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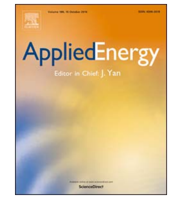

Global transition to low-carbon electricity: A bibliometric analysis

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HIGHLIGHTS

- Since 1990, 13,767 publications have addressed decarbonization of electricity systems.
- Bibliometrics and novel graphics are used to characterize this field of research.
- Successful research involves a range of inter-institutional collaborations.
- We describe three phases of the global transition to low-carbon electricity.
- We also document the evolution of economic and policy analysis.

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ABSTRACT

Decarbonizing the global electricity system is expected to contribute significantly to mitigating climate change. A significant body of research has focused on the development of low-carbon power systems; hence, this bibliometric review is timely. We assess the global scientific research on low-carbon electricity both quantitatively and qualitatively, based on the Science Citation Index Expanded (SCI-Expanded) and Social Sciences Citation Index (SSCI) spanning a quarter century and 13,767 publications. Our analysis illustrates the role of inter-institutional collaboration in successful scientific research on low-carbon power systems. The United States has contributed most to the low-carbon electricity literature with 3074 publications, the highest h-index (58), 8 of the 10 most cited articles, and 4 of the 10 most productive institutions. The Chinese Academy of Science is the most productive institution with 270 publications and notably high levels of international collaboration. Based on an analysis and visualization of author keywords and content analysis, we also characterize three phases of the global transition to low-carbon electricity. The 1990s involved reliance on traditional base-load fuels (coal and nuclear), which spurred the search for cleaner alternatives. These alternatives materialized as the rise of clean coal and wind in the first decade of the 21st century, followed by the growth of solar and natural gas beginning in 2010. Besides this evolution of technologies, we document the transition to more nuanced forms of economic and policy analysis in recent years.

1. Introduction

According to the Intergovernmental Panel on Climate Chante (IPCC), it is extremely likely that at least half of observed global warming since 1950 is due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations [1]. Global climate change appears to be one of the most difficult challenges that human beings have ever faced [2–6]. In particular, electricity generation, by far the single largest source of GHG emissions, accounts for about 40% of the global carbon dioxide emissions [7]. Over the past two decades, the electricity system has undergone significant transformations under the pressures of reducing carbon emissions, meeting increasing electricity demand, providing affordable and reliable electric services, and sustaining economic growth [8–11]. By the adoption of new technologies and the implementation of a variety of measures and policies, methods of producing, transmitting, distributing, and consuming electricity are significantly changing [12,13]. For example, coal consumption experienced the largest percentage decline in power generation, while renewable energy continued to grow steadily, supplying nearly 24% of world electricity in 2015 [14].

As many countries have submitted their pledges to the Nationally Determined Contributions (NDC) to the United Nations Framework

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Convention on Climate Change (UNFCCC),[1] they also committed to CO_2 emission reductions in the electricity sector by setting ambitious mitigation targets. For example, in 2015, according to the U.S. placed its first federal regulations on carbon pollution from electric utilities, targeting a 32% CO_2 reduction by 2030 below 2005 levels.[2] Australia established a goal of 23.5% renewable electricity generation by 2020,[3] while the European Union aimed for 50% renewable electricity by 2030.[4] Recently, China announced to increase the percentage of non-fossil fuel generating capacity to 35% by 2020 in its 13th Five-Year Plan for the power sector.[5] Simultaneously, research on pathways to decarbonizing power sector is booming over the past twenty years. As the status quo of electricity systems across countries varied significantly, scientists and researchers are working independently and collaboratively on new technologies as well as regulatory and policy measures, with the joint efforts of governments, research institutes, and non-profit organizations, aiming to find means to achieve low-carbon, affordable, and reliable electricity systems [15–21].

With a continuously increasing volume of academic outputs, this paper applies bibliometric analysis to assembly and analyze the existing literature on decarbonizing electricity system on a global scale. We not only aim to characterize the basic performance of previous studies, such as the temporal development of scholarly outputs, scientific collaborations, geographical and institutional distributions of publications, but also seek to forecast research trends by using frequency analysis and co-word analysis.

2. Methodology

In this paper, we used a group of keywords representing three aspects of the topic of decarbonizing electricity system: "climate change", "electricity/electric power", and "low carbon". Particularly, specific technologies, such as nuclear, renewable energy, capture and storage, energy efficiency and so on, were used as a searching strategy to access the full of scope of the data.[6] The data were collected from the database of the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), which was accessed on December 26, 2016. Given that the year 1990 serves as the basis of the United Nations Framework Convention on Climate Change (UNFCCC) as the First Assessment Report of the IPCC was completed then, and additionally, prior to 1990, only 8 articles were published intermittently with much information missing. Publications occurring within the timespan from 1990 to 2016 were included with all categories, totaling 14,339 records.[7]

2.1. Bibliometric analysis

Bibliometrics, or the statistical analysis of bibliographers, appears to have been first introduced in 1969 as an "illumination of the processes of science and technology by means of counting documents" [22]. Nowadays, bibliometrics is widely used to evaluate the characteristics of articles, books, and other media of academic outputs, to assess the influence of researchers and institutes, to identify patterns of research collaboration, and to identify and predict trends in given research fields. The mathematical and statistical methods used in bibliometrics are based on three typical models: Bradford literature dispersion law, Lotka's law, and Zipf's law [23–26]. Given the rapid growth of academic outputs, bibliometrics is taken as one of the most important and efficient methods to research libraries of published information – both qualitative data (e.g., hotspots and future research trends) and quantitative information (e.g., temporal and geographic distribution of outputs, leading researchers, and mainstream journals).

2.2. Impact factor and h-index

When measuring the influence of journals, a variety of quantitative tools are provided by the Journal of Citation Report (JCR) to rank, categorize, evaluate and compare journals. The impact factor (IF) is one of them, considered as one of the most influential tools in modern bibliometric studies [27]. By measuring the average number of citations to the articles published in journals within a particular year or period, the impact factor is useful in clarifying the significance of total citation frequencies, thereby accounting for the relative importance of a journal in a given field. Generally, journals with higher impact factors are expected to be more important than those with lower ones [28]. In this study, impact factors of identified journals are recorded from the Journal Citation Reports 2015.

When estimating the influence of individual researchers, the h-index is commonly used. The h-index was initially developed by Jorge Hirsch in 2005 as a process for quantifying the outputs of an individual researcher [29]. This author-level metric attempts to measure both the productivity and citation impact of the publications of a scientist, a scholarly journal, or an institute. It thereby not only simplifies the measures of quantity and impacts in a single value, but it also allows for direct comparisons across and within disciplines [30,31].

2.3. Content analysis

Content analysis is a quantitative method for summarizing any form of content, often in the form of written words or by counting various other aspects of the content, with the expected results of numbers and percentages [17]. This enables a more objective evaluation than comparing content, aiming to analyze research progress, characterize trends, and anticipate changes in a certain research area [32].

Co-word analysis is a technique of content analysis, which is effective in analyzing the co-occurrences of keywords, thereby mapping the strength of association between words in textual data, and identifying relationships and interactions between the topics and emerging research trends [25]. By presenting quantitative information in multidimensional graphs, co-word analysis has an advantage over other content analysis methods [30,31].

