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A bibliographic analysis of recent solar energy literatures: The expansion and evolution of a research field

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ABSTRACT

This paper characterizes the solar energy literature from 1992 to 2011 using bibliometric techniques based on databases of the Science Citation Index and the Social Science Citation Index. Journal articles were the most frequently used document type representing 86.4% (6670) of the records. The pace of publishing in this field increased exponentially over these two decades, with the US accounting for the highest h-index (87) and the most publications (1273), followed by China and India. The US also plays a central role in the collaboration network among the 20 most productive countries, while China and India do not because of their more limited cross-national authorships. The Indian Institute of Technology was the organization with the most records (126), but it has few multinational co-authored articles. In contrast, the Paul Scherrer Institute in Switzerland is central to the collaboration network. The largest number of retrieved journal articles was in the area of energy applications (1059 articles) followed by light absorbing materials (983) and solar cells (420). Energy applications mainly address hydrogen, desalination, air conditioning, drying, heat pumps, biomass, and water splitting, while the light absorbing material mainly cover nano materials, TiO_2, semiconductors, thin films, phase change material and so on. This analysis not only identifies global hotspots in solar energy research, but may also influence researchers' selection of future studies and publications.

1. Introduction

The destabilization of the world's climate, driven by relentless emissions of greenhouse gases, has the potential to accelerate global warming and extreme weather events, exacerbate water and food shortages, damage valuable coastal property, advance the spread of infectious disease, and induce mass migration, potentially leading to a less prosperous and more insecure world [1]. While fossil fuels are being exhausted and the natural environment is deteriorating, the sustainable development of alternative energy resources has become a major concern of many nations.

Among various alternative new energy resources, solar energy is a completely renewable and abundant resource with rapidly declining conversion costs; it therefore is likely to be a popular option for generating electricity in coming years. According to its primary energy product, solar energy conversion methods can be classified into three categories: solar to electricity, solar to liquid fuels, and solar to thermal energy. With the development of science and technology, solar energy research and application have been receiving increasing attention throughout the world and is forecast to play a greater role in the energy mix in upcoming years as shown in Fig. 1.

Corresponding to the increasing recognition of the potential role for solar energy, the associated body of literature has also grown substantially. Thus, it is time to implement bibliometric analytical techniques to evaluate the growing body of literature on solar energy. The Bibliometric technique offers an important quantitative perspective to assessing the development and growth of research on strategic topics. It is a statistical method of bibliography counting to evaluate and quantify the growth of literature for a particular subject [3]. It is worth noting that bibliometrics is quantitative by nature, but is used to make pronouncements about qualitative features. In fact, this is the major feature of all sorts of bibliometric techniques to transform something intangible (scientific quality) into a

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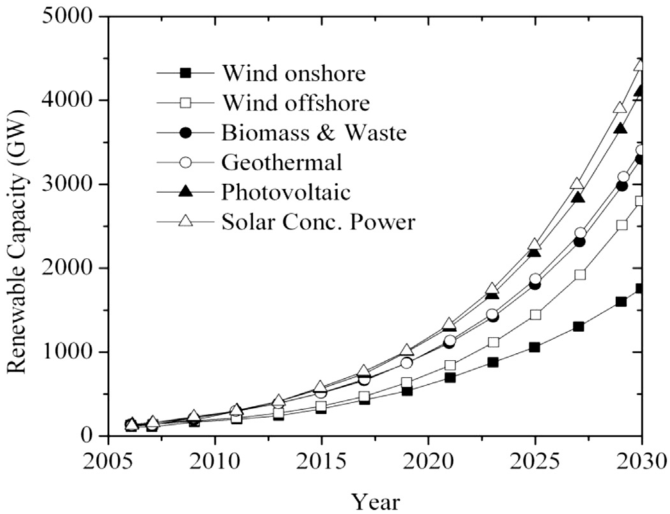

Fig. 1. Development of renewable electricity generating capacities in the world regions [2].

manageable entity. There are two advantages in implementing bibliometric analysis: (1) it provides an assessment of the research or the scientific production in a specific area over a period of time using indicators and the calculation of certain classical laws [4]; (2) it examines science as a knowledge-generating system. Many areas of science have tried to evaluate their evolution or growth by this method and, nowadays, the bibliometric technique has become an indispensable instrument for measuring scientific progress [5].

Originally, the bibliometric method has been applied in library and information sciences as the research methodology for citation analysis and content analysis; the conventional bibliometric method has also been widely applied in various fields by investigating the publication characteristics, such as countries, research organizations, journals, research fields, and citation habits [6–8]. However, in recent years, analyses of word distribution of paper titles, abstracts, and keywords in different periods have been used widely to get more refined information related to the research itself [9–11].

This study aims to investigate the characteristics of the solar energy literature from 1992 to 2011 and its implication using bibliometric techniques. This statistical method of bibliography analysis evaluates and quantifies the growth of publications addressing a particular subject, and examines publication characteristics consisting of countries, research institutes and fields, journals, authors, citation habits and author keywords. Furthermore, some priority research directions with high potential are identified to advance dramatically solar energy conversion to electricity, fuels, and thermal end uses.

2. Methodology

Bibliometrics takes the document system and bibliometric characteristics as the research object, adopts mathematical and statistical methods to research the distributed architecture, quantitative relation, varying pattern and quantitative management of the document information, and then investigates the structure, characteristics and patterns of the underlying science and technology.

2.1. The impact factor and h-index

The statistical analysis of documents is mainly targeted at published literature and authors. It is a necessary foundation and essential condition of document research. Publication statistics generally describe countries, publishing houses, subjects, languages, journals, research institutions and the number of published articles by different authors. Statistics on authors usually concentrate on the change of number of outstanding authors and ordinary authors over time.

Two measures of influence are used in our analysis: the impact factor (IF) and the h-index. The impact factor is one of the most influential tools in modern bibliometrics research. It is used in this paper to assess the solar energy-related journal's relative influence. The impact factor of a given journal was determined for each document as reported in the 2011 Journal Citation Reports. The h-index was first proposed by Hirsch to measure the productivity and impact of published works of not only scientists and scholars [12], but also research organizations, countries, and journals. It is a good indicator of the impact of a scientist or journal and has the advantage of being objective [13,14]. It is defined simply as: “A scientist has index H if H of his/her Np papers have at least H citations each, and the other (Np-H) papers have no more than H citations each,” where Np is the number of papers published over n years [12]. Therefore, the h-index combines a measure of quantity (number of publications) and impact (number of citations) in a single indicator.

2.2. Content analysis

Word frequency analysis is a common form of content analysis. Investigators usually take core words and expressions which indicate the core content of literature as the research object. In this way, they can quantitatively analyze the development trends and changes in scientific research of a certain area. This study analyzes the keywords and headword field of publications and summarizes the hot research content in recent solar energy research.

