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NEW ENERGY TECHNOLOGY RESEARCH
OPPORTUNITIES AND CHALLENGES

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This report is a collaborative effort between three institutes of the Chinese Academy of Sciences and the Nature Research Custom Media team of Springer Nature. The Institutes of Science and Development of the Chinese Academy of Sciences (CASISD) was responsible for the planning of the report series, the design of overall report outline, drafting the report content, and providing data search strategies. The Nature Research Custom Media team was in charge of editing, design and publication of the report. The Wuhan Documentation and Information Center of the Chinese Academy of Sciences was responsible for the classification of new energy technology areas, providing keyword search terms for bibliometric and patent analysis, and drafting the sections on scientific publication analysis, industry transformation analysis and national competitiveness analysis based on the bibliometric data from the Dimensions database of Digital Science. The Guangzhou Institute of Energy Conversion of the Chinese Academy of Sciences organized interviews with leading experts, and summarized expert views from the interviews in support of the analysis of hotspots of new energy technologies and their development trends. Digital Science, a sister company of Springer Nature, was responsible for providing various data metrics on new energy fields for China and the world.

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Abstract

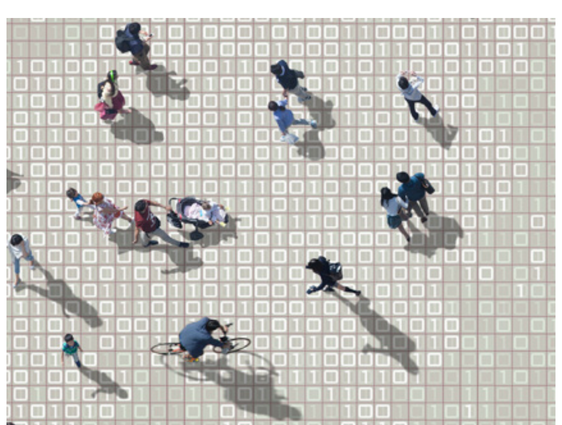
The transition to a low/zero-carbon energy system and the reshaping of the modern energy system are necessary for achieving the Sustainable Development Goals (SDG) of the United Nations. Such a transition must allow for coping with the global climate change crisis, and promoting the 'green recovery' of the world economy in the post-pandemic era. Currently, major countries and regions take the development of new energy technologies as a crucial opportunity to lead the new round of energy revolution and science and technology innovation. New energy technologies are being updated at an unprecedented pace.

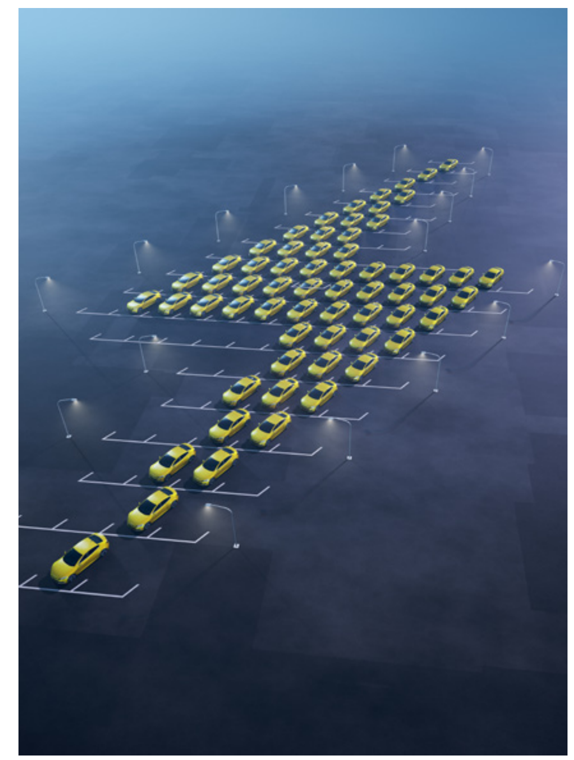
Based on the Dimensions database of Digital Science, this study, combining bibliometric analysis, patent analysis and expert interviews, systematically analyses eight new energy fields, including solar, wind, biomass, geothermal, nuclear, hydrogen, energy storage, and energy internet, as well as 20 subtypes of new energy technologies over the period of 2000-2019 (with a focus on the period of 2015-2019), to reveal hot directions for global new energy research, the potential for industrial transformation, and future development trends. The study takes a global perspective, considering the development of China's new energy technologies and corresponding research patterns, and conducts a comparative analysis of China's research competitiveness with other major countries and regions.

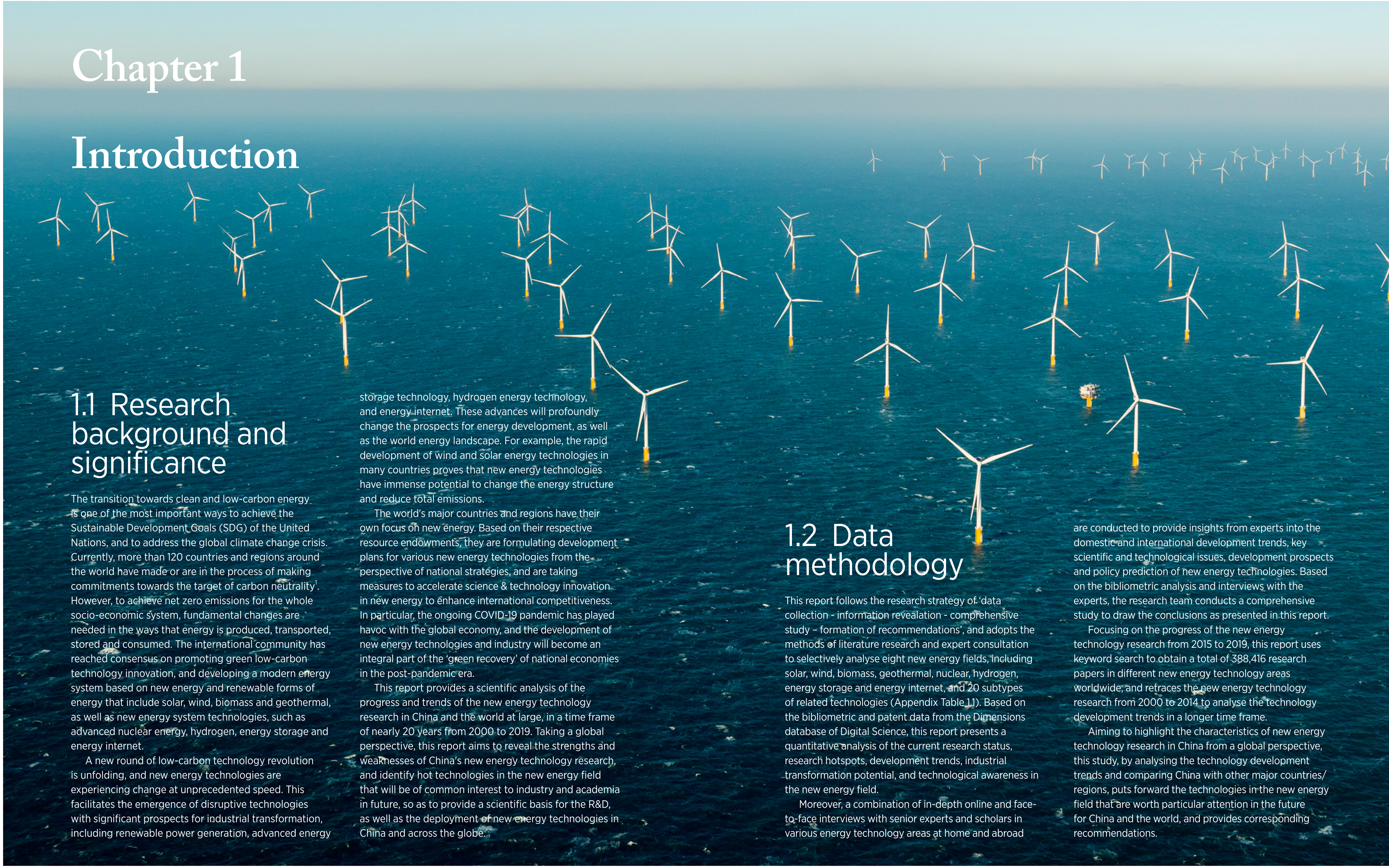
This study reveals that:

1. Global research in the new energy field is in a period of accelerated growth, with solar energy, energy storage and hydrogen energy receiving extensive attention from the global research community.
2. China's total contribution to new energy research is substantial, and the contribution to high-quality research is also large, but compared with the United States, Germany, Japan and other developed countries, China is relatively down the country ranks in terms of average citations per paper in most energy fields, suggesting that its overall efficiency needs improvement.
3. The level of transformation of new energy research to applicable technologies is relatively low globally, and industry-academia-research integration needs to be further strengthened. In general, research transformation for energy storage, biomass energy and solar energy is at a relatively high level, with technologies for lithium-ion batteries and organic solar cells being the hotspots of common interest for both the research community and industry.
4. The qualitative analysis of expert interviews reveals that the rapid progress of energy storage technologies will provide powerful support for large-scale development of renewable power generation and electric vehicles; hydrogen will be an important medium for building future energy systems and realizing the energy revolution; breakthroughs in solar fuel technologies and relevant cost reduction may help reduce dependence on fossil fuels; and energy internet will bring dual advantages of the internet and smart energy systems into full play to realize coordinated optimal allocation of resources.

Contents







Chapter 1

Introduction

1.1 Research background and significance

The transition towards clean and low-carbon energy is one of the most important ways to achieve the Sustainable Development Goals (SDG) of the United Nations, and to address the global climate change crisis. Currently, more than 120 countries and regions around the world have made or are in the process of making commitments towards the target of carbon neutrality[1]. However, to achieve net zero emissions for the whole socio-economic system, fundamental changes are needed in the ways that energy is produced, transported, stored and consumed. The international community has reached consensus on promoting green low-carbon technology innovation, and developing a modern energy system based on new energy and renewable forms of energy that include solar, wind, biomass and geothermal, as well as new energy system technologies, such as advanced nuclear energy, hydrogen, energy storage and energy internet.

A new round of low-carbon technology revolution is unfolding, and new energy technologies are experiencing change at unprecedented speed. This facilitates the emergence of disruptive technologies with significant prospects for industrial transformation, including renewable power generation, advanced energy storage technology, hydrogen energy technology, and energy internet. These advances will profoundly change the prospects for energy development, as well as the world energy landscape. For example, the rapid development of wind and solar energy technologies in many countries proves that new energy technologies have immense potential to change the energy structure and reduce total emissions.

The world's major countries and regions have their own focus on new energy. Based on their respective resource endowments, they are formulating development plans for various new energy technologies from the perspective of national strategies, and are taking measures to accelerate science & technology innovation in new energy to enhance international competitiveness. In particular, the ongoing COVID-19 pandemic has played havoc with the global economy, and the development of new energy technologies and industry will become an integral part of the 'green recovery' of national economies in the post-pandemic era.

This report provides a scientific analysis of the progress and trends of the new energy technology research in China and the world at large, in a time frame of nearly 20 years from 2000 to 2019. Taking a global perspective, this report aims to reveal the strengths and weaknesses of China's new energy technology research, and identify hot technologies in the new energy field that will be of common interest to industry and academia in future, so as to provide a scientific basis for the R&D, as well as the deployment of new energy technologies in China and across the globe.

1.2 Data methodology

This report follows the research strategy of 'data collection - information revealation - comprehensive study – formation of recommendations', and adopts the methods of literature research and expert consultation to selectively analyse eight new energy fields, including solar, wind, biomass, geothermal, nuclear, hydrogen, energy storage and energy internet, and 20 subtypes of related technologies (Appendix Table 1.1). Based on the bibliometric and patent data from the Dimensions database of Digital Science, this report presents a quantitative analysis of the current research status, research hotspots, development trends, industrial transformation potential, and technological awareness in the new energy field.

Moreover, a combination of in-depth online and face-to-face interviews with senior experts and scholars in various energy technology areas at home and abroad are conducted to provide insights from experts into the domestic and international development trends, key scientific and technological issues, development prospects and policy prediction of new energy technologies. Based on the bibliometric analysis and interviews with the experts, the research team conducts a comprehensive study to draw the conclusions as presented in this report.

Focusing on the progress of the new energy technology research from 2015 to 2019, this report uses keyword search to obtain a total of 388,416 research papers in different new energy technology areas worldwide, and retraces the new energy technology research from 2000 to 2014 to analyse the technology development trends in a longer time frame.

Aiming to highlight the characteristics of new energy technology research in China from a global perspective, this study, by analysing the technology development trends and comparing China with other major countries/regions, puts forward the technologies in the new energy field that are worth particular attention in the future for China and the world, and provides corresponding recommendations.

