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A bibliometric analysis of solar power research from 1991 to 2010

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Abstract A bibliometric analysis was performed on solar power-related research between 1991 and 2010 in journals of all the subject categories of the Science Citation Index. "Solar cell", "solar energy", "solar power", "solar radiation" and "solar thermal" were selected as keywords to search in a part of the title, abstract or keywords. The trends were analyzed with the retrieved results in the publication type and language, characters of scientific output, publication distribution by countries, subject categories and journals, and the frequency of title-words and keywords used. Articles on solar power showed a significant growth along with more participation of countries, while the percentage of international papers reduced. The USA was the country with the most related articles and the most-frequent partner among all the international collaborative articles. Articles of Mainland China and South Korea grew much faster than other countries in the latest 5 years. Chemistry and material fields gradually became the mainstream of the solar power research. Synthetically analyzing three kinds of keywords, it showed that thin film solar photovoltaic technology was a hot spot of the solar power research in the past 20 years. "Dye-sensitized solar cell" and "organic" had extremely high increasing rates, which indicated that more attention was paid to kinds of organic solar cells. It could be concluded that the materials of solar cells would be the emphasis of solar power research in the twenty-first century.

Keywords Solar power · Bibliometric · SCI · Solar cell · Materials

Introduction

Solar power techniques include the use of concentrated solar power (CSP) and the photovoltaics (PV) to harness the energy. CSP normally focuses the sun's energy to water or other working mediums for providing the power while PV provides electricity depending on the photoelectric effect.

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The development of solar power techniques starting in the 1860s (Kalogirou 2004), in the form of CSP, was driven by the prediction that traditional energy would soon become scarce. However, in the early twentieth century, the development of solar technique stagnated in the face of the increasing availability of traditional energy. Commercial CSP plants were first considerably developed in the 1970s when oil embargo and energy crisis broke out. The largest solar electric generating system CSP installation could reach up to 354 MW. Similar with CSP, the global PV power industry has advanced considerably over the past 20 years. And manufacturing output has grown by a factor of 200, reaching 5 GW in 2008 (Timothy 2010). The 97 MW Sarnia Photovoltaic Power Plant in Canada is the world's largest photovoltaic plant. Nowadays, experimental high efficiency solar cells already have efficiencies of over 40 % in case of concentrating PV cells (Guter et al. 2009).

The development of solar power technologies will have huge longer-term benefits. Driven by advances in technology, solar thermal electricity (STE), based on CSP technologies, and PV are competitive against oil-fuelled electricity generation in some countries. The High-Renewable scenario variant showed that PV and STE together could provide up to 25 % of global electricity by 2050 (IEA 2011).

In 1989, an analysis of output of the articles from 1970 to 1984, based on the "solar cells", "solar energy", "solar power plants", and "solar radiation measurement", indicated that the growth of the literature had been vigorous after the energy crisis (Garg and Sharma 1991). Despite of the importance and high growth rate in the last 20 years, there have been few attempts to gather data about the worldwide scientific production of solar power-related research recently. Biometric studies in recent years provide an accurate and presumably objective method to measure the contribution of a paper to the advancement of knowledge (Huang and Zhao 2008). Besides, the Science Citation Index (SCI) from Web of Science databases is the most widely accepted and frequently used course database choice for an analysis of scientific publications (Braun et al. 2000).

The purpose of the present research is to analyze the status and trends of solar power research in the last 20 years in order to help researchers understand the panorama of global solar power research, and predict dynamic direction of research.

Materials and methods

The data used in this study was based on the database of SCI published by Thomson Reuters Web of Science, Philadelphia, PA, USA. Publications, with "solar cell*, solar energy*, solar power*, solar radiation*, solar thermal*" in titles, abstracts and keywords (Garg and Sharma 1991) were counted from 1991 to 2010. Articles originating from England, Scotland, North Ireland, and Wales were grouped under the UK heading. Collaboration type was determined by the address of each author, where "independent" was assigned for papers with authors from only one country, while "international collaboration" was assigned for papers with authors from more than one country.

The data was obtained to study the worldwide research activity on solar power in general and determine the research trends and performance including the type and language of publications, characters of scientific output, publication outputs of country, distribution of outputs in subject categories and journals, and frequency of title-words, author keywords, and keywords plus from 1991 to 2010.

Results and discussion

Type of publications and languages of publications

There were 56,290 papers on solar power research in the ISI web database between 1991 and 2010, with 17 document types. There were 45,559 paper articles comprising 80.94 % of the total production, followed by proceedings papers (7189, 12.77 %), reviews (1749, 3.11 %). The others with less significance were news items (476), meeting abstracts (472), editorial materials (291), notes (200), letters (195), corrections (81), book chapters (35), correction additions (16), reprints (11), book reviews (6), discussions (5), biographical items (3), bibliography (1), item about an individual (1). Since original articles was the most-frequently used type, they were used for further analysis. English was the most used language, making up 97.73 % of all the published articles.

