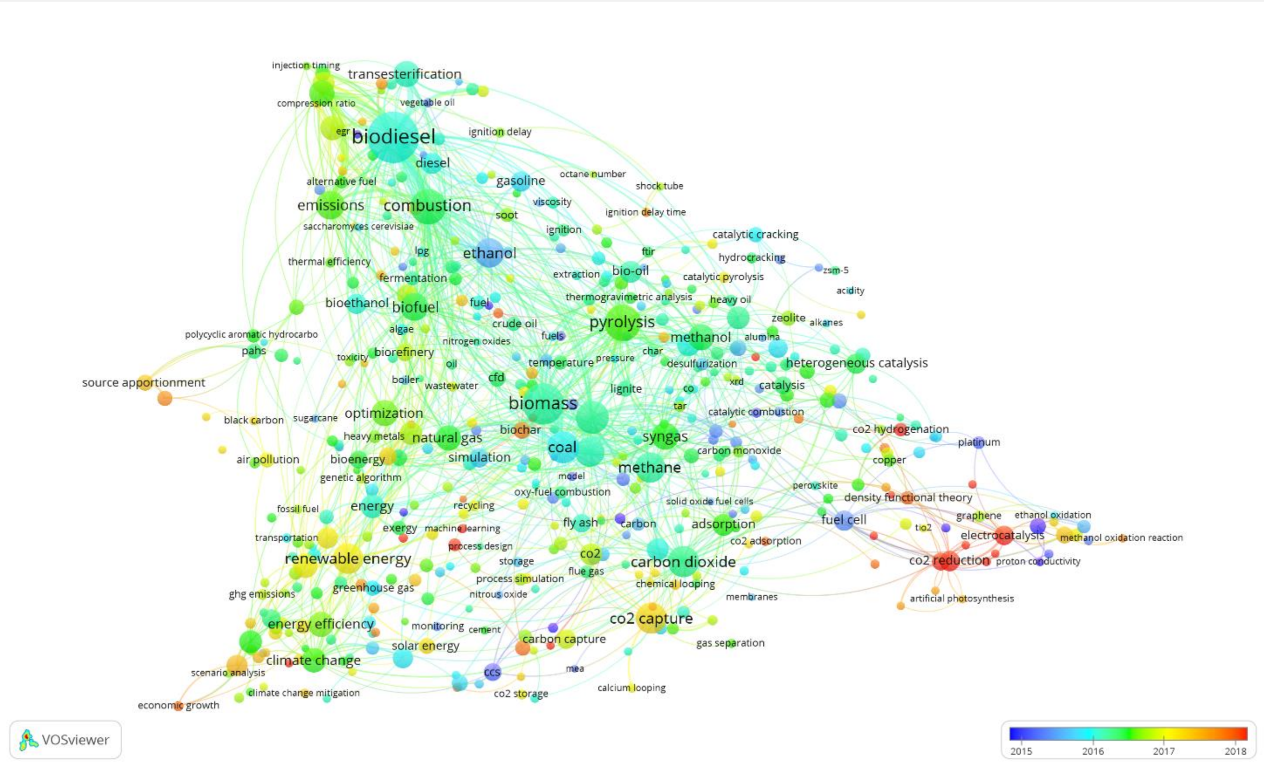


Figure 4.2.5.1 Change in content of global scholarly interest in Carbon Emission Reduction Technology, 2015 –2018

Figure 4.2.5.1 shows that in the sub-field of Carbon Emission Reduction Technology, the author keywords with higher frequency in recent years mainly focus on "carbon dioxide reduction technology (CO_2 reduction)," "electrocatalysis" and "economic growth." This shows that in recent years, researchers have paid more attention to issues such as carbon dioxide emission control and storage, and the trade-off between carbon emissions and economic development.

This change in research focus is also reflected in the social background of China. China has sacrificed the environment to some extent for economic development over the past few decades. At present, with the substantial improvement of the national economic level, the government and all sectors of society are paying more attention to environmental protection, including carbon emissions. In order to quantify and manage the control of carbon emissions by enterprises, in July 2021, China's carbon market was launched, and online trading began in Beijing, Shanghai and Wuhan[29]. The first batch of enterprises put under management were 2,225 key emitters in the power generation industry. According to estimates, these enterprises emitted carbon dioxide exceeding 4 billion tons per year, which also means that China's

[29] Opening of national carbon trade market: http://www.xinhuanet.com/fortune/2021-07/17/c_1127664211.htm (Chinese)

carbon market, once launched, will become the world's largest carbon market covering greenhouse gas emissions. The interdisciplinary research content of the sub-fields of Energy Efficiency Management and and Carbon Emission Reduction Technology will vigorously support the rational control and development of the carbon market.

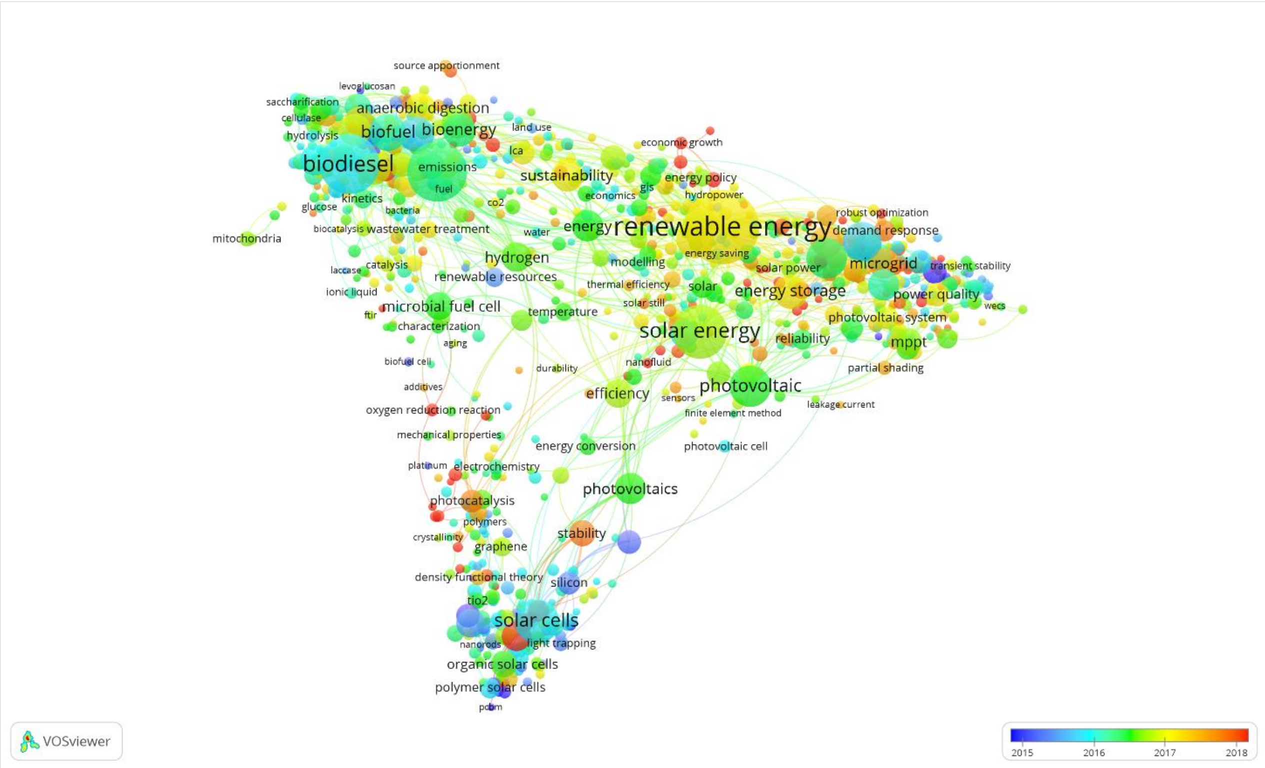


Figure 4.2.5.2 Change in content of global scholarly interest for Renewable Energy, 2015 –2018

Figure 4.2.5.2 shows that in recent years, researchers have paid more attention to solar cells, energy transfer and electrical energy in Renewable Energy, such as "photocatalysis" and "oxygen reduction reaction," while research around keywords such as biodiesel and biofuels is mostly concentrated in 2015 –2016.

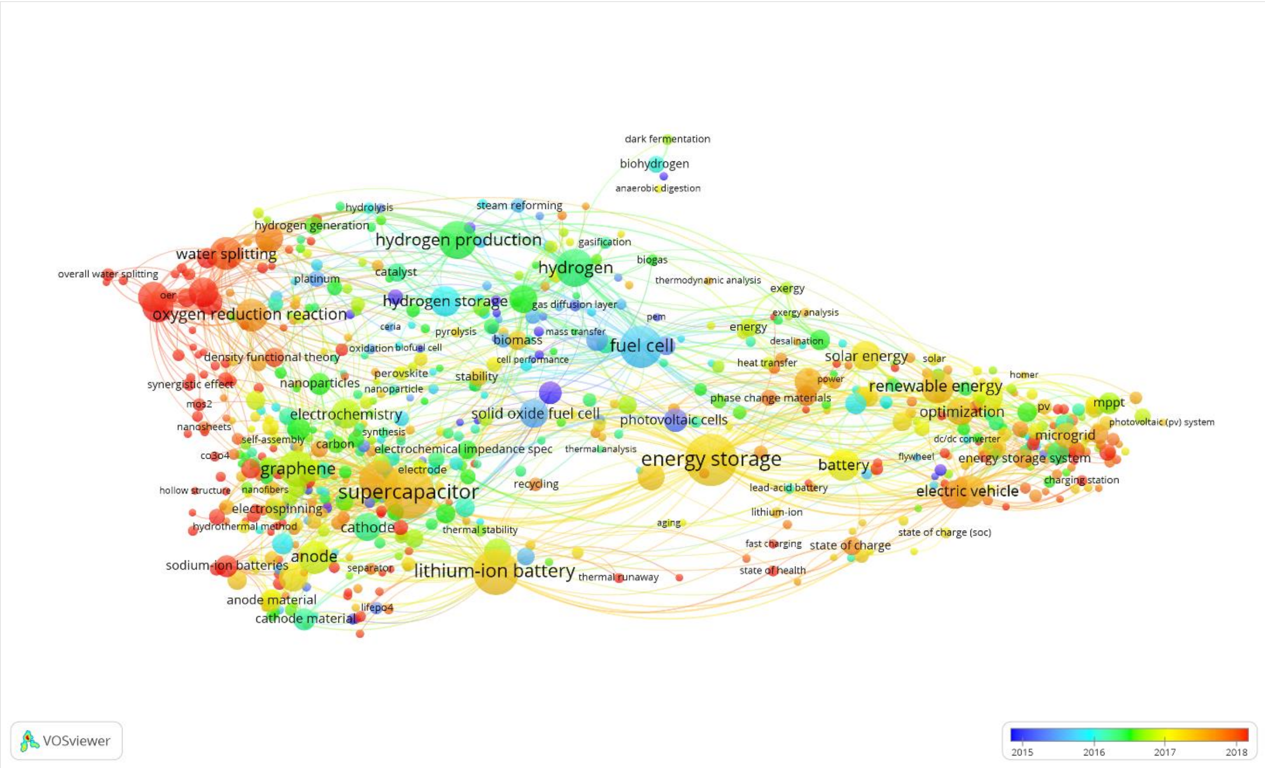


Figure 4.2.5.3 Change in content of global scholarly interest for Energy Storage and Hydrogen Energy, 2015 –2018

Figure 4.2.5.3, the author keywords network diagram, shows that in recent years, the higher frequency author keywords of Energy Storage and Hydrogen Energy sub-field have mainly focused on "overall water splitting," "nanosheets" and "hydrogen generation." This shows that in recent years, researchers have paid more attention to issues such as electrolysis of water to hydrogen technology, fuel cell preparation and nanomaterial applications.

Over the past few decades, great progress has been made in overall water splitting, but there are still many obstacles that are difficult to overcome, such as low efficiency, poor stability, complex systems, cost and safety. In view of these difficulties, there is no shortage of cutting-edge research with strong application potential in the sub-field of Energy Storage and Hydrogen Energy. For example, the research group of Lingyu Piao of the National Center for Nanoscience and Technology proposed a new photocatalytic water splitting route[30], that is, photocatalytic intermediate water splitting (PIWS), which enables remarkable photocatalytic production of both H_2 and H_2O_2 from pure water, with high efficiency and value ($2H_2O \rightarrow H_2 + H_2O_2$). This process has clear advantages in that PIWS is a kinetically advantageous electronic process, and the back-reaction of H_2 and O_2 was significantly inhibited, improving hydrogen production efficiency. Moreover, the products are pure gaseous H_2 and higher value liquid H_2O_2, which are automatically separated, saving the cost of separation and purification, improving the cost-effectiveness and value of the product.

[30]https://doi.org/10.1016/j.nanoen.2019.104287

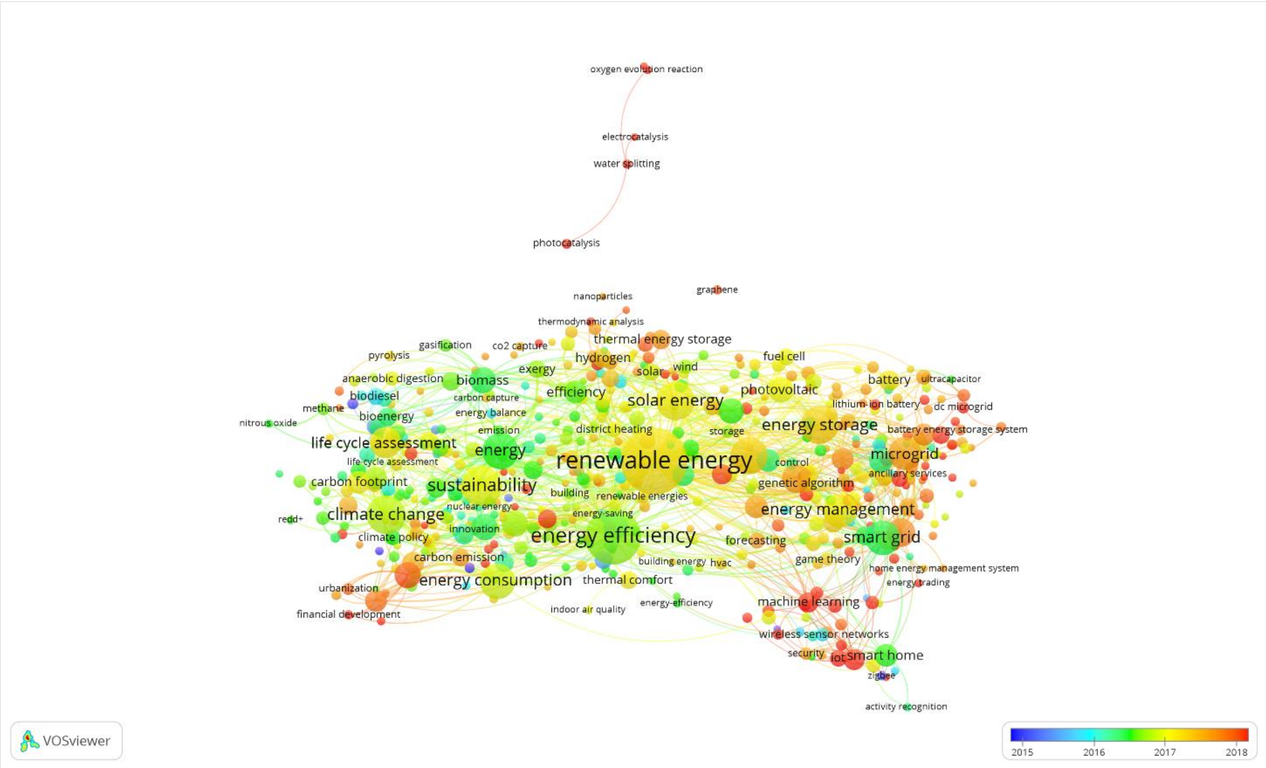


Figure 4.2.5.4 Change in content of global scholarly interest for Energy Efficiency Management, 2015 –2018

Figure 4.2.5.4 shows how author keywords in the sub-field of Energy Efficiency Management have changed over time. It suggests that in recent years, researchers in this sub-field have paid more attention to the application of AI technology in the field and the impact of policy formulation on carbon dioxide emissions, which is reflected in the emergence of author keywords such as "machine learning," "financial development," and "energy trading."

Artificial intelligence (AI) technologies such as machine learning are often used in smart grids and the energy internet. The fact that "energy policy" has received attention in recent years suggests that there is a growing interest in researching the impact of government intervention in the energy market. "Energy Efficiency 2021"[31], released by the International Energy Agency, notes that government policies can help boost efficiency investment in the buildings and construction sector, and are expected to help energy efficiency investment rise by 10% in 2021 to reach nearly $300 billion. At the same time, more stringent standards and regulations, more public spending, incentive structures, and simplified planning laws and procedures can all help increase investment and make energy efficiency projects more attractive to private funding. All this reflects the broad-ranging and interdisciplinary nature of energy efficiency management, such that its development also requires the collaboration of academia, industry, government, and other parties.

[31] Energy Efficiency 2021 – Analysis - IEA

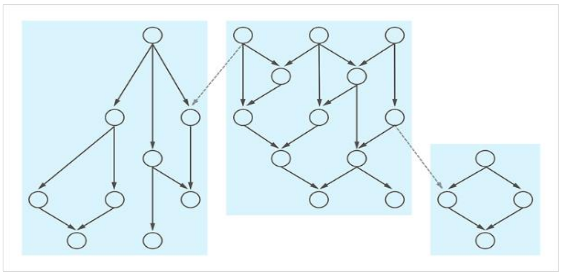
Extensions of the discipline

To gain a more detailed understanding of the hot global research directions encompassed by the Energy Science discipline, the report uses topic clusters. A topic cluster is a collection of publications with a common research interest. Elsevier uses machine learning to divide the entire Scopus publication set into more than 97,000 research topics through their citations and citation relationships, so that the publications under each topic have strong research content relevance. Then, in the same way, these topics are divided into more than 1,500 clusters through citation relationships. Through the examination of the intersection of Energy Science articles and these topic cluster articles, it is possible to reveal the potential directions and extensions of Energy Science.

Extracting the keywords of the topic clusters through certain machine learning algorithms gives a representation of the common focus of the research content of the publication collection. Compared with the already detailed ASJC subject classification, which is at the journal-level, the topic cluster classification is at the article level, enabling revealing more detailed research directions. The topic cluster also has a metric that reflects the degree of research activity—the prominence percentile. Its numerical value can reflect the degree to which the topic cluster is interested by global researchers, or its popularity and development momentum. By looking at the distribution of keywords in the high-prominent topic clusters, researchers can find the characteristic research content in the field, which will provide them some ideas for the exploration of future research directions.

A. Overall discipline hotspot topic clusters and potential research directions

Topic Clusters[32] are clusters of research publications that are more granular than disciplines. All of Scopus's publications are grouped into about 1,500 research topic clusters using the direct citation algorithm that is used to create topics. When the strength of the citation links between topics reaches a threshold, a topic cluster is formed. Thus, topic clusters are collections of publications with similar research interest. Given the granularity of research content covered by a topic cluster, there can be overlapping content between each topic cluster, but normally, publications in a specific topic cluster have strong citation relationships as compared with publications attributed to other topic clusters.



Circles indicate articles, solid arrows indicate strong citation links, and dashed arrows indicate weak citation links. Articles with strong citation linkages are grouped under the same topic, while articles with weak citation linkages are grouped into different topics.

Figure 4.2.1 Scival topic clustering schematic diagram

Keyphrases are extracted using the Elsevier Fingerprint Engine[33] technique. In SciVal, the Elsevier Fingerprint Engine uses text mining and applies a variety of Natural Language Processing techniques to the titles, abstracts, and author keywords of the documents in a publication set, topic or topic cluster to identify important keyphrases. The important keyphrases are selected for each document based on a list of standardized keyphrases using the Inverse Document Frequency (IDF) technique. This technique incorporates a factor that diminishes the weight of words that occur frequently in the set of documents and increases the importance of words that occur rarely, so that keyphrases can be selected in a more balance way. The weighted lists of keyphrases per publication are aggregated up to different entity levels, — in this case, at the topic cluster level, and the word cloud of the top 50 most relevant keywords[34] is used in SciVal to show research content of an entity, or of each topic cluster.

