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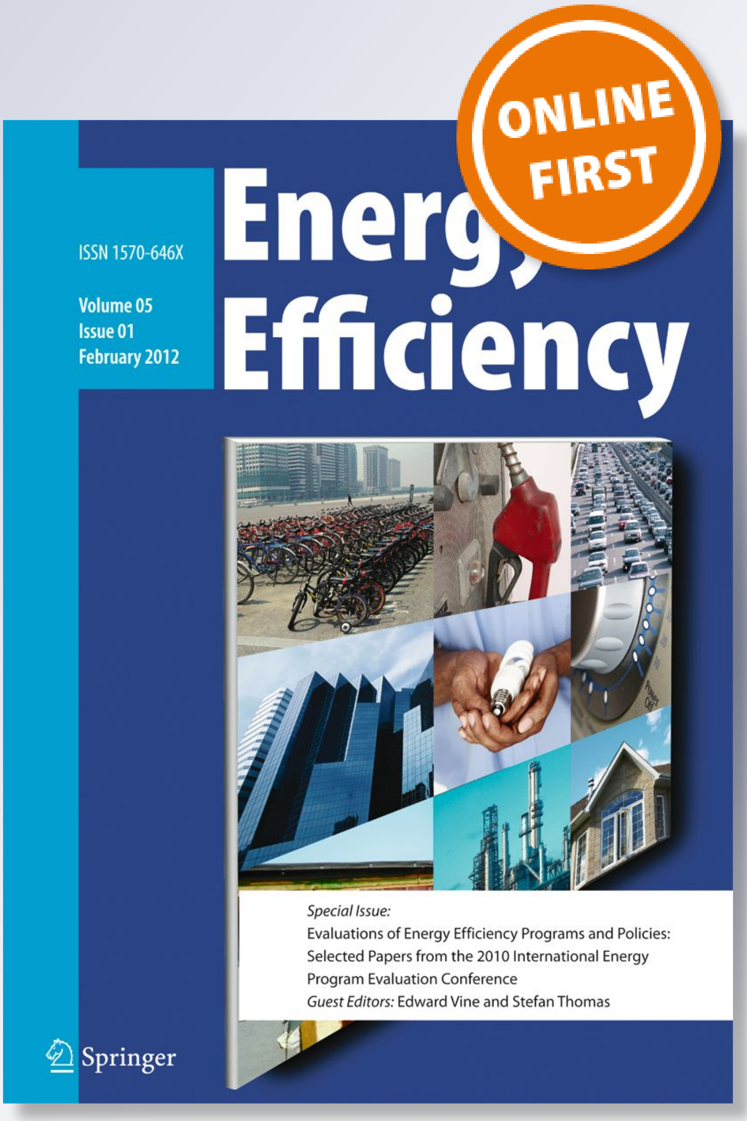

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A bibliometric analysis of recent energy efficiency literatures: an expanding and shifting focus

Huibin Du · Linxue Wei · Marilyn A. Brown · Yangyang Wang · Zheng Shi

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Abstract To meet the energy requirements of sustainable economic growth, policymakers, analysts, and business leaders have increasingly turned to the role that energy efficiency might play. This has resulted in a growing energy efficiency literature, which is examined in this paper. Using bibliometric techniques, we analyze the database of Science Citation Index Expanded and Social Sciences Citation Index covering the 1991–2010 period. Of the 8,244 publications, 78.8 % were journal articles, and about 95.5 % were published in English. Based on the h-index, an evaluative indicator, the USA has produced the most influential set of publications on energy efficiency, followed by Canada, UK, Japan, and China. In contrast, China is second to the USA in the volume of its publications. Correspondingly, the University of California at Berkeley, Chinese Academy of Sciences, and Tsinghua University were the most productive research organizations. The three most common subjects examined in this body of research were "energy and fuels", "environmental sciences", and "electrical and electronic engineering". *Energy Policy* has been the most productive journal, and "A water and heat management model for proton-exchange-membrane fuel-cells", has had the most citations (587 through May 2012). Based on an analysis of article titles and keywords, we conclude that the hotspots of energy efficiency research have been green communications, renewable energy, and energy sustainability; green communications, in particular, has developed rapidly as a focus of energy efficiency publications in recent years.