2.3. The social network

Social network refers to the assemblage of social actors and the relationships between them. That is to say, a social network consists of multiple points (social actors) and the connections between them (the relationships between each social actor). Social network analysis involves quantitative research on the relationships between the social actors, which is presented as a useful extension of conventional forms of analysis. In this paper, this method is used to analyze the collaborative relationships among the 20 most productive countries and institutions.

3. Results

To conduct the pilot study, “solar energy” or “solar energies” is searched for titles, abstracts, and keywords in the database of the Science Citation Index (SCI) and the Social Science Citation Index (SSCI) on December 11, 2012. The documents were collected for the period during 1992–2011, and 7835 documents were obtained. The documents were analyzed according to their type, language(s), publication output, publication patterns, authorship, citation analysis of articles, impact factor (IF), country or countries of publication and keyword distribution, etc.

3.1. Characteristics of publications

These 7835 documents related to solar energy from the SCI and SSCI over the past two decades were categorized into 16 types. The most frequently used document type was “Article” with 86.4% (6770 records) of total publications, followed far behind by “Paper Proceedings” with a mere 11.6% (912 records), “Review” with 8.59%

(673 records), "Meeting Abstract" with 1.54% (121 records) and "Editorial Material" with 1.44% (113 records). The records of other types accounted for less than 1 percent, such as News Item, Note, Letter, Book Chapter, Reprint, Correction, Addition, Discussion, Book Review, Bibliography, and Item about an Individual.

In this paper, only the type of articles is considered. The articles pertaining to solar energy in the SCI and SSCI are available in 20 languages. English is the dominant language with 6571 records. There were other languages used more than once in articles including German (36), Chinese (32), French (28), Spanish (27), Japanese (15), Portuguese (12), Polish (11), Turkish (10), Russian (10), Slovak (4), Romanian (4), and Slovenian (3). Swedish, Ukrainian, Korean, Lithuanian, Italian, Hungarian and Croatian were used in only one article each. English was the dominant language in solar energy research, even in many non-English speaking countries like China, Japan, and Germany, which suggests that the English language is a common medium of communication in these research activities.

Table 1 presents several characteristics of the solar energy publications between 1992 and 2011. The annual number of articles, the average number of authors, and the annual number of cited references has increased significantly. Between 1992 and 1999, the rate of publication on solar energy grows by about 50%, it then experiences a slight decrease in 2001, followed by a steady increase every year through 2011. After 2006, the pace of publication increases substantially, with an average annual growth rate greater than 15%. There was an average of 2.5 authors per solar energy article in 1992, while the number steadily increased to 4.0 in 2011. And the number of references rose from 20 in 1992 to 37.7 in 2011. The progressive increase of publications and references indicate the stable growth and communication in the field of solar energy research during the past 20 years.

3.2. Publication distribution of countries/territories and institutes

Providing the address and affiliations of at least one author, the journal articles can be used to evaluate the contribution of different countries/territories and institutes. Only 6702 articles could be used to analyze the distribution of countries/territories and institutes because 68 articles do not include author addresses in the SCI and SSCI. Of these 6702 articles, 5617 (83.8%) articles are independent publications and the rest involve international collaborations.

Table 1
Characteristics of publications from 1992 to 2011.

PY	TP	AUTP	No. AU	AU/AUTP	NR	NR/TP	PG	PG/TP
1992	147	147	366	2.49	2895	19.69	1414	9.62
1993	159	159	397	2.50	3046	19.16	1547	9.73
1994	175	173	457	2.64	3414	19.51	1613	9.22
1995	172	172	439	2.55	3149	18.31	1719	9.99
1996	226	226	602	2.66	3886	17.19	1842	8.15
1997	210	210	624	2.97	4006	19.08	1959	9.33
1998	227	226	694	3.07	4355	19.19	2048	9.02
1999	255	255	737	2.89	4538	17.80	2259	8.86
2000	224	224	724	3.23	4520	20.18	2300	10.27
2001	208	208	688	3.31	4543	21.84	1969	9.47
2002	222	222	733	3.30	5216	23.50	2305	10.38
2003	244	244	801	3.28	5285	21.66	2454	10.06
2004	286	286	917	3.21	6346	22.19	2881	10.07
2005	310	310	1076	3.47	7707	24.86	2985	9.63
2006	350	350	1248	3.57	8820	25.20	3466	9.90
2007	436	436	1588	3.64	11,050	25.34	3824	8.77
2008	523	523	1876	3.59	14,379	27.49	4609	8.81
2009	630	630	2352	3.73	18,241	28.95	5373	8.53
2010	762	762	3014	3.96	24,749	32.48	6687	8.78
2011	1004	1003	3998	3.99	37,892	37.74	9405	9.37

PY, year; TP, the number of total publications; AUTP, the number of publications including authors' names; AU, the number of authors; NR, the number of cited reference; PG, the number of pages; AU/TP, PG/TP, and NR/TP, the average of authors, pages, and references in a paper.

From 1992 to 2011, 149 countries have contributed to publishing articles about research on solar energy. Thus, three quarters of the world's 196 countries have scientists who are publishing in the field of solar energy. While this shows great geographic breadth, the top 20 countries are responsible for 93.8% of the 6702 articles.

In Table 2, the 20 most productive countries are ranked with respect to the number of total journal articles, the number and the percentage of single country articles and internationally collaborated articles, the first author and corresponding author articles, and so on. In the top 20 countries, there are two countries from North America, seven countries from Asia, eight countries from Europe, one country (Australia) from Oceania, one country (Brazil) from South America, and one (Egypt) from Africa. The US is the most productive country with the largest number in all aspects, followed by China and India except in the international collaboration category. It is worth noting that China ranks second in the number of total publications, single country publications and publications with first author while for the number of internationally collaborative publications China is in the sixth place. Thus it can be seen that international cooperation with Chinese scientists in solar energy is still relatively underdeveloped. There is a lack of wide-ranging cooperation among nations in spite of the growth of solar energy research. India has a similar profile with little international publishing. In contrast, Germany and the U.K. have fewer total publications, but 6–8% of them involve international teaming.

Fig. 2 displays the time-trend analysis of the 6 most productive countries. The US took a leading position during the whole period, with its published articles growing rapidly after 2006. We suspect that this was mainly due to the Renewable Portfolio Standards promulgated by 29 states [27], and the Energy Policy Act passed by the government in 2005. Similar to the US, the increasing speed of publications in China is much faster than the other 5 dominant countries after 2005. The government of China adopted the Renewable Energy Sources Act in 2006. And China's research on solar energy yielded fruitful results through the promotion and guidance of laws, regulations and the 2010–2020 Renewable Energy Medium and Long-term Development Plan. The number of articles covering solar energy among the other 5 countries grew slowly, and they exhibit erratic highs and lows throughout the period. One could come to the conclusion from Fig. 2 that the rapid development of solar energy research was substantially driven by these highly productive countries.