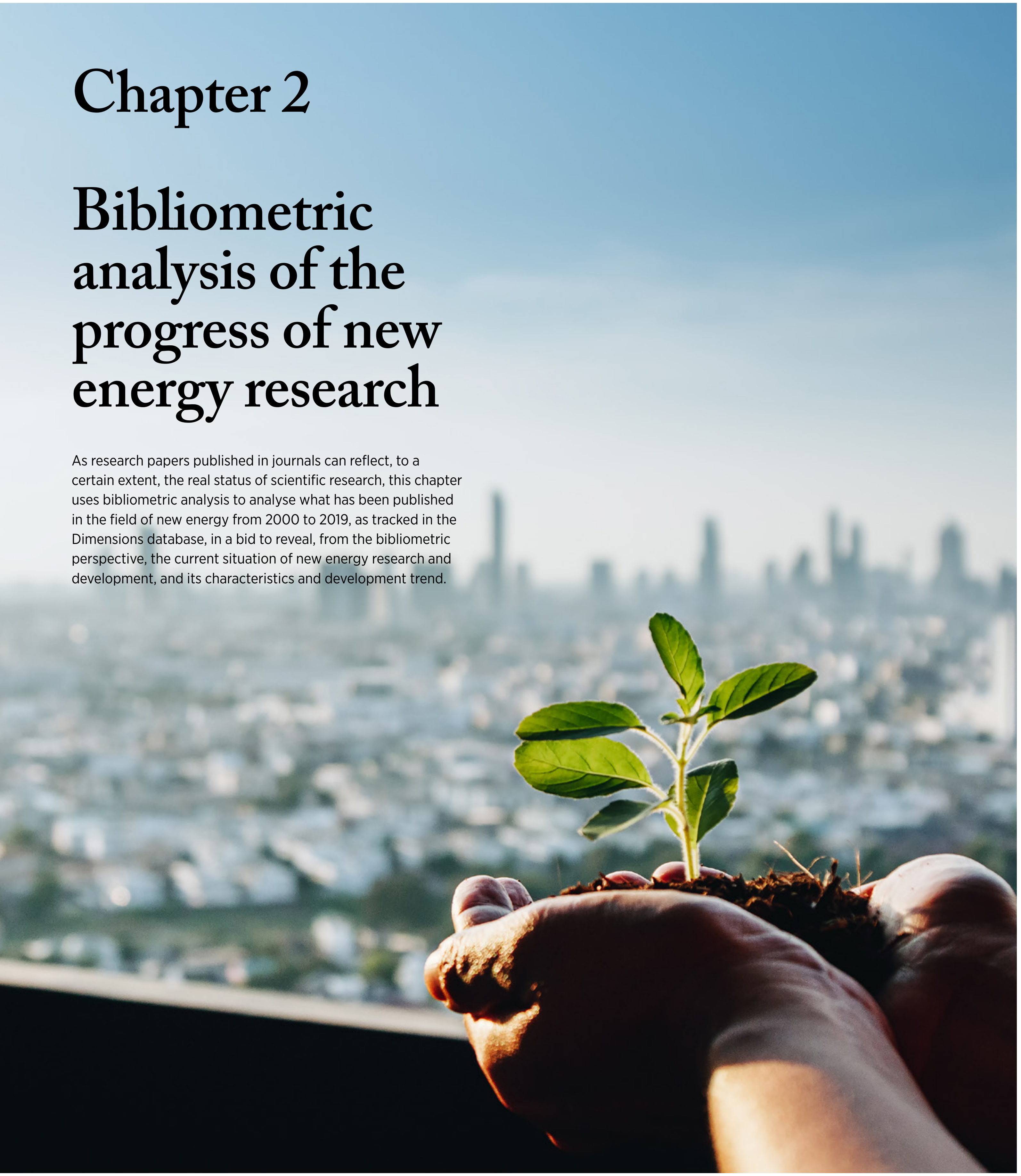
1.3 Main conclusions

(1) Global research on new energy technologies is in a period of accelerated development, with wider attention on three areas, namely, solar energy, energy storage and hydrogen energy. The global top five technology themes showing more promise are battery storage technology, solar photovoltaic technology, solar fuel technology, hydrogen production technology, and architecture and core equipment technologies of energy internet.
(2) China is quite active in the field of new energy research. Its number of publications in the past five years accounts for more than a quarter of the global publications, and the impact indicator of each technology area is higher than the global average, with outstanding performance in solar energy and hydrogen energy. Compared with developed countries such as the United States, Germany and Japan, China's ranking in terms of average citations per paper relatively lags behind in most technology areas, and its overall impact of research output needs to be further improved.
(3) The overall technology transfer rate of global new energy research output is relatively low, and the industry-academia-research integration needs to be further strengthened. In general, technology tranformation of energy storage, biomass and solar energy research is at a relatively high level, with technologies on lithium-ion batteries and organic solar cells being the hotspots of common interest for academia and industry.
(4) Interviews with leading experts in key technology areas reveal that the rapid progress of energy storage technology will provide powerful support for the large-scale development of renewable power generation and electric vehicles; hydrogen energy will be an important medium for building the future energy system and realize the energy transformation; breakthroughs in solar fuel technologies and relevant cost reduction may help reduce dependence on fossil fuels; and energy internet will bring dual advantages of the "internet +" and smart energy into full play to realize the coordinated optimal allocation of energy resources.

1.4 Report structure

This report is divided into six chapters. Chapter 1 is the introduction, while Chapter 2 provides a bibliometric analysis of new energy research papers of China and the world, and summarises the development pattern of new energy technologies through the trends of annual research output. Chapter 3 focuses on the industrial transformation of new energy technologies and their applications, mainly using patent data to analyse the connection between research output and patent, so as to identify new energy technologies that potentially attract more market attention and with more potential for industrial transformation. Chapter 4, based on bibliometric data, analyses the research competitiveness of major countries in the new energy field, and explores the development patterns of new energy in these countries and their relative technological advantages. Chapter 5, based on the Altmetric score of published papers in different areas of new energy and related quantitative analysis, selects hot technologies as the topics of expert interviews, and analyses the development trends, opportunities and challenges of these technologies. Chapter 6 provides the conclusions and implications, predicts the development prospects of new energy technologies, and gives brief policy recommendations in the context of achieving the SDGs.

[1] Data source: https://eciu.net/netzerotracker



Chapter 2

Bibliometric analysis of the progress of new energy research

As research papers published in journals can reflect, to a certain extent, the real status of scientific research, this chapter uses bibliometric analysis to analyse what has been published in the field of new energy from 2000 to 2019, as tracked in the Dimensions database, in a bid to reveal, from the bibliometric perspective, the current situation of new energy research and development, and its characteristics and development trend.

2.1 Analysis of the global development trends

In this study, the global publications in the new energy field are calculated every five years from 2000 to 2019 (Table 2.1), and this reveals that new energy research is in a period of accelerated growth. The number of publications during 2015-2019 in seven technology areas, excluding nuclear energy, accounts for more than 40% of the total works published in the past 20 years. Of these, five areas have their publications in the past five years accounting for more than half of the total research output in the past 20 years.

In terms of the volume, the number of published papers in several new energy areas, such as solar energy, hydrogen energy, energy internet and energy storage, has exceeded 100,000 in the past 20 years. In terms of growth rate, biomass energy is experiencing the fastest growth, with a compound annual growth rate (CAGR[2]) of 236.3% in the past four five-year periods, while the CAGR for wind energy reaches 212.8%. In addition, the CAGRs of energy storage and solar energy, both of which have relatively large market shares, also exceed 100%, reflecting the continuous and widespread interest from the research community in these two fields over a long period of time.

Study of the research output in the 2015-2019 period reveals that the global interest in new energy continues to heat up (Figure 2.1), with 388,416 papers in total published in the new energy field. The total number of publications has grown from 65,381 in 2015 to 95,474 in 2019, with the CAGR reaching 9.9%. To be specific, the number of papers published in the area of solar energy technology exceeds 100,000, while the number of papers published in the areas of energy storage, hydrogen energy and energy internet also exceeds 50,000 each. In terms of growth rate, among the technology areas with more than 10,000 articles published, energy storage has the fastest growth in the past five years, with a CAGR of 15.9%, while the CAGRs of hydrogen energy and energy internet both exceed 10%.

2

$$CAGR(t_0,t_n)=\left(\frac{V(t_n)}{V(t_0)}\right)^{\frac{1}{t_n-t_0}}-1$$

t_0 stands for the initial period, e.g. 2000-2004, the first five-year period; t_n stands for the concluding period, e.g. 2015-2019, the fourth five-year period; $V(t_0)$ stands for the number of publications from 2000-2004; $V(t_n)$ stands for the number of publications from 2015-2019. The CAGR values in this report are calculated according to this formula.

Table 2.1

Number of global publications and its growth, 2000-2019

Technology areas	2000-2019 in total	2000-2004	2005-2009	2010-2014	2015-2019	2015-2019 percentage (%)	CAGR in 4 five-year-period (%)
Solar energy	**185,996**	7,194	16,400	59,379	103,023	55.4	142.8
Hydrogen energy	**173,937**	12,923	33,463	52,736	74,815	43.0	79.6
Energy internet	**131,716**	9,807	17,279	40,232	64,398	48.9	87.5
Energy storage	**125,017**	4,110	8,796	31,578	80,533	64.4	169.6
Nuclear energy	**94,668**	12,140	17,721	29,317	35,490	37.5	43.0
Biomass energy	**77,963**	1,067	7,684	28,615	40,597	52.1	236.3
Wind energy	**8,721**	168	636	2,777	5,140	58.9	212.8
Geothermal energy	**4,009**	383	528	1,084	2,014	50.2	73.9

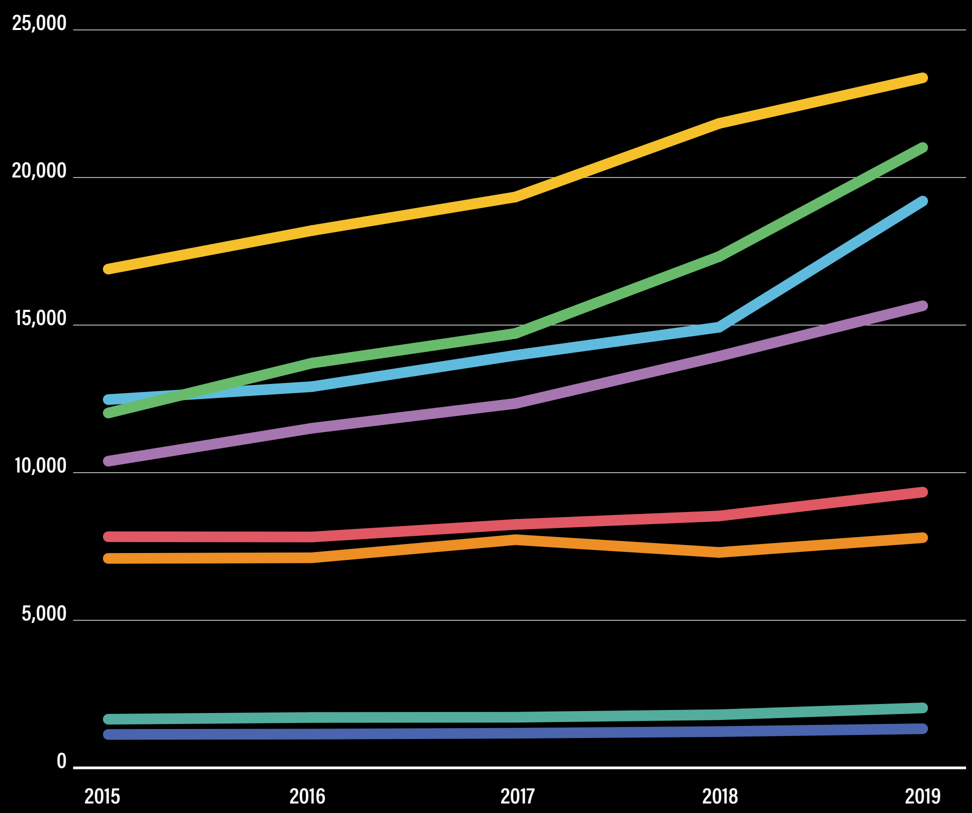
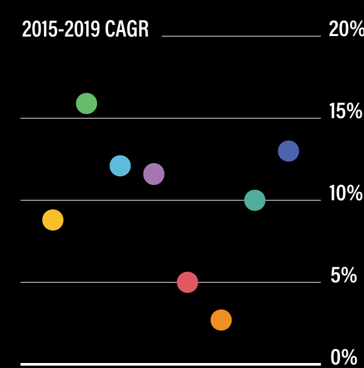


Figure 2.1

Number of global publications and its growth, 2015-2019

Technology areas	In total
Solar energy	103,023
Energy storage	80,533
Hydrogen energy	74,815
Energy internet	64,398
Biomass energy	40,597
Nuclear energy	35,490
Wind energy	5,140
Geothermal energy	2,014



China's contribution to global research in the new energy field is gradually increasing. If excluding Chinese published papers from the global total, as shown in Table 2.2, the total number of global publications in new energy, the number of publications in individual technology areas and the CAGR in the past five years would drop significantly, indicating that China is playing a significant role in global new energy research.

The top 10 highly cited papers reveal the popular research directions in new energy technology areas across the globe (Appendix Table 1.2):
(1) Biomass energy research mainly focuses on lignin pyrolysis, catalysts, pretreatments, microalgae biofuels, bio-refining, etc.;
(2) Energy storage research mainly focuses on the direction of lithium-ion batteries, sodium-ion batteries, lithium-sulfur batteries, positive and negative electrode materials, fast charging technology, etc.;
(3) Geothermal energy research focuses on enhanced geothermal systems (EGS), numerical simulation of geothermal systems, geothermal drilling technologies, etc.;
(4) Hydrogen energy research mainly focuses on the fields of noble metal-free catalysts, metal-organic framework materials, cobalt-based catalysts, bifunctional catalysts, etc.;
(5) Nuclear energy research mainly focuses on nuclear waste disposal technologies, nuclear power plant safety technologies, radiation resistant materials, magnetic confinement fusion, inertial confinement fusion, etc.;
(6) Solar energy research focuses on perovskite solar cells, stacked solar cells, solar photocatalytic hydrogen production, catalysts, semiconductor electrodes, etc.;
(7) Energy internet research focuses on smart energy systems, big data, smart home energy management systems, demand response, etc.;
(8) Wind energy research mainly focuses on high-power energy converters, wind turbines, numerical simulation of wind power, high-proportion stable grid connection of wind power, etc.