Topic Cluster Prominence[35] is an indicator of the level of activity of the particular topic cluster. The indicator uses three metrics to calculate the momentum of the topic cluster: the number of citations, the number of views in Scopus, and the average journal factor CiteScore. The value reflects the attention, popularity and momentum of the topic cluster in a research field, and is found to be positively correlated with research funds and grants. By finding topic clusters with high prominence, researchers or research

[32] Klavans, R., & Boyack, K. W. (2017). Research portfolio analysis and topic prominence. Journal of Informetrics, 11 (4), 1158–1174.

[33] https://service.elsevier.com/app/answers/detail/a_id/27763/supporthub/scival/kw/Fingerprint/

[34] The "III. Research Situation of Discipline Segmentation" section of this subsection and the "(2) Major Subdivision Research Areas - Research Themes" section of each sub-discipline in the next subsection use the research theme (group) keyword to analyze the main research content of the discipline segment.

[35] https://service.elsevier.com/app/answers/detail/a_id/35050/supporthub/scival/

managers can get some insights on which research topics have high momentum, and are likely to be well-funded or have higher grant success rates.

As explained above, a topic cluster is a collection of publications that are grouped together based on their strong citation links. These topic clusters can be used to understand and compare the ongoing research in different countries (regions) in more detail. When combined with topic or topic cluster prominence, they can help keep research managers staying abreast of the latest research trends, and help researchers gain insight into related research topics with high momentum that are adjacent to their current research focuses for future exploration.

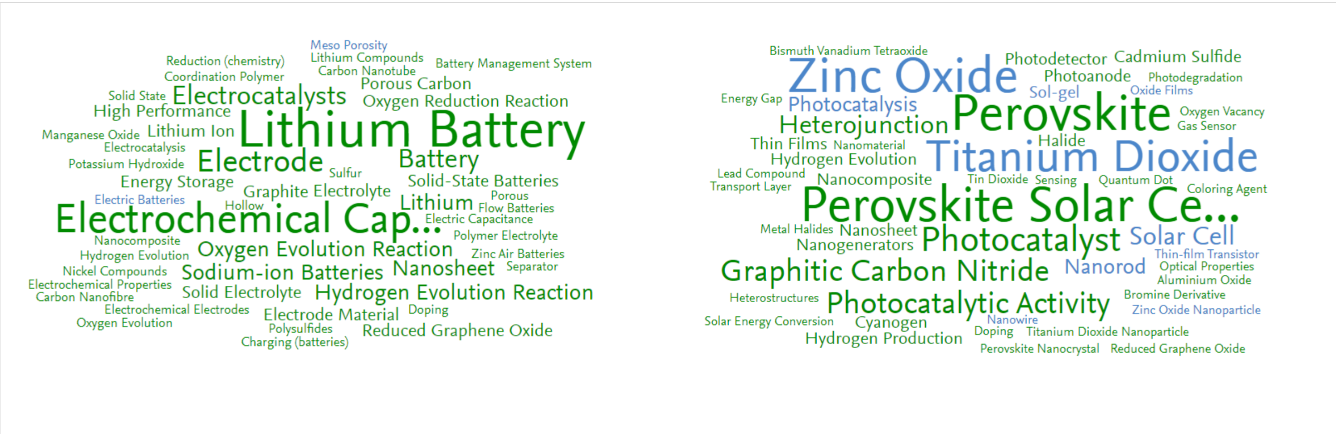
Prominence Percentile	Publications	Share of publications	TC-ID	Top 5 most published keyphrases	Publications share of USA in this TC		Publication share of CHN in this TC	
99.93	153,044		30	Electrode|Lithium Battery|Carbon|Battery|Electrolyte	16%	3.8	69%	2.7
93.91	32,869		340	Solar|Solar Energy|Solar Collector|Solar Energy Conversion|Solar Radiation	11%	1.6	13%	1.2
85.08	22,674		423	Wind Turbine|Wind Power|Wind|Turbine|Rotor	7%	1.8	17%	0.8
95.18	31,753		229	Fuel Cell|Electrode|Proton Exchange Membrane Fuel Cells (PEMFC)|Catalyst|Membrane	10%	1.9	18%	1.5
98.26	48,448		87	Coal|Biomass|Spontaneous Combustion|Pyrolysis|Fuel	6%	1.7	28%	1.2
99.33	80,142		28	Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Net..	7%	2.4	19%	1.3
94.25	32,777		165	Engine|Fuel|Diesel Engine|Emissions|Spontaneous Combustion	7%	2.1	10%	1.3
99.26	49,394		81	Energy|Carbon|Renewable Energy|Climate Change|Sustainable Development	9%	2.3	14%	2.1
93.78	20,298		316	Solid Oxide Fuel Cell|Electrode|Electrolyte|Oxide|Fuel Cell	9%	1.5	17%	1.5
94.72	20,210		271	Cooling|Heat Transfer|Heat Exchanger|Thermodynamics|Exergy	3%	1.6	11%	1.2
96.39	22,962		176	Buildings|Energy Conservation|Energy Efficiency|Energy Consumption|Air	5%	1.9	6%	1.1
99.87	64,151		8	Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst	4%	3.8	19%	2.7
98.46	50,135		13	Electric Potential|Converter|Inverter|Grid|Power Electronics	3%	2.6	7%	1.2
85.02	13,992		256	Spontaneous Combustion|Flame|Fuel|Combustion Chambers|Ignition	7%	1.5	9%	1.0
98.80	24,495		65	Wastewater Treatment|Waste Water|Sewage|Microorganisms|Bioreactor	4%	1.7	9%	1.5
93.38	15,082		177	Nanocrystal|Quantum Dot|Thin Films|Semiconductor|Energy Gap	5%	2.1	7%	1.4
76.72	18,027		97	Silicon|Solar Cell|Thin Films|Crystalline Material|Nanocrystal	4%	1.5	6%	0.8
98.60	21,500		61	Polymers|Organic|Solar Cell|Organic Light-emitting Diodes|Conversion Efficiency	4%	3.6	13%	3.2
99.47	32,500		7	Catalyst|Catalysis|Conversion|Oxidation|Adsorption	3%	1.7	8%	1.3
97.19	13,345		42	Aerosol|Emissions|Air Quality|Atmospheric|Ultrafine Particulate Matter	7%	2.5	8%	1.8
		0% 50%			25% 50% 75%	0.0 2.0 4.0	25% 50% 75%	0.0 2.0 4.0

Figure 4.3.1.1 Topic clusters with the highest number of publications in Energy Science discipline, 2010–2021

Figure 4.3.1.1 shows the top 20 topic clusters with the highest number of papers published in the Energy Science discipline from 2010 to 2021, along with the output count and share of publications under the topic cluster that belong to the discipline, the share and FWCI of publications in the discipline for the US and China, which are the two countries with the highest output volume in the Energy Science discipline. For all the top 20 topic clusters, China has a higher proportion of publications than the US, but the scholarly impact as measured by FWCI is lower than that of the US. For the topic cluster TC30 (related to lithium-ion batteries) China accounts for nearly 70% of the publications, indicating that globally, the majority of output of the topic cluster comes from China. This topic cluster also has the highest prominence score among the most published topic clusters in the Energy Science discipline. TC30 is also the topic cluster with the highest share of publications for both China and the US, respectively, and for China, the topic cluster TC61 (related to organic solar cells) has the highest FWCI.

When looking at the prominence scores of the topic clusters, it can be found that some high-prominence topic clusters (greater than 99% of the prominence percentile) do not necessarily have large share of Energy Science publications, such as TC8, TC7, TC28 and TC81. This means that researchers in the field of Energy Science can consider expanding their research into these global hot research areas. The keyphrases of the topic clusters can provide more details about directions for researchers to explore.

As mentioned earlier, the keyphrases of the topic cluster come from all publications under the topic cluster. The keyphrase word cloud [36] of a topic cluster can show the main content of a topic cluster to a large extent. In the word cloud, the larger the font, the more relevant the keywords. The green keyword means that the number of publications with related content is increasing in recent years, and the blue means that the number of related publications is decreasing in recent years. The following shows keyphrase word clouds of the top six most prominent topic clusters listed in Figure 4.3.1.1.



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.1.2 Keyphrase word clouds of Energy Science discipline topic clusters (TC30, TC8), 2018–2020

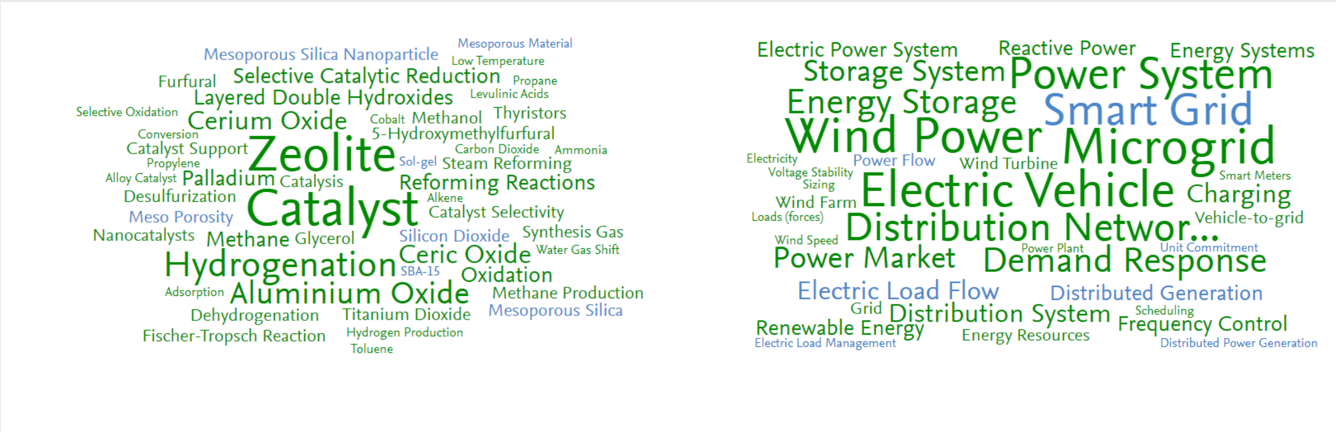
Figure 4.3.1.2 (left) shows that in TC30, the keyphrases of Lithium Battery, Electrochemical Capacitors, Electrode, Electrocatalysts, Battery, Lithium, and Oxygen Evolution Reaction are the most relevant and strongly correlated in this topic cluster. The vast majority of keywords for this topic cluster have also seen increase in relevant publications in recent years.

Figure 4.3.1.2 (right) shows that in TC8, the keyphrases Perovskite, Zinc Oxide, Perovskite Solar Cell, Titanium Dioxide, Photocatalyst, Graphitic Carbon Nitride, and Photocatalytic Activity are the most relevant and strongly correlated in this topic cluster. However, in recent years, publications mentioning Zinc Oxide and Titanium Dioxide have decreased, and those mentioning Perovskites have increased, indicating that perovskite solar cell related research has become more popular in recent years.

Perovskite solar cells are the third generation of solar cells that use perovskite-type organometal halide semiconductors as light-absorbing materials, which have important characteristics such as low cost, high photoelectric conversion efficiency, and huge commercial potential. However, because advances are still needed in battery stability and theoretical research, perovskite solar cells are currently mainly in the laboratory research stage, and only small-scale commercial attempts are made[37].

[36] Based on the algorithm of inverse document frequency (IDF), the relevance of the keywords of the standardized research subject group is calculated, and the keywords with the top 50 degrees of relevance are selected according to the high to low correlation degree.

[37] Analysis of the development of perovskite solar cell technology - Principle| structure| preparation| spraying| organic | inorganic - Sobi Photovoltaic Network (solarbe.com)

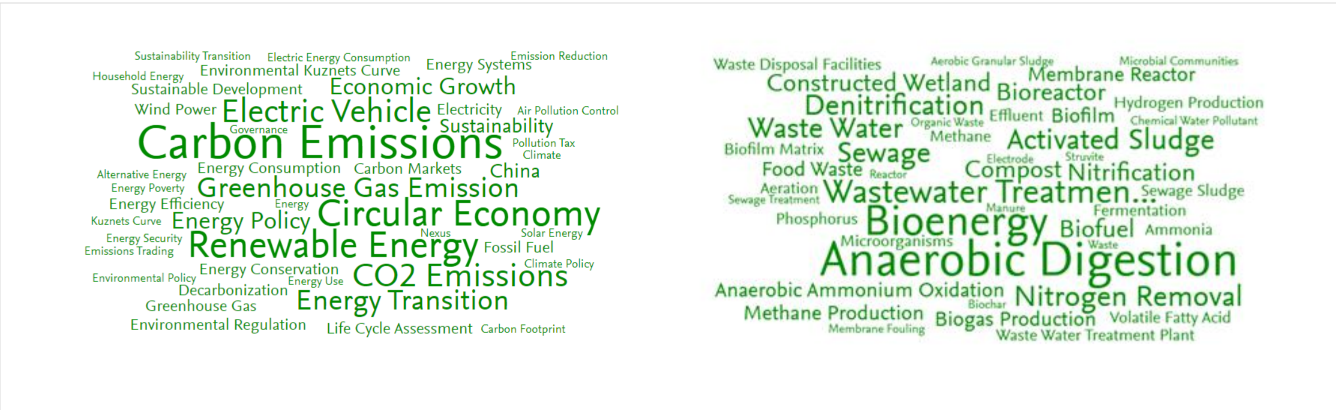


Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.1.3 Keyphrase word clouds of the Energy Science discipline topic clusters (TC7, TC28), 2018 –2020

Figure 4.3.1.3 on the left shows that in the topic cluster TC7, keyphrases Catalyst, Zeolite, Hydrogenation, Aluminum Oxide, Cerium Oxide, Ceric Oxide, Methane, Palladium, Layered Double Hydroxide, and Reforming Reactions are the most relevant and strongly correlated. Also, related articles for the vast majority of these keywords have increased in recent years.

Figure 4.3.1.3 on the right shows that in TC28, the keyphrases of Microgrid, Wind Power, Electric Vehicle, Smart Grid, Power System, Distribution Network, Demand Response, Energy Storage, Power Market, and Storage System are the most relevant and strongly correlated for this topic cluster. Articles mentioning Smart Grid have decreased in recent years.



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.1.4 Keyphrase word clouds of Energy Science discipline topic clusters (TC81, TC65), 2018 –2020

Figure 4.3.1.4 on the left shows that in TC81, the keyphrases Carbon Emissions, Circular Economy, Renewable Energy, Electric Vehicle, CO_2 Emissions, Greenhouse Gas Emission, Energy Transition, Economic Growth and Energy Policy are the most relevant and strongly correlated in this topic cluster. For the vast majority of these keywords, related articles have been increasing in recent years.

Figure 4.3.1.4 on the right shows that in TC65, Anaerobic Digestion, Bioenergy, Wastewater Treatment, Sewage, Waste Water, Activated Sludge, Nitrogen Removal, Denitrification, Biofuel and Compost are the most relevant and strongly correlated keyphrases for this topic cluster. Most of these keyphrases have seen increases of relevant publications in recent years, suggesting their growing popularity.

As can be seen from the above word clouds, the prominent topic clusters covered in the Energy Science discipline mainly focus on lithium batteries, perovskite solar cells, catalysts and catalytic hydrogenation reactions for batteries, microgrid distributed generation and wind power supply, carbon emissions and circular economy, and anaerobic digestion technology and biomass energy utilization. These can also be the directions for expanded and interdisciplinary Energy Science research.

B. Hot topic clusters and potential research directions for sub-fields

(A) Carbon Emission Reduction Technology sub-field

1. Top 10 topic clusters by share of publications in the sub-field

Because of the nature of the Energy Science research field, many topic clusters are multidisciplinary. Analyzing the interdisciplinary nature of topic clusters is helpful to understand the disciplinary extensions of publication collection for a sub-field, and may contribute to the development of diversity in related research fields.

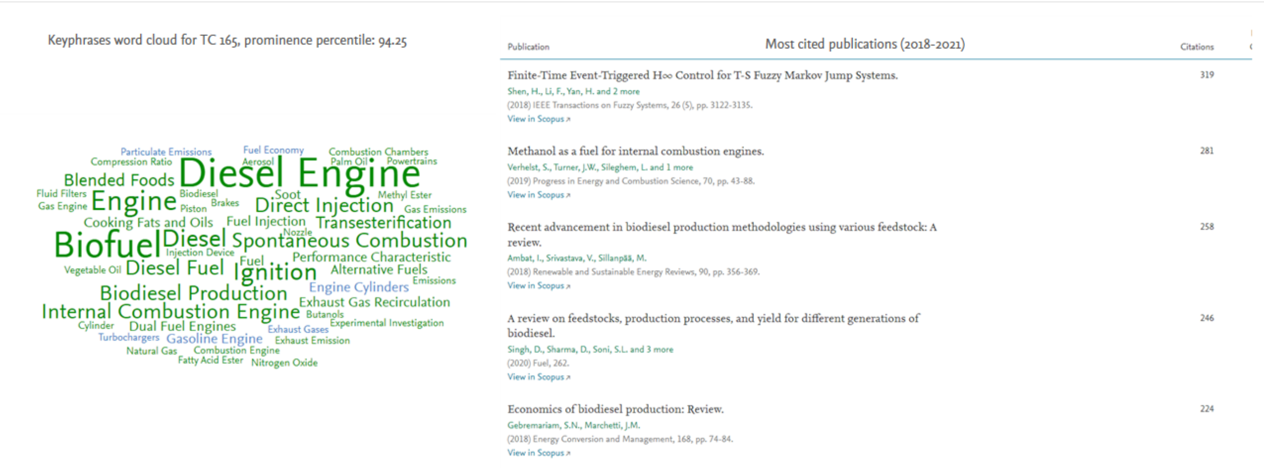
Inherent features of the TC			ASJC distribution of the TC								
TC ID	Top 5 most published keyphrases	Share of publications	Agricultural and Biological Sciences	Chemical Engineering	Chemistry	Earth and Planetary Sciences	Energy	Engineering	Environmental Science	Materials Science	Physics and Astronomy
165	Engine|Fuel|Diesel Engine|Emissions|Spontaneous Combustion	49%		■			■	■	■		
87	Coal|Biomass|Spontaneous Combustion|Pyrolysis|Fuel	49%		■	■		■				
950	Carbon Dioxide|Absorption|Capture|Gas|Amine	38%		■	■		■	■			
256	Spontaneous Combustion|Flame|Fuel|Combustion Chambers|Ignition	37%		■	■		■	■			■
629	Petroleum|Oil|Asphaltenes|Viscosity|Hydrocarbon	27%		■	■		■				
772	Adsorption|Carbon Dioxide|Adsorbent|Capture|Porosity	26%		■	■					■	
635	Carbon Dioxide|Reservoir|Gas|Storage|Injection	25%				■	■	■	■		
490	Biomass|BiofuelBioenergy|Forest|Forestry	21%	■				■		■		
7	Catalyst|Catalysis|Conversion|Oxidation|Adsorption	20%		■	■						
229	Fuel Cell|Electrode|Proton Exchange Membrane Fuel Cells (PEMFC)|Catalyst|Membrane	16%		■	■		■	■		■	■

Figure 4.3.2.1.1 The top 10 topic clusters with the highest proportion of sub-field articles in Carbon Emission Reduction Technology, 2010–2021 (see Appendix VII for details of the color identification and full name of the 27 ASJC subjects)

As shown in Figure 4.3.2.1.1, the top 10 topic clusters for the Carbon Emission Reduction Technology sub-field have rich interdisciplinarity, covering most of the disciplines of chemical engineering, chemistry, energy, and engineering, while also having intersection with environmental science and materials science. Among these top 10 topic clusters, TC165, the one with the largest proportion of the sub-field publications (49%) have intersection with subject areas like chemical engineering, energy, engineering and environmental science.

Keyword word clouds can help present the main content of a topic cluster comprehensively. In addition, the representative or original research content of a topic cluster can also be examined through highly cited articles within the topic cluster. The following summarizes or highlights the core research content of the relevant topic clusters by showing the word cloud diagrams of the top five topic clusters by share of publications in the sub-field and their highly cited articles (see Figure 4.3.2.1.2–6).