Based on the statistics for countries, the cooperative relationships among the top 20 productive countries and regions in the field of solar energy research from 1992 to 2011 are described, as defined by the cooperation network diagram showed in Fig. 3. As can be seen from the diagram, the US has played a key role in the collaboration network of the 20 productive countries and regions; it has had cooperative relationships with each of the other 19 productive countries and regions. Among them, the cooperation between the US and Germany is particularly notable, rising to first place in intensity. Besides, the number of cooperation between the US and Switzerland, the UK, Japan, China and Taiwan region can also be seen in the diagram, topping the other countries and regions. It also is apparent from the diagram that China had partnerships with several other countries, mainly centered on the US, Japan, and Sweden. India's limited amount of international publishing in the solar energy field accounts for its peripheral location in this network diagram, and the thin lines connecting it to other countries.

Table 2
The top 20 productive countries/territories during 1992–2011.

Country	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)	h-index
USA	1273	1 (18.99)	1 (16.65)	1 (14.08)	1 (16.17)	1 (15.84)	87
China	656	2 (9.79)	2 (9.7)	6 (4.62)	2 (9.06)	2 (9.15)	39
India	506	3 (7.55)	3 (7.96)	12 (2.46)	3 (7.12)	3 (6.98)	28
Japan	478	4 (7.13)	4 (6.41)	5 (4.91)	4 (6.13)	4 (6.07)	50
Germany	436	5 (6.51)	6 (4.5)	2 (7.62)	5 (4.92)	5 (4.94)	45
UK	333	6 (4.97)	8 (3.19)	3 (6.41)	8 (3.75)	8 (3.65)	41
Spain	304	7 (4.54)	7 (3.58)	7 (4.29)	7 (3.76)	7 (3.71)	31
France	294	8 (4.39)	9 (2.87)	4 (5.54)	9 (3.13)	9 (3.2)	37
Turkey	282	9 (4.21)	5 (4.58)	20 (1.04)	6 (4.1)	6 (4.14)	30
Italy	223	10 (3.33)	10 (2.44)	9 (3.58)	11 (2.57)	11 (2.68)	33
Switzerland	223	10 (3.33)	12 (2.26)	8 (4)	10 (2.81)	10 (2.76)	41
Canada	201	12 (3)	11 (2.39)	10 (2.79)	12 (2.48)	12 (2.48)	26
Australia	167	13 (2.49)	14 (1.98)	13 (2.33)	13 (2.03)	13 (2.15)	27
Israel	143	14 (2.13)	18 (1.55)	13 (2.33)	15 (1.76)	16 (1.7)	25
South Korea	139	15 (2.07)	17 (1.62)	16 (2)	17 (1.66)	17 (1.69)	17
Taiwan	137	16 (2.04)	13 (2.17)	32 (0.62)	14 (1.89)	14 (1.96)	19
Greece	134	17 (2)	15 (1.94)	20 (1.04)	16 (1.75)	15 (1.76)	21
Sweden	129	18 (1.92)	21 (1.21)	11 (2.54)	20 (1.34)	20 (1.32)	28
Egypt	120	19 (1.79)	16 (1.73)	23 (0.96)	18 (1.64)	18 (1.59)	17
Brazil	111	20 (1.66)	19 (1.46)	18 (1.21)	19 (1.42)	19 (1.46)	14

TP: the number of total publications; SP: the number of single country publications; CP: the number of internationally collaborative publications; FP: the number of publications as first author's country; RP: the number of publications as corresponding author's country; R (%): the rank and the ratio of the number of one country's publications to the total number of publications during 1992–2011.

A total of 3841 institutions contributed to the subject of solar energy according to the 6702 articles with author addresses information. Most of these articles (59.5%) are published independently while the rest of them are inter-institutional. The contribution of the 20 most productive institutes in solar energy research from 1992 to 2011 is shown in Table 3. Among the top 20 institutes, four institutes are from the US and Switzerland, two from China, India, Spain and one from Turkey, France, Israel, Japan, Russia and the UK, respectively. Germany, Italy, Canada, Australia, South Korea, Taiwan, Greece, Sweden, Egypt and Brazil belonged to the 20 most productive countries, but no institutes from these countries appear in the list of the 20 most productive institutes. The Indian Institute of Technology had the maximum contribution with 126 articles in the total volume of publications, followed by the Paul Scherrer Institute in Switzerland (101 articles) and the Chinese Academy of Sciences (91 articles). It is worth noting that, the Indian Institute of Technology, the Chinese Academy of Sciences, the Centre National de la Recherche Scientifique (CNRS), and the Russian Academy of Sciences ranked 1st, 3rd, 6th and 14th respectively, are integrated research centers consisting of many relatively independent institutes distributed across their own countries.

Several of the countries hosting these top 10 institutes have GDPs that are a fraction of the US or China, which had GDPs in 2012, PPP adjusted, of $15.1 trillion and $11.3 trillion, respectively. Switzerland and Israel, for instance had GDPs of $0.34 trillion and $0.24 trillion, respectively, in that same year. Thus, their publication productivity in solar energy research is particularly notable.

In Fig. 4, the growth of the 5 most productive institutes over 20 years is revealed. Research on solar energy was developed earlier in the Indian Institute of Technology and the Paul Scherrer Institute, while solar energy research by the Chinese Academy of Sciences, Shanghai Jiao Tong University, and Ege University surged after 2000 especially after 2008, corresponding to the development of solar energy research in China.

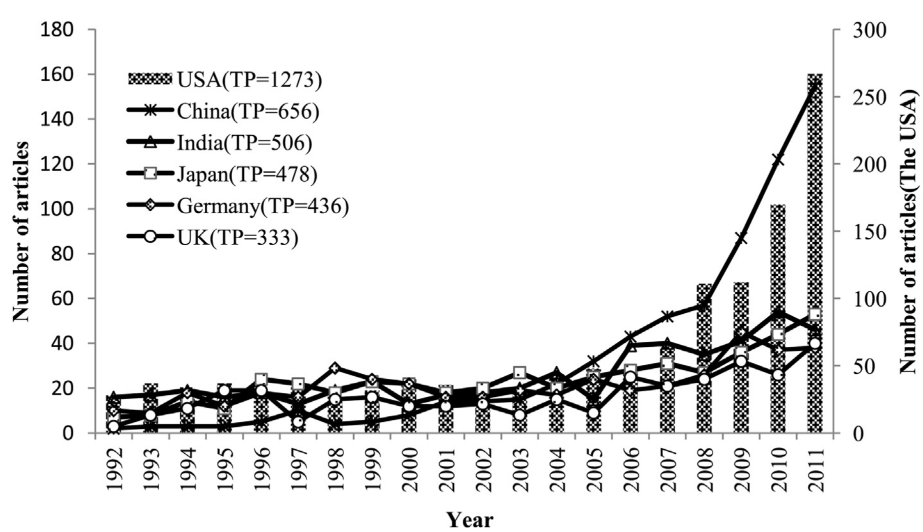

Fig. 2. The annual number of each top 6 productive country during 1992–2011.