3. Results

3.1. Basic characteristics of publications

Of all obtained publication records, nearly 85% fall in the category of "Article", followed by "Proceeding paper" with 9.05%. Other media of materials like editorial material and book chapters are filtered out, with a total of 13,767 records finally selected for this study. They were published in 18 languages, but English (97.15%) is dominant, with Chinese (0.93%) and German (0.76%) next in rank order. A total of 116 research subjects are covered, among which the subject of natural science and engineering dominate (see Table 1). For example, "energy and fuel" accounts for the biggest share, followed by "environmental science", and "chemical engineering". "Economics" is the only social science subject that is among top 10 subjects, at it represents less than 5%. Publications in other social science subjects such as business, management, public policy, and public administration, fall far short of reaching the top ten list.

[1] http://unfccc.int/paris_agreement/items/9485.php.

[2] https://www.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.

[3] https://www.environment.gov.au/climate-change/renewable-energy-target-scheme.

[4] http://ec.europa.eu/energy/en/topics/energy-strategy/2050-energy-strategy.

[5] http://www.sdpc.gov.cn/zcfb/zcfbghwb/201612/P020161222570036010274.pdf.

[6] The search query is specified as follows: TS = ((electricity or "electric power" or "power system" or "power sector" or "power plant*") and (carbon or CO2 or greenhouse or ghg or "climate change") and (green or clean or low-carbon or decarboniz* or mitigat* or nuclear or renewable or hydroelectricity or hydropower or solar or PV or hydrogen or wind or biomass or bioenergy or biofuel or waste or geothermal or "capture and storage" or CCS or energy efficiency or "combined heat and power" or CHP or energy storage)).

[7] For the purpose of this research, we later applied certain filters to the 14,399 records, thus, only 13,767 records were selected in accordance with the search criteria. Details are seen in Section 3.1.

Table 1
Top 10 research subjects during 1990–2016.

Rank	Research area	TP	TP R (%)
1	Energy & Fuels	7157	52.50
2	Environmental Sciences	3381	31.28
3	Environmental Studies	2122	18.81
4	Sustainable Science & Technology	2020	17.86
5	Engineering, Chemical	1662	11.23
6	Engineering, Environmental	366	11.14
7	Thermodynamics	276	8.40
8	Economics	164	4.99
9	Chemistry, Physical	133	4.05
10	Engineering, Electrical & Electronic	113	3.44

Note: TP is the number of total publications; R (%) is the ratio of the publications of one subject to the total publications during 1990–2016.

Table 2
Top 10 productive countries during 1990–2016.

Rank	Country	TP	TP R (%)	h-index
1	USA	3074	22.33	58
2	China	1816	13.19	35
3	UK	1318	9.57	40
4	Germany	849	6.17	30
5	Japan	686	4.98	23
6	Canada	641	4.66	27
7	Australia	600	4.36	29
8	Italy	589	4.28	30
9	Spain	584	4.24	19
10	South Korea	500	3.63	19

Note: TP is the number of total publications; R (%) is the ratio of the publications of one country to the world publications during 1990–2016.

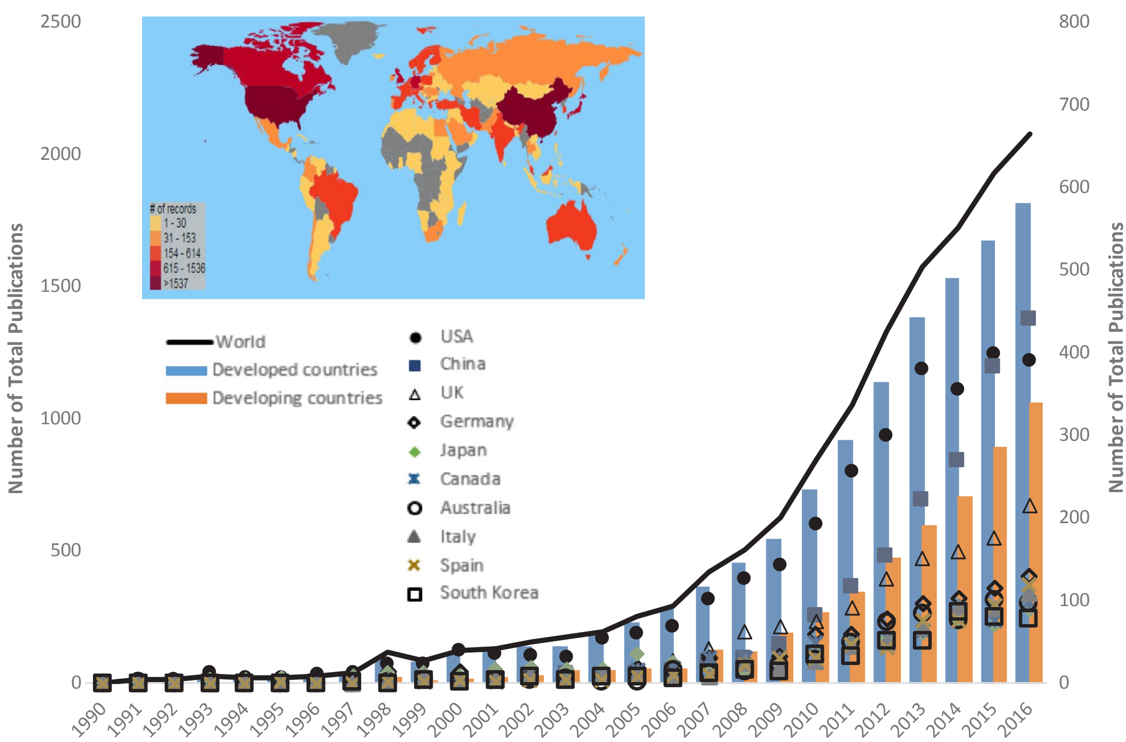

Fig. 1. Total publication performance during 1990–2016. Note: annual outputs of the world, developed countries, and developing countries share the left axis, while annual publications of the top 10 productive countries share the right axis.

3.2. Contributions to publications by years and countries

Fig. 1 illustrates the spatial and temporal distribution of all obtained publications. The black line represents the yearly outputs from 1990 to 2016. While there is an average annual growth of 50% over the past two decades, the growth rate is somewhat uneven. In early years, annual outputs grew slowly up until a spurt of growth in 1998 following the signing of the Kyoto Protocol. These were mainly contributed by developed countries who have maintained over 1000 publications per year since 2012 (Fig. 1). Indeed, the 10 most productive countries are mainly distributed across Europe and North America, among which nine are high-income economies (see Table 2). Actually, similar findings have been reported in other studies [25,28,30,31]. The prominence of research by western countries has been revealed by a variety of university rankings. According to the Times Higher Education[8] and the QS World University Rankings 2016–2017,[9] at least 32 of the world's 100 best universities are from U.S., about 10 from Asia, and the rest are distributed across Europe. In particular, U.S. accounts for 22.33% of the world publications, the largest in total and annual outputs throughout the time span. Second-placed China is the only developing country that ranks in the top 10, taking up 13.19% of the world's total publications, with yearly outputs increasing at a rapid pace since 2008. This is partly because China has launched the reform of its electricity system and prepared for a national carbon market in 2017. The U.K. ranks third and accounts for 9.57% of the world's publications. The number of its annual outputs has been increasing at a very stable rate. Other top 10 most productive countries including Germany (6.17%), Japan (4.98%), Canada (4.66%), Australia (4.36%), Italy (4.28%), Spain (4.24%), and South Korea (3.63%).