Table 2.2

Number of global publications (excluding China) and its growth, 2015-2019

Technology areas	In total	2015	2016	2017	2018	2019	2015-2019 CAGR (%)
Solar energy	84,529	14,689	15,806	16,482	18,256	19,296	7.1
Hydrogen energy	58,489	10,449	10,600	11,063	11,380	14,997	9.5
Energy internet	55,100	9,206	10,069	10,685	11,934	13,206	9.4
Energy storage	52,617	8,260	9,691	9,916	11,242	13,508	13.1
Biomass energy	37,285	6,988	6,938	7,364	7,633	8,362	4.6
Nuclear energy	31,487	6,246	6,144	6,496	6,008	6,593	1.4
Wind energy	4,706	845	894	887	939	1,141	7.8
Geothermal energy	1,747	303	311	330	359	444	10.0
In total[3]	**313,207**	**55,032**	**58,247**	**60,748**	**64,991**	**74,169**	**7.7**

[3] Since a paper may touch on several technology areas, the total number of publications in the new energy field will be less than the sum of papers in all the technology areas.

2.2 Analysis of development in China

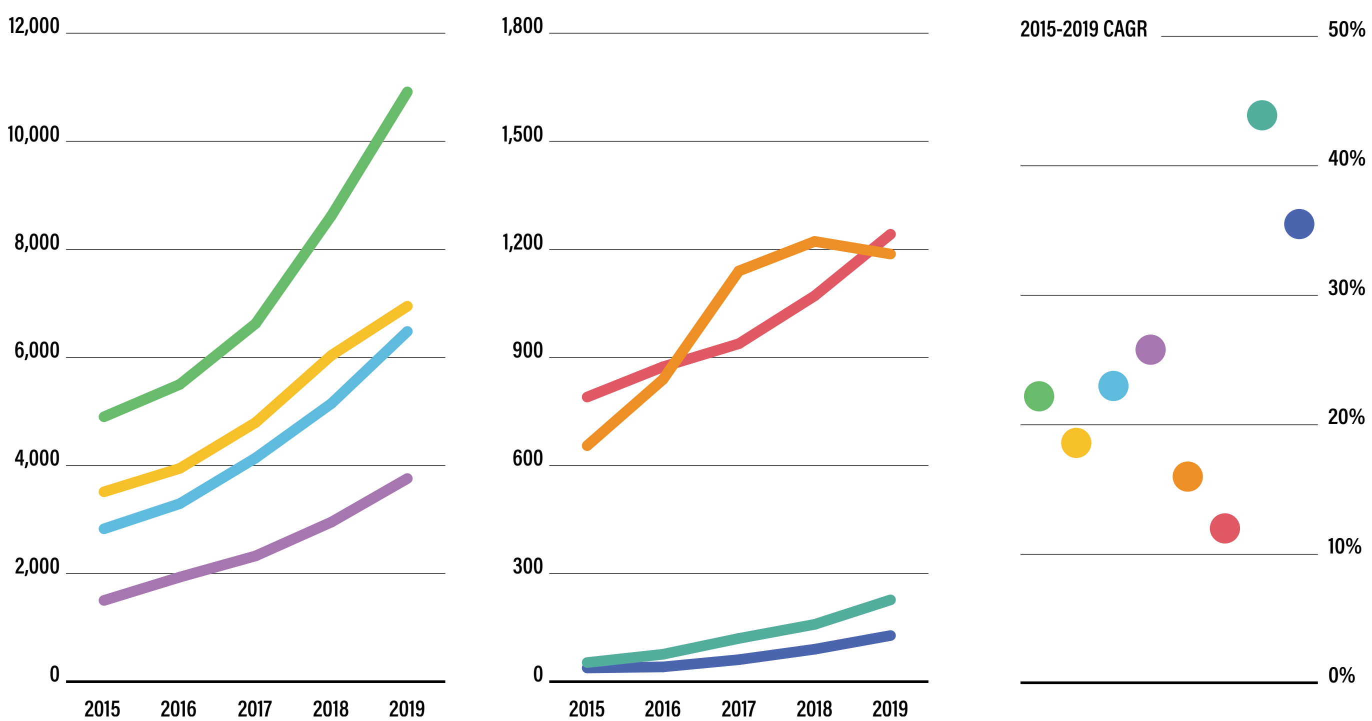
2.2.1 Research activity analysis

From 2015 to 2019, China published 100,528 papers in the new energy field, accounting for almost a quarter of the global total in that period. Of these papers, energy storage has been the most productive technology area in new energy research, with 36,569 papers published. Solar energy research comes next, with 25,244 papers published, while hydrogen energy ranks third with 21,892 publications. In terms of growth rate, among the technology areas with more than 5,000 published papers, energy internet has seen the fastest growth in the past five years, with a CAGR of more than 25%. The CAGR values of hydrogen energy and energy storage are also more than 20% (Figure 2.2). An analysis of the year-on-year development trend of the numbers of publications in each technology area reveals that, possibly due to the small volume of publications, CAGRs of wind energy and geothermal energy areas are higher, compared with other new energy technology areas, while the CAGRs of publications in nuclear energy and biomass energy are low.

Figure 2.2

The growth in Chinese published papers, 2015-2019

Technology areas	In total
Energy storage	36,569
Solar energy	25,244
Hydrogen energy	21,892
Energy internet	12,478
Nuclear energy	5,043
Biomass energy	4,915
Wind energy	635
Geothermal energy	358



In terms of the proportion of Chinese publications[4] against global publications in various areas of new energy research (Table 2.3), Chinese publications account for more than 10%. More specifically, energy storage has the highest percentage, accounting for almost half of the global total (45.4%), showing that energy storage technology research in China dwarfed other areas in terms of level of activity intensity. Chinese published papers in two areas, namely, hydrogen energy (29.3%) and solar energy (24.5%), account for more than 20% of the global total, while Chinese publications in energy internet research account for nearly 20%. In comparison, Chinese publications in the remaining four areas account for a relatively low proportion against the global total.

[4] The Chinese publications are calculated against the requirement that the paper should have at least one author with an affiliation in China.

Table 2.3

Percentage of Chinese publications in global research, 2015-2019

Technology areas	China	Global	% China
Energy storage	36,569	80,533	45.4
Hydrogen energy	21,892	74,815	29.3
Solar energy	25,244	103,023	24.5
Energy internet	12,478	64,398	19.4
Geothermal energy	358	2,014	17.8
Nuclear energy	5,043	35,490	14.2
Wind energy	635	5,140	12.4
Biomass energy	4,915	40,597	12.1

Technology areas	Chinese publica-tions	Average citations-China	Global Publica-tions	Average citations-Global	RACR (%)
Solar energy	25,244	20.8	103,023	13.0	1.6
Hydrogen energy	21,892	17.9	74,815	11.7	1.5
Biomass energy	4,915	14.6	40,597	10.5	1.4
Geothermal energy	358	9.0	2,014	7.0	1.3
Energy storage	36,569	20.5	80,533	17.3	1.2
Energy internet	12,478	8.4	64,398	7.2	1.2
Nuclear energy	5,043	4.3	35,490	3.7	1.2
Wind energy	635	5.8	5,140	5.5	1.0

2.2.2 Research impact analysis

In terms of the average number of citations per paper in various technology areas of China's new energy research (Table 2.4), solar energy has the best performance, with an average citation of 20.8 times. Energy storage follows closely, with an average citation of 20.5 times. The papers published in hydrogen energy and biomass energy also have high impact, with average citations of 17.9 times and 14.6 times, respectively. For other technology areas, the average number of citations per paper is less than 10 times. Further analysis of the relative average citation ratio (RACR)[5] in different technology areas of new energy research in China shows that for all the eight technology areas, the RACR is greater than one, indicating that the impact of Chinese papers in these technology areas is higher than the global average.5 Specifically, China has the best performance in solar energy research, with an RACR of 1.6. Hydrogen energy research comes next, with an RACR of 1.5. Compared with other areas of new energy research, China's research in solar and hydrogen energy has relatively higher global impact.

[5] The relative average citation ratio (RACR) is defined as the average citations received by Chinese publications divided by the average citations received by global publications, indicating the impact of Chinese publications against the global average.

Table 2.4

Average citations and RACR, 2015-2019

An analysis of Chinese published papers that enter global top 10% highly cited papers[6] in various new energy research areas (Table 2.5) reveals that energy storage and solar energy have the best performance, with 4,860 and 4,437 papers entering the global top 10%, respectively. The percentage of papers from China in all the new energy areas exceeds the global average, with solar energy performing the best; 17.6% of Chinese papers published in this area have entered the global top 10%. In addition, Chinese papers in hydrogen energy and biomass energy also have good performance, with 17.2% and 15.1% of papers entering the global top 10%, respectively.

[6] Top 10% highly cited papers refer to the papers whose citations enter the global top 10%.

Table 2.5

China in global top 10% papers

Technology areas	Number of Publications	Number of papers in global top 10%	% of Chinese papers in global top 10%
Solar energy	25,244	4,437	17.6
Hydrogen energy	21,892	3,762	17.2
Biomass energy	4,915	744	15.1
Energy storage	36,569	4,860	13.3
Energy internet	12,478	1,518	12.2
Geothermal energy	358	43	12.0
Nuclear energy	5,043	559	11.1
Wind energy	635	68	10.7

An analysis of papers from China that have entered the global top 1% most highly cited papers[7] in the eight technology areas of new energy, covering 20 technology themes (Table 2.6), reveals that Chinese papers in 14 themes have entered the global top 1%. Among these, papers in eight technology themes outnumber the global average, including in solar fuel technology, hydrogen production technology, battery energy storage technology, solar photovoltaic technology, the technologies underlying energy internet system integration, biomass power generation system, fuel cell technology and the management technologies of energy internet.

[7] Top 1% most highly cited papers refer to the papers of which citations enter the global top 1%.

Table 2.6

Chinese papers published in 14 technology themes entering the global top

Technology areas	Technology themes	Number of publications	Papers entering the global top 1%	% China in global top 1%
Solar energy	Solar fuel technology	7,167	325	4.5
Hydrogen energy	Hydrogen production technology	11,583	363	3.1
Energy storage	Battery energy storage technology	36,569	835	2.3
Solar energy	Solar photovoltaic technology	17,731	391	2.2
Energy internet	Technologies underlying the energy internet system integration	138	3	2.2
Biomass energy	Biomass power generation technology	323	5	1.5
Hydrogen energy	Fuel cell technology	8,971	114	1.3
Energy internet	Management technologies of energy internet	2,599	26	1.0
Biomass energy	Biofuel technology	4,603	29	0.6
Energy internet	Architecture and core equipment technologies of energy internet	10,164	51	0.5
Hydrogen energy	Hydrogen storage technology	1,732	9	0.5
Solar energy	Solar thermal power generation technology	563	3	0.5
Nuclear energy	Nuclear fission energy technology	2,965	3	0.1
Nuclear energy	Nuclear fusion energy technology	2,084	2	0.1

2.3 Identification of technology themes with promising prospects

From the bibliometric perspective, the most promising technology themes can be identified through three indicators: a sizable volume of published papers, a high rate of growth, and a significant number of papers entering the global top 1% most highly cited papers. The performance of 20 technology themes in eight new energy technology areas over the 2015-2019 period is evaluated in terms of the number of publications (P_i), the CAGR (G_i) and the publications entering the global top 1% (T_i)[8]. The top five most promising technology themes (Table 2.7) are: battery energy storage technology, solar photovoltaic technology, solar fuel energy technology, hydrogen production technology, and the architecture and core equipment technologies of energy internet, primarily covering the areas of energy storage, solar energy, hydrogen energy, and energy internet.

[8] The formula to calculate the overall performance score:

$$Score_i = \frac{P_i - \min\limits_{1\leqslant j\leqslant 20}\{P_j\}}{\max\limits_{1\leqslant j\leqslant 20}\{P_j\} - \min\limits_{1\leqslant j\leqslant 20}\{P_j\}} \times \frac{1}{3} + \frac{G_i - \min\limits_{1\leqslant j\leqslant 20}\{G_j\}}{\max\limits_{1\leqslant j\leqslant 20}\{G_j\} - \min\limits_{1\leqslant j\leqslant 20}\{G_j\}} \times \frac{1}{3} + \frac{T_i - \min\limits_{1\leqslant j\leqslant 20}\{T_j\}}{\max\limits_{1\leqslant j\leqslant 20}\{T_j\} - \min\limits_{1\leqslant j\leqslant 20}\{T_j\}} \times \frac{1}{3}$$

Table 2.7

The overall performance of 20 technology themes in the global new energy field, 2015-2019, in terms of the number of publications, CAGR and top 1% papers

Technology areas	Technology themes	2015	2016	2017	2018	2019	Total number of publications	CAGR (%)	Number of global Top 1% papers	Overall performance score
Energy storage	Battery energy storage technology	12,074	13,897	14,992	17,792	21,778	80,533	12.5	1,482	0.9
Solar energy	Solar photovoltaic technology	15,082	15,911	16,610	18,358	19,274	85,235	5	991	0.7
Solar energy	Solar fuel technology	1,743	2,302	2,718	3,562	4,290	14,615	19.7	533	0.6
Hydrogen energy	Hydrogen production technology	3,785	4,410	5,062	6,112	7,538	26,907	14.8	608	0.5
Energy internet	Architecture and core equipment technologies of energy internet	8,256	9,104	9,534	10,595	11,697	49,186	7.2	200	0.4
Hydrogen energy	Fuel cell technology	7,803	7,621	8,146	8,011	11,278	42,859	7.6	262	0.4
Energy internet	Energy internet management technology	2,312	2,638	3,129	3,856	4,650	16,585	15	105	0.3
Energy internet	Technologies underlying energy internet system integration	185	228	271	371	414	1,469	17.5	15	0.3
Biomass energy	Biofuel technology	7,236	7,239	7,689	7,971	8,725	38,860	3.8	203	0.3
Geothermal energy	Hot dry rock thermal technology	205	236	236	274	387	1,338	13.6	3	0.2
Nuclear energy	Nuclear fission energy technology	4,122	4,214	4,825	4,717	5,116	22,994	4.4	21	0.2
Wind energy	Onshore wind energy technology	67	71	77	99	108	422	10	1	0.2
Geothermal energy	Hydrothermal geothermal technology	223	211	260	284	347	1,325	9.2	1	0.2
Solar energy	Solar thermal power generation technology	627	670	796	901	930	3,924	8.2	19	0.2
Wind energy	Offshore wind energy technology	839	892	898	976	1,220	4,825	7.8	6	0.2
Biomass energy	Biomass power generation technology	335	329	346	367	488	1,865	7.8	14	0.2
Hydrogen energy	Hydrogen transport technology	237	276	289	314	341	1,457	7.5	2	0.1
Energy internet	Deep integration technology of energy and information	94	100	114	143	127	578	6.2	6	0.1
Hydrogen energy	Hydrogen storage technology	1,217	1,272	1,243	1,382	1,471	6,585	3.9	32	0.1
Nuclear energy	Nuclear fusion energy technology	2,659	2,590	2,643	2,290	2,422	12,604	-1.8	13	0.1

2.4 Summary

This chapter adopts bibliometric analysis of published papers in the new energy field to reveal development trend of scientific research for China and the world.