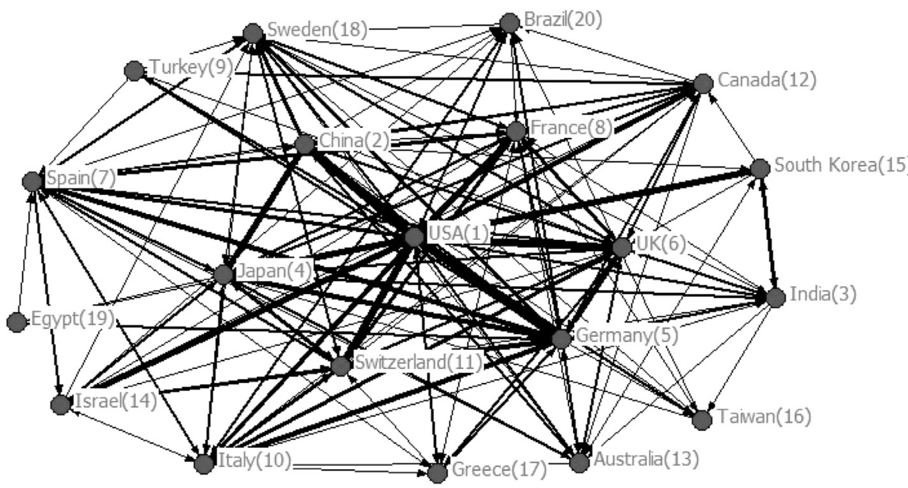

Fig. 3. The cooperation network of the top 20 productive countries/territories.

The cooperative relationship among the most productive institutions in the field of solar energy research from 1992 to 2011 is also analyzed after examining collaborative networks between countries. The corresponding cooperation network diagram is shown in Fig. 5. Institutions that did not have cooperative publications with any of the other 19 institutions do not appear in the diagram.

It can be seen from Fig. 5 that the Paul Scherrer Institute in Switzerland is in the center of the collaboration network among the 20 most productive institutions, with 6 strong cooperation relationships, especially with the Eidgenossische Technische Hochschule Zürich, Switzerland. These two Swiss institutes have produced 38 co-authored publications. The Swiss Federal Institute of Technology in Zurich is also connected closely with these two institute compatriates. These three institutions all had strong cooperation with the Weizmann Institute of Science in Israel, which suggests that the research of Switzerland and Israel were particularly multi-national. The three institutions from China also had good cooperative relationships and the Chinese Academy of Sciences played a key role, but there was limited cooperation with other nations. Thus, solar energy research in China is mainly linked with other domestic research personnel; the internationalization of Chinese research is limited.

The institutes in India and Spain also appear to have minimal international collaboration. Their linkages to the rest of the research network shown in Fig. 5 are enabled by their ties to the three Swiss institutes.

To finalize this analysis of networking in the field of solar energy, we list some of the top subordinates of the top 3 institutes (see Table 4). As the most productive institute on solar energy, the Indian Institute of Technology's most productive subordinate is the Center for Energy Studies (94), followed by the Departments of Mechanical Engineering (13), Physics (9) and Chemical Engineering (7). The Paul Scherrer Institute is the second productive institute with two main subordinates: the Solar Technology Laboratory (48) and the Laboratory of Energy and

Table 3
The top 20 productive institutes during 1992–2011.

Institute	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)	h-Index
Indian Inst Technol, India	126	1 (1.88)	1 (2.46)	9 (1.03)	1 (1.67)	1 (1.63)	20
Paul Scherrer Inst, Switzerland	101	2 (1.51)	11 (0.53)	1 (2.95)	4 (0.72)	5 (0.63)	23
Chinese Acad Sci, China	91	3 (1.36)	3 (1.15)	2 (1.66)	2 (1.03)	3 (0.98)	21
Shanghai Jiao Tong Univ, China	78	4 (1.16)	2 (1.23)	8 (1.07)	2 (1.03)	2 (1.06)	17
Ege Univ, Turkey	54	5 (0.81)	4 (0.85)	23 (0.74)	5 (0.67)	4 (0.67)	18
CNRS, France	51	6 (0.76)	12 (0.5)	7 (1.14)	7 (0.57)	6 (0.58)	16
Weizmann Inst Sci, Israel	50	7 (0.75)	5 (0.63)	13 (0.92)	8 (0.54)	7 (0.49)	16
Osaka Univ, Japan	48	8 (0.72)	7 (0.58)	13 (0.92)	8 (0.54)	7 (0.49)	15
CIEMAT, Spain	47	9 (0.7)	63 (0.23)	4 (1.4)	15 (0.42)	17 (0.4)	20
Natl Renewable Energy Lab, US	45	10 (0.67)	44 (0.28)	6 (1.25)	11 (0.45)	19 (0.38)	20
Russian Acad Sci, Russia	44	11 (0.66)	16 (0.45)	11 (0.96)	13 (0.43)	15 (0.41)	9
ETH, Switzerland	43	12 (0.64)	0	3 (1.58)	17 (0.4)	12 (0.43)	15
NASA, US	42	13 (0.63)	92 (0.18)	5 (1.29)	43 (0.25)	33 (0.31)	16
MIT, US	41	14 (0.61)	12 (0.5)	21 (0.77)	13 (0.43)	12 (0.43)	19
Jai Narain Vyas Univ, India	41	14 (0.61)	6 (0.6)	27 (0.63)	6 (0.58)	17 (0.4)	10
CSIC, Spain	40	16 (0.6)	33 (0.33)	10 (0.99)	34 (0.3)	37 (0.28)	11
Tokyo Inst Technol, Japan	36	17 (0.54)	20 (0.4)	23 (0.74)	20 (0.39)	9 (0.46)	14
Swiss Fed Inst Technol, Switzerland	36	17 (0.54)	35 (0.3)	15 (0.88)	17 (0.4)	15 (0.41)	19
City Univ Hong Kong, China	35	19 (0.52)	15 (0.48)	34 (0.59)	23 (0.37)	19 (0.38)	12
Univ Ulster, UK	35	19 (0.52)	10 (0.55)	51 (0.48)	10 (0.49)	10 (0.44)	9
Ecole Polytech Fed Lausanne, Switzerland	35	19 (0.52)	7 (0.58)	58 (0.44)	15 (0.42)	12 (0.43)	19

TP: the number of total publications; SP: the number of single institute publications; CP: the number of inter-institutionally collaborative publications; FP: the number of publications of as the first author's institute; RP: the number of publications as corresponding author's institute; R (%): the rank and the ratio of the number of one institute's publications to the total number of publications during 1992–2011.