Characteristics of scientific output

The articles devoted to solar power research between 1991 and 2010 were summarized in Table 1. The annual number of pages, cited references, authors and journals publishing the related literature articles increased considerably. The number of articles increased from

Table 1 Characteristics of article outputs from 1991 to 2010

Year	TA	PG	PG/TA	NR	NR/TA	AU	AU/TA	TA/J
1991	851	7834	9.2	16,153	19.0	3379	4.0	3.0
1992	748	6808	9.1	15,166	20.2	2837	3.8	2.6
1993	778	7046	9.1	16,432	21.1	3055	3.9	2.6
1994	1023	9366	9.2	20,917	20.4	4220	4.1	2.9
1995	999	9570	9.6	22,477	22.5	4022	4.0	2.7
1996	1214	11,040	9.1	27,079	22.3	5191	4.3	3.2
1997	1308	12,011	9.2	29,808	22.8	5804	4.4	3.1
1998	1381	12,366	9.0	31,321	22.7	6193	4.5	3.1
1999	1488	13,063	8.8	34,206	23.0	6791	4.6	3.5
2000	1549	14,412	9.3	36,767	23.7	7249	4.7	3.6
2001	1683	14,607	8.7	38,534	22.9	8375	5.0	3.5
2002	1747	15,766	9.0	43,399	24.8	8558	4.9	3.4
2003	2010	17,670	8.8	49,312	24.5	10,244	5.1	3.6
2004	2175	18,481	8.5	54,416	25.0	11,231	5.2	4.4
2005	2626	21,809	8.3	68,893	26.2	13,807	5.3	4.2
2006	3206	25,492	8.0	87,033	27.1	17,373	5.4	4.7
2007	3524	27,649	7.8	101,809	28.9	19,077	5.4	4.7
2008	4448	33,599	7.6	133,965	30.1	24,692	5.6	5.4
2009	5703	41,191	7.2	176,727	31.0	32,633	5.7	5.8
2010	7097	52,127	7.3	242,612	34.2	41,480	5.8	6.9
Total	45,559	371,909	8.6	1,247,027	24.6	236,212	4.8	3.8

TA number of articles, *PG* page count, *PG/TA* the average page count per article, *NR* cited reference count, *NR/TA* the average cited reference count per article, *AU* number of authors, *AU/TA* the average authors per article, *TA/J* the average number of articles published per journal

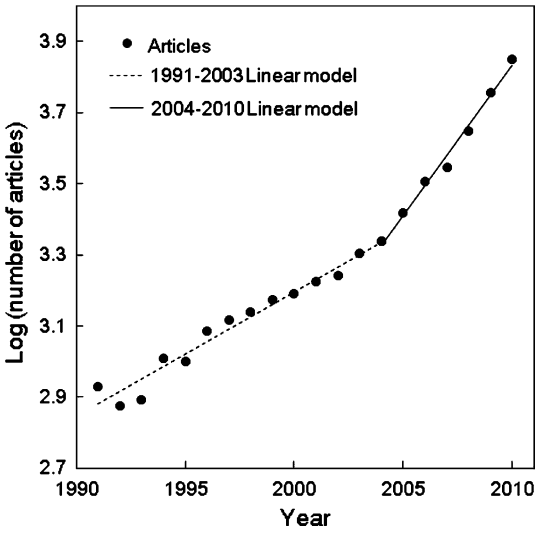


Fig. 1 Log-transformed number of articles on solar power during 1991–2010

851 in 1991 to 7097 in 2010. 19 references were cited per article in 1991, compared to 34 references per article in 2010. The number of authors per article rose from 4.0 to 5.8. Furthermore, the average number of articles per journal rose steadily from 3.0 per journal in 1991 to 6.9 in 2010. However, the average article length per article reduced from 9.2 in 1991 to 7.3 in 2010.

The progression in the number of articles from 1991 to 2010 was further studied in Fig. 1. Significant correlations were found between the log-transformed number of articles and the study period. The growth patterns of the progression were simulated by two linear models with coefficients of determination ($r^2 = 0.962$ and 0.990). Increasing rate for the period of 1991–2003 was 0.035, less than 0.084 for the period of 2004–2010.

Publication distribution by countries

There were 3982 articles without any author address information on the ISI Web of Science. 95.35 % of these articles were published between 1991 and 2000. Of all the 41,577 articles with author address, 30,219 (72.68 %) were independent publications and 11,358 (27.32 %) were international collaborative publications.

There were 137 countries/territories producing SCI papers about solar power. Among them, 17 new countries had article outputs since 1996, and 16 countries just began to publish papers after the year 2006. Though more participation of countries appeared, the percentage of international papers reduced during 1991–2010 (Fig. 2), which was opposed to many other fields (Ho et al. 2010; Li et al. 2009).

The top 20 countries were ranked by the number of publications (Table 2), including Two North and Central American countries, one south American country, ten European countries, six Asian countries, and Australia. Six of the seven major industrialized nations of the world (G7), the USA, Japan, Italy, Germany, UK and France, were in Top 10 countries of articles while Canada took the 12th place. The pattern of domination in publication of the G7 has occurred in most scientific fields (Suk et al. 2011), reflecting the high economy activity and academic level of these countries (Arunachalam and Doss 2000).