(1) The analysis of the intensity of research activity shows that global new energy research is experiencing a period of accelerated growth, and attention of the research community on new energy is constantly increasing. The number of papers published in seven fields, excluding nuclear energy, in a recent five-year period (2015-2019) account for more than 40% of the total publications in the past 20 years. Of these, the number of papers published in solar energy, energy storage and hydrogen energy make up the top three. Over 20 years, the areas of energy storage and solar energy received wider and continuous attention. Among the fields with more than 10,000 publications, the fastest annual growth occurs in energy storage, hydrogen energy and energy internet.

(2) China plays a pivotal role in global new energy research, accounting for almost a quarter of the world's total publications in the past five years. Energy storage, solar energy and hydrogen energy are the most productive areas in China's new energy research. In terms of year-on-year growth, among the areas with more than 5,000 papers published, energy internet, hydrogen energy and energy storage saw the fastest annual growth. In terms of RACR and the global top 10% papers, the impact analysis shows that the research impact of eight areas in China's new energy field outperforms the global average, with solar energy and hydrogen energy research having relatively high global impact. In terms of the global top 1% papers, China outperforms the global average in eight technology themes in the new energy field, including solar fuel technology, hydrogen production technology, battery energy storage technology, solar photovoltaic technology, the technologies underlying energy internet system integration, biomass power generation system, fuel cell technology and the management technologies of energy internet.

(3) The comprehensive evaluation of overall performance of 20 technology themes in global new energy research from 2015 to 2019, in terms of the number of publications, CAGR and top 1% papers, reveals the following themes with promising prospects: battery energy storage technology, solar photovoltaic technology, solar fuel energy technology, hydrogen production technology, and the architecture and core equipment technologies of energy internet, mainly covering the areas of energy storage, solar energy, hydrogen energy, and energy internet.

Chapter 3

Analysis of industrial transformation of new energy technologies

Patent applications usually make reference to academic literature, which, to some extent, reflects the industrial transfer and application of academic research. This chapter analyses the citations of scientific papers in the various technology areas of new energy research, based on patent data collected from 15 patent jurisdictions, including countries and regions (Figure 3.1), in the Dimensions database, to present an industrial transfer analysis of new energy technologies from the perspective of patent metrics. Since the data of the patents approved in mainland China and Japan is not included in the Dimensions database, the country analysis concerning China and Japan is for information only.

Figure 3.1

Patent data of 15 patent jurisdictions in Dimensions database (as of January 2021)

Country/Region	Number of patents
The United States	17,887,969
Germany	7,837,101
European Patent Office	7,123,279
World Intellectual Property Organisation	4,678,704
The United Kingdom	3,813,028
France	3,212,907
Canada	2,973,722
Australia	2,961,017
Russia	1,609,529
India	1,052,216
Switzerland	730,277
The Netherlands	653,901
Hong Kong, China	169,965
New Zealand	136,403
Ireland	121,327

3.1 Analysis of patent citations in new energy research

In terms of the number of patents that have cited academic papers in different technology areas of new energy research, namely, the papers analysed in Chapter 2 of this report, and the number of papers cited by patents (Figure 3.2), energy storage, solar energy and hydrogen energy rank the global top three, respectively, indicating that the industrial attention on these new energy technologies is relatively high. In terms of the proportion of papers cited by patents, energy storage, biomass and solar energy outperform other technology areas, indicating that likely a larger portion of the research output in these new energy technologies have been transferred to the industry.

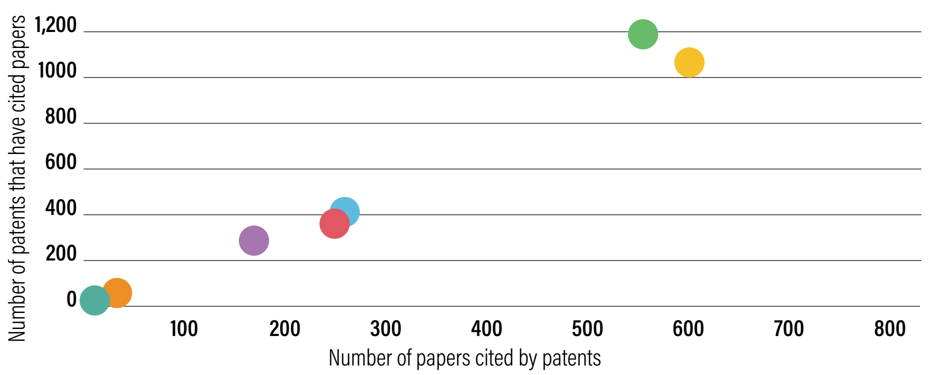


Figure 3.2

Patents that have cited publications and the publications cited by patents in new energy technologies worldwide

Technology areas	The proportion of papers cited by patents
Energy storage	0.69%
Solar energy	0.58%
Hydrogen energy	0.35%
Biomass energy	0.61%
Energy internet	0.26%
Nuclear energy	0.09%
Wind energy	0.14%

In terms of the number of patents that have cited Chinese papers, the top three technology areas are also energy storage, solar energy and hydrogen energy, while in terms of the number of academic papers cited by patents, the top three are energy storage, solar energy and energy internet (Figure 3.3). This indicates, to a certain extent, that the Chinese energy sector pays more attention to energy internet technology.

In terms of the proportion of Chinese papers cited by patents, solar energy, energy storage and biomass energy outnumber other areas, and this can be explained mainly by China's increasing support for these three technologies areas in recent years, as well as the close tie between research and industry.

From a global perspective, the cross-citation between academic papers and patents is relatively low; this might be affected by the incomplete patent statistics in China. A comprehensive analysis of the situations at home and abroad reveals that the future patent technology planning in the new energy field, in domestic market and foreign markets alike, pinpoints energy storage, solar energy and hydrogen energy as the hot areas, while the areas with relatively higher technology transfer rates are energy storage, biomass energy and solar energy.

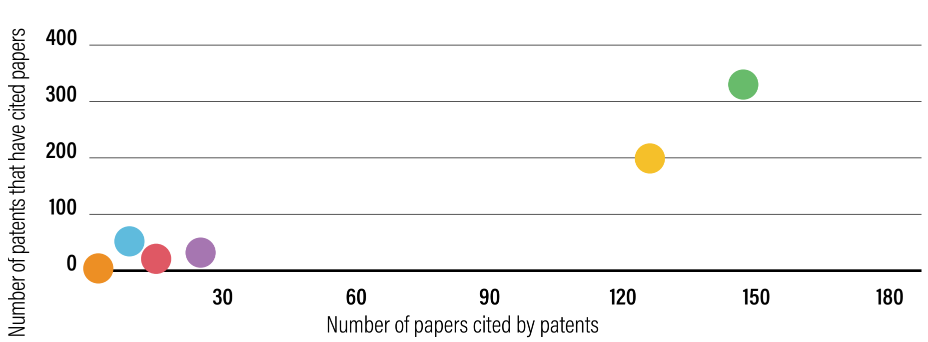


Figure 3.3

Patents that have cited publications and publications cited by patents in new energy technologies in China

Technology areas	The proportion of papers cited by patents in China
Energy storage	0.40%
Solar energy	0.50%
Hydrogen energy	0.04%
Energy internet	0.20%
Biomass energy	0.31%
Nuclear energy	0.04%

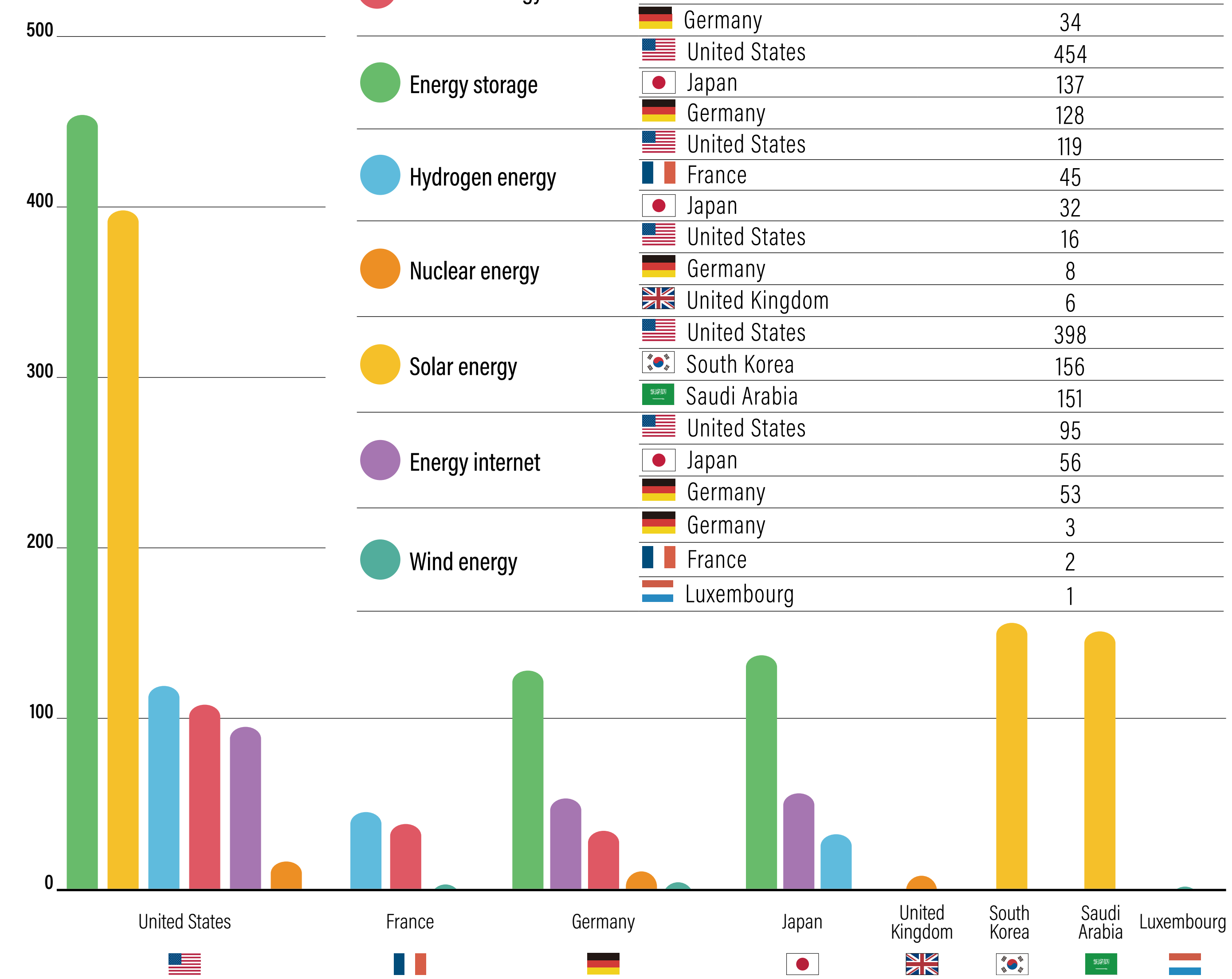
The country analysis of the number of patents that have cited publications in different new energy technologies reveals the top three countries in each technology area, shown in Table 3.1. In terms of the number of patents that have cited publications, the United States has higher rankings in most new energy technologies, indicating the country's greater emphasis on technology transfer of new energy research output. What is worth noting is that the United States outperforms in the areas of biomass energy, energy storage, hydrogen energy, nuclear energy and solar energy, with the number of its patents that have cited publications accounting for more than 50% of the total number of top three countries.

In addition, Germany, France, and Japan also have outstanding overall performance in terms of the number of patents that have cited publications in new energy research. Comprehensive analysis of the number of patents and their rankings shows that France spends more effort in promoting the technology transfer in biomass and hydrogen energy areas, while Japan pays more attention to the technology transfer in the areas of energy storage, energy internet and hydrogen energy, and Germany values more nuclear and wind energy technologies.

Table 3.1

Number of patents that have cited publications in new energy technologies research and the top three patentee countries

Technology areas	Patentee countries	Number of patents that have cited papers
Biomass energy	United States	108
	France	38
	Germany	34
Energy storage	United States	454
	Japan	137
	Germany	128
Hydrogen energy	United States	119
	France	45
	Japan	32
Nuclear energy	United States	16
	Germany	8
	United Kingdom	6
Solar energy	United States	398
	South Korea	156
	Saudi Arabia	151
Energy internet	United States	95
	Japan	56
	Germany	53
Wind energy	Germany	3
	France	2
	Luxembourg	1



3.2 New energy technology hotspots for the research community and industry

The Cooperative Patent Classification (CPC) is a patent classification system jointly developed by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO). It contains the technical information of the patent, which can be used to understand the main technical areas and technical focus of a patent. Based on the CPC classification, this report analyses the technical directions of patents that have cited academic papers on 20 technology themes in the new energy field for China and across the globe. The top five technical directions are listed in Table 3.2 and 3.3. In terms of the number of patents that have cited global publications, the top five technical directions revolve around battery energy storage, solar photovoltaic and fuel cell technology, while in terms of the number of patents that have cited publications for China, the technology hotspots are mainly in battery energy storage and solar photovoltaic technology. In general, lithium-ion batteries and organic solar cells are the technical hotspots of industrial transformation at home and abroad.