Keywords Energy efficiency · Bibliometrics · Impact factor

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Introduction

The growing global demand for electricity and mobility has translated into more than a century of rapidly increasing fossil energy consumption (Fouquet and Pearson 1998). The demand for energy is expected to continue to expand—perhaps by 45% between now and 2030, and by more than 300% by the end of the century (Brown and Sovacool 2012). In many parts of the world, this has created a growing imbalance between energy production and consumption, exacerbating the risk of supply disruptions and the cost of energy imports, which could take a fairly rapid turn for the worse for many countries if alternative fuels and energy efficiency are not widely deployed (IEA 2008). Concerns about available energy

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resources are being matched by a recognition of the heavy environmental toll associated with fossil energy use including ozone layer depletion, smog, acid rain, and climate change (Luis et al. 2007; Ni and Johansson 2004). How can industrialized economies be energized and developing countries be pulled out of poverty without overheating the climate?

To meet the energy requirements of sustainable economic development and population growth, policymakers, business leaders, consumers, and researchers have increasingly turned their attention to the role that energy efficiency might play. Energy efficiency refers to permanent changes in equipment that result in increased energy services per unit of energy consume—what the physicist Amory Lovins calls "doing more with less through smarter technologies" (Lovins 2007). Using energy wisely has been shown to be a valuable "front-line" strategy against global climate change because it offers a "no regrets" approach. Investments in energy efficiency can save consumers money while reducing pollution and greenhouse gas emissions and stretching global energy resources (Brown and Sovacool 2012). In addition to reducing carbon emissions, energy-efficiency improvements tend to be more labor intensive than traditional energy production; as a result, they have been the focus of many "stimulus" programs aimed at generating green jobs to fill the gap in employment created by the global economic recession beginning in 2008. Many argue that in industrial nations, there is a large and growing reservoir of highly cost-effective energy-efficient technologies that are available for deployment: technologies that would be good for consumers, the economy, and the climate.

Corresponding to the increasing recognition of the potential role for energy efficiency, the associated body of literature has also grown substantially. The research related to energy efficiency has become a multidisciplinary field spanning a wide spectrum including studies in renewable energy (Kajikawa et al. 2008), environmental pollution (Shao et al. 2006), energy policy (Hofman and Li 2009), and so on. Thus, it is time to implement bibliometric analytical techniques to evaluate the growing body of literature on energy efficiency. Bibliometric techniques offer an important quantitative perspective to assessing the development and growth of research on the topic of energy efficiency.

Bibliometric techniques involve statistical methods of bibliography counting to evaluate and quantify the growth of literature for a particular subject (Tsay, 2008). 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 strength of bibliometric techniques—to transform something intangible (scientific

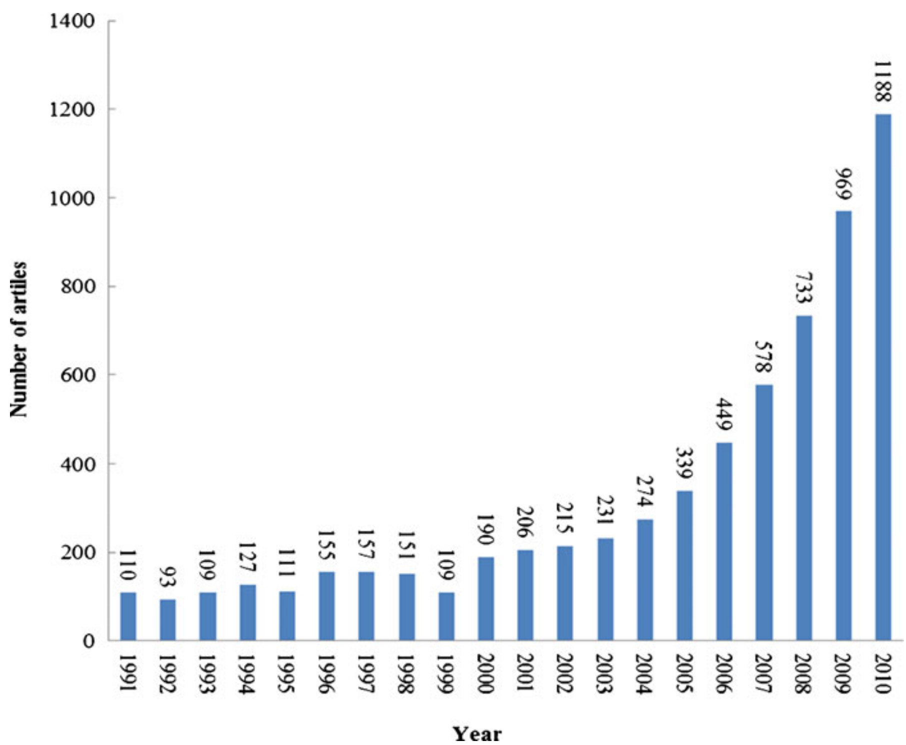

Fig. 1 Annual number of published articles (1991–2010)