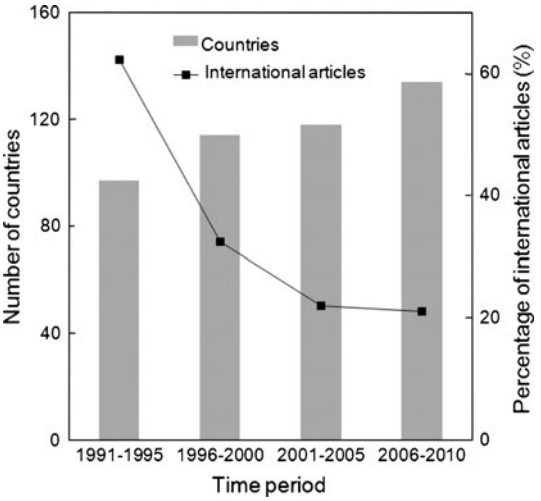


Fig. 2 Growth trends of number of countries and percentage of international articles during 1991–2010

Table 2 Top 20 most productive countries of articles during 1991–2010

Country	TA	TA%	IA	R (%)	CA	R (%)	C%
USA	9081	18.5	6537	1 (21.6)	2544	1 (13.5)	28.0
Mainland China	4562	9.3	3609	2 (11.9)	953	6 (5.0)	20.9
Japan	4491	9.1	3520	3 (11.6)	971	5 (5.1)	21.6
Germany	4449	9.1	2492	4 (8.2)	1957	2 (10.4)	44.0
UK	2240	4.6	998	8 (3.3)	1242	3 (6.6)	55.4
India	2140	4.4	1632	5 (5.4)	508	12 (2.7)	23.7
South Korea	1953	4.0	1436	6 (4.8)	517	11 (2.7)	26.5
France	1941	4.0	920	10 (3.0)	1021	4 (5.4)	52.6
Spain	1723	3.5	1006	7 (3.3)	717	7 (3.8)	41.6
Italy	1310	2.7	709	13 (2.3)	601	9 (3.2)	45.9
Australia	1210	2.5	731	11 (2.4)	479	13 (2.5)	39.6
Canada	1125	2.4	715	12 (2.4)	441	14 (2.3)	38.1
Taiwan	1118	2.3	962	9 (3.2)	161	27 (0.9)	14.4
Netherlands	1117	2.3	565	14 (1.9)	552	10 (2.9)	49.4
Switzerland	1109	2.3	490	16 (1.6)	619	8 (3.3)	55.8
Sweden	788	1.6	404	17 (1.3)	384	15 (2.0)	48.7
Russia	690	1.4	399	19 (1.3)	291	18 (1.5)	42.2
Turkey	622	1.3	520	15 (1.7)	102	32 (0.5)	16.4
Israel	604	1.2	365	20 (1.2)	239	19 (1.3)	39.6
Brazil	599	1.2	404	17 (1.3)	195	22 (1.0)	31.6

TA total articles, *IA* independent articles, *CA* international collaborative articles, *TA%* share in articles, *R* (%) ranking of publication (percentage of all articles published in the years), *C%* the percentage of international collaborative publications in total articles

The USA showed the greatest counts of world articles and the most-frequent partners accounting for 13.5 % of all the international collaborative articles during the last 20 years. Most of countries published more independent articles than the collaborative ones. The

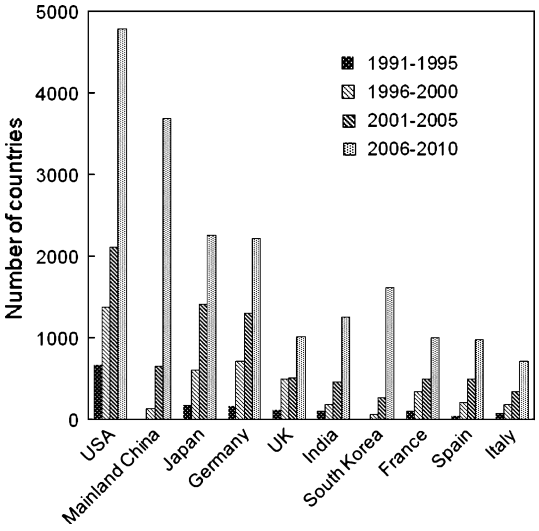


Fig. 3 Article trends of the top ten countries

percentage of international collaborative publications in total articles was less than 30 % among the three most productive countries. On the contrary, except for Turkey, European countries had higher percentage of international collaborative publications. Especially, UK, France and Switzerland had more than a half articles through international collaboration.

An obvious increase could be seen in all these countries, whereas the rapid development of solar power research was partly driven by contributions of these countries (Fig. 3). As two Asian countries, Mainland China and South Korea showed the highest growth pace in recent 5 years. Especially for Mainland China, the number of SCI publications took the 2nd place of Japan in the period of 2006–2010. It may be attributed to the fast growth rate of government investigation in the new energy science.