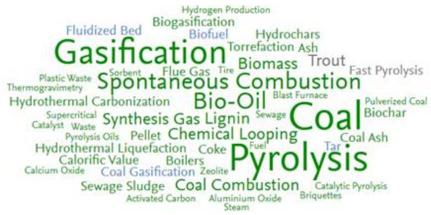
The topic cluster with the highest proportion of publications in the sub-field of Carbon Emission Reduction Technology, TC165, mainly revolves around biomass energy. The analysis of the highly cited publications combined with the keyword word cloud shows that the research content of this topic cluster is mainly related to technologies and methods of biodiesel preparation and its application in diesel combustion engines, including related catalysis, esterification, and transesterification reaction methods and technologies. The research of TC87 also focuses on the utilization of biomass energy, mainly including related biomass rapid thermal cracking to produce oil, catalytic hydrogenation to improve efficiency, and efficient depolymerization of lignin, and related catalytic conversion methods and processes. TC950-related research revolves around the capture and storage process of exhaust gases (carbon dioxide, nitric oxide, sulfur dioxide) produced during combustion. The methods discussed include chemical methods (e.g., absorption of amino acid salt solutions) and physical methods (e.g., far infrared). The study of TC256 is also closely related to the combustion process. An analysis of representative publications in the topic cluster shows that its research mainly includes the exploration of the science and technology of fuel combustion, as well as thermodynamic and chemical kinetic studies related to combustion. The research of TC629 mainly revolves around crude oil and its ancillary products such as asphaltene, oil sands, etc., and the highly cited articles are mainly review papers that discuss some traditional fossil fuel technologies.



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.1.2 Keyphrase clouds and highly cited publications under the topic cluster TC165 for Carbon Emission Reduction Technology sub-field, 2018–2021

Keyphrases word cloud for TC 87, prominence percentile: 98.26

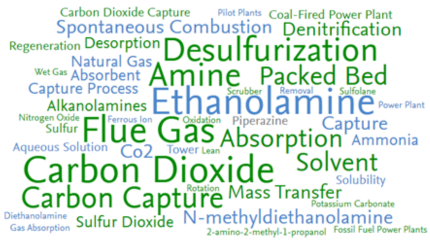


Publication	Citations
Chemicals from lignin: An interplay of lignocellulose fractionation, depolymerisation, and upgrading. Schutyser, W., Renders, T., Van Den Bosch, S. and 3 more (2018) Chemical Society Reviews, 47 (3), pp. 852-908. View in Scopus	1,002
Bright Side of Lignin Depolymerization: Toward New Platform Chemicals. Sun, Z., Fridrich, B., De Santi, A. and 2 more (2018) Chemical Reviews, 118 (2), pp. 614-678. View in Scopus	854
A comprehensive review on the pyrolysis of lignocellulosic biomass. Dhyani, V., Bhaskar, T. (2018) Renewable Energy, 129, pp. 695-716. View in Scopus	581
A review on hydrothermal liquefaction of biomass. Gollakota, A.R.K., Kishore, N., Gu, S. (2018) Renewable and Sustainable Energy Reviews, 81, pp. 1378-1392. View in Scopus	474
A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. Wang, T., Zhai, Y., Zhu, Y. and 2 more (2018) Renewable and Sustainable Energy Reviews, 90, pp. 223-247. View in Scopus	446

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.1.3 Keyphrase clouds and highly cited publications under the topic cluster TC87 for Carbon Emission Reduction Technology sub-field, 2018–2021

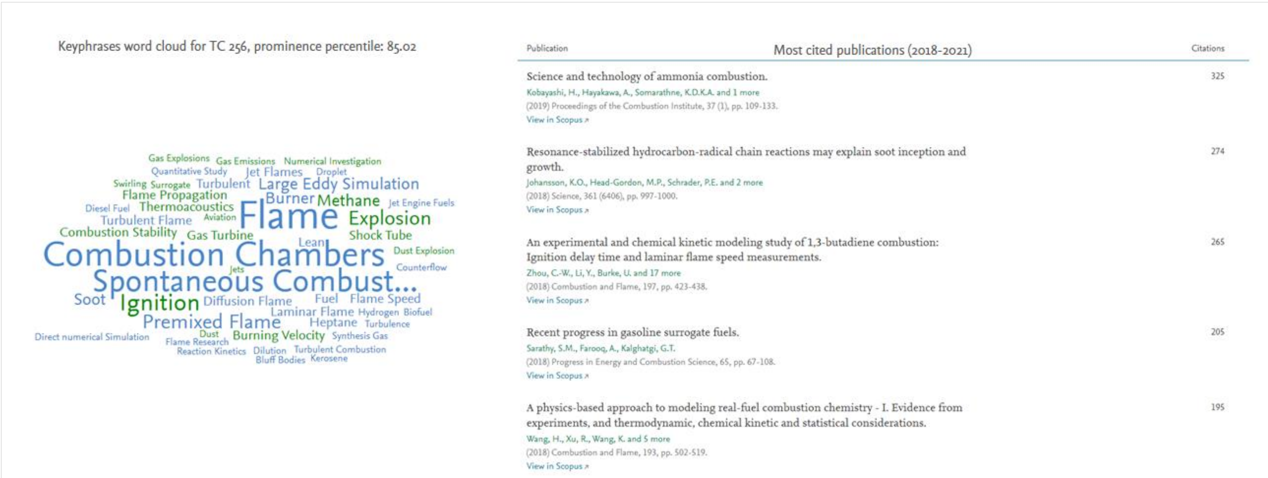
Keyphrases word cloud for TC 950, prominence percentile: 56.52



Publication	Citations
Carbon capture and storage (CCS): The way forward. Bui, M., Adjiman, C.S., Bardow, A. and 27 more (2018) Energy and Environmental Science, 11 (5), pp. 1062-1176. View in Scopus	1,256
Simultaneous absorption of SO2 and NO from flue gas using ultrasound/Fe2+/heat coactivated persulfate system. Liu, Y., Liu, Z., Wang, Y. and 4 more (2018) Journal of Hazardous Materials, 342, pp. 326-334. View in Scopus	147
Outlook of carbon capture technology and challenges. Wilberforce, T., Baroutaji, A., Soudan, B. and 2 more (2019) Science of the Total Environment, 657, pp. 56-72. View in Scopus	141
Assessment of hydrogen direct reduction for fossil-free steelmaking. Vogl, V., Åhman, M., Nilsson, L.J. (2018) Journal of Cleaner Production, 203, pp. 736-745. View in Scopus	134
Simultaneous removal of NO and SO2 using vacuum ultraviolet light (VUV)/heat/peroxymonosulfate (PMS). Liu, Y., Wang, Y., Wang, Q. and 2 more (2018) Chemosphere, 190, pp. 431-441. View in Scopus	117

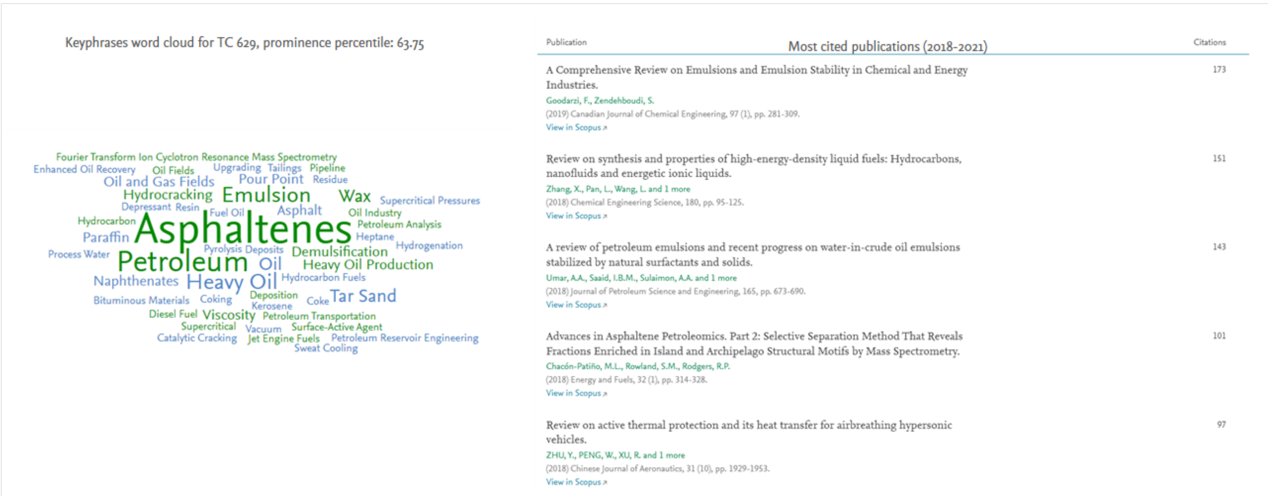
Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.1.4 Keyphrase clouds and highly cited publications under the topic cluster TC950 for Carbon Emission Reduction Technology sub-field, 2018–2021



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.1.5 Keyphrase clouds and highly cited publications under the topic cluster TC256 for Carbon Emission Reduction Technology sub-field, 2018–2021



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.1.6 Keyphrase clouds and highly cited publications under the topic cluster TC629 for Carbon Emission Reduction Technology sub-field, 2018–2021

2. Top 10 topic clusters by prominence

The prominence of the topic cluster reflects the popularity, development momentum, or degree of attention gained by a topic cluster among researchers around the world. Topics or topic clusters with high prominence or momentum are usually likely to be well-funded. Comparing the most prominent and most published topic clusters for a research field may help identify possible extensions of research directions that can be explored for the sub-field.

Inherent features of the TC			ASJC distribution of the TC											
TC ID	Top 5 most published keyphrases	Prominence Percentile	Agricultural and Biological ..	Biochemistry, Genetics and M..	Chemical Engineering	Chemistry	Economics, Econometrics and ..	Energy	Engineeri..	Environmental Science	Immunology and Microbiology	Materials Science	Physics and Astronomy	Social Sciences
30	Electrode|Lithium Battery|Carbon|Battery|Electrolyte	99.93			■	■		■	■			■	■	
8	Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst	99.87				■			■			■	■	
7	Catalyst|Catalysis|Conversion|Oxidation|Adsorption	99.46			■	■								
28	Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Networks	99.33						■	■					
81	Energy|Carbon|Renewable Energy|Climate Change|Sustainable Development	99.26					■	■	■	■				■
65	Wastewater Treatment|Waste Water|Sewage|Microorganisms|Bioreactor	98.80						■		■				
68	Concretes|Cement|Compressive Strength|Mechanical Properties|Aggregates	98.33							■			■		
87	Coal|Biomass|Spontaneous Combustion|Pyrolysis|Fuel	98.26			■	■		■						
35	Soil|Nitrogen|Forest|Phosphorus|Soil Water	98.13	■							■				
119	Cellulose|Lignin|Hydrolysis|Biomass|Pretreatment	97.53		■	■	■		■		■	■	■		

The prominence value is out of 100, and the higher the score, the higher the degree of momentum. For example, a prominence score of 99.9 indicates that the momentum of the topic cluster is more than 99.9% of the topic clusters globally.

Figure 4.3.2.1.7 Top 10 topic clusters by prominence of Carbon Emission Reduction Technology sub-field, 2010 –2021 (See Appendix VII for details of the color identification and full names of the 27 disciplines of ASJC)

As shown in Figure 4.3.2.1.7, all of the top 10 topic clusters by prominence in the sub-field of Carbon Emission Reduction Technology have a prominence score greater than 97, indicating that these topic clusters are more prominent than 97% of the topic clusters globally. However, the degree of overlap between these prominent topic clusters and the top 10 most published topic clusters is low, indicating that there is still room for the sub-field of Carbon Emission Reduction Technology to extend to these hot research directions.

(B) Renewable Energy sub-field

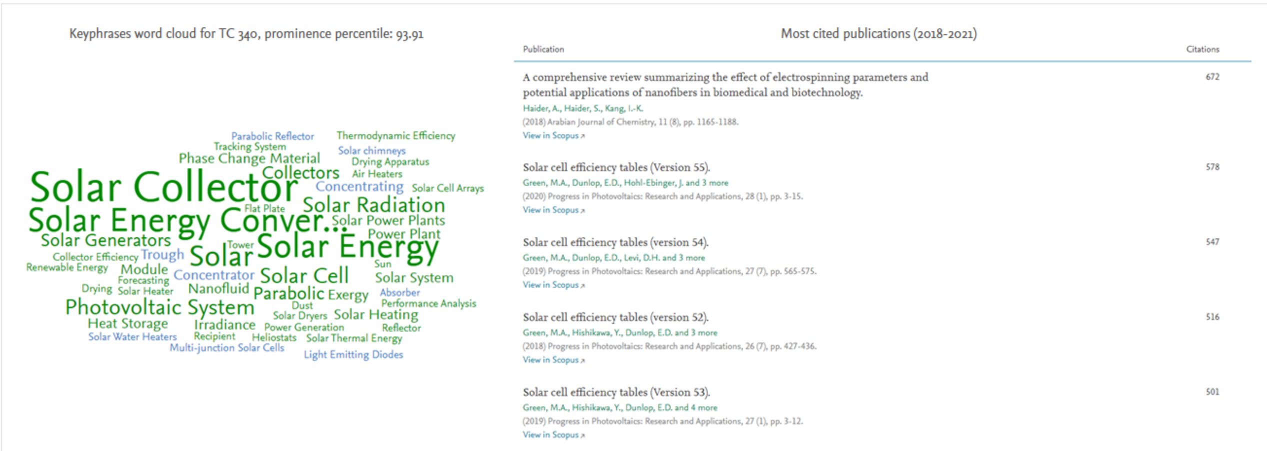
1. Top 10 topics by share of publications in the sub-field

Inherent features of the TC			ASJC distribution of the TC									
TC ID	Top 5 most published keyphrases	Share of publications	Agricultural and Biologi..	Biochemistry, Genetics a..	Chemical Engineering	Chemistry	Energy	Engineering	Environmental Science	Immunology and Microb..	Materials Science	Physics and Astronomy
340	Solar|Solar Energy|Solar Collector|Solar Energy Conversion|Solar Radiation	66%					■	■				
490	Biomass|Biofuel|Bioenergy|Forest|Forestry	54%	■				■		■			
423	Wind Turbine|Wind Power|Wind|Turbine|Rotor	52%					■	■				
517	Microalgae|Biomass|Algae|Biofuel|Lipid	39%	■	■	■		■		■	■		
97	Silicon|Solar Cell|Thin Films|Crystalline Material|Nanocrystal	39%						■			■	■
165	Engine|Fuel|Diesel Engine|Emissions|Spontaneous Combustion	32%			■		■	■	■			
28	Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Networks	32%					■	■				
87	Coal|Biomass|Spontaneous Combustion|Pyrolysis|Fuel	31%			■	■	■					
177	Nanocrystal|Quantum Dot|Thin Films|Semiconductor|Energy Gap	26%				■		■			■	■
8	Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst	23%				■		■			■	■

Figure 4.3.2.2.1 The top 10 topic clusters with the highest proportion of sub-field articles in Renewable Energy, 2010–2021 (see Appendix VII for details of the color identification and full name of the 27 disciplines of ASJC)

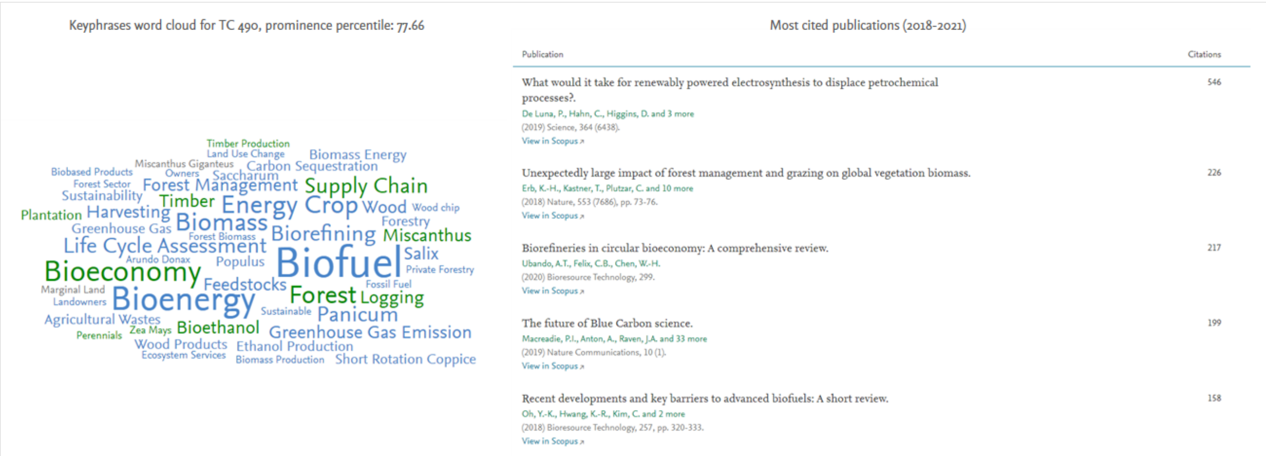
As shown in Figure 4.3.2.2.1, the Renewable Energy sub-field covers more interdisciplinary subjects than the Carbon Emission Reduction Technology sub-field. For Renewable Energy, its top 10 topic clusters cover a range of subject areas, including agricultural and biological sciences, chemical engineering, chemistry, energy, engineering, environmental science, materials science and physics. The collection of articles in TC340, the topic cluster with the largest share (66%), is mainly at the intersection of energy and engineering.

Figure 4.3.2.2.2–6 presents keyphrase cloud maps and highly cited publications for the top 5 topic clusters of Renewable Energy sub-field. As can be seen in the figures, the research of TC340 mainly focuses on the collection, conversion and utilization of solar energy. An analysis of its highly cited publications shows that the topic cluster mainly focuses on photovoltaic cells, and most of the highly cited articles are review papers discussing the efficiency of solar conversion. Topic cluster TC490 focuses on exploring the feasibility and potential barriers to the substitution of traditional energy sources by biofuels and biomass energy. Research into TC423 revolves around the collection, conversion and utilization of wind energy. The highly cited publications show that because these studies are closely related to machinery such as wind turbines and asynchronous generators, the topic cluster has a relatively deep cross-fusion with engineering. TC517 is about alternative and renewable energy research, including the study of microalgae. Microalgae are used in sewage treatment through photosynthesis to enrich sewage with oxygen. It can not only be used to produce biofuels, but can also be used as functional foods, animal feed and in medicines. Similar to TC340, TC97 is also related to solar energy, but unlike TC340, this topic cluster focuses on crystalline silicon solar cells, and its prominence is relatively low (76.62), indicating that relevant research has declining popularity among researchers.