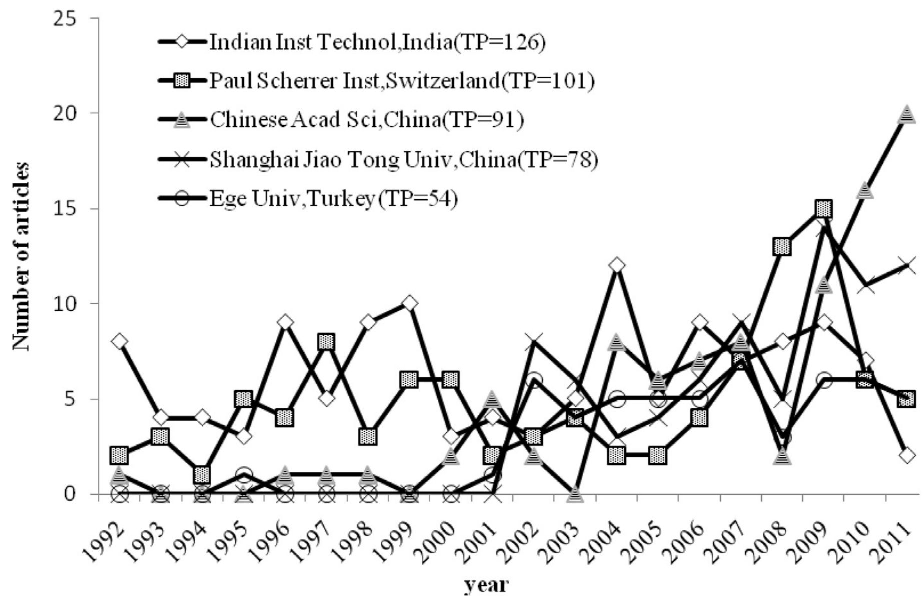

Fig. 4. The growth trend of the top 5 productive institutes during 1992–2011.

Process Technology (12). The third productive institute is the Chinese Academy of Sciences, and its most productive subordinate is Graduate School with 31 publications followed by the Institute of Chemistry (25), and the Institute of Engineering Thermophysics (9). The statistics of top subordinates help us learn more about the institutions that have contributed greatly to solar energy research.

3.3. Subjects covered by solar energy publications

The 6770 articles for solar energy analysis are divided into 163 subject categories in SCI and SSCI. The contribution of the top 20 subjects in solar energy research from 1992 to 2011 is shown in Table 5. Energy & Fuels is the most popular topic, with 2726 records, followed by Materials Science & Multidisciplinary Materials Science with 891 records and Physical Chemistry with 831 records. Public policy, economics and business perspectives do not rise to the short list of topics shown in Table 5.

Fig. 6 illustrates the five most frequent subject categories by number of annual publications, for the set of 6770 articles. The numbers of articles in these five subject categories soared during the period from 2004 to 2011. Energy & Fuels had been in a leading position during 1992–2011. And the other four subjects Multidisciplinary Materials Science, Physical Chemistry, Thermodynamics, and Chemical Engineering, grow more rapidly after 2007, in contrast with the previous steady state. In sum, the main research area of solar energy is Energy & Fuels from 1992 to 2011.

A total of 1290 journals published pertinent literature on solar energy research all over the world during 1992–2011. The publication distribution of journals is shown in Table 6. Here, more than 40% of the solar energy articles appear in the 20 journals listed in Table 6. *Renewable Energy* is the most productive journal with 477 articles, followed by *Solar Energy* (450) and *Energy Conversion and Management* (287). Interestingly, the *Journal of the American Chemical Society*, ranks 15th in the number of articles, but has the highest IF value (9.907) among these 20 journals. Thus, the *Journal*

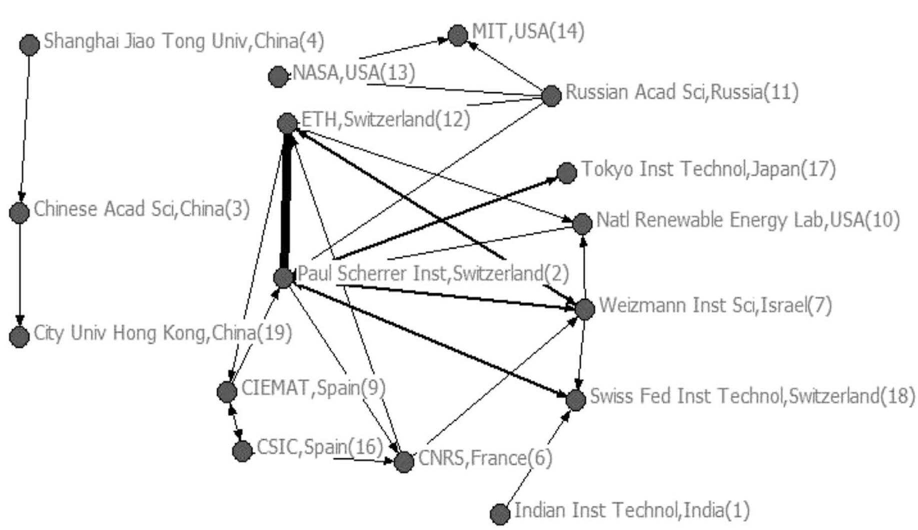

Fig. 5. The cooperation network of the top 20 productive institutions.

Table 4
The subordinates of the top 3 productive institutes.

Institution	Subordinate	TP
Indian Institute of Technology, India	Center for Energy Studies	94
	Department of Mechanical Engineering	13
	Department of Physics	9
	Department of Chemical Engineering	7
	Alternate Hydro Energy Centre	3
Paul Scherrer Institute, Switzerland	Solar Technology Laboratory	48
	Laboratory of Energy and Process Technology	12
Chinese Academy of Sciences, China	Graduate School	31
	Institute of Chemistry	25
	Institute of Engineering Thermophysics	9
	Shanghai Institute of Ceramics	7
	Institute of Electrical Engineering	7

TP: the number of total publications.

Table 5
The 20 most productive subjects during 1992–2011.