Among the 20 technology themes in the new energy field, in terms of the number of patents that have cited publications, the top three technologies are battery energy storage, biofuels and fuel cells. Based on the CPC classification, this study further analyses the technical directions of the above-mentioned three technologies and the top five technical directions are shown in Tables 3.4-3.6.

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For battery energy storage technology, the most citing CPC technologies focus on the lithium-ion battery, electrodes and electrolyte materials. To be specific, the "Li-accumulators" (H01M10/052) is a form of lithium-ion battery electrolyte, the "carbon or graphite" (H01M4/625) a typical battery cathode material, and the "Electrodes based on mixed oxides or hydroxides, or on mixtures of oxides or hydroxides, e.g. LiCoOx" (H01M4/131) are a typical battery anode material. As the most successfully commercialised battery technology in recent years, the lithium-ion battery has been applied in the fields of power supply and electric energy storage, and its key technical directions are in electrolytes and electrode materials. Therefore, the number of patents that have cited publications ranks high in battery energy storage.

In biofuel technology, most of the top five technical hotspots are related to cellulose, indicating that cellulosic biofuel is the hot direction for technology transfer. Currently, cellulose is the commonly used raw material for the second-generation biofuel technology to produce bioethanol, etc. As indicated in Table 3.5, substrates containing cellulosic material, monosaccharides, biocatalytic enzymes as represented by α-amylase, and cellulose pretreatments are hot directions of technology transfer for cellulosic biofuel research.

In fuel cell technology, the top five technology hotspots are related mainly to catalysts and electrolytes. To be specific, in catalyst research, the popular research directions include the characterisation of metal crystallite size (B01J35/006), catalysts containing coordination polymers (B01J31/1691) and the catalyst preparation method of impregnation (B01J37/0201). In electrolyte research, the main hotspots (Table 3.6) include macromolecular compounds (C08J5/2256) and polymeric electrolyte materials (H01M8/1018). The above-mentioned findings are related to the increasing commercialisation of polymer electrolyte fuel cells, as represented by proton exchange membrane fuel cells, in recent years.

Table 3.2

Top five technology hotspots based on the number of patents that have cited global publications (Data from CPC)

Classification number	Title	Number of patents that have cited papers
Y02E60/10	Energy storage	593
H01M10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries	278
Y02E10/549	Organic PV cells	239
H01M10/052	Li-accumulators	210
Y02E60/50	Fuel cells	203

Table 3.3

Top five technology hotspots based on the number of patents that have cited Chinese publications (Data from CPC)

Classification number	Title	Number of patents that have cited papers
Y02E60/10	Energy storage	198
H01M10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries	104
Y02E10/549	Organic PV cells	91
H01M10/052	Li-accumulators	60
H01M4/625	Carbon or graphite	59

Table 3.4 Top five technology hotspots based on the number of patents that have cited global publications in battery energy storage technology (Data from CPC)

Classification number	Title	Number of patents that have cited papers
Y02E60/10	Energy storage	192
H01M10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries	100
H01M4/625	Carbon or graphite	58
H01M10/052	Li-accumulators	57
H01M4/131	Electrodes based on mixed oxides or hydroxides, or on mixtures of oxides or hydroxides, e.g. LiCoOx	50

Table 3.5 Top five technology hotspots based on the number of patents that have cited global publications in biofuel technology (Data from CPC)

Classification number	Title	Number of patents that have cited papers
Y02E50/10	Biofuels	8
C12P7/10	Substrate containing cellulosic material	8
C12P19/02	Monosaccharides (2-ketogulonic acid C12P7/60)	6
C12P19/14	produced by the action of a carbohydrase (EC 3.2.x), e.g. by alpha-amylase , e.g. by cellulase, hemicellulase	6
C12P2201/00	Pretreatment of cellulosic or lignocellulosic materials for subsequent enzymatic treatment or hydrolysis	6

Table 3.6 Top 5 technology hotspots based on the number of patents that have cited global publications in fuel cell technology (Data from CPC)

Classification number	Title	Number of patents that have cited papers
B01J35/006	Metal crystallite size	4
C08J5/2256	based on macromolecular compounds obtained by reactions other than those involving carbon-to-carbon bonds, e.g. obtained by polycondensation	3
B01J31/1691	Coordination polymers, e.g. metal-organic frameworks [MOF] (preparation of metal complexes containing carboxylic acid moieties C07C51/418; MOF's per se C07F)	3
B01J37/0201	Impregnation	3
H01M8/1018	Polymeric electrolyte materials	3

3.3 Summary

This chapter uses patent metrics to make a quantitative analysis of the patents that have cited science and engineering papers, and reveals the industrial transfer opportunities of new energy technologies.

(1) According to the analysis of patents that have cited publications, the research on energy storage, solar energy and hydrogen energy technology has attracted the highest attention from domestic and foreign markets, while the technologies with relatively higher technology-transfer rates are energy storage, biomass energy and solar energy technology. In addition, the analysis of patentee countries reveals that the United States attaches more importance to the technology transfer of the new energy research output.

(2) Based on CPC classification analysis, the study of the hot technical directions of new energy technologies shows that industry as well as the research community at home and abroad are interested in battery energy storage and solar photovoltaic technology, with a particular focus on lithium-ion batteries and organic solar cells. The analysis of the top three hot technical directions in new energy technologies, in terms of number of patents that have cited publications, reveals that, for research into battery energy storage technology, industry and the research community focus on lithium-ion batteries, electrodes and electrolyte materials, while the biofuel technology focuses on substrates containing cellulosic materials, monosaccharides, biocatalytic enzymes as represented by α-amylase, and cellulosic pretreatment, etc. In addition, in fuel cell technology research, industry and research community focus is on the characterisation and preparation of catalysts and polymeric electrolyte materials.

Chapter 4

Comparative analysis of national research output in the new energy field

4.1 Comparative analysis of technology areas by countries

This chapter statistically analyses the top five countries (excluding China) and China in terms of the number of published papers in eight new energy research areas from 2015 to 2019. To be more specific, the comparative analysis is carried out in terms of the total number of publications, the average citation per paper and the number of top 10% highly cited papers covering different technology areas in various countries.

4.1.1 Solar energy

China ranks first in terms of the number of published papers in solar energy (25,244), and is followed by the United States (11,789) and India (7,551) (Table 4.1). In terms of average citations per paper, the United States tops the list with 35 average citations, while China ranks only fifth, with 20.8 average citations, after Germany (26.8), Japan (24.2) and South Korea (23.0). In terms of the number of top 10% highly cited papers, China produced 3,968 papers in solar energy, followed by the United States (1,943) and South Korea (626). To sum up, China has carried out a large volume of research work in the solar energy area, and has produced a substantial research output, some of which has created considerable impact, but the overall impact of the research output still has much room for improvement.

Table 4.1 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the solar energy area

Ranking	Countries	Number of publications
1	China	25,244
2	United States	11,789
3	India	7,551
4	South Korea	5,377
5	Germany	4,764
6	Japan	4,631
		Average citations
1	United States	35.0
2	Germany	26.8
3	Japan	24.2
4	South Korea	23.0
5	China	20.8
6	India	16.2
		Top 10% publications
1	China	3,968
2	United States	1,943
3	South Korea	626
4	United Kingdom	565
5	Germany	551
6	Japan	441

4.1.2 Wind energy

In terms of publications, China, the United Kingdom and the United States are the top three countries in the wind energy area, with China leading the way with 635 papers, indicating its research vitality. However, in terms of average citations per paper and the number of top 10% highly cited papers, China ranks only sixth and third, respectively, indicating that the overall impact of research output needs to be further strengthened (Table 4.2).

Table 4.2 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the wind energy area

Ranking	Countries	Number of publications
1	China	635
2	United Kingdom	610
3	United States	475
4	Germany	364
5	Norway	312
6	Denmark	284
		Average citations
1	United Kingdom	10.9
2	Denmark	9.0
3	United States	9.0
4	Norway	7.5
5	Germany	6.1
6	China	5.8
		Top 10% publications
1	United Kingdom	104
2	United States	72
3	China	68
4	Denmark	43
5	Norway	34
6	Germany	31

4.1.3 Geothermal energy

China has the largest number of published papers (358) in the geothermal energy area, followed by the United States (305), Germany (189), Japan (140), the United Kingdom (104) and Italy (94). In terms of average citations per paper, China ranks only fifth. In terms of the number of top 10% of highly cited papers, China ranks first (with 43), and the United States (41) and Germany (20) rank second and third, respectively (Table 4.3).
In general, China is slightly ahead of the United States in terms of the number of published papers and the number of top 10% highly cited papers in the geothermal energy area, but the overall impact of its research output lags considerably behind.

Table 4.3 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the geothermal energy area

Ranking	Countries	Number of publications
1	China	358
2	United States	305
3	Germany	189
4	Japan	140
5	United Kingdom	104
6	Italy	94
		Average citations
1	United States	12.4
2	United Kingdom	12.2
3	Italy	11.9
4	Germany	9.8
5	China	9.0
6	Japan	7.0
		Top 10% publications
1	China	43
2	United States	41
3	Germany	20
4	United Kingdom	15
5	Italy	13
6	France	12

4.1.4 Biomass energy

In terms of the number of publications, China ranks second (4,915) in the field of biomass energy, while the United States (5,580) ranks first. India (3,792), Brazil (2,513), the United Kingdom (1,407) and Germany (1,279) rank third to sixth, respectively. In terms of average citations per paper, China (14.6) ranks fourth globally, behind the top three of the United Kingdom (17.6), the United States (16.4) and Germany (14.7) (Table 4.4). In terms of the number of top 10% highly cited papers, China produces the most papers (743), followed by the United States (677). Therefore, China has a higher degree of research intensity in the biomass energy area, with a relatively large number of outstanding research papers, but the overall impact of research output needs to be further enhanced.

Table 4.4 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the biomass energy area

Ranking	Countries	Number of publications
1	United States	5,580
2	China	4,915
3	India	3,792
4	Brazil	2,513
5	United Kingdom	1,407
6	Germany	1,279
		Average citations
1	United Kingdom	17.6
2	United States	16.4
3	Germany	14.7
4	China	14.6
5	India	14.3
6	Brazil	9.9
		Top 10% publications
1	China	743
2	United States	677
3	India	428
4	United Kingdom	193
5	South Korea	152
6	Italy	142

4.1.5 Nuclear energy

In terms of number of publications, China ranks second in the nuclear energy area (5,043), with the United States topping the list with a slight advantage (5,129). The two countries are followed in the list by Japan (3,441), France (2,050), Germany (2,018) and Russia (1,813). In terms of the number of top 10 % highly cited papers, the United States (824) still tops the list, with China (559) in second place. In terms of average citations per paper, China ranks only fifth (4.3), and the top countries are the United States (7.8), Germany (7.7), France (6.1) and Japan (5.5) (Table 4.5). In conclusion, China has a reasonably large number of published papers and the top 10% of highly cited papers in the nuclear energy area, but the overall research impact is relatively small.

Table 4.5 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the nuclear energy area

Ranking	Countries	Number of publications
1	United States	5,129
2	China	5,043
3	Japan	3,441
4	France	2,050
5	Germany	2,018
6	Russia	1,813
		Average citations
1	United States	7.8
2	Germany	7.7
3	France	6.1
4	Japan	5.5
5	China	4.3
6	Russia	3.3
		Top 10% publications
1	United States	824
2	China	559
3	Japan	411
4	Germany	334
5	United Kingdom	266
6	France	256

4.1.6 Hydrogen energy

In the hydrogen energy area, China has an absolute lead in the number of publications (21,892), followed by the United States (8,413), Japan (4,317), India (3,635), South Korea (3,469) and Germany (3,105). In terms of average citations per paper, the United States ranks first (19.8), followed by China (17.9), Germany (15.7), South Korea (14.7), India (12.2) and Japan (10.8). In terms of the number of top 10% of highly cited papers, China (3,762) and the United States (1,264) rank first and second, respectively, followed by the United Kingdom (341), South Korea (329), Germany (320) and India (291) (Table 4.6). To sum up, both China and the United States have, to a certain degree, leading advantages in terms of research activity intensity and the impact of research output.

Table 4.6 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the hydrogen energy area

Ranking	Countries	Number of publications
1	China	21,892
2	United States	8,413
3	Japan	4,317
4	India	3,635
5	South Korea	3,469
6	Germany	3,105
		Average citations
1	United States	19.8
2	China	17.9
3	Germany	15.7
4	South Korea	14.7
5	India	12.2
6	Japan	10.8
		Top 10% publications
1	China	3,762
2	United States	1,264
3	United Kingdom	341
4	South Korea	329
5	Germany	320
6	India	291

4.1.7 Energy storage

China also has the obvious lead in publications in energy storage (36,569), followed by the United States (11,119), South Korea (5,448), Germany (3,402), India (3,380) and Japan (2,821). In terms of the number of average citations per paper, China (20.5) ranks fourth, behind the top three of the United States (32.2), Germany (23.8) and South Korea (21.3). In terms of the number of top 10% of highly cited papers, China ranks number one (4,860), followed by the United States (1,672), South Korea (469), Germany (317), the United Kingdom (205) and Japan (177) (Table 4.7). In conclusion, China has a relatively intense research activity in energy storage, and has produced a large number of highly cited research results, but the overall impact of research output still lags behind the United States, Germany, South Korea and other leading countries in energy storage technology.