Distribution of output in subject categories and journals

There were 122 subject categories related to the research topic of solar power on the ISI Web of Science. Top 20 subject categories with the most articles were analyzed in Table 3, containing the rank and the percentage of the paper quantities in four periods (every 5 years from 1991 to 2010), and the extent along 20 years. The five most common categories were physics, materials sciences, chemistry, energy & fuels, and engineering. The most rapid growth was the chemistry field from 3.9 to 15.5 %. Besides, the article percentage in polymer science, materials sciences and optics also had a significant growth. On the contrary, a decrease of percentage appeared in some practical categories: energy & fuels, meteorology & atmospheric sciences, agriculture, mechanics, astronomy & astrophysics, oceanography, and forestry. We could indicate that more attention about solar power was paid to basic field, such as chemistry and material, in the period of large-scale application of solar power technology.

There were 45,559 papers published in a wide range of 2924 journals. Table 4 lists the 20 journals with the greatest number of published paper (more than 300) on solar power research. *Solar energy materials and solar cells* ranked first with 2858 published papers and *Thin solid films* ranked second with 1899, indicating that solar power research in solar cells area attracted more attentions.

Table 3 Top 20 subject categories with the most articles for 5-year periods

Subject categories	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Physics	14,275	18.3	2 (14.7)	1 (16.8)	1 (19.4)	2 (18.4)	
Materials Sciences	13,575	17.4	3 (11.8)	3 (13.2)	2 (16.9)	1 (19.6)	++
Chemistry	9,048	11.6	8 (3.9)	6 (4.6)	4 (9.2)	3 (15.5)	+++
Energy & Fuels	8,059	10.3	1 (15.9)	2 (14.1)	3 (11.7)	4 (7.9)	—
Engineering	5,679	7.3	4 (9.1)	4 (8.1)	5 (7.2)	5 (6.6)	-
Meteorology & Atmospheric Sciences	3,071	3.9	5 (6.6)	5 (7.0)	6 (4.9)	8 (2.4)	–
Environmental Sciences & Ecology	2,664	3.4	6 (4.7)	7 (4.4)	7 (3.5)	7 (2.8)	-
Agriculture	1,617	2.1	7 (4.6)	8 (3.3)	8 (2.0)	12 (1.3)	–
Polymer Science	1,193	1.5	29 (0.5)	26 (0.6)	12 (1.3)	9 (2.0)	++
Electrochemistry	1,170	1.5	13 (1.5)	20 (1.0)	13 (1.2)	10 (1.7)	+
Geology	1,153	1.5	12 (1.8)	9 (2.0)	9 (1.9)	13 (1.1)	-
Thermodynamics	1,104	1.4	9 (2.8)	10 (1.9)	11 (1.5)	14 (1.0)	-
Optics	907	1.2	20 (0.8)	19 (1.1)	19 (0.9)	11 (1.5)	+
Water Resources	819	1.0	18 (1.1)	17 (1.3)	14 (1.2)	15 (0.9)	
Mechanics	801	1.0	10 (1.8)	11 (1.6)	15 (1.2)	18 (0.7)	–
Astronomy & Astrophysics	713	0.9	11 (1.8)	15 (1.3)	16 (1.2)	19 (0.5)	–
Crystallography	646	0.8	24 (0.6)	22 (0.7)	20 (0.8)	16 (0.8)	
Marine & Freshwater Biology	631	0.8	19 (1.0)	13 (1.4)	17 (1.1)	20 (0.5)	-
Oceanography	590	0.8	15 (1.4)	14 (1.4)	18 (0.9)	22 (0.4)	–
Forestry	559	0.7	16 (1.3)	12 (1.4)	21 (0.7)	24 (0.3)	–

TA total articles in the 20 years, *R* (%) ranking of subject categories (percentage of all articles in the years), *Extent* the increasing extent (+, ++, +++) or the decreasing extent (-, –, —) of percentage of articles in the 20 years (no symbol means little changes in percentage)

Table 4 Top 20 journals with the most articles during 1991–2010

Journals	TA
Solar energy materials and solar cells	2858
Thin solid films	1899
Applied physics letters	1549
Journal of applied physics	1258
Solar energy	1078
Renewable energy	991
Journal of physical chemistry C	797
Journal of geophysical research-atmospheres	582
Progress in photovoltaics	576
Journal of physical chemistry B	539
Energy conversion and management	474
Journal of non-crystalline solids	413
Journal of crystal growth	400
Journal of materials chemistry	389
Journal of the American chemical society	382
Synthetic metals	355
Journal of photochemistry and photobiology A-chemistry	340
Chemistry of materials	331
Journal of the electrochemical society	323
Applied surface science	318