Subject	TP	%
Energy & Fuels	2726	40.27
Materials Science, Multidisciplinary	891	13.16
Chemistry, Physical	831	12.27
Thermodynamics	715	10.56
Engineering, Chemical	708	10.46
Chemistry, Multidisciplinary	554	8.18
Physics, Applied	525	7.75
Mechanics	463	6.84
Engineering, Mechanical	442	6.53
Environmental Sciences	376	5.55
Physics, Nuclear	293	4.33
Physics, Condensed Matter	285	4.21
Electrochemistry	278	4.11
Nanoscience & Nanotechnology	269	3.97
Water Resources	262	3.87
Engineering, Electrical & Electronic	196	2.90
Engineering, Environmental	174	2.57
Engineering, Civil	163	2.41
Construction & Building Technology	154	2.27
Meteorology & Atmospheric Sciences	152	2.25

TP: the number of total publications.

of the American Chemical Society is a core journal with a large influence on solar energy research. Fig. 7 shows the trends of the top 6 journals. It is notable that *Solar Energy* soars rapidly after 2004, while the other four journals fluctuate over the two decades.

3.4. Main solar energy research fields

The review and analysis of keywords from retrieved articles can be organized around "hot topics" pertinent to solar energy, including basic elements of solar energy research such as photovoltaic, hydrogen, photochemistry, thermal, solar storage, conversion efficiency, and solar energy applications [15]. Some of these are listed in Table 7 according to the rank of keywords and the hotspot analysis of pertinent literature. The largest number of retrieved journal articles shown in the table is in the area of energy applications (1059 articles) followed by light absorbing material (983) and solar cells (420). Less research attention is paid to topics such as thermal science (394) and photovoltaic materials (371).

3.4.1. Thermal

Light and heat utilization of solar radiation involves solar energy being collected, utilized by interaction with the substance, and converted into heat. Therefore, it is of special interest to see publications on the thermal science of solar energy. Under this topic, 394 references were retrieved in the SCI and SSCI databases. In the solar energy heat utilization, the key is converting the sun's radiant energy into heat. Solar energy is more dispersed, so the collector is the key part of a variety of solar installations. And how to concentrate solar energy is also worthy of discussion. There are three basic heat transfer mechanisms: heat conduction, heat convection and heat radiation. As to solar energy, solar installations, solar heat storage devices and heat utilization systems are three important elements of heat transfer. It can be seen that the topic of solar collectors (120) is the top thermal subject, followed by heat transfer (74) and thermal storage (71).

3.4.2. Solar energy conversion

A photovoltaic power generation system consists of multiple components like cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output [16]. Within the area of photovoltaic power generation the majority of published research (371) focused on photovoltaics. Another research focus is solar cells (420), addressing such aspects as dye-sensitized solar cells, photovoltaic cells, fuel cells, and photo electrochemical cells. It is apparent in Table 7 that publications about photovoltaic power generation have increased by many folds in the first few years of the new century as compared to those made

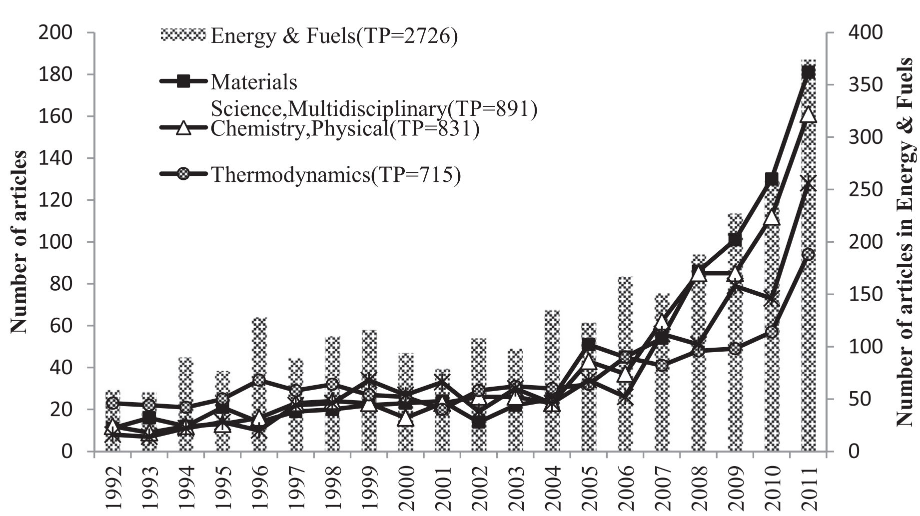

Fig. 6. The number of articles of the top 5 productive subject categories.

Table 6
The 20 most productive journals during 1992–2011.

Journal name	R	TP (%)	IF 2011
Renewable Energy	1	477 (7.05)	2.978
Solar Energy	2	450 (6.65)	2.475
Energy Conversion and Management	3	287 (4.24)	2.216
Solar Energy Materials and Solar Cells	4	196 (2.9)	4.542
Desalination	5	184 (2.72)	2.59
International Journal of Hydrogen Energy	6	153 (2.26)	4.054
Journal of Solar Energy Engineering-Transactions of the Asme	7	138 (2.04)	0.846
Energy	8	131 (1.94)	3.487
Applied Energy	9	115 (1.7)	5.106
International Journal of Energy Research	10	108 (1.6)	2.122
Applied Thermal Engineering	11	106 (1.57)	2.064
Energy and Building	12	98 (1.45)	2.386
Journal of Physical Chemistry C	13	72 (1.06)	4.805
Energy Policy	14	69 (1.02)	2.723
Journal of the American Chemical of Society	15	63 (0.93)	9.907
Journal of Photochemistry and Photobiology A-Chemistry	16	60 (0.89)	2.421
Material Letters	17	59 (0.87)	2.307
Thin Solid Films	18	51 (0.75)	1.89
Energy Sources	19	46 (0.68)	–
Energy & Environmental Science	20	45 (0.66)	9.01

TP: the number of total publications; R (%): The rank and the ratio of the number one journal's publications to the total number of publications during 1992–2011; IF: impact factor; "–": missing impact factor.

during the nineties of the last century. To improve the efficiency of photovoltaics, a small number of studies were devoted to light absorbing material.

3.4.3. Light absorbing materials

All solar cells require a light absorbing material to be present within the cell structure to absorb photons and generate free electrons via the photovoltaic (PV) effect. The PV effect is the basis of the conversion of light to electricity in photovoltaic, or solar cells. Therefore, it is of special interest to see the dominant emerging solar PV materials. Under this topic, 983 references were retrieved in the SCI and SSCI databases. In this field, nano-material (322) was the largest area of research. In recent years, with the rapid development of nano-materials, it is also recognized that it can be used in the field of solar light absorbing material. Nano-materials is only a general concept, we can see that TiO_2 (titanium oxide), semiconductor, thin films and phase change materials are the top five light absorbing materials being researched. TiO_2 is very suitable for solar cells of a kind of chemical substances, TiO_2 production technology and the methods of characterization are already being characterized, but there is a lot of space for research. Solar photovoltaic power generation systems involve the use of solar cell semiconductor material to create the photovoltaic effect. Therefore, semiconductors ranked third among light absorbing materials. Phase change materials in solar heat pump systems are introduced to develop fatty acids-like phase-change materials suitable for solar heat pump systems. Global PV application markets are still growing due to the high conversion rate and price reductions.