It is notable that as developing countries nowadays are beginning to

[8] https://www.timeshighereducation.com/world-university-rankings/2017/world-ranking#!/page/0/length/25/sort_by/rank/sort_order/asc/cols/stats.

[9] https://www.topuniversities.com/university-rankings/world-university-rankings/2016.

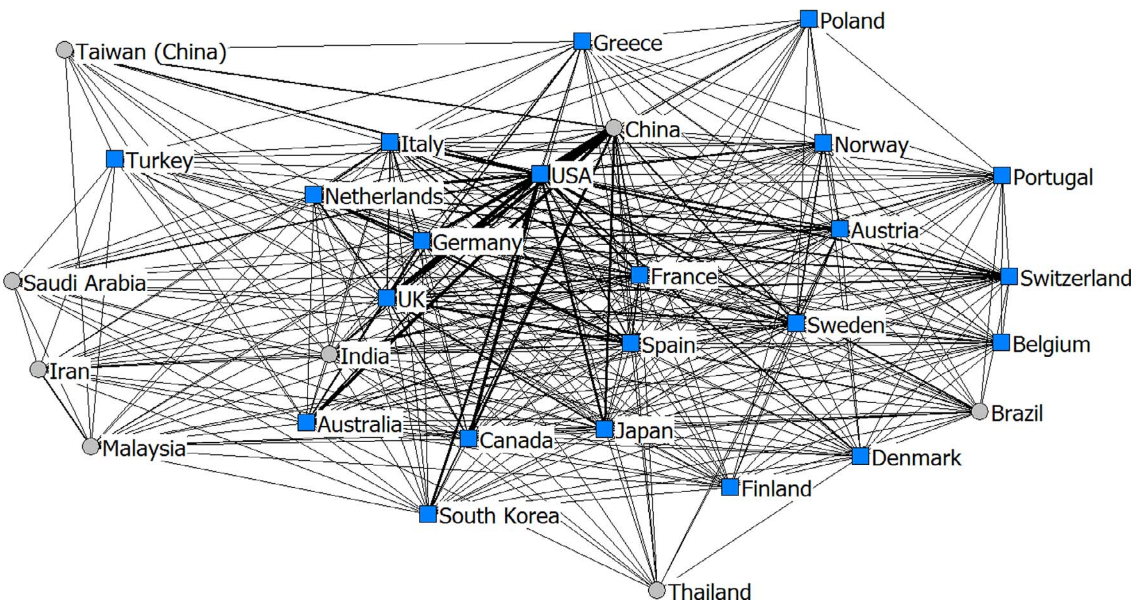

Fig. 2. Co-authorships within top 30 productive countries during 1990–2016. Note: Blue square represents OECD countries, grey round represents non-OECD countries; the wider the line is, the stronger collaboration is developed within two countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
The 10 most productive institutes during 1990–2016.

Rank	Institute	Country	TP	TP RW (%)	TP RC (%)	TC	h-index
1	Chinese Academy of Science	China	270	1.96	14.87	3970	31
2	Tsinghua University	China	187	1.36	10.30	2978	26
3	University of California, Berkeley	USA	184	1.34	5.99	4607	33
4	Carnegie Mellon University	USA	135	0.98	4.39	4124	36
5	Massachusetts Institute of Technology	USA	132	0.96	4.29	2672	29
6	Imperial College of Science, Technology & Medicine	UK	127	0.92	9.64	4442	30
7	North China Electric Power University	China	119	0.86	6.55	527	14
7	Stanford University	USA	119	0.86	3.87	3423	31
9	Utrecht University	Netherlands	118	0.86	27.57	3791	31
10	Technical University of Denmark	Denmark	102	0.74	7.74	2300	26

Note: TP is the number of total publications; RW (%) is the ratio of the total publications of one institute to those of the world during 1990–2016; RC (%) is the ratio of the total publications of one institute to those of the corresponding country during 1990–2016; TC is the number of total citations during 1990–2016.

raise the concern of climate change adaptation and environmental protection, a rapid increase in research outputs is seen from Fig. 1. From 2005 to 2015, the research records contributed by developing countries other than China rise from 44 to 513; indeed, India, Brazil, Malaysia, Iran, Saudi Arabia, and Thailand are also now included in the top 30 productive countries (see Fig. 2). In addition, more opportunities for co-operation are emerging within countries reflecting their distinct expertise, knowledge, and other resources [33]. Based on the social network analysis, the co-authoring relationship among the 30 countries by the cooperation network diagram is shown in Fig. 2. The U.S. seems to be the center of the global networks, working with all the other top 30 productive countries except Malaysia. The U.K. and Germany are playing a leading role in connecting European countries like France, Italy, Netherlands, Spain, Switzerland, Sweden and so on. It is apparent that China also has close partnerships with many countries, especially with U.S. resulting in more than 200 co-authored publications. Intensive collaboration with Canada, U.K., Australia, and Japan can be easily seen. Note the peripheral location of many other countries with thin or missing connecting lines.

3.3. Contributions to publications by institutes

Statistical results show that the topic of green electricity is being researched across 1887 institutes. Table 3 lists the top 10 most productive institutes from 1990 to 2016, of which four come from the U.S., three from China, and the rest from the U.K., Netherlands, and Denmark. Notably, the Chinese Academy of Science has 270 publications – more than any other institution and nearly 2% of the world's publications in this field, accompanied by 3970 citations. Tsinghua University, one of the best universities in China, is second in terms of productivity, with 187 publications and a total of 2978 citations. In third place (ranked by productivity) is the University of California, Berkeley, from U.S., with 184 publications with a total of 4607 citations. The fourth-placed Carnegie Mellon University also from the U.S. has the highest h-index and a total of 4124 citations. It is worth noting that although Utrecht University from the Netherlands and the Technical University of Denmark are placed at the end of this list, they have relatively high h-indexes.

Interestingly, three of the ten's best universities in the world according to the Times Higher Education and the QS World University Rankings 2016–2017 (namely Stanford University, the Massachusetts Institutes of Technology, and the Imperial College of Science, Technology & Medicine), have been quite active in the area of low-carbon electricity.

Scientific research on low-carbon electricity is becoming a strongly collaborative endeavor, both domestically and internationally. The strength of cooperation among nations and institutions is a function of many factors including the internal dynamics of science as well as science policy initiatives [34]. Fig. 3 shows the cooperative relationships between the top 30 productive research institutes.