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

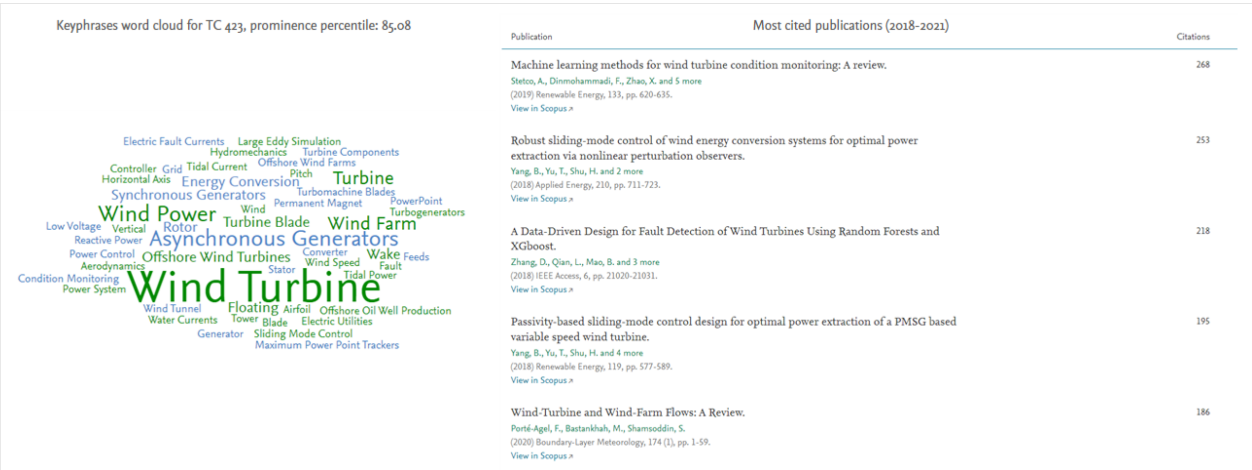
Figure 4.3.2.2.2 Keyphrase clouds and highly cited papers under the topic cluster TC340 of Renewable Energy sub-field, 2018–2021



Publication	Citations
What would it take for renewably powered electrosynthesis to displace petrochemical processes?. De Luna, P., Hahn, C., Higgins, D. and 3 more (2019) Science, 364 (6438). View in Scopus ↗	546
Unexpectedly large impact of forest management and grazing on global vegetation biomass. Erb, K.-H., Kastner, T., Plutzar, C. and 10 more (2018) Nature, 553 (7686), pp. 73-76. View in Scopus ↗	226
Biorefineries in circular bioeconomy: A comprehensive review. Ubando, A.T., Felix, C.B., Chen, W.-H. (2020) Bioresource Technology, 299. View in Scopus ↗	217
The future of Blue Carbon science. Macreadie, P.I., Anton, A., Raven, J.A. and 33 more (2019) Nature Communications, 10 (1). View in Scopus ↗	199
Recent developments and key barriers to advanced biofuels: A short review. Oh, Y.-K., Hwang, K.-R., Kim, C. and 2 more (2018) Bioresource Technology, 257, pp. 320-333. View in Scopus ↗	158

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

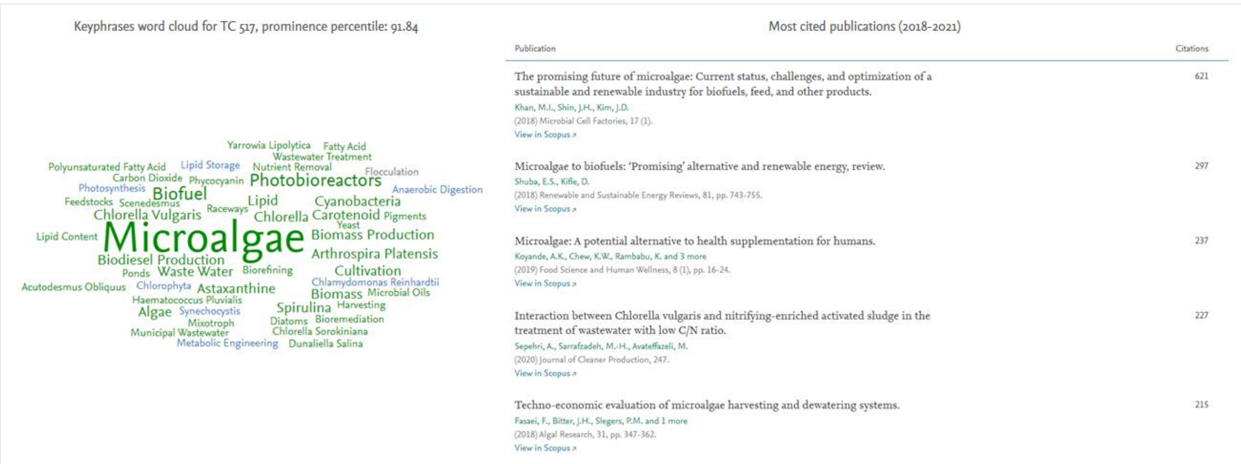
Figure 4.3.2.2.3 Keyphrase clouds and highly cited papers under the topic cluster TC490 of Renewable Energy sub-field, 2018–2021



Publication	Citations
Machine learning methods for wind turbine condition monitoring: A review. Stetco, A., Dinmohammadi, F., Zhao, X. and 5 more (2019) Renewable Energy, 133, pp. 620-635. View in Scopus ↗	268
Robust sliding-mode control of wind energy conversion systems for optimal power extraction via nonlinear perturbation observers. Yang, B., Yu, T., Shu, H. and 2 more (2018) Applied Energy, 210, pp. 711-723. View in Scopus ↗	253
A Data-Driven Design for Fault Detection of Wind Turbines Using Random Forests and XGboost. Zhang, D., Qian, L., Mao, B. and 3 more (2018) IEEE Access, 6, pp. 21020-21031. View in Scopus ↗	218
Passivity-based sliding-mode control design for optimal power extraction of a PMSG based variable speed wind turbine. Yang, B., Yu, T., Shu, H. and 4 more (2018) Renewable Energy, 119, pp. 577-589. View in Scopus ↗	195
Wind-Turbine and Wind-Farm Flows: A Review. Porté-Agel, F., Bastankhah, M., Shamsoddin, S. (2020) Boundary-Layer Meteorology, 174 (1), pp. 1-59. View in Scopus ↗	186

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.2.4 Keyphrase clouds and highly cited papers under the topic cluster TC423 of Renewable Energy sub-field, 2018–2021

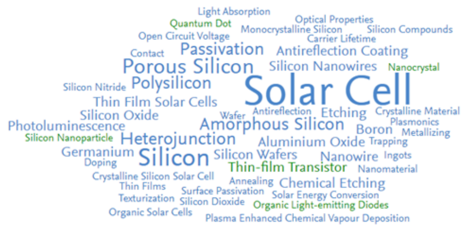


Publication	Citations
The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Khan, M.I., Shin, J.H., Kim, J.D. (2018) Microbial Cell Factories, 17 (1). View in Scopus ↗	621
Microalgae to biofuels: 'Promising' alternative and renewable energy, review. Shuba, E.S., Kifle, D. (2018) Renewable and Sustainable Energy Reviews, 81, pp. 743-755. View in Scopus ↗	297
Microalgae: A potential alternative to health supplementation for humans. Koyande, A.K., Chew, K.W., Rambabu, K. and 3 more (2019) Food Science and Human Wellness, 8 (1), pp. 16-24. View in Scopus ↗	237
Interaction between Chlorella vulgaris and nitrifying-enriched activated sludge in the treatment of wastewater with low C/N ratio. Sepehri, A., Sarrafzadeh, M.-H., Avateffazeli, M. (2020) Journal of Cleaner Production, 247. View in Scopus ↗	227
Techno-economic evaluation of microalgae harvesting and dewatering systems. Fasaei, F., Bitter, J.H., Slegers, P.M. and 1 more (2018) Algal Research, 31, pp. 347-362. View in Scopus ↗	215

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.2.5 Keyphrase clouds and highly cited papers under the topic cluster TC517 of Renewable Energy sub-field, 2018–2021

Keyphrases word cloud for TC 97, prominence percentile: 76.72



Publication	Citations
Most cited publications (2018-2021)	
Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells. Haase, F., Hollemann, C., Schäfer, S. and 5 more (2018) Solar Energy Materials and Solar Cells, 186, pp. 184-193. View in Scopus ↗	304
Oxide textures - A Mini-Atlas. Haggerty, S.E. (2019) Oxide Minerals: Petrologic and Magnetic Significance, pp. 129-220. View in Scopus ↗	203
Passivating Contacts for Crystalline Silicon Solar Cells: From Concepts and Materials to Prospects. Melskens, J., Van De Loo, B.W.H., Macco, B. and 3 more (2018) IEEE Journal of Photovoltaics, 8 (2), pp. 373-388. View in Scopus ↗	195
Clinical cancer nanomedicine. Wolfram, J., Ferrari, M. (2019) Nano Today, 25, pp. 85-98. View in Scopus ↗	182
Biocompatible and biodegradable inorganic nanostructures for nanomedicine: Silicon and black phosphorus. Qiu, M., Singh, A., Wang, D. and 4 more (2019) Nano Today, 25, pp. 135-155. View in Scopus ↗	180

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.2.6 Keyphrase clouds and highly cited papers under the topic cluster TC97 of Renewable Energy sub-field, 2018–2021

2. Top 10 topic clusters by prominence

Inherent features of the TC			ASJC distribution of the TC									
TC ID	Top 5 most published keyphrases	Prominence Percentile	Chemical Engineering	Chemistry	Earth and Planetary Scie..	Economics, Econometric..	Energy	Engineering	Environmental Science	Materials Science	Physics and Astronomy	Social Sciences
30	Electrode|Lithium Battery|Carbon|Battery|Electrolyte	99.93	■	■			■	■		■	■	
8	Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst	99.87		■				■		■	■	
22	Graphite|Carbon Nanotube|Carbon|Composite|Nanomaterial	99.73		■				■		■	■	
47	Nanocrystal|Plasmonics|Plasmon|Nanomaterial|Gold	99.53		■				■		■	■	
7	Catalyst|Catalysis|Conversion|Oxidation|Adsorption	99.46	■	■								
28	Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Networks	99.33					■	■				
81	Energy|Carbon|Renewable Energy|Climate Change|Sustainable Development	99.26				■	■	■	■			■
5	Climate Change|Rain|Climate|Climate Models|Precipitation	99.13			■				■			
65	Wastewater Treatment|Waste Water|Sewage|Microorganisms|Bioreactor	98.80					■		■			
61	Polymers|Organic|Solar Cell|Organic Light-emitting Diodes|Conversion Efficiency	98.60		■				■		■	■	

The prominence value is out of 100, and the higher the score, the higher the degree of momentum. For example, a prominence score of 99.9 indicates that the momentum of the topic cluster is more than 99.9% of the topic clusters globally.

Figure 4.3.2.2.7 Top 10 topic clusters by prominence of Renewable Energy sub-field, 2010 –2021 (See Appendix VII for details of the color identification and full names of the 27 disciplines of ASJC)

As Figure 4.3.2.2.7 shows, eight of the top ten most prominent topic clusters for the Renewable Energy sub-field have a prominence score of greater than 99, meaning that these topic clusters are followed more than 99% of the topic clusters globally, indicating that the field is active or of high momentum. However, the percentage of Renewable Energy-related articles in these topic clusters is low, usually below 20%, suggesting that the sub-field touches on some of the hot research areas, but could continue to expand in these directions.

(C) Energy Storage and Hydrogen Energy sub-field

1. Top 10 topics by share of publications in the sub-field

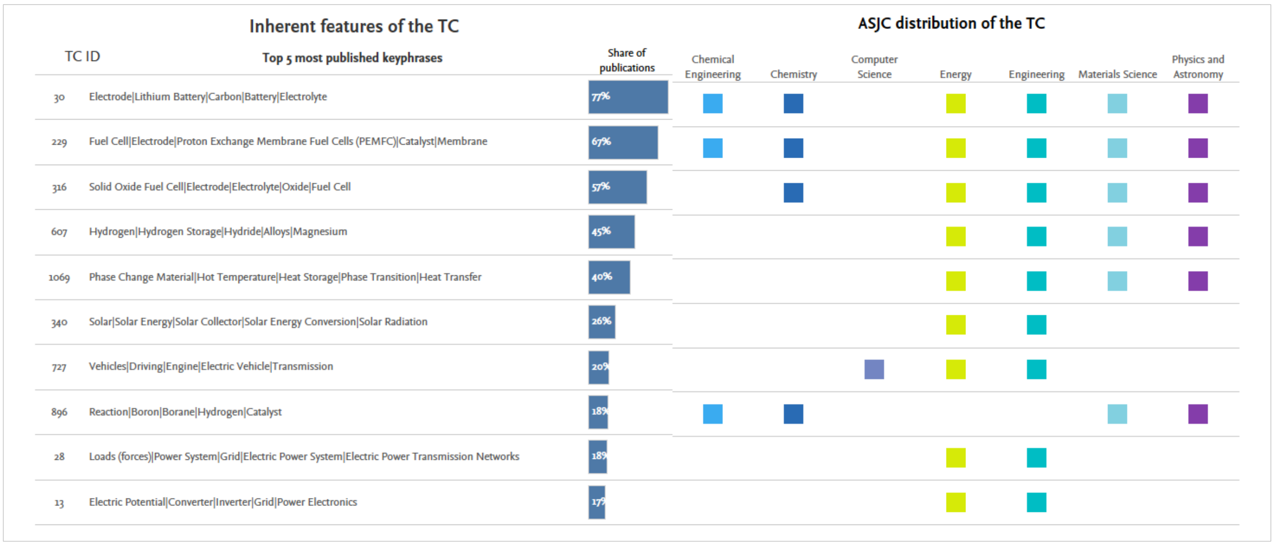
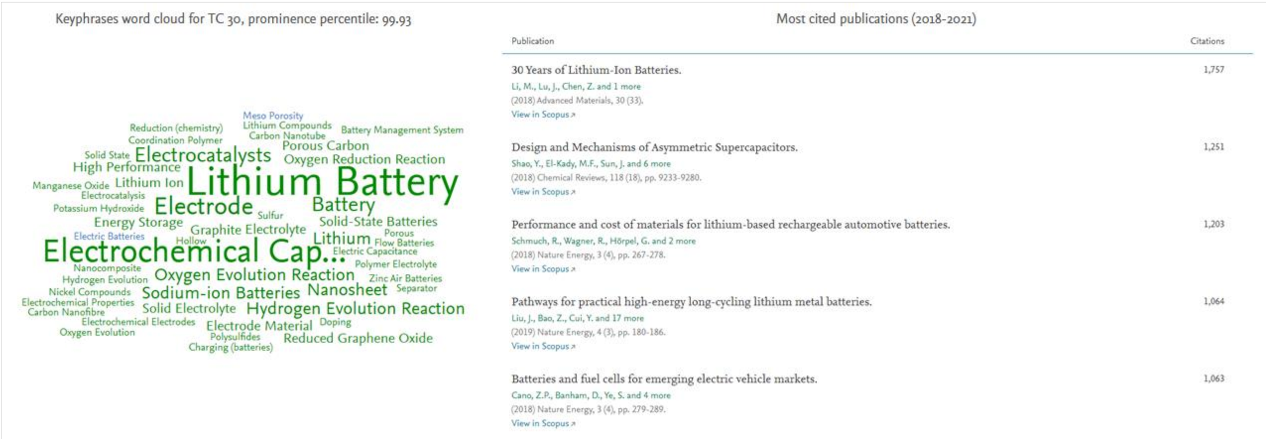


Figure 4.3.2.3.1 The top 10 topic clusters with the highest proportion of sub-field articles in Energy Storage and Hydrogen Energy, 2010–2021 (see Appendix VII for details of the color identification and full name of the 27 disciplines of ASJC)

Figure 4.3.2.3.1 shows that the sub-field of Energy Storage and Hydrogen Energy also intersects with a wide range of subject areas, covering chemical engineering, chemistry, energy, engineering, materials science and physics. Among the top 10 topic clusters, TC30 is the topic cluster with the largest share of publications in the sub-field (77%), and it is composed of publications covering multiple subject areas including chemistry, chemical engineering, energy, engineering, materials science and physics.

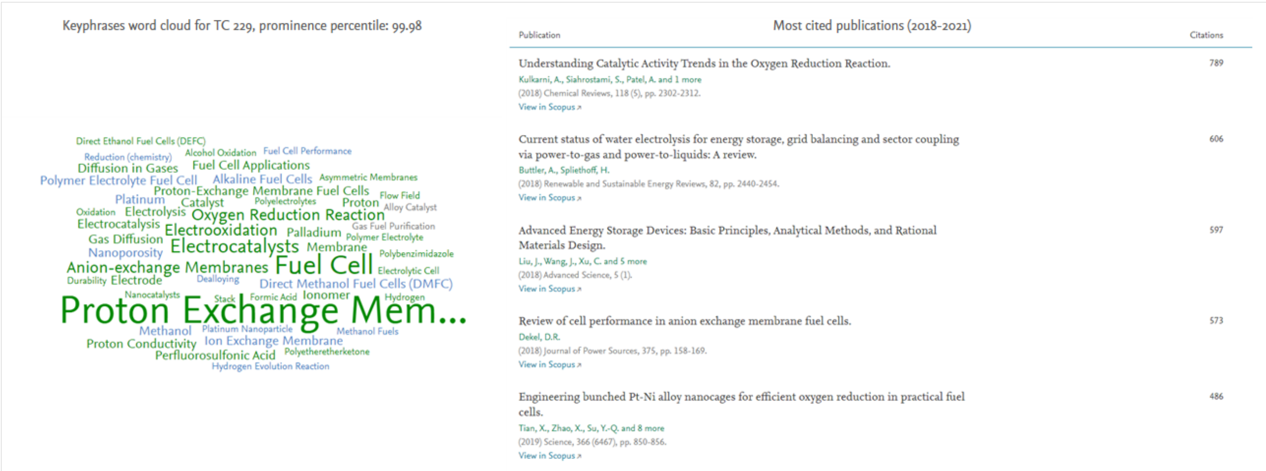
It can be seen from the keyphrase cloud of the top five topic clusters of Energy Storage and Hydrogen Energy (Figure 4.3.2.3.2–6) and the highly cited publications of each topic cluster that the research content of the TC30 topic cluster mainly revolves around lithium-ion batteries and supercapacitor technology, including the exploration of the properties and performances of electrolytes and electrode materials used in these energy storage devices. The research content of TC229 is mainly about the preparation of electrocatalysts for oxygen reduction reactions and related technologies in fuel cell development, and proton exchange membrane fuel cells are one of its concerns. TC316 focuses on solid oxide fuel cell-related technologies; while TC607 focuses on the preparation and storage of hydrogen. TC1069 is mainly about research on thermal energy storage, especially geothermal energy storage and phase change energy storage materials.



Publication	Citations
30 Years of Lithium-Ion Batteries. Li, M., Lu, J., Chen, Z. and 1 more (2018) Advanced Materials, 30 (33). View in Scopus	1,757
Design and Mechanisms of Asymmetric Supercapacitors. Shao, Y., El-Kady, M.F., Sun, J. and 6 more (2018) Chemical Reviews, 118 (18), pp. 9233-9280. View in Scopus	1,251
Performance and cost of materials for lithium-based rechargeable automotive batteries. Schmuch, R., Wagner, R., Hörpel, G. and 2 more (2018) Nature Energy, 3 (4), pp. 267-278. View in Scopus	1,203
Pathways for practical high-energy long-cycling lithium metal batteries. Liu, J., Bao, Z., Cui, Y. and 17 more (2019) Nature Energy, 4 (3), pp. 180-186. View in Scopus	1,064
Batteries and fuel cells for emerging electric vehicle markets. Cano, Z.P., Banham, D., Ye, S. and 4 more (2018) Nature Energy, 3 (4), pp. 279-289. View in Scopus	1,063

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

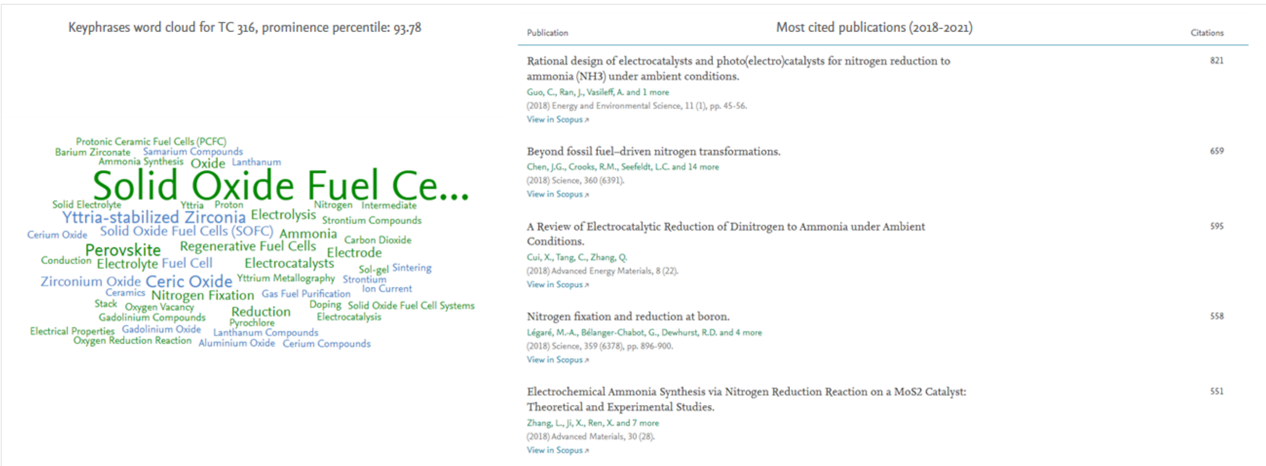
Figure 4.3.2.3.2 Keyphrase cloud and highly cited papers under the topic cluster TC30 of Energy Storage and Hydrogen Energy sub-field, 2018–2021