quality) into a manageable entity. Bibliometrics gives us a tool that can be easily scaled from micro (scientist and institute) to macro (national and global) levels (Wallin 2005). There are two advantages in implementing bibliometric analysis: first, it provides an assessment of the research or scientific productivity in a specific area over a period of time using indicators and the calculation of certain classical laws (Garfield 1979); second, it examines science as a knowledge-generating system (Van Raan 2005). Many areas of science have tried to evaluate their evolution or growth by this method and, nowadays, bibliometric techniques have become an indispensable instrument for measuring scientific progress (Van Raan 2004).

Originally, bibliometric methods have been applied in library and information sciences as the research methodology for citation analysis and content analysis (Zhang et al. 2010b); conventional bibliometric methods have also been widely applied in various fields by investigating the characteristics of publications, such as author affiliation with research organizations, countries of residence, journals, research fields, and citation habits (Rodríguez and Moreiro 1996; Chen et al. 2005; Chiu and Ho 2007). In recent years, analysis of word distribution of paper titles, abstracts, and keywords in different periods has been used widely to get more refined information related to the research itself (Xie et al. 2008; Li et al. 2009; Zhang et al. 2010a, b).

The aim of this study is to quantitatively and qualitatively evaluate global trends of the energy efficiency research literature from 1991 to 2010. It uses bibliometric methods to examine publication characteristics consisting of countries, research organizations, journals, research fields, and citation habits and content analysis (specifically, words in paper titles, author keywords, and keywords plus). Our conclusions not only provide a better understanding of global hotspots of energy efficiency research, but may influence researchers' future studies and publications.

Data sources and methodology

Bibliometric methods

Bibliometrics is described as "a generic term for quantitative analyses of relevant characteristics of the contents of scientific and technological texts, mostly across a set of research publications" (Kinney 2007). The data for this paper were collected from the online version of Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) both produced by the former Institute for Scientific Information, nowadays Thomson Scientific. Here, we used "energy efficiency" or "energy efficiencies" as search phrases to search in titles, abstracts and keywords at one time from SCIE and SSCI during1991–2010 and obtained 8, 244 documents which include author names, titles, abstracts, published dates, document types, addresses, and cited references. Articles from Hong Kong were included under China's heading, while articles originating from England, Scotland, Northern Ireland, and Wales were reclassified into the UK. In the analysis of countries, collaboration types were determined by the addresses of authors, and territories are treated as countries. The single-country publication was assigned if addresses of the authors in one article were in the same country, while the international collaborative publication was assigned where authors resided in different countries. In the same way, the contribution of different research organizations was determined by addresses of authors. The single-research organization publication

Table 1 Characteristics of publication by year (1991–2010)

Year	TP	AU	AU/TP	NR	NR/TP
1991	110	267	2.4	1,550	14.1
1992	93	243	2.6	1,598	17.2
1993	109	263	2.4	1,878	17.2
1994	127	330	2.7	2,275	17.9
1995	111	268	2.5	1,460	13.2
1996	155	356	2.3	3,382	21.8
1997	157	409	2.6	2,932	18.7
1998	151	420	2.8	3,119	20.7
1999	109	278	2.6	2,006	18.4
2000	190	500	2.6	3,732	19.6
2001	206	583	2.8	4,537	22.0
2002	215	626	2.9	4,857	22.6
2003	231	682	3.0	5,656	24.5
2004	274	875	3.2	6,558	23.9
2005	339	1,093	3.2	7,944	23.4
2006	449	1,421	3.2	10,698	23.8
2007	578	1,841	3.2	14,474	25.0
2008	733	2,300	3.2	17,707	24.2
2009	969	3,172	3.3	24,544	25.3
2010	1,188	3,999	3.4	33,223	28.0

TP number of publications, *AU* number of authors, *NR* number of cited references for all publications per year, *AU/TP* and *NR/TP* average number of authors, references per article was applied when the addresses of authors were from the same research organization, while inter-institutionally collaborative publication was designated to the literature that was coauthored by researchers from multiple research organizations.