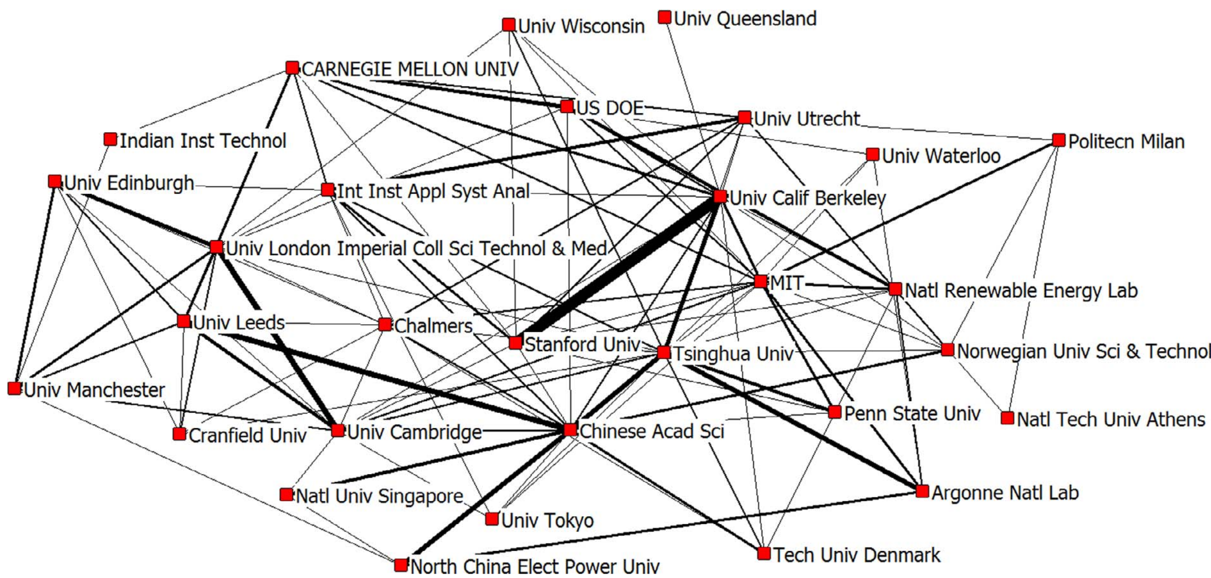

Fig. 3. Co-authorships within top 30 productive institutes during 1990–2016. Note: Nodes represent organizations and lines represent the collaborative relationship. The darker a line, the stronger cooperative efforts are developed between two organizations.

Several clusters of institutions co-located in industrialized countries have close co-authorships, but have limited collaborations with foreign institutes based on co-authored publications. For example, the University of California, Berkeley and Stanford University, have the strongest partnership with 13 co-authored papers. Similarly, the Imperial College of Science, Technology & Medicine and Cambridge University also actively collaborate.

In contrast, the Chinese Academy of Science and Tsinghua University from China are strong hubs of both domestic and international collaboration. Tsinghua University also works closely with a myriad of U.S. institutes such as the Massachusetts Institute of Technology, the University of California, Berkeley, Pennsylvania State University, and Argonne National Laboratory. The Chinese Academy of Science has actively collaborated with a variety of institutes across the world such as the University of Leeds (U.K.), the National University of Singapore (Singapore), and North China Electric Power University (China).

At the other extreme, two of the 10 most productive institutes – the Massachusetts Institute of Technology and the Technical University of Denmark – have relatively weak levels of both domestic and international co-authorship across institutes in this broad field of electricity decarbonization.

This analysis illustrates the many alternative pathways to successful scientific research. One involves strong institutions with mostly internal teaming (e.g., in the U.S.). A second involves the close coupling of nearby domestic institutions (e.g., U.S. and U.K. partnerships). A third approach is characterized by broadly-based and geographically dispersed international collaboration (e.g., with China).

3.4. Contributions to publications by authors

A total of 7436 authors contributed to publications on electricity decarbonization during the 25-year study period. Table 4 lists the ten most productive authors between 1990 and 2016, and they come from China, Canada, the U.S., the Netherlands, China, Romania and Switzerland. With three of the top ten most productive authors, China's prominence exceeds the U.S. and Canada, which each have two. Thus, China's research output is exceptional, but its influence on global research trends is more limited. With high outputs but low citations, Chinese scholars are currently far from spreading their work to a highly influential stage. Similar findings have been identified in prior studies assessing the performance of Chinese scholarship in particular fields of research such as energy efficiency [35].

Table 4
The 10 most productive authors during 1990–2016.

Rank	Author	Country	TP	TP RW (%)	TP RC (%)	TC	h-index
1	Ibrahim Dincer	Canada	51	0.37	7.96	1468	21
2	Bruce E. Logan	USA	45	0.33	1.46	4775	21
3	Andre Faaij	Netherlands	37	0.27	8.64	1588	22
3	Guohe Huang	China	37	0.27	2.04	501	14
5	Yongping Yang	China	36	0.26	1.98	346	9
5	Marc A. Rosen	Canada	36	0.25	5.46	1247	18
7	Edward S. Rubin	USA	35	0.25	1.14	1795	21
7	Calin-Cristian Cormos	Romania	35	0.25	37.23	726	16
9	Hongguang Jin	China	33	0.24	1.82	612	13
10	Francois Marechal	Switzerland	31	0.23	11.19	452	14

Note: TP is the number of total publications; RW (%) is the ratio of the total publications of one author to those of the world during 1990–2016; RC (%) is the ratio of the total publications of one author to those of the corresponding country during 1990–2016; TC is the number of total citations during 1990–2016.

Our research based on an expansive sweep of research fields does not support the explanation that China's impact factors are the results of weak global collaborative networks as suggested by others [36] including a review of solar publications that indicated limited cross-national authorships by Chinese researchers [32]. Indeed, we find the opposite to be the case in the broad field of low-carbon electricity research: Chinese multinational collaborations based on co-authorship are strong. A second possible cause of the limited impact and citations suggested by prior research is the lower visibility from less developed social media in China [37], thus weakening the influence of China's research outputs. By actively attending international conferences, Chinese scholars might be able to overcome this disadvantage by circulating their recent findings, receiving feedback from their peers, and thereby broadening their global networks with more possible collaboration and influence.

Ibrahim Dincer from the University of Ontario has the most publications. According to his academic website, his areas of research are wide-ranging and include drying, energy and exergy analyses, energy conversion and management, heat and mass transfer, hydrogen and fuel cell systems, refrigeration, renewable energies, thermal energy storage, thermodynamics.

Table 5
The 10 most productive journals during 1990–2016.

Rank	Journal	TP	TP R (%)	TC	IF 2015
1	Energy Policy	1015	7.37	21,216	3.045
2	Energy	785	5.70	14,071	4.292
3	Applied Energy	664	4.82	10,051	5.746
4	Renewable & Sustainable Energy Reviews	652	4.74	12,462	6.798
5	Energy Conversion and Management	419	3.04	7547	4.801
6	International Journal of Hydrogen Energy	410	2.98	8909	3.205
7	International Journal of Greenhouse Gas Control	309	2.24	6705	4.064
7	Journal of Cleaner Production	304	2.21	2876	4.959
9	Renewable Energy	262	1.90	4236	3.404
10	Environmental Science & Technology	261	1.90	11,564	5.393

Note: TP is the number of total publications; R (%) is the ratio of the total publications of one journal to those of the world during 1990–2016; TC is the number of total citations during 1990–2016; IF is the Impact Factor of the journal in 2015.
Data source: https://jcr.incites.thomsonreuters.com/JCRJour-nalHomeAction.action.

Bruce E. Logan from Pennsylvania State University, the second most productive author, focuses on the development of new renewable energy technologies, such as microbial fuel cells and thermal batteries, for achieving an energy sustainable water infrastructure.

Andre Faaij from Utrecht University is also the third largest producers of publications in this field. Additionally, he has the highest h-index among the top 10 productive authors. According to his academic website, his interests are similarly broad and include the bio-based economy, renewable energy, transport and alternative fuels, capture and storage of CO_2, modeling and scenario analyses of energy systems, technological learning and innovation in energy systems and energy policy.