Analysis of title-words

The title of articles showed the core information of the research. For better analysis, title-words with general meanings, such as "effect", "performance", "study" and "based", were excluded from this statistic. Otherwise, the title-words such as "cell" and "cells", "film" and "films" were grouped into "cell" and "film". The percentages of Top 30 title-words were presented in Table 5. Other than the terms "solar", "cell" and "radiation" used for searching, "film", "silicon", "thin", "photovoltaic" and "dye-Sensitized" were the most five frequently title-words used in the 20-year research period. The most rapid growth was "dye-Sensitized" from 0.02 to 0.8 %, which was highly accorded with the prediction that dye-sensitized solar cells were currently the most efficient third-generation solar technology. Dye-sensitized solar cell, which is based on the dye as a sensitizer, are a new type of solar cell that mimics photosynthesis in plants. Unlike traditional solar cells, this cell could work effectively in low light conditions and are less susceptible to lose the heating energy. The system with this technology has become a validated and credible competitor to solid-state junction devices for the conversion of solar energy into electricity (Michael 2003). Its research area focuses on five parts: semiconductor thin film, sensitizers, electrolyte, electrode and conductive substrate. Especially, the TiO_2 and ZnO semiconductor thin films have become the hottest spot in the area, which both showed marked increases from 1991 to 2010. By modifying TiO_2 and ZnO, the photovoltaic efficiency could get an 50 % increase (Rhee & Kwon 2011). In addition, the words "organic" also had an apparently high growth rate from 0.09 to 0.67 %, which showed that organic solar cell research has attracted scientific and economic interest by a rapid increase in power conversion efficiencies. This was achieved by the introduction of new materials (e.g. HBC-PhC_{12} and $PC_{71}BM$), improved materials

Table 5 Top 30 most frequency of title-words for 5-year periods

Title-words	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Solar	15,820	3.80	1 (1.37)	1 (4.30)	1 (3.99)	1 (3.81)	-
Cell	10,775	2.59	9 (0.31)	2 (2.25)	2 (2.74)	2 (2.95)	+
Film	5,519	1.32	6 (0.51)	3 (1.20)	3 (1.55)	3 (1.41)	
Silicon	3,845	0.92	3 (0.68)	4 (1.15)	4 (1.10)	5 (0.83)	-
Thin	3,214	0.77	22 (0.12)	6 (0.88)	5 (0.91)	7 (0.78)	
Photovoltaic	3,089	0.74	5 (0.54)	9 (0.51)	7 (0.64)	4 (0.88)	+
Radiation	2,517	0.60	7 (0.48)	5 (1.14)	6 (0.78)	14 (0.42)	–
Dye-Sensitized	2,337	0.56	29 (0.02)	27 (0.09)	11 (0.47)	6 (0.80)	+++
TiO_2	2,032	0.49	24 (0.07)	20 (0.19)	8 (0.59)	25 (0.22)	++
Energy	2,026	0.49	13 (0.24)	7 (0.66)	10 (0.51)	11 (0.45)	-
System	1,951	0.47	4 (0.57)	8 (0.55)	9 (0.52)	15 (0.41)	-
Surface	1,910	0.46	8 (0.47)	10 (0.50)	12 (0.45)	13 (0.44)	-
Organic	1,882	0.45	23 (0.09)	26 (0.1)	20 (0.28)	8 (0.67)	+++
Layer	1,640	0.39	14 (0.22)	13 (0.34)	21 (0.26)	12 (0.44)	+
Synthesis	1,563	0.38	25 (0.07)	29 (0.08)	23 (0.23)	9 (0.56)	++
Optical	1,482	0.36	16 (0.21)	15 (0.31)	15 (0.33)	16 (0.41)	+
Polymer	1,470	0.35	27 (0.07)	30 (0.06)	22 (0.25)	10 (0.51)	++
Deposition	1,340	0.32	19 (0.15)	16 (0.28)	14 (0.38)	19 (0.33)	
Temperature	1,336	0.32	11 (0.27)	14 (0.33)	13 (0.44)	20 (0.31)	
Thermal	1,274	0.31	12 (0.27)	11 (0.36)	18 (0.28)	21 (0.31)	
Water	1,211	0.29	10 (0.28)	12 (0.36)	16 (0.29)	23 (0.23)	-
Heterojunction	1,116	0.27	17 (0.18)	23 (0.13)	24 (0.21)	18 (0.34)	+
ZnO	1,008	0.24	26 (0.07)	28 (0.06)	30 (0.14)	17 (0.35)	++
Chemical	944	0.23	18 (0.17)	19 (0.21)	19 (0.27)	27 (0.22)	
Light	917	0.22	15 (0.21)	18 (0.21)	25 (0.21)	24 (0.23)	

Table 5 continued

Title-words	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Thin-film	913	0.22	2 (0.81)	22 (0.16)	26 (0.20)	30 (0.17)	–
Oxide	878	0.21	21 (0.14)	25 (0.11)	29 (0.16)	22 (0.30)	++
Nanocrystalline	775	0.19	30 (0.02)	24 (0.13)	17 (0.28)	28 (0.18)	
Carbon	769	0.18	28 (0.02)	21 (0.17)	28 (0.16)	26 (0.22)	+
Power	768	0.18	20 (0.14)	17 (0.22)	27 (0.19)	29 (0.18)	

TA total articles in the 20 years, *R* (%) ranking of subject categories (percentage of all articles in the years), *Extent* the increasing extent (+, ++, +++) or the decreasing extent (-, –, —) of percentage of articles in the 20 years (no symbol means little changes in percentage)

engineering (e.g. heterojunction and nanocrystalline), and more sophisticated device structures (Hoppe and Sariciftci 2004). The dye-sensitized solar cell also uses organic dyes to generate electricity from light. Besides, the words "synthesis", "oxide" and "polymer" also had a significant growth, which also indicated that the materials of solar cells was the mainstream research in the solar power field.