Table 4.7 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the energy storage area

Ranking	Countries	Number of publications
1	China	36,569
2	United States	11,119
3	South Korea	5,448
4	Germany	3,402
5	India	3,380
6	Japan	2,821
		Average citations
1	United States	32.2
2	Germany	23.8
3	South Korea	21.3
4	China	20.5
5	Japan	17.0
6	India	12.9
		Top 10% publications
1	China	4,860
2	United States	1,672
3	South Korea	469
4	Germany	317
5	United Kingdom	205
6	Japan	177

4.1.8 Energy internet

In energy internet, China is first in terms of research papers publications (12,478), followed by the United States (8,908), the United Kingdom (3,321), India (3,253), Germany (2,772) and Italy (2,191). In terms of average citations per paper, China ranks fifth, with the top four countries being the United Kingdom (14.1), the United States (13.5), Italy (10.9) and Germany (9.3). When it comes to the number of top 10% of highly cited papers, China ranks first (1,521), followed by the United States (1,287) and the United Kingdom (527) (Table 4.8).
To sum up, China's research output in global energy internet is substantial, and the size of high quality research output is also large, but the overall impact of the research output is still wanting.

Table 4.8 Number of publications, average citations per paper: the top 10% publications by countries (top six) in the energy internet area

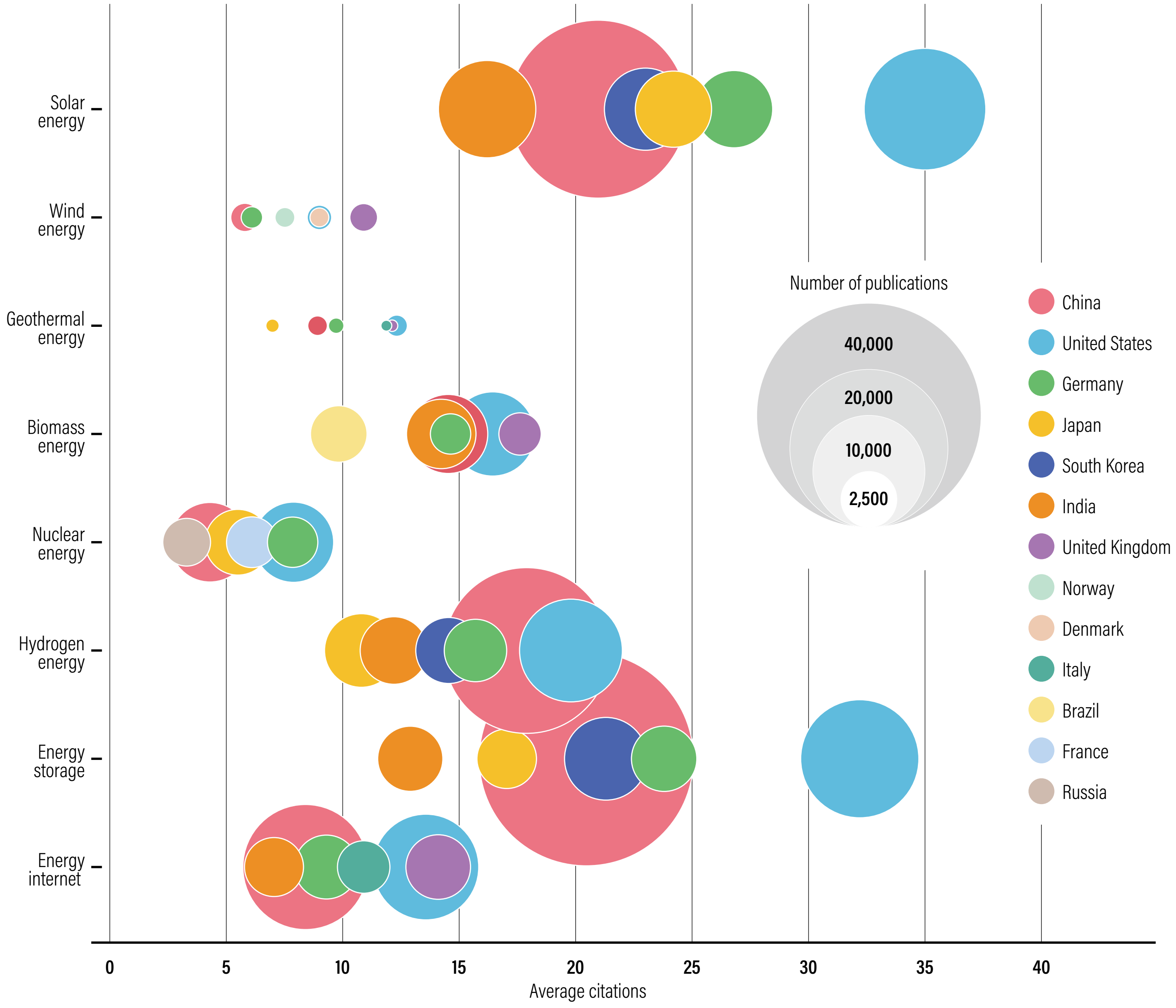
Ranking	Countries	Number of publications
1	China	12,478
2	United States	8,908
3	United Kingdom	3,321
4	India	3,253
5	Germany	2,772
6	Italy	2,191
		Average citations
1	United Kingdom	14.1
2	United States	13.5
3	Italy	10.9
4	Germany	9.3
5	China	8.4
6	India	7.0
		Top 10% publications
1	China	1,521
2	United States	1,287
3	United Kingdom	527
4	India	249
5	Italy	247
6	Germany	221

4.2 Overall comparison of countries by technology areas

In terms of the ranking of research activity intensity (the number of publications) and the impact (average citations per paper) in the eight technology areas of the new energy field (Figure 4.1), all the technology areas of the United States, China and Germany are in the top six, indicating the comprehensive planning and strong research strength of these countries in the field. In terms of research activity, China has a high ranking in six technology areas, with obvious leads in energy storage, solar energy and hydrogen energy, while the United States enjoys an obvious lead in biomass energy and nuclear energy. In terms of research impact, the United States has a clear lead, ranking in the top three in all the eight technology areas when it comes to average citations per paper. Its lead, compared with China, is especially obvious in energy storage, solar energy and nuclear energy.

Figure 4.1

Benchmarking of China and the top five countries (excluding China)



4.3 Summary

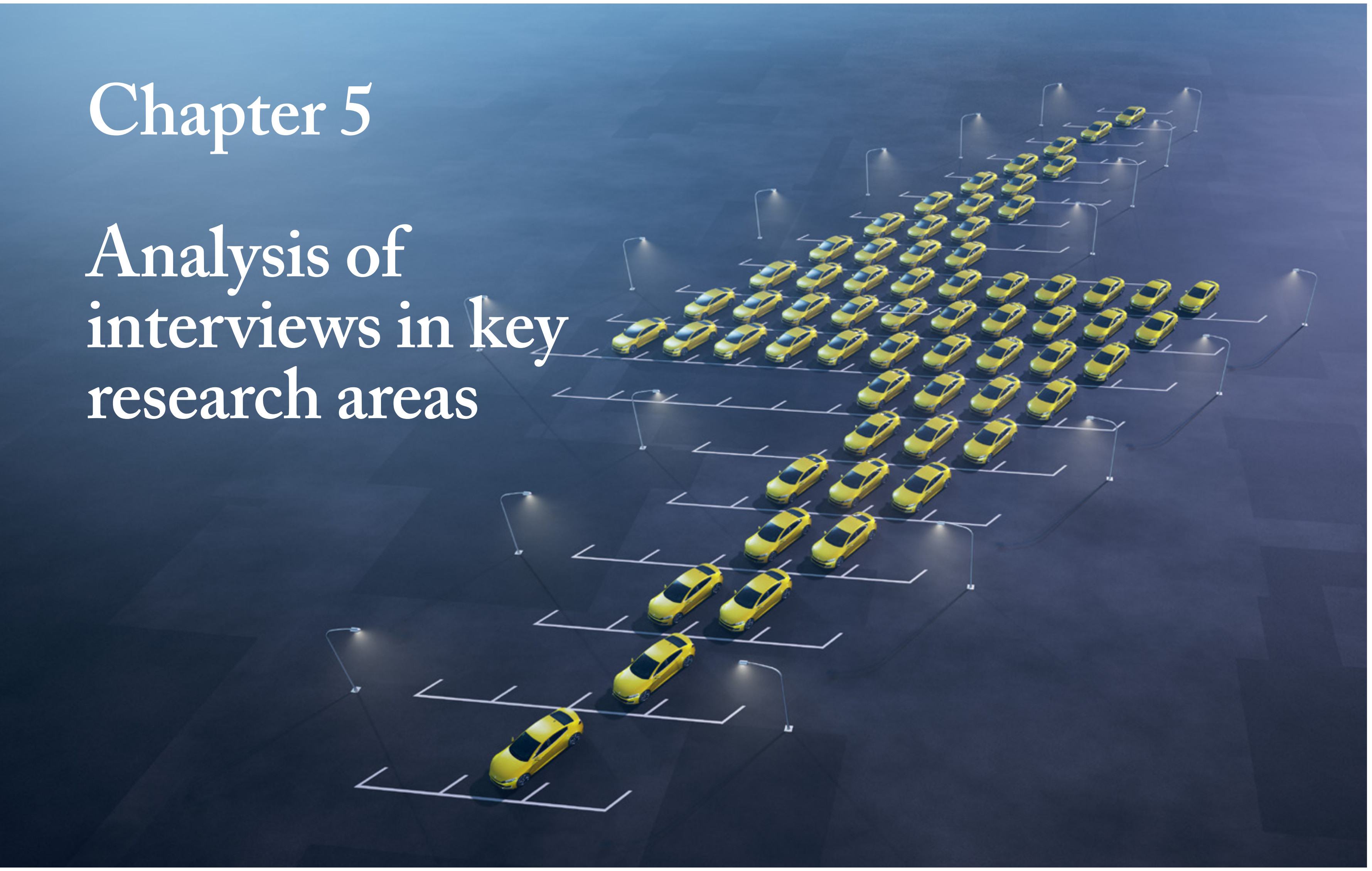
This chapter is devoted to the comparative study of national competitiveness through the analysis of three performance metrics of individual countries, including the number of publications, the average citations per paper, and the number of papers in the top 10% of highly cited papers. The conclusions are as follows:

(1) In terms of the ranking of research activity intensity (the number of publications) and the impact (average citations per paper) in eight technology areas in the new energy field (Figure 4.1), all the technology areas of the United States, China and Germany are in the top six, indicating the comprehensive planning and strong research strength of these countries in the field. In terms of average citations per paper, the United States is ranked in the top three in all eight technology areas, showing the higher overall impact of its research output.

(2) In terms of number of publications, China is ranked in the top two in all eight technology areas, indicating its substantial research output in the new energy field, as well as its intensity of research activity. A comprehensive analysis of the average citations and the number of top 10% highly cited papers shows that China ranks high in terms of the number of highly cited papers in all technology areas, but in terms of average citations per paper, China is down the country ranks in most technology areas, indicating that its overall impact of research output needs to be further enhanced.

Chapter 5

Analysis of interviews in key research areas



Society has entered the fourth industrial revolution. Rapid breakthroughs in digital technology, internet information technology, and new energy and renewable energy technologies have provided the stimulus for the rapid development of emerging industries and pushed society towards a path of efficient, green, intelligent and ecologically sustainable development. The comprehensive analysis of global new energy research in this report shows that the growth in the quantity and quality of global papers in new energy fully reflects the research community's immense interest and R&D investment in basic theoretical research and breakthroughs in the key scientific questions in this field.

For renewable energy, the progress in solar photovoltaic power generation technology and wind power generation technology and the rapid cost reduction will lead to the dramatic increase in global installed capacity, followed by a significantly increased pace in R&D into solar fuel, biomass utilisation, offshore wind and geothermal energy, reflecting societal expectation for unleashing of the potential for all kinds of renewable energy resources. In the field of new energy, hydrogen energy – as a secondary energy with zero-carbon emission – has become a global research hotspot in recent years. It will not only change the energy structure for transport systems, it is also expected to play an important role in renewable energy power integration, increasing the resilience and flexibility of the energy system. Energy storage and energy internet technologies also show a high degree of research activity intensity, indicating that the risk factors and crucial links of the future energy system have become new research hotspots, in areas such as multi-energy coupling, digital transformation, smart control and demand-response.

To sum up, the increasing risk of climate change urgently calls for energy transformation. All countries are trying to improve their competitiveness of energy science and technology innovation, and enhance the competitive edge of their emerging energy industry. This will become the strong driving force for the continuously active scientific research in the new energy field with the aim of multi-point breakthroughs.

5.1 Energy storage technology providing necessary support to the large-scale development of renewable energy and electric vehicles

Energy storage technology has become an integral part of the modern energy system. Energy storage has received extensive and continuous attention from the research community over a period of 20 years. Among the 20 technology themes in global new energy research, the overall performance score of battery energy storage technology in the field of energy storage ranks first in terms of the number of publications and its growth rate.

Renewable energy power generation, smart grids, distributed multi-energy complementary systems, and electric vehicles are key directions for countries across the globe to realize the transition to a low-carbon power system. What's more, energy storage technology provides the indispensable technical support for realising that transformation, and it is a key node of the soft link in the future energy system, characterised by flexibility, inclusiveness and balanced functions.

On the power supply side, the breakthroughs and application of large-capacity and large-scale energy storage technology will efficiently solve the randomness and volatility of renewable energy utilisation, and greatly reduce the wind and photovoltaic energy curtailment and the dependence of power system on base load supply.

On the demand side, energy storage technology can break through the temporal and spatial paring limitations on both sides of power supply and demand, shift the demand peak and fill the valley, and modulate frequency and amplitude to achieve efficient, flexible and low-cost system operation. In addition, the more prominent contribution of energy storage technology advancement is the driving of the development of power batteries, in a bid to solve the problem of a clean energy substitute for fuel energy in transport, comply with the forbiddance of high-carbon energy in the transport sector and facilitate the development of the electric vehicle industry.