Guohe Huang from North China Electric Power University and the University of Regina has the largest number of publications in the low-carbon electricity system, focusing on water resources and environmental systems engineering, simulation of hydrological and environmental systems, planning of energy and environmental management systems, climate modeling and downscaling.

3.5. Distribution of journals

Statistical results show that a total of 763 journals published literature pertinent to pathways to achieve a low-carbon electricity sector during our 25-year study period. Table 5 lists the top 10 peer-reviewed journals which account for nearly 37% of the world total outputs. *Energy Policy* is the most productive journal with 1015 publishing records, followed by *Energy* (785) and *Applied Energy* (664). Interestingly, the fourth-placed *Renewable and Sustainable Energy Reviews* has the highest IF value (6.798) among these 10 journals, while the first-place journal has the lowest IF value of these top-ten journals. *Applied Energy* and *Environmental Science & Technology,* also have IF values that exceed 5. All of these journals are core to research with significant influences on low-carbon electricity research. However, there appears to be a trade-off between the volume vs. the impact of publications.

3.6. The most cited articles

The number of times an article is cited in scientific journals indicates its impacts not only on a specific field, but on the authors and published journals [38]. Table 6 lists the most frequently cited articles in the field of electricity decarbonization spanning the period of 1990–2016. These articles were all published by U.S. and U.K. authors prior to 2010. Two of them were solely authored, and five had only two authors. The most frequently cited article entitled "Meeting the clean energy demand: Nanostructure architectures for solar energy conversion" was authored by Prashant Kamat and published in *Journal of Physical Chemistry C* in *2007*. It has been cited 1391 times by 2016, followed by "A class of non-precious metal composite catalysts for fuel cells" by R. Bashyam and P. Zelenay published in *Nature* and "Amine Scrubbing for CO_2 Capture" by GT Rochelle published in *Science*. Bruce E Logan, the second largest contributor, co-authored one article discussing the use of microbial fuel cell in electricity generation, which was published in *Environmental Science and Technology* with a total of 874 citations. The fact that only two of these top ten articles were published in the top 10 journals in this field illustrates the breadth of outlets that researchers are utilizing to disseminate their findings. Two of the authors of these top ten articles are also among the top ten most productive authors.

More interestingly, these highly influential academic studies have addressed a variety of clean technologies though much attention addresses the topic of energy storage. In particular, seven out of the ten most cited articles were discussing the improvements in efficiency and effectiveness of fuel cells and lithium-ion batteries by innovating the chemical reaction and material processing. Besides, the significance of carbon capture technology in climate change mitigation was also discussed in [39,40].

4. Research hotspot and trend

4.1. Research hotspots

Quantitative analysis of article titles, abstracts, and keywords is often used to characterize historical studies and forecast future directions. In particular, author keywords are valuable because they reflect an article's theme and preferences in the eye of authors [49]. Excluding those 2615 articles that lacked author-provided keywords, 11,152 articles were analyzed. A total of 22,859 keywords were given by the authors; however, it often occurs that a single topic can be described by a variety of terms. For example, "life cycle assessment" is synonymous with "life cycle analysis", "life cycle inventory", and "LCA". Therefore, we merged abbreviations, singular or plural, gerund of the similar expressions and re-sorted the cleaned author keywords in a descending order. The most frequently used keywords are arrayed in Table 7 and classified into five broad categories covering three types of technologies (renewables, carbon capture and storage (CCS), and low-carbon non-renewables), electricity generation, environmental impact, and economic/policy analysis.

Renewable energy has been a highly ranked keyword across the 25-year period, rising to the top most recently. Within that category, biomass has dropped from 1 to 4, while solar has increased from 9 to 3. Even though fossil-based technologies are less populated in recent two decades, clean coal technologies, particularly CCS, has gained 14 rankings to become second in use as a keyword within the 13,767 publications. Fuel cells, energy efficiency, and combined heat and power have consistently ranked in the top 10–20.

Environmental impacts have also been increasingly emphasized over the past several decades as decarbonizing the power system has gained traction as a means to reduce greenhouse gases, particularly CO_2 emissions, and to address wastewater treatment issues. Large gains have been experiences by four cross-cutting economic/policy analysis topics: life cycle assessment (LCA), policy, cost, and optimization. LCA can be used to identify the environmental profile in the current and future national or regional power system. Cost of electricity supply, transmission and consumption is another concern in the low-carbon transition since less carbon-intensive technologies, such as nuclear and CCS, are relatively more capital intensive. Numerous studies have examined the use of policies and regulations to enhance the appeal of low-carbon technological options.

Given the above considerations, Fig. 4 illustrates the knowledge evolution of technology options by listing the rankings of 12 generating

Table 6
The 10 most cited articles during 1990–2016.

Title	Author	Year	CC	TA	TI	TC	Journal
Meeting the clean energy demand: Nanostructure architectures for **solar** energy conversion	Kamat [41]	2007	USA	1	1	1391	Journal of Physical Chemistry C
A class of non-precious metal composite catalysts for **fuel cells**	Bashyam and Zelenay [42]	2006	USA	2	1	1096	Nature
Amine scrubbing for **CO_2 capture**	Rochelle [40]	2009	USA	1	1	1085	Science
A polymer electrolyte-based rechargeable lithium/oxygen **battery**	Abraham and Jiang [43]	1996	USA	2	1	1028	Journal of the Electrochemical Society
Electricity production by **Geobacter sulfurreducens** attached to electrodes	Bond and Lovely [44]	2003	USA	2	1	983	Applied and Environmental Microbiology
Thermal decomposition of the non-interstitial hydrides for the **storage** and production of **hydrogen**	Grochala and Edwards [45]	2004	UK	2	3	958	Chemical Reviews
Advanced anodes for high-temperature **fuel cells**	Atkinson et al. [46]	2004	UK	8	7	908	Nature Materials
Electricity generation using an air-cathode single chamber microbial **fuel cell** in the presence and absence of a proton exchange membrane	Liu and Logan [47]	2004	USA	2	2	874	Environmental Science and Technology
Advancesn in **CO(2) capture** technology – The US Department of Energy's Carbon Sequestration Program	Figueroa et al. [39]	2008	USA	5	2	856	International Journal of Greenhouse Gas Control
A direct-methane **fuel cell** with a ceria-based anode	Murray et al. [48]	1999	USA	3	1	846	Nature

Note: TP is the number of total publications; CC is the corresponding author's country; TA is the number of co-authors; TI is the number of co-authoring institutes; TC is the number of total citations during 1990–2016.

technologies over three periods. Unlike the first decade, occurrences of each technology are substantially increasing throughout the recent 20 years in the context of the global awareness of climate change mitigation and environmental protection. In specific, the non-hydro renewable energy is consistently concentrated, and CCS is taking the most significant leap. Biomass, fuel cell, solar, CCS, and energy efficiency are holding a stable position in top 5, and each technology has embedded a group of techniques. For examples, biomass spans forest biomass, woody, cellulosic, and lignocellulosic biomass, microbial and algal biomass, as well as palm oil and biodiesel. Solar associates with solar PV panels, solar thermal assemblies, solar panel, solar chimney, solar power towers and concentrating solar collectors, as well as utility-scale solar farms and distributed rooftop systems with or without battery storage. CCS is massively clustered by the pre-combustion and post-combustion capture with an intensive engagement in the cost-benefit analysis. Similarly, wind is demonstrating itself by advancing to sixth place, largely for offshore wind. While conventional coal, natural gas and hydropower still are and will continue to serve as key base-load generation resources, since they are mature technologies, our results highlight the shifting breakthroughs of new technologies. Notably, as

Table 7
Top 30 mostly frequently used keywords during 1990–2016.