Publication	Citations
Understanding Catalytic Activity Trends in the Oxygen Reduction Reaction. Kulkarni, A., Siahrostami, S., Patel, A. and 1 more (2018) Chemical Reviews, 118 (5), pp. 2302-2312. View in Scopus	789
Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Buttler, A., Spliethoff, H. (2018) Renewable and Sustainable Energy Reviews, 82, pp. 2440-2454. View in Scopus	606
Advanced Energy Storage Devices: Basic Principles, Analytical Methods, and Rational Materials Design. Liu, J., Wang, J., Xu, C. and 5 more (2018) Advanced Science, 5 (1). View in Scopus	597
Review of cell performance in anion exchange membrane fuel cells. Dekel, D.R. (2018) Journal of Power Sources, 375, pp. 158-169. View in Scopus	573
Engineering bunched Pt-Ni alloy nanocages for efficient oxygen reduction in practical fuel cells. Tian, X., Zhao, X., Su, Y.-Q. and 8 more (2019) Science, 366 (6467), pp. 850-856. View in Scopus	486

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.3.3 Keyphrase cloud and highly cited papers under the topic cluster TC229 of Energy Storage and Hydrogen Energy sub-field, 2018–2021



Publication	Citations
Rational design of electrocatalysts and photo(electro)catalysts for nitrogen reduction to ammonia (NH_3) under ambient conditions. Guo, C., Ran, J., Vasileff, A. and 1 more (2018) Energy and Environmental Science, 11 (1), pp. 45-56. View in Scopus	821
Beyond fossil fuel–driven nitrogen transformations. Chen, J.G., Crooks, R.M., Seefeldt, L.C. and 14 more (2018) Science, 360 (6391). View in Scopus	659
A Review of Electrocatalytic Reduction of Dinitrogen to Ammonia under Ambient Conditions. Cui, X., Tang, C., Zhang, Q. (2018) Advanced Energy Materials, 8 (22). View in Scopus	595
Nitrogen fixation and reduction at boron. Légaré, M.-A., Bélanger-Chabot, G., Dewhurst, R.D. and 4 more (2018) Science, 359 (6378), pp. 896-900. View in Scopus	558
Electrochemical Ammonia Synthesis via Nitrogen Reduction Reaction on a MoS_2 Catalyst: Theoretical and Experimental Studies. Zhang, L., Ji, X., Ren, X. and 7 more (2018) Advanced Materials, 30 (28). View in Scopus	551

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.3.4 Keyphrase cloud and highly cited papers under the topic cluster TC316 of Energy Storage and Hydrogen Energy sub-field, 2018–2021

Keyphrases word cloud for TC 607, prominence percentile: 67.56

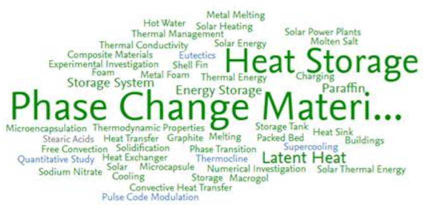
Most cited publications (2018-2021)

Publication	Citations
Hydrogen energy, economy and storage: Review and recommendation. Abe, J.O., Popoola, A.P.I., Ajenifuja, E. and 1 more (2019) International Journal of Hydrogen Energy, 44 (29), pp. 15072-15086. View in Scopus ↗	750
Hydrogen production, storage, transportation and key challenges with applications: A review. Abdalla, A.M., Hossain, S., Nisfindy, O.B. and 3 more (2018) Energy Conversion and Management, 165, pp. 602-627. View in Scopus ↗	448
Large-scale storage of hydrogen. Andersson, J., Grönkvist, S. (2019) International Journal of Hydrogen Energy, 44 (23), pp. 11901-11919. View in Scopus ↗	272
Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives. Bellosta von Colbe, J., Ares, J.-R., Barale, J. and 24 more (2019) International Journal of Hydrogen Energy, 44 (15), pp. 7780-7808. View in Scopus ↗	267
Magnesium based materials for hydrogen based energy storage: Past, present and future. Yartys, V.A., Lototskyy, M.V., Akiba, E. and 32 more (2019) International Journal of Hydrogen Energy, 44 (15), pp. 7809-7859. View in Scopus ↗	261

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.3.5 Keyphrase cloud and highly cited papers under the topic cluster TC607 of Energy Storage and Hydrogen Energy sub-field, 2018–2021

Keyphrases word cloud for TC 1069, prominence percentile: 86.76



Most cited publications (2018-2021)

Publication	Citations
Recent developments in phase change materials for energy storage applications: A review. Nazir, H., Batool, M., Bolivar Osorio, F.J. and 6 more (2019) International Journal of Heat and Mass Transfer, 129, pp. 491-523. View in Scopus ↗	515
An overview of thermal energy storage systems. Alva, G., Lin, Y., Fang, G. (2018) Energy, 144, pp. 341-378. View in Scopus ↗	417
A comprehensive review of thermal energy storage. Sarbu, I., Sebarchievici, C. (2018) Sustainability (Switzerland), 10 (1). View in Scopus ↗	371
Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage. Lin, Y., Jia, Y., Alva, G. and 1 more (2018) Renewable and Sustainable Energy Reviews, 82, pp. 2730-2742. View in Scopus ↗	346
Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage–A review. Umair, M.M., Zhang, Y., Iqbal, K. and 2 more (2019) Applied Energy, 235, pp. 846-873. View in Scopus ↗	321

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.3.6 Keyphrase cloud and highly cited papers under the topic cluster TC1069 of Energy Storage and Hydrogen Energy sub-field, 2018–2021

2. Top 10 topic clusters by prominence

<table>
<tr><th colspan="3">Inherent features of the TC</th><th colspan="9">ASJC distribution of the TC</th></tr>
<tr><th>TC ID</th><th>Top 5 most published keyphrases</th><th>Prominence Percentile</th><th>Chemical Engineering</th><th>Chemistry</th><th>Economics, Econometrics a..</th><th>Energy</th><th>Engineering</th><th>Environmental Science</th><th>Materials Science</th><th>Physics and Astronomy</th><th>Social Sciences</th></tr>
<tr><td>30</td><td>Electrode|Lithium Battery|Carbon|Battery|Electrolyte</td><td>99.93</td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td></td><td>■</td><td>■</td><td></td></tr>
<tr><td>8</td><td>Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst</td><td>99.87</td><td></td><td>■</td><td></td><td></td><td>■</td><td></td><td>■</td><td>■</td><td></td></tr>
<tr><td>22</td><td>Graphite|Carbon Nanotube|Carbon|Composite|Nanomaterial</td><td>99.73</td><td></td><td>■</td><td></td><td></td><td>■</td><td></td><td>■</td><td>■</td><td></td></tr>
<tr><td>47</td><td>Nanocrystal|Plasmonics|Plasmon|Nanomaterial|Gold</td><td>99.53</td><td></td><td>■</td><td></td><td></td><td>■</td><td></td><td>■</td><td>■</td><td></td></tr>
<tr><td>7</td><td>Catalyst|Catalysis|Conversion|Oxidation|Adsorption</td><td>99.46</td><td>■</td><td>■</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>28</td><td>Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Networks</td><td>99.33</td><td></td><td></td><td></td><td>■</td><td>■</td><td></td><td></td><td></td><td></td></tr>
<tr><td>81</td><td>Energy|Carbon|Renewable Energy|Climate Change|Sustainable Development</td><td>99.26</td><td></td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td></td><td></td><td>■</td></tr>
<tr><td>71</td><td>Coordination Polymer|Ligands|Crystal Structure|Hydrogen Bond|Crystal</td><td>99.20</td><td></td><td>■</td><td></td><td></td><td></td><td></td><td>■</td><td>■</td><td></td></tr>
<tr><td>65</td><td>Wastewater Treatment|Waste Water|Sewage|Microorganisms|Bioreactor</td><td>98.80</td><td></td><td></td><td></td><td>■</td><td></td><td>■</td><td></td><td></td><td></td></tr>
<tr><td>61</td><td>Polymers|Organic|Solar Cell|Organic Light-emitting Diodes|Conversion Efficiency</td><td>98.60</td><td></td><td>■</td><td></td><td></td><td>■</td><td></td><td>■</td><td>■</td><td></td></tr>
</table>

The prominence value is out of 100, and the higher the score, the higher the degree of momentum. For example, a prominence score of 99.9 indicates that the momentum of the topic cluster is more than 99.9% of the topic clusters globally.

Figure 4.3.2.3.7 Top 10 topic clusters by prominence of Energy Storage and Hydrogen Energy sub-field, 2010–2021 (See Appendix VII for details of the color identification and full names of the 27 disciplines of ASJC)

Similar to the Renewable Energy sub-field, the Energy Storage and Hydrogen Energy sub-field also has eight of its top 10 most prominent topic clusters with a prominence score higher than 99 (see Figure 4.3.2.3.7), which means that these topic clusters are more prominent than 99% of the topic clusters worldwide, indicating that the sub-field also has a fairly high degree of popularity or momentum. Similarly, the overlap between these high-prominence topic clusters and the topic clusters with the highest proportion of documents published in this sub-field is not high. But note that the topic cluster TC30, which has the highest proportion of publications in the sub-field of Energy Storage and Hydrogen Energy, is also the most prominent, indicating that research in this sub-field has contribute a lot to the globally hot research area of lithium batteries.

(D) Energy Efficiency Management sub-field

1. Top 10 topics by share of publications in the sub-field

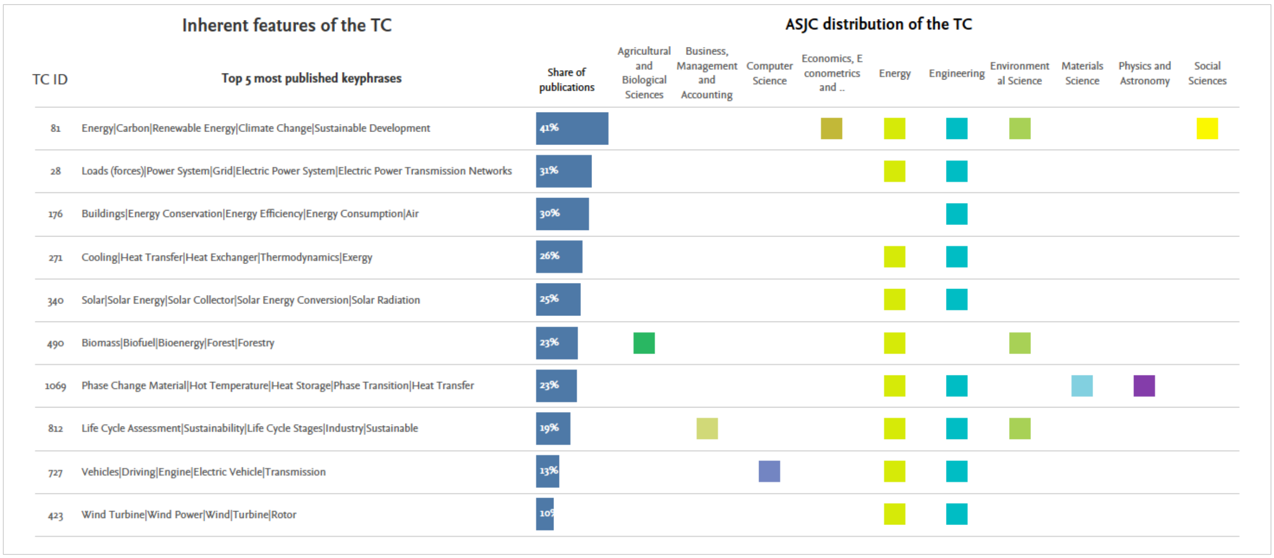
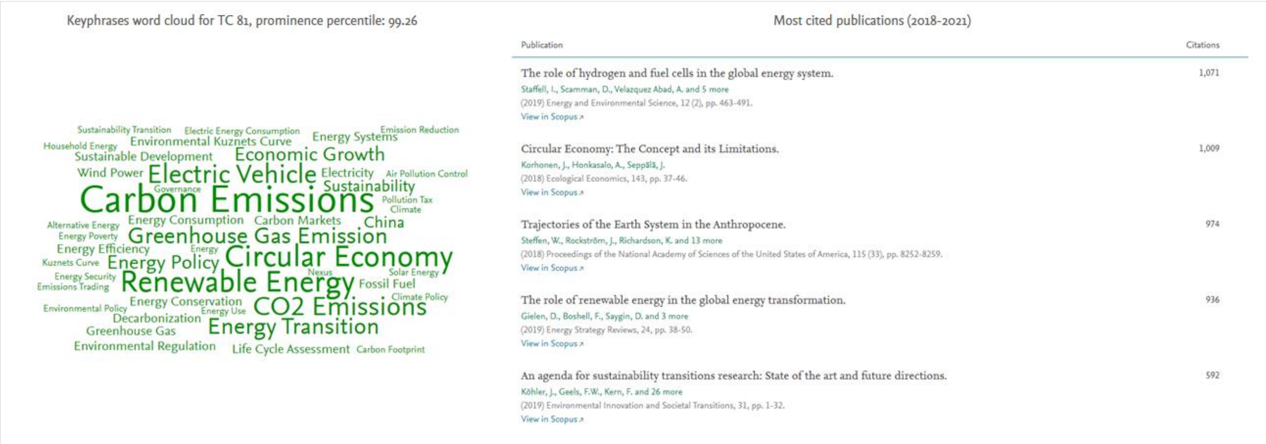


Figure 4.3.2.4.1 The top 10 topic clusters with the highest proportion of sub-field articles in Energy Efficiency Management, 2010 –2021 (see Appendix VII for details of the color identification and full name of the 27 disciplines of ASJC)

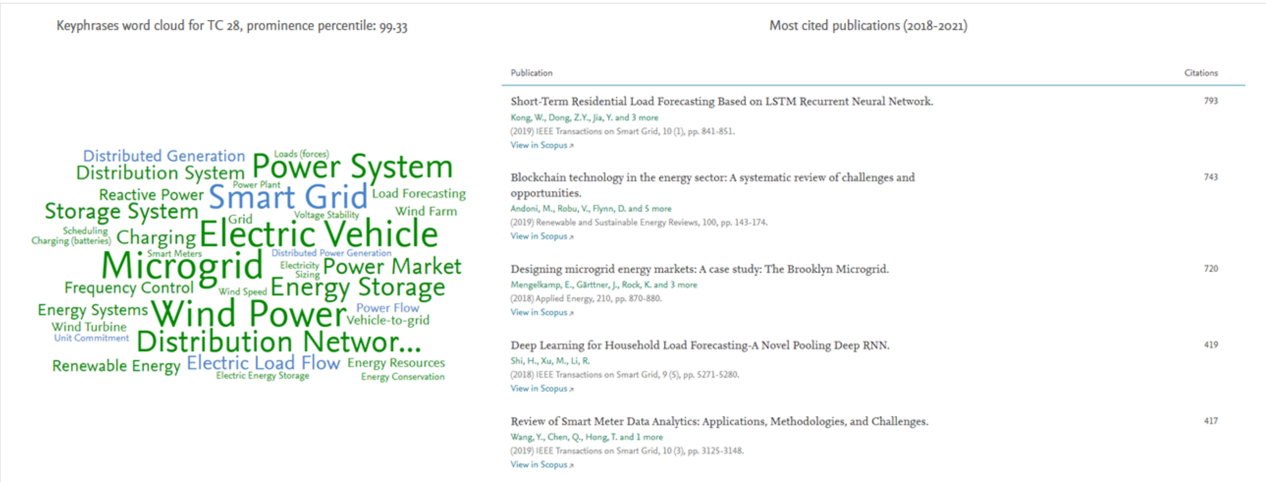
Figure 4.3.2.4.1 shows that the interdisciplinary nature of the sub-field of Energy Efficiency Management is somewhat different from that of the other three sub-fields. While its top 10 topic clusters by share of publications in the sub-field are mainly in energy and engineering subjects, there is also some intersection with social sciences, economics, computer science and environmental sciences as well. TC81, the topic cluster with the largest proportion of publications (41%) in Energy Efficiency Management, covers energy, engineering, environmental science, social science, econometrics and finance.

Figure 4.3.2.4.2–6 presents keyphrase word clouds of the top five topic clusters published in the sub-field of Energy Efficiency Management and their highly cited papers. As can be seen from the figures, the research content of TC81 mainly focuses on the relationship between carbon emissions and economic development, focusing on the impact of energy technologies on the global energy system and energy transition, including circular economy and some related energy policies. The research content of TC28 mainly focuses on microgrid technologies, using distributed methods, AI technologies and other ways to coordinate and control, to improve efficiency, and thus, realize the optimization of microgrids. TC176 focuses on energy efficiency improvement for buildings, including how to build sustainable, environmentally friendly buildings and indoor systems such as air conditioning. Due to the COVID-19 pandemic, the number of citations for such studies has risen in recent years. The research of TC271 revolves around energy efficiency improvements in heating and heating systems, along with relevant waste heat recovery and utilization technologies. TC340 is a topic cluster that intersects with renewable energy research. The topic cluster mainly focuses on the collection, conversion and utilization of solar energy. An analysis of representative articles of the topic cluster shows that the topic cluster mainly focuses on photovoltaic cells, and most of its highly cited publications are review articles discussing solar energy efficiency.



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

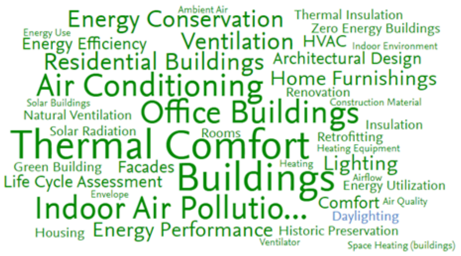
Figure 4.3.2.4.2 Keyphrase cloud and highly cited papers under the topic cluster TC81 of Energy Efficiency Management sub-field, 2018–2021



Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.4.3 Keyphrase cloud and highly cited papers under the topic cluster TC28 of Energy Efficiency Management sub-field, 2018–2021

Keyphrases word cloud for TC 176, prominence percentile: 96.39



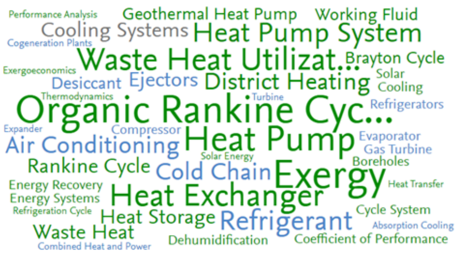
Most cited publications (2018-2021)

Publication	Citations
Respiratory virus shedding in exhaled breath and efficacy of face masks. Leung, N.H.L., Chu, D.K.W., Shiu, E.Y.C. and 11 more (2020) Nature Medicine, 26 (5), pp. 676-680. View in Scopus ↗	1,028
Airborne transmission of SARS-CoV-2: The world should face the reality. Morawska, L., Cao, J. (2020) Environment International, 139. View in Scopus ↗	763
Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. Bourouiba, L. (2020) JAMA - Journal of the American Medical Association, 323 (18), pp. 1837-1838. View in Scopus ↗	663
A review of data-driven building energy consumption prediction studies. Amasyali, K., El-Gohary, N.M. (2018) Renewable and Sustainable Energy Reviews, 81, pp. 1192-1205. View in Scopus ↗	628
Aerosol and Surface Distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in Hospital Wards, Wuhan, China, 2020. Guo, Z.-D., Wang, Z.-Y., Zhang, S.-F. and 16 more (2020) Emerging Infectious Diseases, 26 (7), pp. 1586-1591. View in Scopus ↗	551

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.4.4 Keyphrase cloud and highly cited papers under the topic cluster TC176 of Energy Efficiency Management sub-field, 2018–2021

Keyphrases word cloud for TC 271, prominence percentile: 94.72



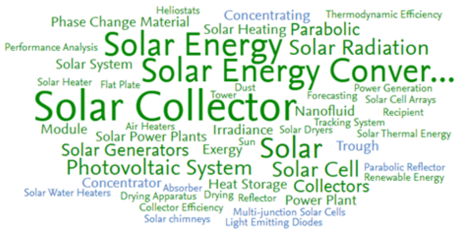
Most cited publications (2018-2021)

Publication	Citations
Exergy: Energy, Environment and Sustainable Development. Dincer, I., Rosen, M.A. (2020) Exergy: Energy, Environment and Sustainable Development, pp. 1-703. View in Scopus ↗	924
Waste heat recovery technologies and applications. Jouhara, H., Khordehgah, N., Almahmoud, S. and 3 more (2018) Thermal Science and Engineering Progress, 6, pp. 268-289. View in Scopus ↗	328
The status of 4th generation district heating: Research and results. Lund, H., Østergaard, P.A., Chang, M. and 11 more (2018) Energy, 164, pp. 147-159. View in Scopus ↗	250
Adsorption-based atmospheric water harvesting device for arid climates. Kim, H., Rao, S.R., Kapustin, E.A. and 4 more (2018) Nature Communications, 9 (1). View in Scopus ↗	234
A global review of enhanced geothermal system (EGS). Lu, S.-M. (2018) Renewable and Sustainable Energy Reviews, 81, pp. 2902-2921. View in Scopus ↗	229

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.4.5 Keyphrase cloud and highly cited papers under the topic cluster TC271 of Energy Efficiency Management sub-field, 2018–2021

Keyphrases word cloud for TC 340, prominence percentile: 93.91



Most cited publications (2018-2021)

Publication	Citations
A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and biotechnology. Haider, A., Haider, S., Kang, I.-K. (2018) Arabian Journal of Chemistry, 11 (8), pp. 1165-1188. View in Scopus ↗	672
Solar cell efficiency tables (Version 55). Green, M.A., Dunlop, E.D., Hohl-Ebinger, J. and 3 more (2020) Progress in Photovoltaics: Research and Applications, 28 (1), pp. 3-15. View in Scopus ↗	578
Solar cell efficiency tables (version 54). Green, M.A., Dunlop, E.D., Levi, D.H. and 3 more (2019) Progress in Photovoltaics: Research and Applications, 27 (7), pp. 565-575. View in Scopus ↗	547
Solar cell efficiency tables (version 52). Green, M.A., Hishikawa, Y., Dunlop, E.D. and 3 more (2018) Progress in Photovoltaics: Research and Applications, 26 (7), pp. 427-436. View in Scopus ↗	516
Solar cell efficiency tables (Version 53). Green, M.A., Hishikawa, Y., Dunlop, E.D. and 4 more (2019) Progress in Photovoltaics: Research and Applications, 27 (1), pp. 3-12. View in Scopus ↗	501

Keyphrase size represents relevance; green means the number of relevant articles has been increasing in recent years; blue means the number of relevant articles has been decreasing in recent years.