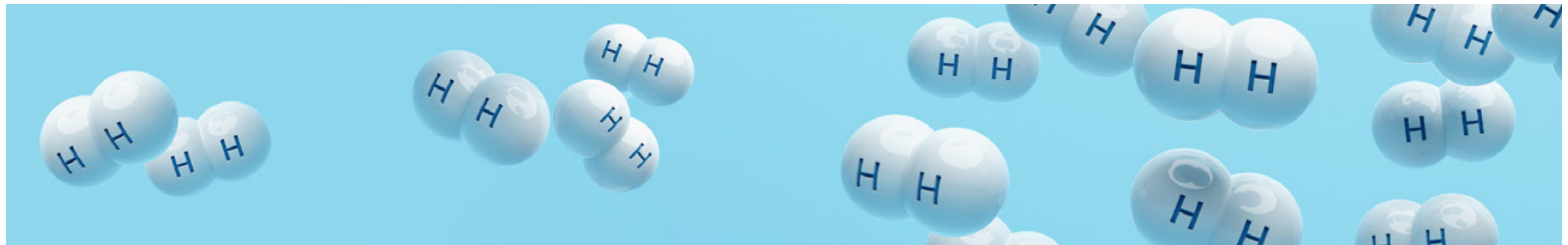
China's energy storage industry has risen rapidly to the forefront of the world energy landscape. According to the Energy Storage Industry Research White Paper 2020, jointly released by the Special Committee on Energy Storage of China Energy Research Society and other institutions, the global accumulative installed capacity of battery energy storage in 2019 was 9,520.5MW, of which the lithium-ion battery energy storage accounted for 88.6%.

Although China's energy storage industry came into being rather late, its development momentum in recent years has been remarkable. The cumulative installed capacity of battery energy storage that has been put into operation has reached 1,709.6MW, of which the lithium-ion battery energy storage accounts for 60%. From 2015 to 2019, the accumulative installed capacity of lithium-ion battery energy storage has experienced average year-on-year growth of more than 100%. As the industry crucial in connecting and supporting the three key industries endorsed in the "12th Five-Year Plan" (2011-2015) and the "13th Five-Year Plan" (2016-2020) – namely the new energy industry, the new energy vehicles industry and the new materials industry – the development of the energy storage battery industry has been encouraged by a series of polices from the Chinese government, and the research and development of its core technologies has been listed as the key directions for breakthroughs.

The rapid development of the electric vehicle industry, in particular, has led to the continuous high-speed growth of China's energy storage battery market.

Innovative breakthroughs have been achieved during the rapid development of core energy storage battery technologies. With the extensive application of energy storage technologies in energy production, consumption and the transition to low-carbon and smart energy, it is increasingly urgent to improve the safety, energy density, battery capacity, endurance capacity and service life of energy storage batteries, while reduce the costs of these products. The bibliometric and patent analyses of this report show that battery materials such as electrode materials and electrolytes are the research focus for improving the performance of batteries. The leading expert in this field believed that lithium-iron phosphate (LFP) and ternary lithium batteries have become the main technical direction for battery material innovation.

The breakthrough routes for improving battery performance mainly include the innovation of the energy storage battery system structure, optimisation of pack volume use, improvement of battery energy density and safety, and significant reduction of battery cost. For example, Contemporary Amperex Technology Co. Limited (CATL) has come up with the CTP (cell to pack), and BYD auto has released the 'blade battery'. In addition, due to the significant cost reduction of photovoltaic (PV) and wind power, the scale of centralised renewable energy power generation will continue to expand, while the potential for distributed renewable energy power generation will also be released. Also, accelerated growth is expected in distributed multi-energy complementary systems deployed at green electricity production bases, industrial parks, building clusters, as well as in installed capacity of energy storage battery in independent renewable energy systems, which urgently requires continuous breakthroughs in core energy storage battery technologies. In addition, the battery decay and waste disposal of electric vehicles also needs to be actively addressed.



5.2 Hydrogen energy, under the global spotlight, is gradually becoming an indispensable element of the future energy system

In the energy system of the future, hydrogen energy will be an important secondary form of energy, with zero carbon emissions. The research on hydrogen production, storage, and transport, and the utilisation of hydrogen energy, is growing rapidly. As the first technical direction to receive considerable attention in the hydrogen energy area, hydrogen fuel cells or hydrogen engines can transform traditional transportation systems, and solve the problem of urban air pollution and decarbonisation caused by the fuel consumption in the transport sector. With the rapid increase of the scale of renewable energy power generation, the integration capacity of the power grid has become a bottleneck. Water Electrolysis for Hydrogen Production can flexibly integrate the wind and photovoltaic energy curtailment, and the scale of photovoltaic and wind power generation can break free of the limitations of the demand from the consumer side and the integration capacity of the power grid. Meanwhile, hydrogen production from renewable energy will become a sustainable source of green hydrogen.

Hydrogen energy is an important element in the push towards the deep decarbonisation of the energy system. Since the signing of the Paris Agreement, countries around the world have been under immense pressure to save energy and reduce emissions. The development of hydrogen energy has become an important element in facilitating the deep decarbonisation of transport and industry. Since 2018, many countries, including Japan, South Korea, Australia, the United Kingdom and France, have released their latest planning in the field of hydrogen energy. Japan has set a specific goal that by 2025 hydrogen energy will be fully popularised in transport, and its application in power generation, industry and households will be expanded. What's more, by 2030, the cost of hydrogen energy will be no higher than that of traditional energy. The EU Hydrogen Strategy released in July 2020 puts forward the TOWARDS A HYDROGEN ECOSYSTEM IN EUROPE: A ROADMAP TO 2050, which states that the goal before 2030 is to rapidly reduce carbon emissions from the hydrogen production process and develop other forms of low-carbon hydrogen to support the transition to renewable-energy hydrogen production. In addition, the EU has evaluated the contribution of hydrogen energy to the realisation of climate-neutral aviation and believes that hydrogen-powered aviation has the potential to become an intrinsic part of the future aviation technology portfolio.

China is active in the R&D of key technologies of hydrogen energy. The earliest planning of hydrogen energy development in China is the listing of hydrogen fuel cell vehicles as one development direction of new energy vehicles. However, compared with pure electric vehicles and hybrid vehicles, hydrogen-fuel-cell vehicles are still in the demonstration stage, due to the constraints of hydrogen production technology, the high cost of hydrogen fuel cells and the layout of hydrogen stations. In the Government Work Report in 2019, China included hydrogen energy in its energy mix for the first time. Local governments with the capacity to develop hydrogen energy have also included the building of hydrogen energy industry chains and a hydrogen energy utilisation demonstration in their Energy Development Plans of the 14th Five-Year Plan (2021-2025).

Correspondingly, China is at the forefront of key research areas such as hydrogen production, hydrogen storage and hydrogen refuelling. In order to achieve the goal of being carbon neutral by 2060 in China, hydrogen energy in future will not only be used as clean, zero-carbon power in road transport, water transport and aviation, but will also change some energy-consuming processes in high-carbon industries that are difficult to be replaced by electricity. In addition, China's renewable energy resource endowment is not spatially consistent with the areas with heavy energy demand, while hydrogen energy will play an important role as a feedstock, a form of energy storage and carrier, and an intermediate material in the transformation of renewable energy into electricity, fuel and bulk chemicals. This will accelerate the shift towards low carbon in China's energy system.

5.3 The R&D of solar fuel technology is the research front of new energy technology

The R&D of zero-carbon solar fuel technology enjoys close attention from the research community. Solar fuels include photocatalytic hydrogen production and photocatalytic reduction of CO_2, preparation of carbon-based fuels and high-value chemicals, artificial photosynthetic systems and so on. Solar fuel research is at the forefront in terms of both the number of publications and attention received, indicating mankind's constant pursuit of harnessing sustainable natural resources (water, CO_2) and energy (solar energy), so as to obtain green fuels through more ecological and efficient conversion mechanisms. Photocatalytic water splitting for hydrogen production – that is, direct decomposition of water for hydrogen production by solar energy photocatalysis – is the earliest step in studying solar fuel preparation. However, at present photocatalytic hydrogen production is still in the laboratory research stage. Seeing that hydrogen production can become practical in application only when it reaches 1,000 cubic metres per hour, there is still a long way to go before photocatalytic water splitting for hydrogen production is used for practical application, especially taking into account that the efficient photocatalyst is still in the bottleneck stage of R&D in the new energy field.

Electrocatalytic technology has accelerated the development of solar fuel. Technological progress in solar energy power generation and wind power generation has led to a rapid lowering of costs, with the resultant competitiveness in the market. The significant increase in installed capacity of global photovoltaic power generation and wind power generation has driven the use of renewable energy electricity for Water Electrolysis for Hydrogen Production, which has quickly become a green, sustainable route for solar fuel production. In addition, hydrogen and carbon dioxide (CO_2) can be converted, through catalytic reaction, into hydrocarbon fuels such as methanol, which is a carrier of hydrogen with the advantage of reducing the safety risk of hydrogen storage and transport. At the same time, carbon dioxide can be reduced into chemicals. For instance, the Chinese Academy of Sciences has proposed a technical route of low-carbon multi-energy integrated preparation of liquid fuels and chemicals that has made breakthroughs in efficient, cheap and stable water splitting photoelectric catalyst technology and cheap, high selectivity catalytic carbon dioxide hydrogenation to methanol. Using wind and photovoltaic power generation for Water Electrolysis for Hydrogen Production as the intermediate step, this route obtains methanol by synthesising hydrogen and carbon dioxide.

In recent years, the use of High Concentrated Photo Voltaics for the preparation of fuels has gradually become the research front for basic research. For instance, the thermal chemical decomposition of carbon dioxide and water by solar energy will produce hydrocarbons. Another example is the production of hydrogen through the chemical chain of methane driven by High Concentrated Photo Voltaics.

Reducing the preparation cost of solar energy fuel is vital to industrialisation. Hydrogen is a basic raw material for the petrochemical industry. Renewable energy power generation enables the production and supply of electricity at affordable prices, thus promoting the indirect access to solar energy through Water Electrolysis for Hydrogen Production, and making possible the obtaining of hydrogen-based chemicals and hydrocarbon fuels through different process routes. The bibliometric analysis of this report reveals the research fronts in the field of hydrogen energy research around the world, including how to reduce the cost of Water Electrolysis for Hydrogen Production, and the safety risk of hydrogen energy storage, transport and utilisation.

5.4 The energy internet integrates new crossover technologies such as intelligent energy, big data and the internet of things

Energy internet is a new type of infrastructure for modern energy systems. With the increasing demand for energy and the emergence of the trend towards electrification, the formation of a diversified energy structure dominated by oil, gas, coal and renewable energy in the future will be accelerated, and the transition to a non-fossil-energy structure will be completed by the middle of this century. While the energy technology innovation in individual energy areas are still significant, it is becoming increasingly urgent and compulsory to achieve the system technology breakthroughs, such as the integration and combination of multiple energies and its further matching, smart operations, the two-way interaction of supply and demand, and multi-web interaction systems. At the same time, modern energy systems definitely need support from the integration of cross-disciplinary sciences and technologies, such as big data mining, information flow management, detection and network ubiquity, and decision optimisation. The bibliometric analysis and patent analysis in this report finds that four technologies enter the Top 10 technology themes with the most promise: the architecture and the core equipment technologies of energy internet, management technologies of energy internet, and technologies underlying the energy internet system integration. This fully demonstrates the importance of the research on modern energy systems featuring energy internet.

China still needs to strengthen its research into core technologies of energy internet. In terms of the total number of published papers in the field of new energy research in China from 2015 to 2019, the energy internet technology ranks fourth, and the number of publications in two technology themes of the energy internet experienced rapid growth, namely "technologies underlying the energy internet system integration" and "management technologies of the energy internet". In addition, the comparison among countries reveals that China has published the most papers in the energy internet area and the number of highly cited papers also ranks highly, indicating that the Chinese research community pays great attention to the theoretical frontier research of energy internet, and China has certain competitiveness in energy internet research. However, China ranks only fourth in terms of average citations per paper, indicating that the quality and impact of Chinese research papers still have a gap to close with the United Kingdom and the United States, and that it is necessary to strengthen and improve research in this area.

Applied basic research and technology development will enjoy continuous attention. In the scenario of a carbon-neutral global landscape, the energy system will be characterised by diversity, intelligence, safety and flexibility, highlighting the importance of energy internet technology and smart technology, and indicating that applied basic research and applied technology R&D will receive continuous attention. However, for the time being, energy internet research still needs to focus on the following problems.

First, special attention should be given to the research of architecture and core equipment technologies of the energy internet, and technical breakthroughs should be made in the intelligent transformation of energy production and consumption, energy system planning, multi-energy flow energy switching and routing technology, intelligent energy transmission technology, and intelligent network coordinated control technology. Second, focus should be given to the research of energy systems' big data acquisition, and mining and utilisation technology, with projected breakthroughs in energy internet communication, the integration of energy information technology with Cyber-Physical Systems, energy big data application technology, management technologies of the energy internet and so on. Third, attention should be given to the practical energy internet technology transfer and application, with expected breakthroughs in research design, demonstration application and practical implementation of multi-disciplinary information network infrastructure and energy infrastructure chains.

5.5 Summary

At present, more than 120 countries and regions around the world have made or are in the process of making commitments to the target of carbon neutrality by the middle of this century. As a necessary pathway to achieve carbon neutrality, there is an urgent need to step up the process of integrating new energy and renewable energy into the mainstream of the energy system. This transformative energy transition will orchestrate major innovations in energy knowledge and technology systems, promoting breakthroughs in basic theory, technological chains and industrial models. Based on bibliometric and patent analyses, it is difficult for this report to accurately predict quantitatively the future technology research and industrial development. However, the conclusion of this study presents the current hot spots of basic research and applied basic research with the highest growth potential and attention in the global new energy field.