Keywords	Total	Rank				
		1990–1995	1996–2000	2001–2005	2006–2010	2011–2016
Renewable energy↑	1351	9	13	3	2	1
Biomass	1020	1	1	2	3	4
Solar↑	953	9	3	9	7	3
Wind	519	12	23	17	9	12
Hydropower	136	16	26	21	28	29
CCS↑	1311	16	16	10	1	2
Coal	284	11	10	19	16	23
Natural gas	178	20	23	23	27	24
IGCC	146	12	21	29	23	28
Fuel cell	930	7	5	6	4	5
Hydrogen	614	16	10	7	5	14
Energy efficiency	386	12	10	17	18	17
Nuclear	357	5	7	11	14	18
Combined Heat and Power	266	20	18	20	20	20
Electricity generation	557	6	3	4	10	13
Gasification	424	2	8	15	15	16
Exergy	237	24	26	24	21	21
Energy storage↑	231	27	18	27	30	19
Cogeneration	154	20	21	21	22	30
Absorption	152	12	23	25	23	27
Greenhouse gas	793	4	2	1	6	7
CO_2 emissions	583	2	6	5	11	8
Sustainability↑	527	16	17	12	13	9
Environment	277	7	9	16	19	22
Wastewater	164	27	26	27	25	25
Life cycle assessment↑	674	27	14	13	12	6
Policy↑	562	20	18	8	8	10
Optimization↑	424	24	29	25	26	11
Cost↑	415	24	14	14	17	15
Uncertainty	136	27	30	29	29	26

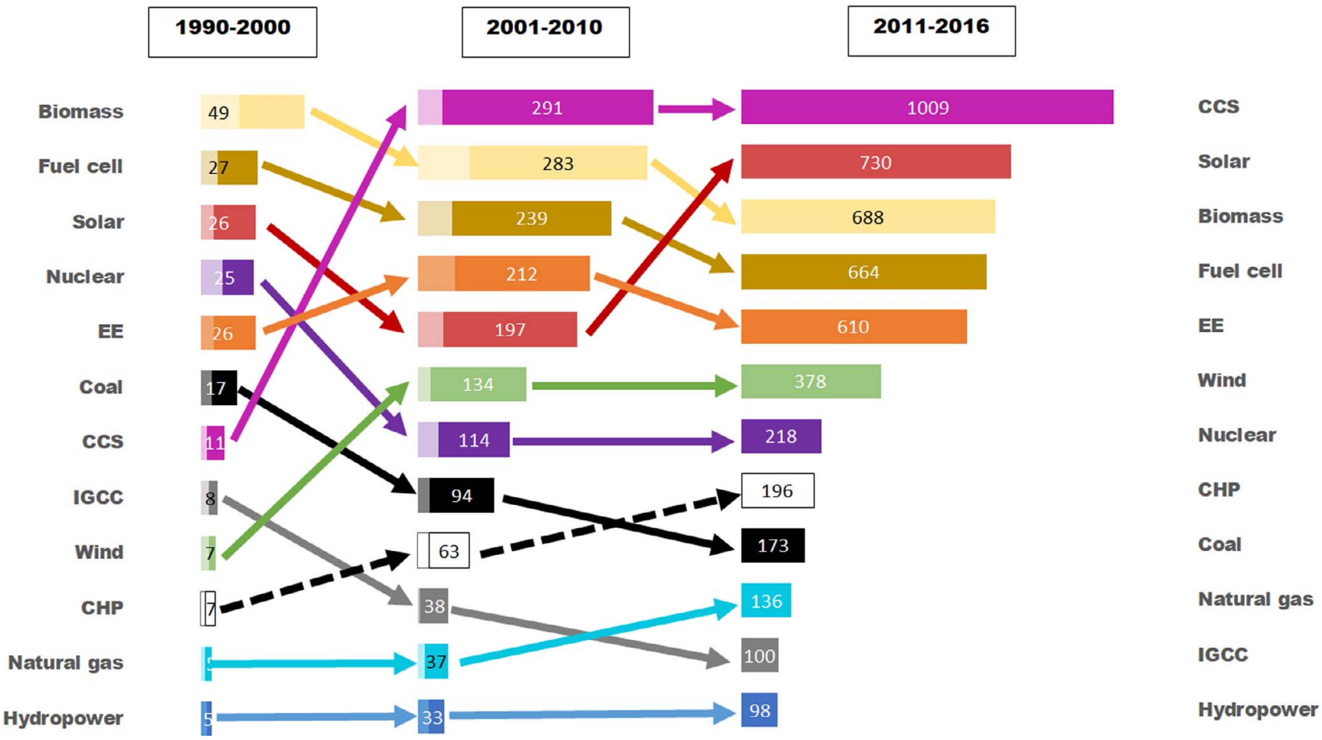

Fig. 4. 2016. Note: EE is short for energy efficiency. Numbers represent the total occurrences of each keyword, while the order of each bar implies the rankings in a period.

long as fossil fuels continue to play strongly in primary energy consumption, the urgency of CCS deployment will continue.

Fig. 5 further illustrates this evolution of research hotspots, by showing the growth in occurrence of keywords over time and the strength of correlations between subjects. The cost of renewable energy and solar and their link to energy storage, are strongly represented in the most recent "wheel" of keywords reflecting the growing competitiveness of solar systems and their ongoing need for energy storage to address their intermittency. In contrast, the pairing of biomass and hydrogen was a strong linkage in early years, but it is no longer a dominant pairing in today's research, as biomass has slipped from first to third place and hydrogen has dropped to fourteenth place in the