Figure 4.3.2.4.6 Keyphrase cloud and highly cited papers under the topic cluster TC340 of Energy Efficiency Management sub-field, 2018–2021

2. Top 10 topic clusters by prominence

Inherent features of the TC			ASJC distribution of the TC												
TC ID	Top 5 most published keyphrases	Prominence Percentile	Agricultural and Biological ..	Business, Management and Ac c..	Chemical Engineering	Chemistry	Computer Science	Decision Sciences	Economics, Econometrics and ..	Energy	Engineer..	Environmental Science	Materials Science	Physics and Astronomy	Social Sciences
30	Electrode|Lithium Battery|Carbon|Battery|Electrolyte	99.93			■	■				■	■		■	■	
8	Titanium Dioxide|Zinc Oxide|Photocatalytic Activity|Nanocrystal|Photocatalyst	99.87				■					■		■	■	
28	Loads (forces)|Power System|Grid|Electric Power System|Electric Power Transmission Networks	99.33								■	■				
81	Energy|Carbon|Renewable Energy|Climate Change|Sustainable Development	99.26							■	■	■	■			■
65	Wastewater Treatment|Waste Water|Sewage|Microorganisms|Bioreactor	98.80								■		■			
13	Electric Potential|Converter|Inverter|Grid|Power Electronics	98.46								■	■				
68	Concretes|Cement|Compressive Strength|Mechanical Properties|Aggregates	98.33									■		■		
87	Coal|Biomass|Spontaneous Combustion|Pyrolysis|Fuel	98.26			■	■				■					
35	Soil|Nitrogen|Forest|Phosphorus|Soil Water	98.13	■									■			
146	Supply Chain|Industry|Suppliers|Manufacturing|Supply Chain Management	98.06		■			■	■			■				

The prominence value is out of 100, and the higher the score, the higher the degree of momentum. For example, a prominence score of 99.9 indicates that the momentum of the topic cluster is more than 99.9% of the topic clusters globally.

Figure 4.3.2.4.7 Top 10 topic clusters by prominence in the Energy Efficiency Management sub-field, 2010–2021 (See Appendix VII for details of the color identification and full names of the 27 subjects of ASJC)

Four of the top 10 topic clusters by prominence for the sub-field of Energy Efficiency Management have a prominence score greater than 99, and all topic clusters have a prominence score greater than 98 (see Figure 4.3.2.4.7), indicating high level of research activity for this field. However, only one of these high-prominence topic clusters (TC81) has more than 10% of publications in energy efficiency management. Given the high level of attention paid to research on energy technology, carbon emissions and economic development, and energy policy, these are also directions that researchers in the sub-field of Energy Efficiency Management can continue to pursue. The popularity of these research directions also suggests that energy research, especially energy efficiency management research, involves many fields of science and technology, economy and policy, and thus, requires the cooperation of all sectors of society.

Conclusion

The importance of the Energy Science discipline

– In the past 10 years, global research output in the field of Energy Science is increasing and its output as a proportion of overall output across all disciplines is also increasing, which means the subject area is actively and rapidly developing. At the global level, the countries involved in Energy Science research are widely distributed and participate in frequent international cooperation and exchanges. Total worldwide funding for Energy Science has reached nearly $105 billion. Energy Science has become a research field with wide participation and interest from countries around the world.

– In contrast to other disciplines, Energy Science research has very strong disciplinary integration, and its knowledge sources and knowledge output involve a wide variety of disciplines, including closely related disciplines such as materials science, engineering, chemistry, physics, and environmental science disciplines, but also biology, computer science, social sciences, economics and finance and business management. In general, areas with rich interdisciplinary cross-connections are likely to result in more important research findings.

– In terms of its disciplinary characteristics, Energy Science is mainly at the applied technology stage, which will directly promote the scientific and technological progress of the industry. The rapid growth of Energy Science and the intersection with "Net Zero" research directly reflect the importance of Energy Science for China and the world to achieve the goal of "double carbon," and that the main contents of the four sub-fields of Energy Science are directly related to the transformation of the energy structure worldwide.

– As of the research focuses and disciplinary extensions, the field of Energy Science involves some of the hottest research topics globally, as represented by the many high-prominence topic clusters included by the discipline. Researchers in the field can extend their research to further explore these hot research areas by enhancing interdisciplinary collaboration.

Advantages and challenges for China in the field of Energy Science

– The discipline of Energy Science in China has played a leading role in the world in terms of the output volume of publications, and it has also made great contributions to the research output of the Asia–Pacific region and the world. Research activity in the field of Energy Science in China is significantly higher than in other benchmarking countries, and it is increasing. The scholarly impact of China's Energy Science research has been growing in the past 11 years, highlighting the simultaneous development of "quality" and "quantity"; at the same time, the scholarly impact of key benchmarking countries has declined to varying degrees. Notably, China has the highest scholarly impact of Energy Science publications resulting from international collaboration, ahead of other benchmarking countries.

– However, there is still a gap between China and the United Kingdom and the United States in the scholarly impact of publications and the average output per researcher. In the past decade, although the scholarly impact of China's Energy Science research has grown, catching up with Germany and Japan, there is still a certain gap in its FWCI with the UK and the US. The patent uptake of China's Energy Science publications is still relatively low in terms of average number of patent citations per publication or proportion of publications cited by patents, though the total number of patent citations is high, given its large volume of publications. Moreover, the scholarly impact of academic–corporate collaborative publications by Chinese enterprises also lags that of enterprises in Europe, the US and Japan.

Future development of the field of Energy Science

– The analysis of the performance of various forms of research cooperation in the field of Energy Science shows that increasing the proportion of research in the form of international collaboration will effectively promote the overall scholarly impact of the discipline. In view of the fact that the scholarly impact of China's internationally-collaborative Energy Science research ranks among the top in the world, and the proportion of China's international collaboration is to be further increased, encouraging large-scale international collaboration will help enhance China's overall scholarly impact in Energy Science research.

– The scholarly impact of academic–corporate collaboration in Energy Science research of Chinese enterprises is lower than that of enterprises in Europe, the US and Japan. Enterprises involved in the field of Energy Science in the US, UK, Germany, Japan and other developed countries are involved not only in the traditional energy field, but also in some high-tech fields of machinery, manufacturing, and engineering, which embodies the transformation of the world's energy structure in the industrial community. At present, a number of Chinese enterprises have proposed solutions for energy reform, and enterprises engaged in Energy Science research in China are also expanding beyond the traditional energy field.

– In terms of research funding, countries around the world have heavily invested in Energy Science research, and the National Natural Science Foundation of China has funded the world's largest number of publications in the field. More funding will undoubtedly be of great help to researchers of the field in carrying out basic research and pioneering exploration, and for talent development and capacity building.

– Using Elsevier's characteristic indicator "topic clusters," through the study of the intersection of Energy Science publications and publications under the topic clusters, it is possible to reveal the potential development direction and extension of Energy Science research. When combined with the prominence of the topic clusters, keyphrase cloud maps and highly cited publications, topic cluster analysis can help suggest some globally hot research areas for researchers and research managers in Energy Science to explore new fronts.

In summary, this report conducts a preliminary study of the research landscape of Energy Science through the construction and analysis of the discipline of Energy Science and its four sub-fields, in the hope to provide strategic advice and guidance for science and technology policy-making at the macro level. The report inevitably has certain limitations: for example, big data iterative algorithms for discipline definition, even if supplemented by manual interpretation by domain experts to control machine learning results, are still unable to achieve 100% accuracy, meaning the definition of the Energy Science discipline is still to be improved. This report focuses on the analysis of disciplinary development and its changing trends from the perspective of scientific bibliometrics; it lacks systematic analysis of patent data. In addition, this report would benefit from further expert interpretation and judgment regarding research content of the field; adding more systematic data and supplementing it with more expert guidance and interpretation will improve the analysis in the future.

Major events for the project

November 2020: A working group was established

May 4, 2021: A work agreement was signed

June 4, 2021: The analysis part of the project officially started

Due to the wide range of technologies and disciplines involved and included in the energy field and the large amount of publication data, it is necessary to limit the analytical scope of the report to the rapid development and change within the past decade. After in-depth discussion with the expert team of Xiamen University and Tan Kah Kee Innovation Laboratory, it was proposed to divide the Energy Science discipline analyzed in this report into the four sub-fields of Carbon Emission Reduction Technology, Renewable Energy, Energy Storage and Hydrogen Energy, and Energy Efficiency Management. On this basis, the expert team defined and described the meaning of each sub-field and provided nearly a thousand search keywords and a golden publication set. They also discussed and manually screened the many iterations of query search results from the Elsevier research analytics team.

November 2, 2021: Interim review of the 2021 edition of the analytical report was held

After several months of cooperation and efforts by the expert team at Xiamen University and Tan Kah Kee Innovation Laboratory and the research analytics team at Elsevier, the first draft of the 2021 edition of the report was completed and a review meeting was held. The internal expert team participating in the project had in-depth discussions on issues including interpretation of interdisciplinarity, collection of funding data statistics, screening of academic–corporate collaboration data, multi-angle analysis of corporate research contributions, analysis of the intersection with Net-Zero Carbon Emission research, definition and naming of research topics, keyword searches, and data differentiation for publications by different units of the Chinese Academy of Sciences. The expert team agreed that pure data interpretation based on the iteration results from running the algorithm has limitations, and more manual screening and interpretation are needed.

January 13, 2022: Final review of the 2021 edition of the analytical report was held

Elsevier further revised and refined the content of the analytical report based on the mid-term review feedback, and the final review of the 2021 version of the report was held. The internal team of experts involved in the project provided guidance on the overall interpretation of the report, the verification of the rationality and validity of the analytical results, and the classification of disciplines and research areas. The experts generally believed that the report needed to be further improved, and thus, suggested adding some supplementary analysis, including the analysis of applied research and technology, national collaboration trends, nuclear energy and traditional fuel technology such as coal power, and more, so as to show multiple angles and multiple views of the development of the Energy Science. After that, Elsevier made the corresponding data and analysis changes and updated the report based on the recommendations.

May 25, 2022: Internal review of the 2022 edition of the analytical report was held

After listening to Elsevier's briefing of the analytical results, the team of experts involved in the project pointed out that in addition to an analysis of overall publications in the field, high-impact publications, such as the top 10% highly cited publications in the field, should also be analyzed and discussed. Elsevier responded to the recommendation by adding relevant data and analysis.

June 1, 2022: Mid-term review of the 2022 edition of the analytical report was held

In order to further ensure the quality of the report, the review expert group composed of internal experts from Xiamen University, Tan Kah Kee Innovation Laboratory, Collaborative Innovation Center of Chemistry for Energy Materials, and editors and publishers of Elsevier made suggestions on issues such as report positioning, methodology and metrics descriptions, keyword classification, funding and patent data analysis, and data segmentation for units under the Chinese Academy of Sciences. In addition, the expert group also suggested adding analysis on the changes in the number of researchers and their productivity, the impact of the COVID-19 pandemic, and the research impact of enterprises to enrich the analytical angles of the report and enhance the interpretation. Considering time constraints and data limitations, Elsevier took some expert suggestions and updated the analysis and the report correspondingly.

June 23, 2022: Final review of the 2022 edition of the analytical report was held

To further improve the quality of the report, the project team invited seven well-known experts, including five academicians of the Chinese Academy of Sciences, to participate in the final review of the report. Experts offered their review and suggestions, covering the classification of keywords and research fields (basic research vs. applied research), patent analysis (particularly in nuclear energy and coal power), funding data collection (especially research funding by leading enterprises in the energy industry), identification of original research and parent patents, and data differentiation for different units of the Chinese Academy of Sciences. Most of these issues had been raised at previous review meetings, but were not fully resolvable due to data limitations and time constraints. It is hoped that these issues will be better addressed in the new edition of the report and that the report can be improved in future.

Postscript

The production of the “Landscape and Development Trends of Energy Research” report lasted one and a half years from conception and preparation to completion and release. From the perspective of bibliometric analysis, the report conducts a comprehensive and meticulous analysis of the development status and trends of new technologies and disciplines in the energy field globally, with a view to providing objective reference data for relevant decision-making departments, scientific research institutions and industries, and to pushing forward establishing Energy Science as a first-level discipline in China. The analysis of the report is mainly based on the Scopus abstract and citation database owned by Elsevier, with machine learning, big data analysis and other tools, supplemented by manual identification methods. It was conducted by Xiamen University, Tan Kah Kee Innovation Laboratory, Collaborative Innovation Center of Chemistry for Energy Materials expert team and Elsevier's analysis team, leveraging their respective strengths. The team had in-depth discussions of the methods used for classification of the research fields, keyword extraction, and statistical benchmark setting. Issues such as statistical caliber, interdisciplinarity and extensibility of fund and patent data were discussed in more than 10 meetings, and after great effort from relevant experts and analysts, this report was finally produced.

To further ensure the quality of the report, Xiamen University and Tan Kah Kee Innovation Laboratory invited more than 10 academicians and well-known experts from all research areas in the energy field to guide the internal review and external review. The experts offered many valuable opinions and suggestions on the classification of keywords and research fields (basic research vs. applied research), funding data collection (especially research funding by enterprises), patent data analysis, data refinement for different units of the Chinese Academy of Sciences, identification of articles and patents of originality and influence, and analysis of per capita research output. Unfortunately, some of the recommendations have not yet been implemented because the machine learning classification method has yet to be improved at this stage, and because of the limitations of the analytical software and databases, as well as time constraints. We look forward to collecting feedback and suggestions from all parties after the release of the report, and then further strengthening the depth and breadth of the analysis by optimizing data processing techniques, improving data collection methods, and promoting database interoperability. We expect to provide more comprehensive and detailed reference data and information for administrators, academic researchers and enterprise researchers in the energy sector.

Finally, we would like to express sincere thanks to the experts, analysts and all those who participated in the production of this report or offered guidance and suggestions.

Appendix I

Keyword Sequence

The method of keyword sequence was used to collect and classify articles of each sub-field in the Scopus database: Elsevier's research analytical team takes the keywords and journals provided by experts as the initial input data, and expands and restricts the keywords and their fields and associated fields through high-frequency iteration and keyword co-occurrence in the entire Scopus database, so that the arrangement and combination of keyword sequences are highly correlated with the content of the discipline. The team quantitatively limit the accuracy and scope of the anthology through the accuracy index and recall index of the keyword sequence. To summarize, the keyword sequence is formed from objective data supplemented by manual identification by experts in the research field. The keyword sequence will be located in the title, abstract and keywords of each scientific research article (including index keywords and author keywords) to form a collection of scientific research articles for each sub-disciplinary.