Analysis of author keywords and keywords plus

As author keyword analysis could offer intact words reflecting the research trend which is concerned by researchers, it is proved to be important for monitoring the developing of science (Li et al. 2009). Examination of author keywords revealed that 40,129 author keywords were used from 1991 to 2010. Among them, eight-fifty percent of them (34,111) appeared only once or twice. These words maybe reflected a lack of continuity in research and a wide difference in research focuses (Chuang et al. 2007). Table 6 showed the top 30 most active author keywords in the 20 years.

The three most frequently used keywords, "solar cell", "solar energy" and "solar radiation", were keywords used for searching in this study. Except for these words, two of the most frequently used keywords were "thin film" and "photovoltaic", which was highly accorded with that fact that the thin film photovoltaic cell is now available in large modules (Chopra et al. 2004). All the efforts need to be focused on improving the efficiency and lowering the cost of the thin film photovoltaic cell. To achieve these goals, many kinds of advanced solar materials and new fabrication methods should be developed with a focus on high-performance and low-cost, including CdTe and crystalline silicon. Similarly, "organic solar cell" and "organic semiconductor" had become a new focus in the last 10 years, the percentage of which increased from 0.04 to 0.26 % in the period of 2001–2005 to 0.02 and 0.26 % in the period of 2006–2010. In addition, "silicon", "optical properties", "photoluminescence", "ZnO", "X-ray diffraction", and "photoconductivity" also had high growth in ranking of frequency. As mentioned before, some of keywords belonging to materials science mainly about solar cell had a significant growth. Except for these old and basic materials, more attention was paid to kinds of organic solar cells which are easy fabrication, mechanical flexibility and low cost (Currie et al. 2008). "X-ray diffraction" and "photoluminescence" were two techniques for measuring structure of materials. On the contrary, a decline in the percentage of the keywords "solar energy", "solar radiation", "temperature", "amorphous silicon" and "photosynthesis" was visible. Low power efficiency of amorphous silicon and the limit of materials of photosynthesis for generating electricity might lead to the lower development.

Most of the top 30 author keywords were related with "solar cell". In order to study the global trends on solar power further, the comparison among "solar cell", "solar energy", "solar power", "solar radiation" and "solar thermal" was taken during the period of 1991–2010 (Fig. 4). The number of articles on solar cell had a significant growth during 2000–2010 while the growth of solar radiation and solar energy was comparatively less. The articles related to "solar power" and "solar thermal" were in a very small number. The fact could indicate that solar cell was a completely leading role in the solar power research because of the large-scale application.

Keyword plus, which provides search terms extracted from the titles of papers cited in each new article in the ISI database, is an independent supplement for title-words and author keywords (Garfield 1990). By the analysis of keyword plus, the similarities and differences among title-words, author keywords and keyword plus could been figured out, which could make the research more reliable and objective. Similar with the results of