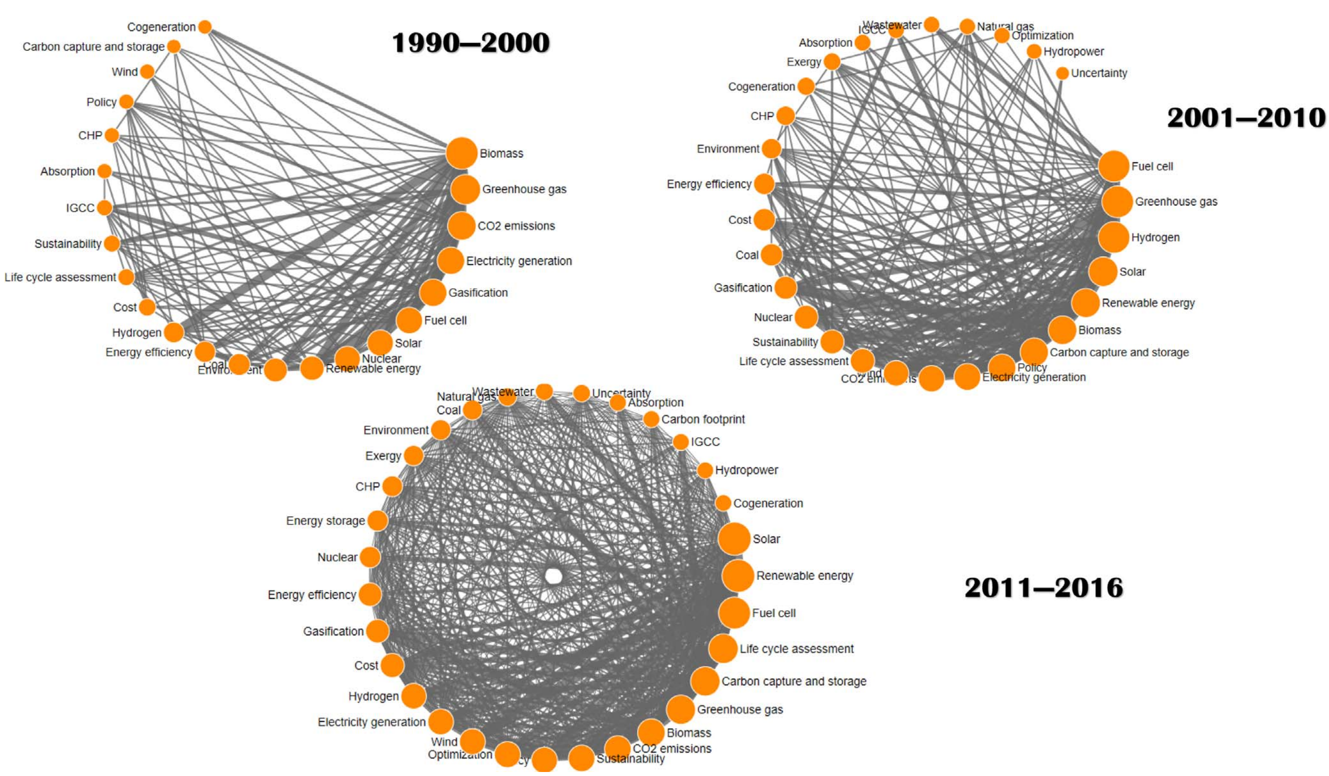

Fig. 5. Evolution of top 30 frequently used subjects in author keywords over three periods. Note: Nodes represent research hotspots and lines represent collaborative relationship. The bigger the node is, the more total occurrences the keyword has; the darker the line is, the stronger the correlations between two keywords.

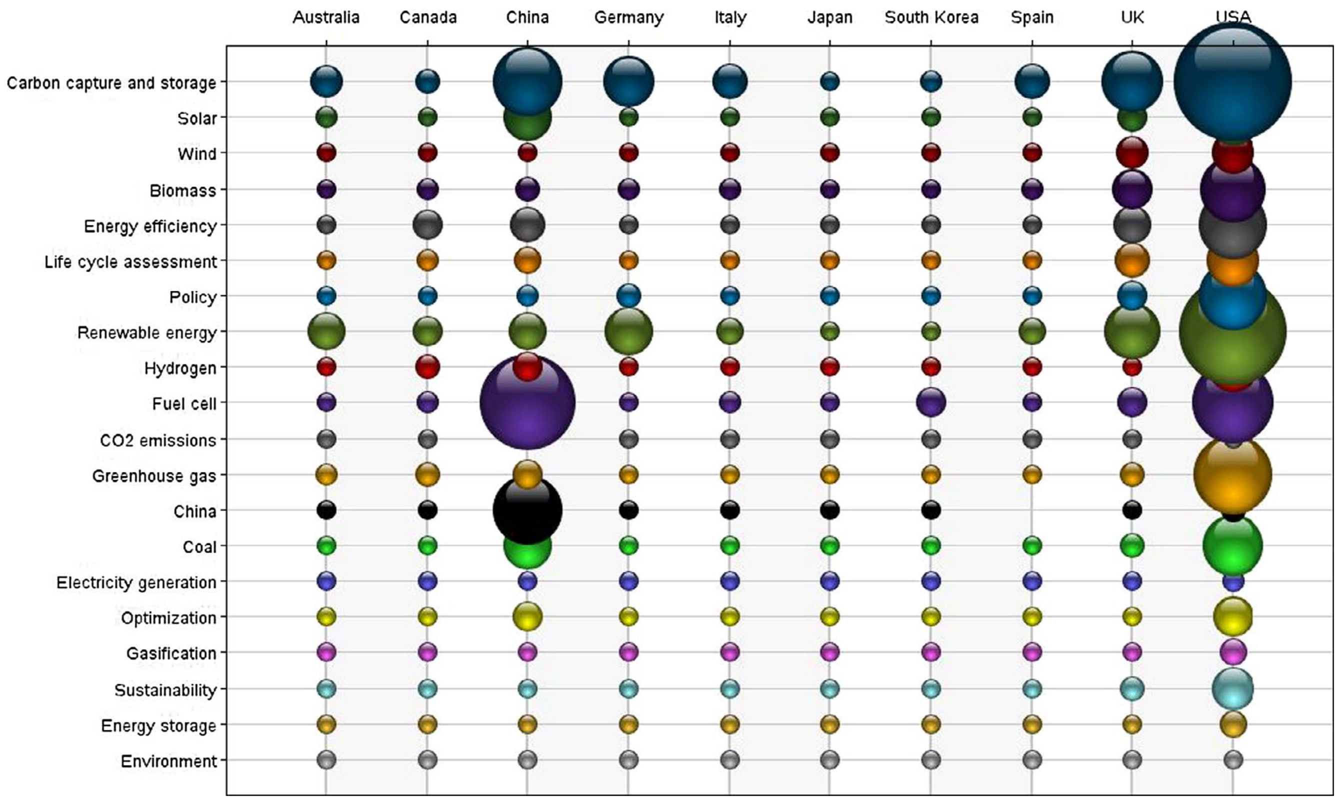

Fig. 6. Co-word analysis of research hotspots and the 10 most productive countries.

ranking of keywords. Biomass power systems in many countries today can no longer compete with natural gas generation or alternative renewables such as wind and solar. While hydrogen as an energy carrier continues to attract research investments, it is not yet ready for widespread deployment and therefore has not attracted as much analysis and publication productivity compared with other renewable resources (National Academy of Sciences, 2016).

Examining the subjects that are added to consecutive wheels in Fig. 4 highlights the emergence of more nuanced forms of economic and policy analysis in recent years. Uncertainty and optimization did not rise to prominence in the field of power system transition before the 2001 decade, and carbon footprints did not become a common subject until 2011.

4.2. Research trend

Co-word analysis examines the relationship between keywords, and has proved to be efficient in revealing and grasping the progress of new frontiers of science [50]. Fig. 6 visualize the co-occurrence relationship among the top 20 research hotspots. In other words, co-word analysis, along with the frequency analysis, describes the historical features with an attempt to forecast future trends.

Seven of the hotspots identified together in Table 7, and in Figs. 4–6 are described below. Three of the top five with the most publications (renewable energy, carbon capture and utilization, and fuel cells) are also experiencing an increasing rate of publication growth over time and are therefore seen to be particularly notable.