In the field of new energy technologies, the research strength and level of Chinese scholars are constantly improving, especially in energy storage, solar energy, hydrogen energy and biomass energy. In addition, the scale and development speed of China's new energy industry are among the best in the world. It is imperative to grasp the opportunities in new energy development, and efforts should be made to strengthen original innovation, both in theory and technology, disruptive innovation and integration of reconstruction innovation, so as to meet the major science and technology needs of the international research frontier and the transition of China's energy system to one that is green and low carbon. At the same time, based on the huge market for the development of the Chinese new energy sector, efforts should be made to speed up technology transfers and cost reductions, so as to gain competitiveness in science and technology innovation, as well as in the market.

Chapter 6

Conclusions and implications

New energy technology innovations and disruptive energy technology breakthroughs have evolved as the key means to continuously change the world energy landscape and enable the carbon neutral actions of all countries across the globe. In the new energy race, the major countries and regions in the world are focusing on the development of new energy technologies to lead the latest round of the energy revolution. With the strong support of various energy technology planning and R&D funds, global energy technology innovations are continuing to emerge, and the interest from around the world is unprecedentedly high in researchers in new energy technology.

Based on the Dimensions database of Digital Science, this study, adopting the methodology of bibliometric analysis and interviews with leading experts, reviews the literature in 20 technology themes in eight new energy research areas over the 2000-2019 period and objectively reveals, from a global perspective, the development trends and research hotspots of the new energy technology field, in order to present the implications of scientific research directions related to global energy, and to support China's energy strategic planning.

From the perspective of global energy research:
Firstly, global research in the field of new energy is entering a period of rapid growth, to which the Chinese researchers have made prominent contributions. In the 2015-2019 period, researchers around the world have published almost 390,000 papers in eight new energy areas, namely solar energy, hydrogen energy, energy internet, energy storage, nuclear energy, biomass energy, wind energy and geothermal energy, with a CAGR of 9.9%, reflecting the continuously rising interest in global research of new energy technologies.

More specifically, in terms of the number of publications, the contribution of Chinese researchers in the above-mentioned eight areas reaches as high as 25.9%, and its impact (as indicated by average citations per paper) in individual areas is higher than the global average, fully reflecting the rapid rise of China in the field of new energy research.

In addition, the new energy areas that have produced the most papers globally in the past five years are solar energy, energy storage and hydrogen energy, while the top three technology themes with the most promising prospects are battery energy storage technology, solar photovoltaic technology and solar fuel technology.

In light of the research trends in the new energy technology field, the government should study the policy measures that could promote new energy technology innovation, further increase financial investment in R&D of new energy technologies and their innovations, and actively guide and support the joint research of the research community and industry in the innovation of new energy technologies so as to promote rapid breakthroughs in these technologies. From a global perspective, China can serve as an important link in promoting collaborative research in this field.

Secondly, the industry-academia-research integration in new energy technologies still needs to be strengthened, given the low rate of cross-citation between patents and publications on new energy technologies. In terms of the percentage of publications cited by patents out of the total publications in the new energy field, the technology transfer rate in energy storage, biomass energy and solar energy is relatively high. Lithium-ion batteries and organic solar cells are the global technical hotspots. In terms of country difference, China's transfer of research output in new energy technology is close to the global average; in comparison, the overall transfer of research output in the United States is relatively high, while Germany, France and Japan also have prominent performances.

In the future, how to give full play to the pivotal role of the consortia of industry-academia-research in breaking the bottleneck of key technologies is the game changer to determine whether the new energy technology can be transformed into productivity.

In the shift from the development pattern relying on scale expansion to quality development, China needs to take the lead in exploring and promoting the actual contribution-oriented evaluation and incentive mechanism, where the quality of scientific and technological output in new energy industry is valued, encourage new energy enterprises to directly participate in the innovation process, and adhere to problem-oriented research, so as to promote the transfer of science and technology research output.

Thirdly, the leading countries in new energy research have made major contributions to the development of new energy, but there are differences in research efficiency. In terms of the number of publications, China ranks the global top two in eight new energy areas, indicating its intense research activity in major directions of new energy research. Comprehensive analysis of the research impact (average citations per paper and the number of highly cited papers) in eight technology areas shows that China ranks in the top six in terms of the number of highly cited papers, but well down the country ranks in terms of average citations per paper in most technology areas. This indicates that China needs to improve the efficiency in new energy technology research.

By contrast, the United States and Germany enjoy higher research efficiency in the field of new energy technology, because both the number of publications and the research impact of the two nations are at the forefront of global new energy research.

The past 20 years have witnessed the rapid development of new energy technologies, and the total research output and high quality research of individual countries play an important role in promoting the development of new energy. For the next development stage, all countries should give special attention to the efficiency of high-quality research incubation, while maintaining the volume of research output, so as to improve the competitive edge in the field.

From the perspective of supporting China's strategic energy planning:
First, breakthroughs in large-scale energy storage technology and their popularisation provide strong support for the development of renewable energy. The rapid rise of renewable energy, such as wind and solar, as well as the smart grid industry, has made energy storage technology a technical barrier that countries around the world need to overcome. Efficient large-scale energy storage technology is the key technology for realising the popularisation and application of renewable energy. It can solve the dilemma of the time difference between power generation and electricity consumption, and can accommodate the impact brought about by the direct grid-connection of intermittent renewable energy power generation. It is a key soft link node of the future energy system characterised by flexibility, inclusiveness and balanced functions. China should further optimise the policy mechanism to promote the development of the energy storage industry, orchestrate long-term capital investment through financial and market-oriented measures, build a reserve system for energy storage technology innovation, strengthen research on the integrated application of new energy and energy storage, and step up the breakthroughs in large-scale energy storage technology and their commercial applications.

Second, hydrogen energy will be an important medium for building the future energy system and realize energy transformation. With the global transition to a low-carbon and zero-carbon society, the breakthrough in the use of hydrogen energy technology becomes an important direction for the development of clean energy. A number of countries and regions around the world have issued strategic roadmaps for the development of hydrogen energy and have undertaken hydrogen energy planning from a national strategy perspective. As an important energy medium for the coordinated, complementary and optimised interconnection of various energy networks, hydrogen energy can improve the utilisation rate of renewable energy, help realize the coupling of the power grids and gas networks, increase the flexibility of power systems, and at the same time can fulfill the function of energy storage: energy integration and storage can be realized through renewable energy water electrolysis for hydrogen production.

Therefore, it is necessary to strengthen the top-level design of hydrogen energy development, clarify the large-scale application scenarios, reasonably propose the hydrogen energy development roadmaps under various scenarios, and formulate corresponding standards and specifications, so as to accelerate the development of industrial chains, such as green hydrogen production, storage, transport, and their applications.

Third, breakthroughs in solar fuel technology and its cost reduction may help reduce the dependence on oil. Solar fuel synthesis technology is gradually transiting from basic scientific research to feasible industrial technology, which is expected to fundamentally change the status of over-reliance on fossil resources in energy and chemical sectors. The progress of solar power generation technology and wind power generation technology will further reduce the cost of power generation, enabling renewable energy water electrolysis for hydrogen production to quickly become a green and sustainable route for solar fuel production. The cost reduction and efficiency improvement is the key challenge in using solar energy to turn water and carbon dioxide into fuel or chemicals.

China should continue to intensify the research and development of solar fuel technology, strengthen the R&D of integrated application technology of solar power generation and construction infrastructure etcetera, select areas with abundant sunlight resources to carry out pilot and demonstration projects, and step up the industrialisation process of solar technology.

Last but not least, energy internet will bring dual advantages of the "internet +" and intelligent energy into full play, helping to realize coordinated optimal allocation of energy resources. Energy internet can realize the reconstruction of the energy production and consumption order. It can also integrate energy production, transport, storage, consumption, market operation and other links with information communication technology, hence creating new business models to realize a new energy ecosystem of energy sharing. The construction of energy internet needs to strengthen the integrated application of mobile internet, cloud computing, big data and internet of Things technologies in an intelligent grid, build financial support platforms, strengthen the management system of shared energy infrastructure construction, realize the marketing of energy internet, and build a safe, efficient and sustainable smart energy system.

China should actively promote research and development of key technologies for energy internet, strengthen connectivity among the various energy networks, promote the construction of comprehensive energy network infrastructure, and improve the energy internet service and management, as well as the operation mechanism.

Appendix

Table 1.1 20 technology themes in eight new energy technology areas

Technology areas	Technology themes
Solar energy	Solar photovoltaic technology
	Solar thermal power generation technology
	Solar fuel technology
Wind energy	Onshore wind technology
	Offshore wind technology
Geothermal energy	Hot dry rock technology
	Hydrothermal geothermal technology
Biomass energy	Biomass power generation technology
	Biofuel technology
Nuclear energy	Nuclear fission energy technology
	Nuclear fusion energy technology
Hydrogen energy	Hydrogen production technology
	Hydrogen storage technology
	Hydrogen transport technology
	Fuel cell technology
Energy storage	Battery energy storage technology
Energy internet	Architecture and core equipment technologies of energy internet
	Deep integration technologies of energy and information
	Technologies underlying the energy internet system integration
	Management technologies of the energy internet

Table 1.2 Top 10 highly cited papers in individual new energy technology areas

Technology areas	Titles of the published paper	Citations
Biomass energy	Occurrence of the potent mutagens 2- nitrobenzanthrone and 3- nitrobenzanthrone in fine airborne particles	2,262
	Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review	1,048
	Pretreatment of lignocellulose: Formation of inhibitory by-products and strategies for minimizing their effects	724
	Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach	723
	Review and evaluation of hydrogen production methods for better sustainability	657
	Microalgae biorefinery: High value products perspectives	638
	Paving the Way for Lignin Valorisation: Recent Advances in Bioengineering, Biorefining and Catalysis	628
	Bioenergy and biofuels: History, status, and perspective	622
	Cell disruption for microalgae biorefineries	576
	Waste biorefinery models towards sustainable circular bioeconomy:Critical review and future perspectives	568
Energy storage	Li-ion battery materials: present and future	8,552
	Sodium-ion batteries: present and future	6,048
	Hierarchical porous nitrogen-doped carbon nanosheets derived from silk for ultrahigh-capacity battery anodes and supercapacitors	4,716
	Electrochemical capacitors: mechanism, materials, systems, characterization and applications	3,585
	Metallic 1T phase MoS2 nanosheets as supercapacitor electrode materials	3,357
	Advances in lithium–sulfur batteries based on multifunctional cathodes and electrolytes	3,260
	Lithium battery chemistries enabled by solid-state electrolytes	3,092
	30 Years of Lithium-Ion Batteries	2,940
	A phosphorene–graphene hybrid material as a high-capacity anode for sodium-ion batteries	2,828
Geothermal energy	Laboratory simulation of binary and triple well EGS in large granite blocks using AE events for drilling guidance	912
	A global review of enhanced geothermal system (EGS)	744
	Enhanced geothermal systems (EGS): A review	393
	A review of geothermal energy resources, development, and applications in China: Current status and prospects	320
	A simplified coupled hydro-thermal model for enhanced geothermal systems	304

Geothermal energy	Numerical simulation of the heat extraction in EGS with thermalhydraulic-mechanical coupling method based on discrete fractures model	300
	Assessing whether the 2017 Mw 5.4 Pohang earthquake in South Korea was an induced event	285
	Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells	280
	A review of developments in carbon dioxide storage	256
	Designing multi-well layout for enhanced geothermal system to better exploit hot dry rock geothermal energy	252
Hydrogen energy	Recent Advances in Electrocatalysts for Oxygen Reduction Reaction.	7,125
	Noble metal-free hydrogen evolution catalysts for water splitting	4,122
	An efficient molybdenum disulfide/cobalt diselenide hybrid catalyst for electrochemical hydrogen generation	2,720
	A review on g-C3N4-based photocatalysts	2,490
	Recent advances in transition metal phosphide nanomaterials: synthesis and applications in hydrogen evolution reaction	2,190
	Recent Progress in Cobalt-Based Heterogeneous Catalysts for Electrochemical Water Splitting	2,098
	A metal–organic framework-derived bifunctional oxygen electrocatalyst	1,970
	Recent advancements in Pt and Pt-free catalysts for oxygen reduction reaction	1,954
	Design of electrocatalysts for oxygen- and hydrogen-involving energy conversion reactions	1,803
	Efficient hydrogen evolution catalysis using ternary pyrite-type cobalt phosphosulphide	1,800
Nuclear energy	Magnetospheric Multiscale Overview and Science Objectives	523
	Inertial-confinement fusion with lasers	510
	NB-CNN: Deep Learning-Based Crack Detection Using Convolutional Neural Network and Nave Bayes Data Fusion	412
	Long-term storage of spent nuclear fuel	372
	Umbellate distortions of the uranyl coordination environment result in a stable and porous polycatenated framework that can effectively remove cesium from aqueous solutions	358
	Managing the Risks of Organizational Accidents	346
	Research progress of perovskite materials in photocatalysis- and photovoltaics-related energy conversion and environmental treatment	342
	Review of supercritical CO2 power cycle technology and current status of research and development	325
	In-situ TEM observation of the response of ultrafine- and nanocrystalline-grained tungsten to extreme irradiation environments	312
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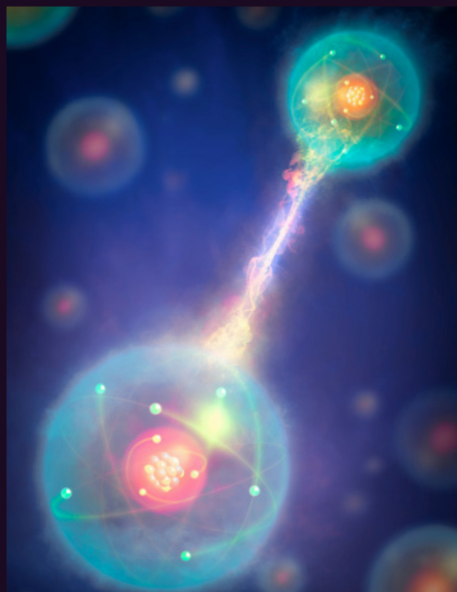

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