Carbon Emission Reduction Technology sub-field

query : (TITLE-ABS-KEY((({Coal} OR {fossil fuel} OR {fossil fuels} OR {coalbed methane} OR {lignite} OR {low-carbon fuel} OR {low-carbon fuels} OR {fossil energies} OR {fossil energy}) AND ({combustion} OR {flame} OR {flames} OR {pyrolysis} OR {ignition} OR {oxidation} OR {burning} OR {gasification} OR {IGCC} OR {Integrated Gasification Combined Cycle} OR {liquefaction} OR {polygeneration} OR {methanol conversion} OR {conversion of methanol} OR {methanol production} OR {methanation} OR {production of methanol} OR {methanogenesis} OR {chemical looping combustion} OR {Chemical-Looping Combustion} OR {coking} OR {coal hydrogenation} OR {coal utilization} OR {coal utilisation} OR {utilization of coal} OR {utilisation of coal} OR {thermogravimetric} OR {thermochemistry} OR {flammability} OR {furnaces} OR {furnace} OR {thermal load} OR {fischer-tropsch} OR {fischer tropsch})) OR (({Coal} OR {coalbed methane} OR {lignite} OR {fossil energies} OR {fossil energy}) AND ({fuel} OR {fuels})) OR (({crude oil} OR {Crude Petroleum} OR {asphalt} OR {asphaltenes} OR {asphaltene} OR {gasoline} OR {diesel fuels} OR {diesel fuel} OR {oil shale} OR {oil sands} OR {oil sand} OR {heavy oil} OR {residual fuel} OR {residual fuels} OR {petroleum gas} OR {petroleum gases} OR {petrochemicals} OR {petrochemical} OR {petroleum coke} OR {heavy resids} OR {heavy resid} OR {paraffin} OR {paraffins} OR {alkane} OR {alkanes} OR {light olefin} OR {light olefins} OR {butane} OR {butanes} OR {petroleum reservoir} OR {petroleum reservoirs} OR {biofuel} OR {biofuels} OR {biodiesel} OR {renewable biomass resources} OR {renewable biomass resource}) AND ({flames} OR {flame} OR {combustion} OR {pyrolysis} OR {ignition} OR {oxidation} OR {burner} OR {burners} OR {burning} OR {distillation} OR {gasification} OR {calcination} OR {coking} OR {refining} OR {refinery} OR {refineries} OR {aqueous-phase reforming} OR {aqueous phase reforming} OR {hydrogen production} OR {hydrodesulfurization} OR {hydrocarbons exploration} OR {hydrocarbon exploration} OR {hydrocarbons generation} OR {hydrocarbon generation} OR {hydrocarbons reforming} OR {hydrocarbon reforming} OR {dehydrogenation} OR {oxydehydrogenation} OR {hydroisomerization} OR {hydrogenation} OR {Catalytic Cracking} OR {Cracking (chemical)} OR {hydrocracking} OR {Thermal cracking} OR {catalyst deactivation} OR {thermal effects} OR {thermal effect} OR {octane number} OR {energy utilization} OR {energy utilisation} OR {fischer-tropsch} OR {fischer tropsch} OR {Calorimetry} OR {Calorimetries})) OR (({crude oil} OR {Crude Petroleum} OR {asphalt} OR {asphaltenes} OR {asphaltene} OR {gasoline} OR {oil shale} OR {oil sands} OR {oil sand} OR {heavy oil} OR {petroleum gas} OR {petroleum gases} OR {petrochemicals} OR {petrochemical} OR {petroleum coke} OR {heavy resids} OR {heavy resid} OR {paraffin} OR {paraffins} OR {alkane} OR {alkanes} OR {light olefin} OR {light olefins} OR {butane} OR {butanes} OR {petroleum reservoir} OR {petroleum reservoirs} OR {biodiesel} OR {renewable biomass resources} OR {renewable biomass resource}) AND ({fuels} OR {fuel})) OR (({natural gas} OR {natural gases} OR {synthesis gas} OR {synthesis gases} OR {syngas} OR {hydrocarbon fuel} OR {hydrocarbon fuels} OR {gas hydrates} OR {gas hydrate} OR {methane} OR {ethane} OR {propane} OR {ethylene} OR {propene} OR {Methanol} OR {Ethanol} OR {alkane} OR {alkanes} OR {olefin} OR {Olefins} OR {Dimethyl ether} OR {Isobutanol} OR {Higher alcohols} OR {Higher alcohol} OR {fusel oil} OR {biodiesel} OR {petroleum gas} OR {petroleum gases}) AND ({Methane steam reforming} OR {steam methane reforming} OR ({Methane to ethylene} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({Methane-to-ethylene} and ({catalyst}or {catalysts} or {catalysis} or {catalytical})) OR ({Methane direct-conversion} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({Methane direct conversion} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR {combustion} OR {gasification} OR {liquefaction} OR {fuel} OR {fuels} OR {flame} OR {flames} OR {pyrolysis} OR {ignition} OR {burner} OR {burning} OR {energy utilization} OR {energy utilisation} OR {fuel consumption} OR {fischer-tropsch} OR {fischer tropsch} OR {Host-guest interaction} OR (({methanol-to-hydrocarbon} or {methanol to hydrocarbon}) and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR (({methanol-to-hydrocarbons} or {methanol to hydrocarbons}) and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({ethanol to methane} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR (({methanol synthesis} or {synthesis of methanol} or {methanol conversion} or {conversion of mthanol} or {coupling of methanol} or {methanol coupling}) and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR (({methane synthesis} or {synthesis of methane} or {methane conversion} or {conversion of methane} or {coupling of methane} or {methane coupling}) and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({methane to methanol} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR {Syngas Conversion} OR {C-h bond functionalization} OR {carbon-hydrogen bond functionalization} OR ({CO conversion} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({conversion of CO} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({carbon monoxide conversion} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR ({conversion of carbon monoxide} and ({catalyst} or {catalysts} or {catalysis} or {catalytical})) OR (({oxidation of CH_4} or {oxidation of methane} or {methane oxidation}) and ({catalyst} or {catalysts} or {catalysis} or {catalytical})))) OR (({Greenhouse gas emissions} OR {global carbon dioxide emissions} OR {global CO_2 emissions} OR {Greenhouse gas emission} OR {global carbon dioxide emission} OR {global CO_2 emission} OR {Greenhouse gases emission} OR {Greenhouse gases emissions} OR {flue gases} OR {flue gas}) AND ({renewable energy resources} OR {solar energy} OR {natural gas} OR {wind power} OR {power generation} OR {energy storage} OR {energy utilisation} OR {energy utilization} OR {fuel consumption} OR {electricity generation} OR {energy efficiency} OR {biofuel} OR {biofuels} OR {fossil fuel} OR {fossil fuels})) OR (({carbon dioxide} OR {co2}) AND ({carbon dioxide capture} OR {CO_2 capture} OR {carbon capture} OR {carbon sequestration} OR {Chemical looping combustion} OR {Chemical-Looping Combustion} OR {Artificial photosynthesis} OR {Mineral carbonation} OR {emission control} OR {Biodiesel Production} OR {Carbonization} OR {power generation} OR {electricity generation} OR {energy storage} OR {energy utilization} OR {fuel consumption} OR {Microalgae biomass production} OR {carbon dioxide hydrogenation} OR {CO_2 hydrogenation} OR {hydrogenation of carbon dioxide} OR {hydrogenation of CO_2} OR {CO_2 hydrogenation} OR {fischer-tropsch} OR {fischer tropsch} OR {electrochemical reduction} OR {electrochemical CO_2 reduction} OR {electrochemical carbon dioxide reduction} OR {electrocatalytic CO_2 reduction} OR {Electrocatalytic reduction} OR {electrocatalytic carbon dioxide reduction} OR {electroreduction} OR {photoreduction} OR {photocatalytic reduction} OR {photocatalytic CO_2 reduction} OR {photocatalytic carbon dioxide reduction} OR ({electrocatalysts} and ({CO_2 reduction} or {carbon dioxide reduction})) OR ({electrocatalyst} and ({CO_2 reduction} or {carbon dioxide reduction})) OR ({photoelectrochemical} and ({CO_2 reduction} or {carbon dioxide reduction})) OR {C-h bond functionalization} OR {carbon-hydrogen bond functionalization} OR {Electrochemical carboxylation} OR {Direct Interspecies Electron Transfer})) OR ({Hydrogen production} and {CO oxidation}) OR ({hydrogenation} and {Fischer Tropsch synthesis}) OR (({Zeolite} or {Zeolites}) and (({Cracking} and ({catalyst} or {Catalytic})) or {Heterogeneous catalysts} or {Heterogeneous catalyst} or {heterogeneous catalysis}))))

Renewable Energy sub-field

query : (TITLE-ABS-KEY(({biomass} AND ({activation energy} OR {biochemistry} OR {bioelectric energy sources} OR {biofuel} OR {biofuels} OR {biogas} OR {coal combustion} OR {combustion} OR {electricity generation} OR {energy conversion} OR {energy efficiency} OR {energy utilization} OR {Energy wood} OR {fuel} OR {fuels} OR {gasification} OR {hydrogen production} OR {pyrolysis} OR {renewable energy resource} OR {renewable energy resources} OR {renewable resource} OR {renewable resources} OR {sustainable development} OR {synthesis gas} OR {thermogravimetric analysis})) OR ({bioethanol} AND ({biochemistry} OR {bioconversion} OR {biogas} OR {energy conservation} OR {energy utilization} OR {fuel} OR {fuels} OR {renewable energy resource} OR {renewable energy resources} OR {renewable resource} OR {sustainable development})) OR {biochemical fuel cells} OR {biochemical fuel cell} OR {Biodiesel} OR {Biodiesels} OR {Biofuel} OR {Biofuels} OR {biomass burning} OR {biomass energy} OR {biomass power} OR {Biomass-fired power} OR {Renewable fuel} OR {Renewable fuels} OR {photovoltaic cell} OR {photovoltaic cells} OR {photovoltaic effect} OR {photovoltaic effects} OR {Photovoltaic power} OR {photovoltaic system} OR {photovoltaic systems} OR {solar cell} OR {solar cells} OR {Solar energy} OR {Solar Energy Conversion} OR {solar heating} OR {solar power generation} OR {solar power plant} OR {solar power plants} OR {Solar thermal energy} OR {solar water heater} OR {Wind energy} OR {wind power} OR {Tidal energy} OR {Tidal Power} OR {Alternative Energy} OR {Bio energy} OR {Bioeconomy} OR {Bio-economy } OR {bioelectric energy sources} OR {Bioenergy} OR {Bio-energy} OR {Biorefineries} OR {Bio-refineries} OR {Biorefinery} OR {Bio-refinery} OR {energy crop} OR {Hybrid energy} OR {Hybrid renewable} OR {Microbial fuel cell} OR {Microbial fuel cells} OR {Renewable Electricity} OR {Renewable Energy} OR {Renewable Energy Resources} OR {Renewable Resource} OR {Renewable Resources} OR {Sustainable energy} OR (bio* AND ({Carbon dioxide fixation} OR {CO_2 fixation} OR {Carbon dioxide utilization} OR {CO_2 utilization} OR {Carbon dioxide utilisation} OR {CO_2 utilisation} OR {carbon dioxide capture} OR {CO_2 capture} OR {carbon capture}))))

Energy Storage and Hydrogen Energy sub-field

query : (TITLE-ABS-KEY(({alloy} OR {alloys} OR {anode} OR {anodes} OR {binder} OR {binders} OR {cathode} OR {cathodes} OR {charging (batteries)} OR {compound} OR {compounds} OR {dielectric material} OR {dielectric materials} OR {electric discharges} OR {electric field} OR {electric fields} OR {electrode} OR {electrodes} OR {electrolyte} OR {electrolytes} OR {energy storage} OR {interface process} OR {interface processes} OR {ions} OR {Ions exchange membrane} OR {SEI film} OR {SEI layer} OR {separator} OR {separators} OR {solid electrolyte interface film} OR {solid electrolyte interface layer} OR {Battery Management Systems} OR {Battery Management System}) AND ({battery} OR {batteries})) OR {photovoltaic cells} OR {photovoltaic cell} OR {Al air battery} OR {Al air batteries} OR {Al O_2 battery} OR {Al O_2 batteries} OR {Al oxygen battery} OR {Al oxygen batteries} OR {Al-air battery} OR {Al-air batteries} OR {alkaline battery} OR {alkaline batteries} OR {Al-O_2 battery} OR {Al-O_2 batteries} OR {Al-oxygen battery} OR {Al-oxygen batteries} OR {Aluminum air battery} OR {Aluminum air batteries} OR {Aluminum oxygen battery} OR {Aluminum oxygen batteries} OR {Aluminum-air battery} OR {Aluminum-air batteries} OR {Aluminum-oxygen battery} OR {Aluminum-oxygen batteries} OR {electric battery} OR {electric batteries} OR {flow battery} OR {flow batteries} OR {K ion battery} OR {K ion batteries} OR {K-ion battery} OR {K-ion batteries} OR {lead battery} OR {lead batteries} OR {lead-battery} OR {lead-batteries} OR {lead acid battery} OR {lead acid batteries} OR {lead-acid battery} OR {lead-acid batteries} OR {li air battery} OR {li air batteries} OR {li ion battery} OR {li ion batteries} OR {Li O_2 battery} OR {Li O_2 batteries} OR {Li oxygen battery} OR {Li oxygen batteries} OR {li-air battery} OR {li-air batteries} OR {li-ion battery} OR {li-ion batteries} OR {Li-O_2 battery} OR {Li-O_2 batteries} OR {Li-oxygen battery} OR {Li-oxygen batteries} OR {lithium battery} OR {lithium batteries} OR {lithium air battery} OR {lithium air batteries} OR {lithium ion battery} OR {lithium ion batteries} OR {Lithium oxygen battery} OR {Lithium oxygen batteries} OR {lithium sulfur battery} OR {lithium sulfur batteries} OR {lithium-air battery} OR {lithium-air batteries} OR {lithium-ion battery} OR {lithium-ion batteries} OR {Lithium-oxygen battery} OR {Lithium-oxygen batteries} OR {lithium-sulfur battery} OR {lithium-sulfur batteries} OR {Manganese air battery} OR {Manganese air batteries} OR {Manganese oxygen battery} OR {Manganese oxygen batteries} OR {Manganese-air battery} OR {Manganese-air batteries} OR {Manganese-oxygen battery} OR {Manganese-oxygen batteries} OR {Mercury battery} OR {Mercury batteries} OR {Mercury oxide battery} OR {Mercury oxide batteries} OR {metal air battery} OR {metal air batteries} OR {metal-air battery} OR {metal-air batteries} OR {Mg air battery} OR {Mg air batteries} OR {Mg O_2 battery} OR {Mg O_2 batteries} OR {Mg oxygen battery} OR {Mg oxygen batteries} OR {Mg-air battery} OR {Mg-air batteries} OR {Mg-O_2 battery} OR {Mg-O_2 batteries} OR {Mg-oxygen battery} OR {Mg-oxygen batteries} OR {Miniature battery} OR {Miniature batteries} OR {Na ion battery} OR {Na ion batteries} OR {Na-ion battery} OR {Na-ion batteries} OR {Ni Cd battery} OR {Ni Cd batteries} OR {Ni-Cd battery} OR {Ni-Cd batteries} OR {Nickel Cadmium battery} OR {Nickel Cadmium batteries} OR {Nickel Metal Hydride battery} OR {Nickel Metal Hydride batteries} OR {Nickel-Cadmium battery} OR {Nickel-Cadmium batteries} OR {nickel-metal hybride battery} OR {nickel-metal hybride batteries} OR {nuclear battery} OR {nuclear batteries} OR {potassium ion battery} OR {potassium ion batteries} OR {Potassium-ion battery} OR {Potassium-ion batteries} OR {primary battery} OR {primary batteries} OR {rechargeable battery} OR {rechargeable batteries} OR {redox battery} OR {redox batteries} OR {secondary battery} OR {secondary batteries} OR {Sodium based battery} OR {Sodium based batteries} OR {sodium ion battery} OR {sodium ion batteries} OR {Sodium sulfur battery} OR {Sodium sulfur batteries} OR {Sodium-based battery} OR {Sodium-based batteries} OR {sodium-ion battery} OR {sodium-ion batteries} OR {Sodium-sulfur battery} OR {Sodium-sulfur batteries} OR {Solid State battery} OR {Solid State batteries} OR {Solid-State battery} OR {Solid-State batteries} OR {Zinc air battery} OR {Zinc air batteries} OR {Zinc oxygen battery} OR {Zinc oxygen batteries} OR {zinc-air battery} OR {zinc-air batteries} OR {zinc-oxygen battery} OR {zinc-oxygen batteries} OR {Zn air battery} OR {Zn air batteries} OR {Zn O_2 battery} OR {Zn O_2 batteries} OR {Zn oxygen battery} OR {Zn oxygen batteries} OR {zn-air battery} OR {zn-air batteries} OR {zn-O_2 battery} OR {zn-O_2 batteries} OR {zn-oxygen battery} OR {zn-oxygen batteries} OR (({Alkaline Water} OR {Ammonia decomposition} OR {Biohydrogen} OR {catalysis} OR {catalysts} OR {catalytical} OR {Electrocatalysis} OR {Electrocatalysts} OR {electrochemistry} OR {Electrolysis} OR {Electrolytic } OR {energy efficiency} OR {Exergy} OR {fuel} OR {fuels} OR {gas producers} OR {Gasification} OR {H_2 evolution} OR {hydrogen evolution} OR {hydrogen storage} OR {hydrogen-storage} OR {hydrolysis} OR {Methane decomposition} OR {Methanol steam} OR {NH_3 decomposition} OR {Photocatalysis} OR {Photocatalysts} OR {Photocatalytic} OR {Photoelectrochemical } OR {Photofermentation} OR {Reforming Reactions} OR {Solar energy} OR {solar power generation} OR {Solar reactor} OR {Solar reactors} OR {Steam Reforming} OR {Water Gas Shift} OR {Water-Gas Shift} OR {Water-Gas-Shift}) AND {hydrogen production}) OR (({Coal storage} OR {dehydrogenation} OR {desorption} OR {electrolysis} OR {energy efficiency} OR {energy storage} OR {energy storages} OR {fossil fuels} OR {fuel cells} OR {fuel storage} OR {gas adsorption} OR {hydride} OR {hydrides} OR {hydrogen fuel} OR {hydrogen fuels} OR {hydrogen production} OR {hydrogenation} OR {Metal borohydride} OR {Metal borohydrides} OR {Metal organic framework} OR {Metal organic frameworks} OR {Metalorganic Framework} OR {Metal-organic framework} OR {Metalorganic Frameworks} OR {Metal-organic frameworks} OR {renewable energy resource} OR {renewable energy resources} OR {solar energy} OR {solar power generation} OR {storage alloy} OR {storage alloys} OR {Underground gas storage} OR {wind power}) AND ({hydrogen storage} or {hydrogen-storage})) OR ({fuel cell} OR {fuel cells} OR {supercapacitor} OR {supercapacitors} OR {double layer capacitor} OR {double layer capacitors} OR {double-layer capacitor} OR {double-layer capacitors} OR {pseudocapacitor} OR {pseudocapacitors} OR {pseudo-capacitor} OR {pseudo-capacitors} OR {electrochemical capacitor} OR {electrochemical capacitors} OR {Volumetric capacitance} OR {Volumetric capacitances} OR {ultracapacitor} OR {ultracapacitors} OR {Volumetric capacity} OR {Volumetric capacities} OR {ultracapacitor} OR {ultracapacitors}) OR (({pumped} OR {pump} OR {pumps } OR {photovoltaic} OR {reversible turbine} OR {reversible turbines} OR {Synchronous Generator} OR {Synchronous Generators} OR {compressed air} OR {compressed-air} OR {compressor} OR {trigeneration} OR {Combined cooling heating and power} OR {cogeneration} OR {Combined heat and power production} OR {gas turbine} OR {gas turbines} OR {wind power} OR {wind turbine} OR {wind turbines} OR {heat storage} OR {Photovoltaic-hydro} OR {Wind-hydro} OR {Fused salts} OR {Fused salt} OR {Molten salts} OR {Molten salt} OR {Molten-salt} OR {Molten-salts} OR {electric power transmission networks} OR {Electric power distribution} OR {electric power systems} OR {electric power system} OR {flywheels} OR {flywheel} OR {power electronics} OR {solar energy} OR {Smart grid}) AND ({energy storage} OR {energy storages})) OR {electric energy storage} OR {cryogenic energy storage} OR {Electrochemical energy storage} OR (({oxygen evolution reaction} OR {hydrogen evolution reaction} OR {H_2 evolution reaction} OR {O_2 evolution reaction} OR {water splitting}) AND ({Photocatalytic} OR {photocatalyst} OR {photocatalysts} OR {electrocatalyst} OR {electrocatalysts} OR {electrocatalysts} OR {electrochemical})))

Energy Efficiency Management sub-field

query : (TITLE-ABS-KEY((({alternative energy} OR {Renewable electricity} OR {Renewable energy} OR {solar energy} OR {Sustainable energy}) AND ({climate change} OR {cost} OR {costs} OR {Electricity consumption} OR {Electrification} OR {Energy consumption} OR {Energy efficiency} OR {Forecasting} OR {Natural gas consumption} OR {Reliability} OR {Resilience} OR {Sustainability} OR {Uncertainty} OR {energy potential})) OR ({energy efficiency} AND ({cost benefit analysis} OR {cost effectiveness} OR {cost reduction} OR {cost-benefit analysis} OR {economic analysis} OR {energy intensity} OR {energy management} OR {energy storage} OR {environmental impact} OR {environmental impacts} OR {heat transfer} OR {life cycle} OR {power generation} OR {renewable resource} OR {renewable resources} OR {sustainable development} OR {heating} OR {solar power} OR {photovoltaic system} OR {economic and social effects})) OR ({energy conservation} AND ({sustainable development} OR {energy management} OR {heating} OR {renewable energy resources} OR {economic analysis} OR {cost benefit analysis} OR {cost effectiveness} OR {cost reduction} OR {cost-benefit analysis} OR {economic and social effects})) OR (({energy utilization} OR {energy utilisation}) AND ({sustainable development} OR {energy management} OR {heating} OR {renewable energy resources} OR {economic analysis} OR {cost benefit analysis} OR {cost effectiveness} OR {cost reduction} OR {cost-benefit analysis} OR {economic and social effects})) OR ({oil price} AND ({alternative energy} OR {energy efficiency} OR {energy management} OR {energy market} OR {energy policy} OR {energy utilisation} OR {energy utilization} OR {gas emissions} OR {sustainable development})) OR ({Energy Economic} OR {Energy Economics}) OR (({alternative energy} OR {Atmospheric pollutant emission} OR {Atmospheric pollutant emissions} OR {Carbon dioxide emission} OR {Carbon dioxide emissions} OR {Carbon emission} OR {Carbon emissions} OR {CO_2 emission} OR {CO_2 emissions} OR {emission control} OR {emission reduction } OR {emission reductions} OR {Energy and environment} OR {Energy system} OR {Energy systems} OR {GHG emission} OR {GHG emissions} OR {Greenhouse gas emission} OR {Greenhouse gas emissions} OR {Greenhouse gases emission} OR {Greenhouse gases emissions} OR {Renewable electricity} OR {Renewable energy} OR {renewable source} OR {renewable sources} OR {Sustainable energy}) AND ({Agent-based modeling} OR {Convergence analysis} OR {Cross-sectional dependence} OR {Decision making} OR {decision theory} OR