(1) Renewable energy

“Renewable energy” is the most commonly used keyword throughout the entire time span with 1351 occurrences. Accompanied by the increased awareness of using renewable energy to reduce carbon emissions from electricity generation, research associated with renewable energy has been escalating since 2005. Overall, researchers have paid the most attention to biomass with 1020 occurrences, followed by solar and wind. Academic publications on solar power have been increasing at an exceptionally fast rate, accompanied by hydrogen production (614) and a series of frontier technologies and applications. It is forecast that breakthroughs in solar development will continue to emerge from advances in scientific fields such as nanoscience materials and molecular biology [32,51–57]

The U.S. and U.K. have produced the largest number of publications in wind and biomass, while the U.S. and China have had the most publications on solar energy. Fig. 5 demonstrates a strong relationship between “renewable energy” with “sustainability”, “policy”, and “greenhouse gas”. “Solar” often co-occurs with “wind”, while “biomass” is often mentioned with “gasification”.

(2) Carbon capture and storage

“Carbon capture and storage (CCS)” has a total of 1311 occurrences with a continuing growth (see Table 7). Though CCS is widely assumed to be one of the possibilities to continue the application of fossil fuels while achieving a sustainable electricity production, it is challenged by inefficiencies and high costs [58–66]. The U.S., China, U.K., Germany, Italy, and Spain, in particular, have generated a great number of publications that address CCS (see Fig. 6). However, given that few breakthroughs have occurred either in terms of technical progress or penetration rates in new coal- and gas-fired power plants, some have called for focusing CCS utilization on industrial and bioenergy applications [67]. In academic research, “CCS” often occurs with “coal” and “gasification” (see Fig. 5).

(3) Fuel cells

At third place “Fuel cell” has 930 occurrences (see Table 7). In the earlier time, fuel cells were focused primarily on vehicles and stationary power applications. In recent years, with the applications and markets being expanded, the fuel cell has taken on new roles as sources of backup, emergency, and auxiliary power [68–75]. According to Table 7, publications associated with fuel cells in the recent 10 years are 12 times as large as those during 1990–2010. Statistics show that "Fuel cell" often occurs with "Hydrogen" and "Biomass" (see Fig. 5). Also as is shown in Fig. 6, fuel cell publications are one of the few topics where China exceeds the U.S., with South Korea and the U.K. coming next in numerical order.

(4) Energy efficiency

Considered as one of the largest energy resources [76] and a "hidden fuel", energy efficiency is cost competitive with many energy supply resources, while also increasing energy security and lowering carbon emissions [35,77–81]. In particular, the U.S., China, U.K., and Germany have an exceptional contribution to literature associated with energy efficiency, which also is closely related to "renewable energy" and "greenhouse gas" (see Table 7). As Fig. 3 shows, energy efficiency and renewable energy are often coupled in publications, and they both are strongly represented in the policy literature, where similar financial incentives and regulations often apply to this class of alternative resources [82].

(5) Life Cycle Assessment

Life cycle assessment (LCA) is a technique for comprehensively assessing energy and environmental impacts of a product or a system [66]. In the most recent five years, LCA publications have expanded fivefold. The U.S., U.K., and China have produced the most publications on LCA in our database. By applying LCA to energy systems, their lifetime of impacts can be evaluated, often providing evidence of collateral benefits from fossil-free electricity systems [83–85]. "Renewable energy" and "Greenhouse gas" have a very strong co-occurrence relationship with "LCA".

(6) Policy

Policy has long been emphasized owing to its decisive influence over the implementation of energy technologies. The domain of policies can be specific to climate policy, energy policy, environmental regulation, electricity policy, fiscal management, and many other categories. The magnitude of research assessing the effects of single policies such as net metering or carbon taxes or portfolios or policies has been increasing over the past two decades [86–91]. The level of sophistication of this research has also increased with the use of macroeconomic models, game theory, econometric analysis, consumer choice models, decision analysis, and other advanced quantitative and qualitative approaches. The U.S. dominated as authors of the publications in our database, followed by the U.K., Germany, and China.

(7) Energy storage

Energy storage is widely recognized as an important approach for enabling the grid integration of large quantities of renewables [92–99]. According to Table 7, "energy storage" is growing at a rapid pace, with an increase from 12 occurrences during 2006–2010 to 210 in the recent five years. Unlike the other topics, neither the U.S. nor China strongly dominates this field of publication (see Fig. 6). This is consistent with the findings of a review of the clean energy R & D goals set by the 23 countries participating in "Mission Innovation." Myslikova, Gallagher, and Zhang (2017) conclude that funding for energy storage research is inadequate relative to the high priority given to this technology area by these 23 member countries.

5. Conclusion

In this study, bibliometric methods were used to examine the characteristics of the literature on decarbonizing electricity systems from 1990 to 2016 based on the SCI and SSCI databases. In total, 13,767 records were obtained and analyzed in different categories including publication year, authors, journals, countries, institutes, and author keywords. A statistical evaluation of the results reveals that the literature on the low-carbon electricity system has been attracting an exceptionally high level of attention. Publications in 18 languages were available, with English being dominant (97.15%) in the world's publication records.

The U.S. contributed most to the low-carbon electricity literature with 3074 publications, the highest h-index (58), 8 of the 10 most cited articles, and 4 of the 10 most productive institutions. The Chinese Academy of Science is the most productive institution with 270 publications, China has 3 of the 10 most productive authors, and several of its institutes have notably high levels of international collaboration. Despite these strong collaborations and exceptional research productivity, China's influence on global research trends is more limited based on measures such as citations and Impact Factors. Consistent with this finding, the Chinese Academy of Science is the most productive institution with 270 publications, but its ranking on the h-index and citations suggests a lower level of influence and impact. In contrast, Carnegie Mellon University has the highest h-index but has half as many publications (135).

Our research does not support the explanation that the modest impact factors of China and the Chinese Academy of Science are the results of weak global collaborative networks. Rather we suggest that China's less developed social media may be a barrier to exerting strong influence in low-carbon research fields. Our analysis illustrates the many alternative pathways to successful scientific research. The Chinese Academy of Science and Tsinghua University from China are hubs of international collaboration. Nearby institutions often have close partnerships, such as (1) the University of California, Berkeley and Stanford University and (2) the Imperial College of Science, Technology & Medicine and the University of Cambridge. Other institutes are more inwardly focused in terms of their teaming relationships.

Among the top 10 productive authors, three come from China. Ibrahim Dincer from the University of Ontario is the largest individual contributor with 51 published records and the second highest h-index of 21. The journal *Energy Policy* with the largest published records of 1015 peer-reviewed articles, together with the journal *Energy*, *Applied Energy, Renewable & Sustainable Energy Reviews, Energy Conversion and Management, International Journal of Hydrogen Energy, International Journal of Greenhouse Gas Control, Journal of Cleaner Production, Renewable Energy,* and *Environmental Science & Technology,* contributes nearly 37% to the total journal literature on low-carbon electricity system. As the subject of energy and fuels is mostly covered by the 13,767 publications, the most highly cited article entitled "Meeting the clean energy demand: Nanostructure architectures for solar energy conversion", solely authored by Prashant Kamat and published in *Journal of Physical Chemistry C* in *2007*, has been cumulatively cited 1391 times through 2016.

Based on our bibliometric analysis and visualization of author keywords and content analysis, we characterize the global transition to low-carbon electricity. The reliance on traditional baseload coal and nuclear fuels in the 1990s spurred the search for cleaner alternatives resulting in the rise of CCS and wind in the first decade of the 21st century, and the growth of solar and natural gas (including CHP) in the second decade. We conclude that the recent rise of green electricity policy analysis and life cycle assessment will likely become more prominent in the future [100–102] and that the steady focus on energy efficiency will continue [82].

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