3.4.4. Energy applications

Much of the published research on solar energy is focused on energy applications, assessing hydrogen, desalination, drying, heat pump, biomass, air conditioning and so on.

The energy applications literature concentrates on hydrogen studies carried out to investigate the development of hydrogen production, distribution, and storage technologies [3]. While, the keyword "hydrogen" is not a focus of research from 1992 to 2001, since entering the 21st century, using solar energy to manufacture hydrogen has received extensive attention because it has the potential to effectively solve the energy problem, form a sustainable energy system, and reduce greenhouse gases. And the frequency of occurrence of the corresponding keywords "hydrogen" jumps to the top 3. Moreover, the frequency of occurrence of "hydrogen production" has also increased significantly, which is contrasted with the situation that hasn't appeared in the prior 10 years. With the same situation, the keyword "photovoltaic" which is ranked third in the total frequency of occurrence also gets rapid development after 2002.

Desalination is the second major area of solar energy application research (192 out of 1059 articles). The combination of solar energy collection system and desalting process is a kind of sustainable sea water desalination technology to alleviate the water shortage situation. Using solar energy to desalinate sea water mainly utilizes its thermal effect and luminous effect. The desalination method that

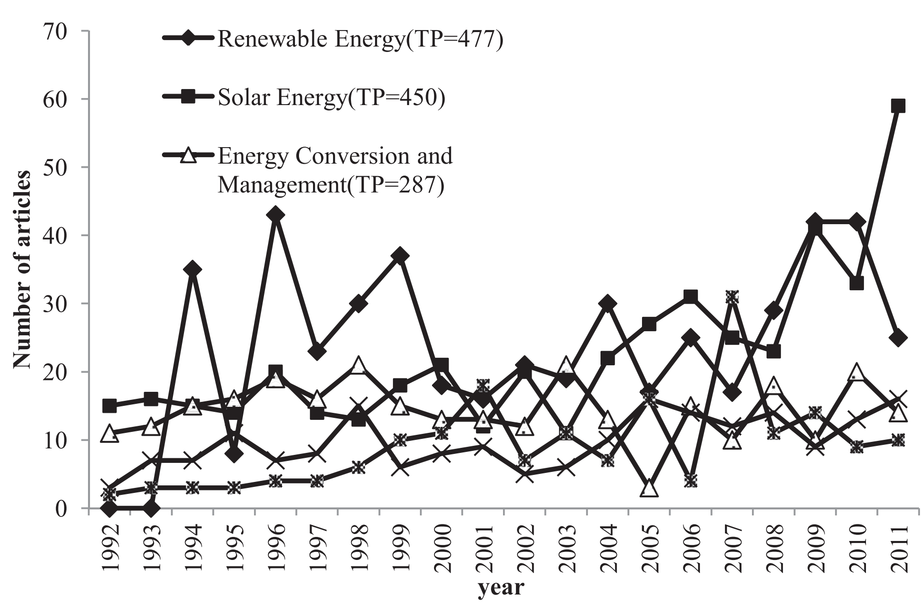

Fig. 7. The number of articles of the top 5 productive journals during 1992–2011.

Table 7
The number of publications by main topic and subtopic.

Main topics and subtopics	Number of publications (1992–2011)	Number of publications (1992–1996)	Number of publications (1997–2001)	Number of publications (2002–2006)	Number of publications (2007–2011)
Energy applications	1059	73	148	233	605
Hydrogen	321	15	17	65	224
Desalination	192	9	51	42	90
Air conditioning (cooling)	190	7	19	45	119
Drying	114	19	33	25	37
Heat pump	94	8	14	32	40
Biomass (microalgae)	89	13	14	18	44
Water splitting	59	2	0	6	51
Light absorbing material	983	39	81	209	634
Nano material	322	2	12	58	250
TiO2\Titanium	191	8	0	50	113
Semi conduct(s)	124	15	17	18	74
Thin film(s)	93	2	12	18	61
Phase change material	77	5	8	30	34
Silicon (Si)	64	2	14	11	37
Zinc oxide (ZnO)	51	0	4	13	34
Fill factor	32	1	6	8	17
Photo (electro) chemistry	29	4	8	3	14
Solar cell(s)	420	19	41	108	252
Solar cell(s)	247	9	34	63	141
Fuel cell(s)	45	3	3	11	28
Dye solar cells	72	0	0	22	50
Photovoltaic cell(s)	31	2	2	7	20
Photo electrochemical cell(s)	25	5	2	5	13
Thermal	394	31	47	92	224
Solar collector	120	9	17	35	59
Heat transfer	74	12	6	11	45
Thermal storage	71	4	7	18	42
Thermal performance	43	1	3	5	34
Geothermal energy	29	5	6	8	10
Solar chimney	29	0	3	8	18
Concentrated solar energy	28	0	5	7	16
Photovoltaic(s)&PV	371	20	31	67	253
Photovoltaic effect	200	12	18	39	131
Photovoltaic (PV) system(s)	106	5	9	20	72
PVT	26	2	0	3	21
Photovoltaic (PV) array(s)	11	0	3	0	8
Organic photovoltaic(s)	10	0	0	2	8
Photovoltaic generator(s)	9	1	0	1	7
Grid connected photovoltaic(s)	9	0	1	2	6

makes use of the solar energy thermal effect is driving the sea water to make the phase change and separation using the solar thermal collected. In contrast, the desalination method that makes use of the solar energy luminous effect is driving the dialysis process to produce fresh water using the electricity produced by the photoelectric effect. Today, the desalination method that is applied most is multistage distillation and reverse osmosis (3 articles). They represent different desalting approaches.

Solar air conditioning (190 articles) refers to any air conditioning (cooling) system that uses solar power. This can be done through passive solar, solar thermal energy conversion and photovoltaic conversion (sunlight to electricity). The USEnergy Independence and Security Act of 2007 authorized funding for a new solar air conditioning research and development program, to develop and demonstrate multiple new technology innovations and mass production economies of scale. Solar air conditioning will play an increasing role inzero-energy and energy-plus buildings designs.

As a branch of solar energy utilization, techniques of solar energy drying also receive attention (114 articles). It has developed in recent years because of growing energy and environmental problems. This research is mainly concentrated in the developed countries such as the US, the UK, France, Germany, Canada, Australia, New Zealand and Japan. The future development direction is increasing efficiency of solar drying devices and cost reductions.