Table 6 Top 30 most frequency of author keywords used for 5-year periods

Author keywords	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Solar cell	3492	3.26	1 (2.25)	1 (3.51)	1 (3.65)	1 (3.14)	
Solar energy	964	0.90	3 (1.78)	2 (1.39)	4 (0.84)	4 (0.66)	–
Thin film	919	0.86	13 (0.15)	4 (1.06)	2 (0.94)	2 (0.82)	+
Solar radiation	855	0.80	2 (1.79)	3 (1.15)	3 (0.85)	7 (0.53)	–
Photovoltaic	808	0.76	7 (0.36)	5 (0.61)	5 (0.58)	3 (0.68)	+
Silicon	530	0.50	8 (0.20)	6 (0.44)	7 (0.42)	6 (0.55)	++
Dye-sensitized solar cell	515	0.48	29 (0)	27 (0.08)	6 (0.50)	5 (0.63)	+++
Optical properties	413	0.39	9 (0.20)	10 (0.29)	9 (0.27)	8 (0.43)	+
Photoluminescence	312	0.29	14 (0.12)	15 (0.23)	16 (0.22)	9 (0.37)	+
ZnO	311	0.29	16 (0.10)	26 (0.09)	26 (0.12)	20 (0.17)	+
TiO_2	304	0.28	24 (0.04)	25 (0.1)	10 (0.27)	23 (0.15)	
Semiconductor	299	0.28	22 (0.05)	7 (0.40)	13 (0.26)	13 (0.24)	
Titanium dioxide	250	0.23	25 (0.04)	14 (0.25)	8 (0.30)	15 (0.21)	
Temperature	249	0.23	4 (0.59)	9 (0.30)	14 (0.24)	17 (0.18)	–
X-ray diffraction	247	0.23	23 (0.05)	20 (0.14)	18 (0.19)	10 (0.30)	++
Electrode position	242	0.23	20 (0.07)	13 (0.27)	21 (0.18)	14 (0.22)	
Organic solar cell	215	0.20	26 (0.04)	30 (0.05)	17 (0.20)	11 (0.26)	++
Amorphous silicon	211	0.20	5 (0.41)	8 (0.36)	12 (0.27)	29 (0.10)	–
Photosynthesis	197	0.18	6 (0.40)	12 (0.27)	20 (0.18)	24 (0.14)	–
Simulation	190	0.18	12 (0.18)	17 (0.21)	22 (0.17)	19 (0.17)	
Organic semiconductor	178	0.17	27 (0.02)	29 (0.07)	30 (0.08)	12 (0.26)	++
CdTe	171	0.16	21 (0.07)	11 (0.29)	11 (0.27)	30 (0.08)	
Photoconductivity	164	0.15	17 (0.09)	28 (0.08)	28 (0.10)	16 (0.21)	+
Hydrogen	163	0.15	15 (0.12)	24 (0.11)	25 (0.12)	18 (0.18)	+
Photocatalysis	160	0.15	18 (0.09)	19 (0.16)	24 (0.15)	21 (0.15)	

Table 6 continued

Author keywords	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Sputtering	153	0.14	10 (0.19)	21 (0.13)	29 (0.09)	22 (0.15)	
Micro crystalline silicon	153	0.14	30 (0)	22 (0.13)	15 (0.23)	27 (0.11)	
Renewable energy	151	0.14	11 (0.19)	23 (0.12)	27 (0.12)	25 (0.14)	
Heterojunction	148	0.14	19 (0.09)	16 (0.23)	19 (0.19)	26 (0.14)	
Climate change	141	0.13	28 (0.02)	18 (0.20)	23 (0.16)	28 (0.1)	

TA total articles in the 20 years, *R* (%) ranking of subject categories (percentage of all articles in the years), *Extent* the increasing extent (+, ++, +++) or the decreasing extent (-, –, —) of percentage of articles in the 20 years (no symbol means little changes in percentage)

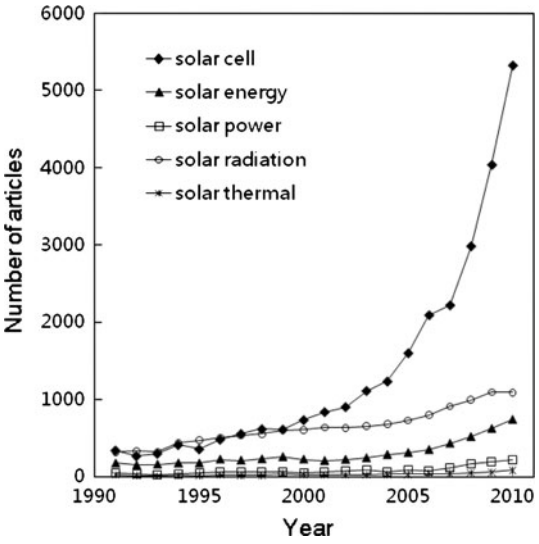


Fig. 4 Article trends of the five keywords

author keywords, "solar cell", "solar radiation", "temperature", "sensitized solar cell", "thin film", "optical properties", "semiconductor", "photovoltaic cell", "silicon", "solar energy", "TiO_2", "climate" and "titanium dioxide" also appeared in the top 30 most frequently of keywords plus used (Table 7). As same as the analysis of author keywords, the keywords plus related to materials sciences were given more attention. Additionally, "polymer", "conjugated polymer", "nanoparticle" and "morphology" which didn't appear in the top of the author keywords, also showed an increase.

Conclusion

In this study on solar power research, some significant points have been obtained on the research performance throughout the period from 1991 to 2010. There are 45,559 articles in 2924 journals listed in 122 SCI subject categories. The articles-related increased fast in the last 20 years. The research on solar power focused on physics, materials Sciences, chemistry, energy & fuels, and engineering fields. Meanwhile, more attention was paid to polymer science and optics fields. Most of the articles were published on *Solar energy materials and solar cells*. It is obvious that the solar cell materials was a hot spot of the solar power research. There were 137 countries producing SCI papers about solar power. The USA showed the greatest count of world articles and the international collaborative articles. Mainland China and South Korea showed the highest growth pace during 1996–2010. Though more participation of countries appeared, the percentage of international papers reduced during the last 20 years. Comparing with other continents, European countries had more percentage of international collaborative publications.