{Decision-making} OR {decomposition analysis} OR {Dependency and heterogeneity} OR {Direct and indirect effects} OR {Environmental Kuznets curve} OR {Environmental Kuznets curves} OR {Game theory} OR {General equilibrium} OR {Geographic information systems} OR {Geographical information systems} OR {granger causality} OR {Incentive scheme} OR {Incentive schemes} OR {Index decomposition analysis} OR {Input output analysis} OR {Input-output analysis} OR {Integrated assessment model} OR {Life cycle assessment} OR {Linear programming} OR {Load forecasting} OR {Meta frontier} OR {metafrontier} OR {Meta-frontier} OR {Multiobjective optimization} OR {Multi-objective optimization} OR {Multiregional input-output analysis} OR {Optimal control} OR {Optimal operation} OR {Optimal planning} OR {Optimal scheduling} OR {Optimization algorithm} OR {Panel causality test} OR {Panel cointegration} OR {Panel data} OR {Panel data analysis} OR {Panel threshold model} OR {Polygeneration} OR {Portfolio approach} OR {Robust optimization} OR {scenario analysis} OR {Sensitivity analysis} OR {Stochastic frontier analysis} OR {Stochastic programming} OR {Structural decomposition analysis} OR {System Modelling} OR {Aggregate embodied intensity} OR {Ancillary service} OR {Ancillary services} OR {Building performance simulation} OR {Carbon footprint} OR {Carbon intensity} OR {Carbon market} OR {Carbon price} OR {Carbon productivity} OR {Community energy} OR {Critical infrastructure} OR {Critical infrastructures} OR {Demand response} OR {Demand side management} OR {demand-side management} OR {economic analysis} OR {Economic development} OR {Economic dispatch} OR {Economic growth} OR {Economic growths} OR {electricity price} OR {Embodied emission} OR {Embodied emissions} OR {Emission mitigation} OR {energy policy} OR {environmental tax} OR {environmental taxes} OR {Financial development} OR {Green technology innovation} OR {Green technology innovations} OR {Grid integration} OR {Interconnected infrastructure} OR {Levelized cost} OR {Microgrid} OR {micro-grid} OR {national strategy} OR {Paris Agreement} OR {Peer-to-peer} OR {Policy actor} OR {Policy actors} OR {Policy adoption} OR {Policy cognition} OR {Policy coordination} OR {Policy development} OR {Policy diffusion} OR {Policy effectiveness} OR {Policy evolution} OR {Policy incentive} OR {Policy incentives} OR {Policy innovation} OR {policy maker} OR {policy makers} OR {policy making} OR {Policy recommendation} OR {Policy recommendations} OR {Policy reform} OR {Policy review} OR {policymaker} OR {policymakers} OR {Political connection} OR {Political ideology} OR {Political orientation} OR {Power-to-Gas} OR {Price elasticity} OR {Price Dynamic} OR {price dynamics} OR {trade offs} OR {trade off} OR {trade-offs} OR {trade-off} OR {tradeoffs} OR {tradeoff} OR {Rebound effect} OR {Sector coupling} OR {Smart cities} OR {Smart city} OR {Smart grid} OR {Spatial econometric model} OR {Supply chain} OR {Sustainable cities} OR {Sustainable city} OR {Techno-economic analysis} OR {Technology adoption} OR {Technology legitimacy} OR {Technology transfer} OR {Urban form} OR {Urban planning} OR {Urbanisation} OR {Urbanization} OR {Vehicle-to-grid} OR {Wholesale electricity market} OR {Wholesale electricity markets} OR {Willingness to accept} OR {Willingness to pay} OR {Willingness-to-accept} OR {Willingness-to-pay} OR {Climate policy} OR {Distribution network} OR {Distribution networks} OR {Energy access} OR {Energy analysis} OR {Energy balance} OR {Energy efficient appliance} OR {Energy efficient appliance} OR {Energy efficiency} OR {Energy flexibility} OR {Energy infrastructure} OR {Energy infrastructures} OR {Energy Management} OR {Energy modelling} OR {Energy saving} OR {Energy savings} OR {Energy sharing} OR {Energy sustainability} OR {Energy transition} OR {Energy transitions} OR {Energy-climate-water nexus} OR {Energy-efficient appliance} OR {Energy-saving} OR {Energy-savings} OR {Environment impact} OR {Environment impacts} OR {Environment policy} OR {Environment regulation} OR {Environment regulation} OR {Environment regulations} OR {Environment regulations} OR {Environment tax} OR {Environment taxes} OR {Environmental impact} OR {Environmental impacts} OR {Environmental policy} OR {Environmental regulation} OR {Environmental regulations} OR {Environmental tax} OR {Environmental taxes} OR {Fuel efficiency} OR {Green growth} OR {Low carbon economy} OR {Low carbon energy transition} OR {Low carbon technologies} OR {Low carbon technology} OR {Low-carbon economy} OR {Low-carbon energy transition} OR {Low-carbon technologies} OR {Low-carbon technology} OR {Organic Rankine cycle} OR {pollution monitoring} OR {Technology innovation} OR {Waste heat recovery} OR {waste utilisation} OR {waste utilization} OR {Water energy nexus} OR {Water-energy nexus})) OR ({Building energy demand} OR {Building energy management} OR {Building energy policy} OR {Building energy system} OR {Building energy systems} OR {Building energy transition} OR {Building microgrid operation} OR {Energy efficient building} OR {Energy efficient buildings} OR {Energy saving building} OR {Energy saving buildings} OR {Energy-efficient building} OR {Energy-efficient buildings} OR {Energy-saving building} OR {Energy-saving buildings} OR {Green building} OR {Green buildings} OR {Green communities} OR {Green community} OR {intelligent building} OR {intelligent buildings} OR {Residential net-zero energy building} OR {Zero energy building} OR {Zero energy buildings} OR {Carbon emission trading} OR {Carbon emissions trading} OR {Carbon mitigation policy} OR {Carbon policy} OR {Climate change mitigation} OR {Electricity policy} OR {Emission embodied in trade} OR {Emission reduction policy} OR {Emission tax} OR {Emission taxes} OR {Emission Trading Scheme} OR {Emission Trading Schemes} OR {Emissions embodied in trade} OR {Emissions tax} OR {Emissions taxes} OR {Emissions Trading Scheme} OR {Emissions Trading Schemes} OR {energy justice } OR {energy justices} OR {energy market} OR {energy markets} OR {energy policy} OR {Energy security} OR {Energy tax} OR {Energy taxes} OR {EU decarbonisation} OR {EU decarbonization} OR {power market} OR {power markets} OR {Renewable energy policy} OR {Combined cooling heating and power} OR {Combined heat and power system} OR {Combined heat and power systems} OR {Cooling, heating, and power system} OR {Cooling, heating, and power systems} OR {Decentralized energy systems} OR {Decentralized energy systems} OR {Distributed battery energy storage systems} OR {Distributed energy system} OR {distributed energy systems} OR {Distributed battery energy storage systems} OR {Distributed hydrogen-based multi-energy system} OR {Distributed hydrogen-based multi-energy systems} OR {Electrical energy system} OR {Electrical energy systems} OR {Energy construction adjustment} OR {energy consumption information system} OR {energy consumption information systems} OR {Energy hub} OR {Energy hubs} OR {Energy management control system} OR {Energy management control systems} OR {Energy management system} OR {Energy management systems} OR {Energy storage system} OR {Energy storage systems} OR {Energy system analyses} OR {Energy system analysis} OR {Energy system flexibility} OR {Energy system integration} OR {Energy system integration} OR {Energy system model} OR {Energy system modeling} OR {Energy system optimization} OR {Energy system optimization} OR {Energy system resilience} OR {Energy system simulation} OR {Energy system transition} OR {Energy systems analyses} OR {Energy systems analysis} OR {Energy systems flexibility} OR {Energy systems integration} OR {Energy systems integration} OR {Energy systems model} OR {Energy systems modeling} OR {Energy systems optimization} OR {Energy systems optimization} OR {Energy systems resilience} OR {Energy systems simulation} OR {Energy systems transition} OR {energy-consumption information system} OR {energy-consumption information systems} OR {Energy-cyber-physical system} OR {Energy-cyber-physical systems} OR {Fuel Switching System} OR {Fuel Switching Systems} OR {Future energy system} OR {Future energy systems} OR {Hierarchical home energy management system} OR {Hierarchical home energy management systems} OR {High-penetration renewable energy system} OR {High-penetration renewable energy systems} OR {Hybrid electrochemical energy storage system} OR {Hybrid electrochemical energy storage systems} OR {Hybrid energy system} OR {Hybrid energy systems} OR {Hybrid renewable energy system} OR {Hybrid renewable energy systems} OR {Integrated community energy system} OR {Integrated community energy systems} OR {Integrated energy system} OR {Integrated energy systems} OR {Integrated urban energy system} OR {Integrated urban energy systems} OR {Low carbon energy system} OR {Low carbon energy systems} OR {Low energy harvesting system} OR {Low energy harvesting systems} OR {Low-carbon energy system} OR {Low-carbon energy systems} OR {Multi carrier energy system} OR {Multi carrier energy systems} OR {Multi energy system} OR {Multi Energy systems} OR {Multi-carrier energy system} OR {Multi-carrier energy systems} OR {multi-energy hybrid power system} OR {multi-energy hybrid power systems} OR {multi-energy power system} OR {multi-energy power systems} OR {Multi-energy system} OR {Multi-Energy systems} OR {Power system flexibility} OR {renewable electricity system} OR {renewable electricity systems} OR {Renewable energy system} OR {Renewable energy systems} OR {Residential solar photovoltaic system} OR {Residential solar photovoltaic systems} OR {Smart energy system} OR {Smart Energy Systems} OR {Smart local energy system} OR {Smart local energy systems} OR {Solar Assisted Annual Cycle Energy System} OR {Solar Assisted Annual Cycle Energy Systems} OR {Urban energy system} OR {Urban energy systems} OR {Vehicle grid integration} OR {Vehicle-grid integration} OR {Hybrid energy harvesting})))

Appendix II

Scopus database

Scopus is Elsevier's abstract and citation database of peer-reviewed literature, covering 77.3 million documents published in over 39,000 journals, book series, and conference proceedings by some 5,000 publishers.

Scopus coverage is multilingual and global: approximately 46% of titles in Scopus are published in languages other than English (or published in both English and another language). In addition, more than half of Scopus's content originates from outside North America, representing many countries in Europe, Latin America, Africa, and the Asia-Pacific region.

Scopus coverage is also inclusive across all major research fields, with 13,300 titles in the Physical Sciences, 14,500 in the Health Sciences, 7,300 in the Life Sciences, and 12,500 in the Social Sciences (the latter including some 4,000 Arts & Humanities related titles). Titles covered are predominantly serial publications (journals, trade journals, book series, and conference material), but a considerable number of conference papers are also covered from stand-alone proceedings volumes (a major dissemination mechanism, particularly in the Computer Sciences). Acknowledging that a great deal of important literature in all fields (but especially in the Social Sciences and Arts & Humanities) is published in books, Scopus began to increase book coverage in 2013. By 2018, Scopus included 1.75 million book items, 400,000 of which are in the Social Sciences and 290,000 of which are in Arts & Humanities.

Appendix III

Scival database

SciVal is a web-based analytics solution with unparalleled flexibility that provides access to the research performance of over 20,000 academic, industry and government research institutions and their associated researchers, output and metrics. SciVal allows you to visualize your research performance, benchmark relative to peers, develop strategic partnerships, identify and analyze emerging research trends, and create uniquely tailored reports. See http://www.scival.com

Data source:

SciVal is based on output and usage data from Scopus, the world's largest abstract and citation database for peer-reviewed publications. SciVal uses Scopus data from 1996 to the current date and covers over 55 million records from 24,000 serial titles from 5,000+ publishers, including the following:

- 2,000+ peer-reviewed journals
- 360 trade publications
- 1,100 book series
- 5.5 million conference papers

Metrics:

SciVal offers a broad spectrum of industry-accepted and easy-to-interpret metrics including Snowball Metrics, which are global standard metrics defined and agreed by higher education institutions for institutional strategic decision-making through benchmarking. Metrics in SciVal help in measuring an institution's or a country's productivity, citation impact, collaboration, subject disciplinarity, and more.

Appendix IV

Funding Institutional Database

Elsevier's Funding Institutional provides a holistic solution for the research funding landscape. The analytical tool supports and optimizes the entire pre-application workflow. It provides insight into the funding landscape, helps research managers and researchers identify funding opportunities, and assists in application and resource allocation decisions.

1. Data source

Funding Institutional's funding data, obtained directly from funder websites, which is re-empowered by Elsevier with its internal data, currently covers:

- 4,300 Government and privately funding organizations;
- Over 18,000 ongoing funded projects;
- More than $6.3 million has been awarded for research funded projects.

2. Application Scenario

With Funding Institutional's numerous application scenarios and features, users can:

- Improve the success rate of funding: Improve the success rate of funding by supporting decision making, analyzing the history of funding awarded, and identifying the most eligible researchers.
- Reveal new funding sources: Discover new funding sources through keyword or category searches.
- Save time and resources: Save time and resources by consolidating grant workflows and merging funder data into a single, comprehensive overview.
- Support Strategic Decision Making: Support strategic decision making by consolidating data on funding awarded, funders, and funding opportunities.

Appendix V

Description of quantitative metrics

Scholarly Output: The output of publications counts all the publications including journal publications, conference proceedings, review publications and publication series of the evaluated subject, representing the scientific research output of the evaluated subject in a fixed period of time.

Citation: Citation is a formal reference to earlier work made in an article or patent, frequently to journal publications. A citation is used to credit the originator of an idea or finding. The number of citations received by a publication or patent from subsequently published articles is a proxy for the influence or impact of the publication. In this report, "citations" refer to citations by any Scopus-indexed publication, whereas citations made by other types of documents (e.g., patents, clinical guidelines) specifically reference the type of document that the citation was made in (e.g., as "patent citations" or "citations in clinical guidelines").

Field Weighted Citation Index (FWCI): Field-Weighted Citation Impact (FWCI) is an indicator of the citation impact of a publication. It is calculated by comparing the number of citations actually received by a publication with the number of citations expected for a publication of the same document type, publication year, and subject. An FWCI of more than 1.00 indicates that the entity's publications have been cited more than would be expected based on the global average for similar publications; for example, a score of 2.11 means the entity's publications have been cited 111% more than the world average. An FWCI of less than 1.00 indicates that the entity's publications have been cited less than would be expected based on the global average for similar publications; for example, an FWCI score of 0.87 means the publications have been cited 13% less than the world average.

Compound Annual Growth Rate (CAGR): is the annual growth rate over a specific period of time, calculated as the n-square root of the total growth rate percentage, with n being equal to the number of years in the period in question as: (current number/starting number)^(1/year) - 1.

Academic research collaboration contains three categories: international collaboration, national collaboration and institutional collaboration, of which:

- International Collaborative Publication: refers the publication published by multiple authors, and at least one of the authors is affiliated with a foreign research institution (this author is not affiliated with the same institution), which indicates that the publication originates from the results of international collaboration.

- National Collaborative Publication: refers to the publication published by multiple authors, none of whom are affiliated with foreign research institutions, but at least one of the authors is affiliated with another national research institution (this author is not affiliated with the same institution), which indicates that the publication is the result of national collaboration.

- **Institutional Collaborative Publication**: refers to the publication is published by multiple authors, and the authors are neither affiliated with foreign research institutions nor with other national research institutions, but all of them are affiliated with the same institution, which indicates that the publication is the result of institutional collaboration.

- **Single Authorship** means that the publication is published by one author, and this item is presented as a comparison item.

Academic-corporate Collaboration: Academic-corporate Collaboration is defined as a publication in which at least one author is affiliated with a corporation and at least one author is affiliated with an academic institution.

Topic Cluster: There is a level above the topic, and each topic is clustered into a topic cluster, which also adopts the same direct citation algorithm. Topic cluster can represent a certain breadth of research content, and there are about 1,500 topic clusters in total.

Topic Prominence: This indicator is linearly calculated using three indicators of topics: number of citations, number of views in Scopus, and average journal factor CiteScore, which reflects the attention, popularity, and development momentum of the topic by scholars worldwide, and the prominence is positively correlated with research funding and grants. By looking for topics with high prominence, we can guide researchers and research managers to get more funding. More information on Topics and topic prominence is available at: https://www.elsevier.com/solutions/scival/releases/topic-prominence-in-science and https://service.elsevier.com/app/answers/detail/a_id/28428/.

Appendix VI

Description of comparators

The countries and regions using comparative analysis in this report include: Mainland China, the United States, Japan, Germany, the United Kingdom, Europe (aggregate region), Asia Pacific (aggregate region) and the world.

The EU region contains 28 countries including Austria, Belgium, Bulgaria, Cyprus, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

The Asia-Pacific region includes 59 countries including China, in order, China, India, Japan, Australia, Korea, Taiwan, Malaysia, Singapore, Hong Kong, Indonesia, Pakistan, New Zealand, Thailand, Vietnam, Bangladesh, Philippines, Kazakhstan, Macau, China, Sri Lanka, Georgia, Nepal, Armenia, Azerbaijan Uzbekistan, Brunei Darussalam, Mongolia, Cambodia, Myanmar, Fiji, Kyrgyzstan, Laos, Papua New Guinea, New Caledonia, Tajikistan, French Polynesia, North Korea, Bhutan, Guam, Solomon Islands, Maldives, Vanuatu, Samoa, Timor-Leste, Turkmenistan, Micronesia (Federated States of), Palau, Tonga, American Samoa Cook Islands, Kiribati, Marshall Islands, Northern Mariana Islands, Turks and Caicos Islands, Tuvalu, Nauru, Niue, United States Minor Outlying Islands, Wallis and Futuna, Norfolk Island.

Appendix VII

Description of ASJC subject areas

The main subject classification used by Scopus is the All Science Journal Classification (ASJC). This classification method is used by Elsevier's internal experts to classify scientific publications in the entire Scopus library using journals as the filtering level, which is divided into 27 major categories and 334 sub-categories. 27 major categories are shown in the table below, and 27 major categories are color-coded in the report as shown below.

Scopus Subject Classification - 27 ASJC subject areas	
General (multidisciplinary journals such as Nature and Science)	Immunology and Microbiology
Agricultural and Biological Sciences	**Materials Science**
Arts and Humanities	Mathematics
Biochemistry, Genetics and Molecular Biology	**Medicine**
Business, Management and Accounting	Neuroscience
Chemical Engineering	**Nursing**
Chemistry	Pharmacology, Toxicology and Pharmaceutics
Computer Science	**Physics and Astronomy**
Decision Sciences	Psychology
Earth and Planetary Sciences	**Social Sciences**
Economics, Econometrics and Finance	Veterinary Sciences
Energy	**Dentistry**
Engineering	Health Professions
Environmental Science	

27 ASJC subject areas full name and color identification

COMP	Computer Science	MEDI	Medicine
MATH	Mathematics	PHAR	Pharmacology, Toxicology and Pharmaceutics
PHYS	Physics and Astronomy	HEAL	Health Professions
CHEM	Chemistry	NURS	Nursing
CENG	Chemical Engineering	DENT	Dentistry
MATE	Materials Science	NEUR	Neuroscience
ENGI	Engineering	ARTS	Arts and Humanities
ENER	Energy	PSYC	Psychology
ENVI	Environmental Science	SOCI	Social Sciences
EART	Earth and Planetary Sciences	BUSI	Business, Management and Accounting
AGRI	Agricultural and Biological Sciences	ECON	Economics, Econometrics and Finance
BIOC	Biochemistry, Genetics and Molecular Biology	DECI	Decision Sciences
IMMU	Immunology and Microbiology	MULT	Multidisciplinary
VETE	Veterinary		

About

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As the company's research intelligence team, Elsevier Research Analytics leverages Scopus, the world's largest abstract and citation database, Elsevier's global network of experts, and other rich data assets to provide customized analytics services to help institutions or individuals gain insights and improve their research strategies and impact through extensive quantitative analysis and qualitative research, and improve their ability to develop, execute, and evaluate research strategies and performance, assisting for smart research comprehensively. Elsevier's research analytics team provides services in the following areas.

- Identify the research results of institutions and individuals and analyze the data using multiple indicators to quantify the reach and impact of the research results;
- Find institutional or individual topics and trends in world topics to help develop research plans;
- Use global data to differentiate institutions or individuals, pointing out weaknesses and highlighting strengths;
- Understand the scientific performance and impact of candidates and exploring collaboration targets and PI candidates;
- Keep track of the research collaboration of institutions or individuals and guiding the strategic planning of research collaboration.