The solar energy heat pump technology that has evolved over the last half century integrates solar energy utilization techniques into heat pump technologies. Many energy researchers have devoted themselves to this technology (94 articles). Some developing countries such as Turkey (47 articles) and Mexico have done a great deal of research on it in recent years. One of the major constraints that restricts the development and extension of the solar energy heat pump is its higher initial investment. In addition, energy policies and fuel prices also influence the economical efficiency directly. In particular, there is a new direction of solar energy heat pump technology called PV Solar Assisted Heat Pump (PV-SAHP), which is a photovoltaic power system which provides electricity for the heat pump.

Biomass (89 articles) is biological material derived from living, or recently living organisms which is a renewable, low-carbon fuel that is already widely available throughout the European Union. Its development is mainly concentrated on the following three aspects, which include looking for biomass resources, research on biomass conversion technology, and improving the ecological and environmental efficiency of the biomass energy.

3.5. The most highly cited articles

Table 8 lists the most highly cited articles, the total citations of articles, average annual citations of articles, article's name, journal's name and the country of origin, for 1992–2011 [17–37]. Yearly variations in the number of citations can be used to trace the impact of publications. It can be seen that the most highly cited article is entitled "Plastic solar cells" authored by Christoph J. Brabec, N.

Table 8
Most frequently cited articles during 1992–2011.

Year	TC-2011	TC/Y	Article	Journal	Country
1992	269	13	The deep, hot biosphere	Proceeding of the National Academy of the Sciences of the United States of America	US
1993	291	15	Effects of altervalent cation doping of TiO_2 on its performance as a photocatalyst for water cleavage	Journal of Physical Chemistry	Greece
1994	244	14	Spectroscopic, photoconductivity, and photocatalytic studies of TiO_2 colloids: naked and with the lattice doped with cr3+, fe3+, and v5+ cations	Langmuir	France, Canada
1995	183	11	Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, USA	International Journal of Remote Sensing	US
1996	518	32	Subpicosecond interfacial charge separation in dye-sensitized nanocrystalline titanium dioxide films	Journal of Physical Chemistry	UK, Switzerland
1997	340	23	An iodine/triiodide reduction electrocatalyst for aqueous and organic media	Journal of the Electrochemical Society	Switzerland
1998	262	19	19.8% efficient “honeycomb” textured multicrystalline and 24.4% monocrystalline silicon solar cells	Applied Physics Letters	Australia, Italy
1999	421	32	Acid-base equilibria of (2,2 ′-bipyridyl-4,4 ′-dicarboxylic acid) ruthenium (II) complexes and the effect of protonation on charge-transfer sensitization of nanocrystalline titania	Inorganic Chemistry	Switzerland
2000	310	26	Highly efficient photon-to-electron conversion with mercurochrome-sensitized nanoporous oxide semiconductor solar cells	Solar Energy Materials and Solar Cells	Japan
2001	2375	216	Plastic solar cells	Advanced Functional Materials	Austria, Netherlands
2002	308	31	Investigations of metal-doped titanium dioxide photocatalysts	Applied Catalysis B-Environmental	Slovakia, UK
2003	328	36	Design of new coumarin dyes having thiophene moieties for highly efficient organic-dye-sensitized solar cells	New Journal of Chemistry	Japan
2004	636	80	High efficiency carrier multiplication in PbSe nanocrystals: implications for solar energy conversion	Physical Review Letters	US
2005	2312	330	High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends	Nature Material	US
2006	765	128	Powering the planet: Chemical challenges in solar energy utilization	Proceeding of the National Academy of the Sciences of the United States of America	US
2007	302	60	New non-oxide photocatalysts designed for overall water splitting under visible light	Journal of Physical Chemistry C	Japan
2008	425	106	In situ formation of an oxygen-evolving catalyst in neutral water containing phosphate and Co2+	Science	US
2009	521	174	Battery materials for ultrafast charging and discharging	Nature	US
2010	277	139	Enhanced absorption and carrier collection in Si wire arrays for photovoltaic applications	Nature Materials	US
2011	82	82	Synthesis of fluorinated polythienothiophene-co-benzodithiophenes and effect of fluorination on the photovoltaic properties	Journal of the American Chemical Society	US

TC: Total citations; TC/Y: Average annual citations since publication.

Serdar Sariciftci and Jan C. Hummelen, and published in Advanced Functional Materials in 2001, with 2375 citations. The article which is the second most highly cited paper is entitled “High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends” published in Nature Materials in 2005 with 2312 citations and the most annual citations at 330. It can be seen that 9 articles include authors from the US, 3 from Switzerland, 3 from Japan, 2 from the UK, and Austria, Netherlands, Slovakia, Greece, Australia, Italy, France, and Canada appear only once. During the time period between 1992 and 2011, major progress has been achieved in the areas of photo catalysis, bio-energy, and nano materials. Many articles on these subjects are among those with the highest numbers of citations, reflecting their impact on solar energy research. It is also interesting to note that highly cited research is published in a large number of different scientific journals with or without high impact factors, but always in the English language.

4. Conclusions

Using bibliometric methods, we have examined the characteristics of the solar energy literature from 1992 to 2011 based on the SCI and SSCI databases. The study reveals that the literature on solar energy has grown exponentially over the past 20 years. In language analysis, the articles pertaining to solar energy in the SCI and SSCI are available in 20 languages, with English being dominant, accounting for 6571 records (96.8%). The US is an important contributor to the solar energy literature with the highest h-index (87) and the most publications (1273), followed by China and India. And the US has played a key role in the collaboration network of the 20 productive countries and regions. The Indian Institute of Technology is the largest institution (publishing 126 papers), but its international collaboration is very limited. While the Paul Scherrer Institute in Switzerland is in the center of the collaboration network among the 20 most productive institutions, with 6 strong cooperation relationships, especially with the Eidgenossische Technische Hochschule Zürich, Switzerland.

The study also finds that five core journals, namely Solar Energy, Renewable Energy, Energy Conversion and Management, Solar Energy Materials and Solar Cells, and International Journal of Hydrogen Energy, contribute about 23% to the total journal literature on solar energy. “Energy & Fuels” is the hottest subject with the most solar energy publications. On the other hand, the most highly cited article entitled “Plastic solar cells”, authored by Christoph J. Brabec, N.

Serdar Sariciftici and Jan C. Hummelen and published in Advanced Functional Materials had been cited 2375 times. The most frequently covered applications of solar energy, such as hydrogen production, desalination, drying, heat pumps, biomass and air conditioning, are also described. The rapid advances on the scientific frontiers of nanoscience and molecular biology will likely provide a strong foundation for future breakthroughs in solar energy conversion.

These results illustrate the value of bibliometric techniques and keyword analysis as methods for revealing research trends globally. This paper should be useful for solar conversion system manufacturers, academicians, solar energy researchers, and policy decision makers by identifying solar energy's expanding and shifting focus.

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