By analyzing the title-words, "film", "silicon", "thin", "photovoltaic" and "dye-sensitized" were the most five frequently title-words used in the 20-year research period, which indicated that compared to some practical applications, the materials of solar cells is the mainstream research in the solar power field. The same trend could be found from the distribution of author keywords and keywords plus, the two most frequently keywords were "thin film" and "photovoltaic", which were highly accorded with the fact that the

Table 7 Top 30 most frequency of keywords plus used for 5-year periods

Keywords plus	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Solar cell	7706	3.25	1 (2.89)	1 (2.79)	1 (3.23)	1 (3.37)	
Film	3070	1.29	2 (2.30)	2 (2.20)	2 (1.19)	2 (1.45)	–
Thin Film	2558	1.08	3 (0.84)	3 (0.86)	4 (0.99)	3 (1.20)	+
Solar radiation	2555	1.08	6 (0.59)	4 (0.81)	3 (1.11)	13 (0.51)	–
Temperature	1550	0.65	5 (0.69)	5 (0.79)	6 (0.64)	7 (0.59)	–
Surface	1403	0.59	4 (0.81)	7 (0.62)	5 (0.66)	21 (0.39)	–
Sensitized solar cell	1341	0.57	29 (0)	30 (0)	28 (0.14)	4 (0.86)	+++
Optical properties	1330	0.56	8 (0.54)	11 (0.43)	12 (0.40)	5 (0.64)	
Light	1178	0.50	13 (0.44)	6 (0.65)	7 (0.61)	18 (0.43)	–
Deposition	1110	0.47	14 (0.40)	13 (0.39)	8 (0.47)	15 (0.49)	+
Device	1076	0.45	21 (0.11)	22 (0.15)	9 (0.47)	6 (0.60)	++
Polymer	1061	0.45	20 (0.11)	26 (0.06)	13 (0.38)	10 (0.57)	++
Conjugated polymer	1045	0.44	27 (0.02)	28 (0.02)	18 (0.32)	8 (0.59)	++
Semiconductor	993	0.42	11 (0.47)	14 (0.39)	11 (0.41)	16 (0.45)	
Morphology	964	0.41	22 (0.08)	27 (0.03)	29 (0.14)	9 (0.59)	++
Photovoltaic cell	961	0.41	26 (0.03)	24 (0.07)	17 (0.34)	12 (0.52)	++
Electrode	960	0.40	15 (0.31)	16 (0.25)	15 (0.34)	17 (0.45)	+
Water	950	0.40	10 (0.49)	8 (0.54)	10 (0.41)	11 (0.52)	
Recombination	805	0.34	17 (0.24)	21 (0.17)	20 (0.30)	20 (0.39)	+
Nanoparticle	798	0.34	30 (0)	29 (0.01)	30 (0.13)	14 (0.49)	++
Spectroscopy	791	0.33	18 (0.20)	15 (0.25)	14 (0.37)	22 (0.34)	
Light emitting diodes	784	0.33	25 (0.04)	25 (0.07)	24 (0.26)	19 (0.42)	
Silicon	731	0.31	7 (0.55)	12 (0.43)	19 (0.32)	26 (0.25)	–
Solar energy	728	0.31	16 (0.29)	17 (0.25)	23 (0.28)	23 (0.32)	–
Absorption	648	0.27	9 (0.52)	9 (0.44)	21 (0.28)	29 (0.22)	–
TiO_2	614	0.26	23 (0.08)	23 (0.11)	25 (0.22)	24 (0.31)	+

Table 7 continued

Keywords plus	1991–2010 TA	1991–2010%	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2010 R (%)	1991–2010 Extent
Chemical vapor deposition	597	0.25	28 (0.01)	20 (0.18)	16 (0.34)	25 (0.26)	
Climate	580	0.24	12 (0.46)	10 (0.44)	22 (0.28)	30 (0.17)	–
Titanium dioxide	515	0.22	19 (0.13)	19 (0.20)	26 (0.20)	28 (0.23)	+
Photoluminescence	495	0.21	24 (0.08)	18 (0.20)	27 (0.17)	27 (0.23)	+

TA total articles in the 20 years, *R* (%) ranking of subject categories (percentage of all articles in the years), *Extent* the increasing extent (+, ++, +++) or the decreasing extent (-, –, —) of percentage of articles in the 20 years (no symbol means little changes in percentage)

thin film photovoltaic cell is now available in large modules. "Dye-sensitized solar cell", "organic solar cell" and "organic semiconductor" had extremely high increasing rates in the latest decade, which indicated that dye-sensitized solar cell and other organic solar cells are still in the early stage of their development. As organic materials are relatively cheap and some improvements in the structure (e.g. the nanoscale morphology with novel low band gap materials) have increased the power conversion efficiencies (Hoppe and Sariciftci 2004), it could be expected that more attention would be paid to kinds of organic solar cells. Though most of the solar power papers dealing with SCI are basic research, the orientation of solar power research is to meet the need of application. Furthermore, solar cell was a completely leading role in the solar power research area. The materials of solar cells, especially the organic solar cells, were emphasis of solar power research in the twenty-first century. The findings of this study could help relevant researchers understand the performance of solar power research in the world, and direct for further research.

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