These documents from the SCIE and SSCI for this paper were evaluated by considering document types, languages, subject categories, journals, countries, research organizations, titles, author keywords, and keywords plus, h-index, and impact factor.

H-index and impact factor

The h-index was first proposed by Hirsch to measure the productivities and impacts of the published works of not only scientists and scholars (Hirsch 2005), 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 (Kinney 2007). It is defined simply as: "A scientist has index h if h of his/her N_p papers have at least h citations each, and the other (N_p-h) papers have no more than h citations each," where N_p is the number of papers published over n years (Hirsch 2005). Therefore, the h-index combines a measure of quantity (number of publications) and impact (number of citations) in a single indicator (Vieira and Gomes 2011). The h-index has been seen as having the advantage of the broad impact of a scientist's cumulative research contributions to distinguish between a "one-hit wonder" and an enduring performer. Furthermore, the h-index has a more qualified strength in prediction than those used commonly, such as number of publications and so on (Hirsch 2005, 2007; Cronin and Meho 2006). In this paper, based on the literature of energy efficiency, the h-indexes of research organizations, countries, and journals were calculated, while the h-index of each author was computed to evaluate his/her achievements, respectively.

The impact factor (IF), one of the most influential tools in modern bibliometrics research and academia, was used in this paper to assess the energy efficiency-related journals' relative influence. It is calculated by dividing the number of citations in the JCR year by the total number of articles published in the two previous years (Fu et al. 2010).

Table 2 Top 20 most productive countries (1991–2010) with the number of publications, and h-index, etc.

Country	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)	h-index (R)
USA	1,799	1 (28.4)	1 (25.2)	1 (46.8)	1 (24.6)	1 (24.1)	69 (1)
China	669	2 (10.6)	2 (9)	2 (19.3)	2 (9.2)	2 (9.4)	28 (5)
UK	448	3 (7.1)	3 (6)	3 (13)	3 (5.8)	3 (5.8)	32 (2)
Canada	358	4 (5.7)	5 (4.7)	5 (10.9)	4 (4.9)	4 (5)	32 (2)
Japan	344	5 (5.4)	4 (4.8)	6 (8.9)	5 (4.7)	5 (4.7)	31 (4)
Germany	295	6 (4.7)	7 (3.5)	4 (11.1)	7 (3.6)	7 (3.7)	24 (8)
South Korea	262	7 (4.1)	6 (3.8)	10 (6.3)	6 (3.7)	6 (3.8)	19 (14)
Sweden	203	8 (3.2)	9 (2.8)	11 (5.3)	8 (2.9)	8 (2.8)	25 (7)
Netherlands	202	9 (3.2)	11 (2.5)	9 (6.9)	10 (2.7)	9 (2.7)	28 (5)
Italy	201	10 (3.2)	12 (2.5)	7 (7)	11 (2.6)	10 (2.7)	24 (8)
India	196	11 (3.1)	8 (2.9)	15 (4.3)	9 (2.8)	11 (2.7)	17 (16)
Taiwan	182	12 (2.9)	10 (2.6)	15 (4.3)	12 (2.5)	12 (2.5)	17 (16)
Spain	178	13 (2.8)	13 (2.5)	12 (4.7)	13 (2.4)	13 (2.4)	18 (15)
France	167	14 (2.6)	17 (1.9)	7 (7)	15 (2)	15 (2)	24 (8)
Turkey	153	15 (2.4)	14 (2.4)	21 (2.3)	14 (2.3)	14 (2.3)	21 (11)
Australia	143	16 (2.3)	16 (1.9)	14 (4.4)	17 (1.8)	17 (1.8)	20 (13)
Russia	131	17 (2.1)	15 (2.1)	24 (1.9)	16 (1.9)	16 (1.9)	13 (19)
Brazil	106	18 (1.7)	18 (1.5)	18 (2.8)	18 (1.4)	18 (1.3)	9 (20)
Switzerland	93	19 (1.5)	22 (0.9)	12 (4.7)	21 (1.1)	20 (1.1)	21 (11)
Greece	85	20 (1.3)	19 (1.2)	24 (1.9)	19 (1.2)	19 (1.2)	15 (18)

TP number of publications, *TP R* rank and the percentage of total publications, *SP R* single country's publications, *CP R* international collaboration publications, *FP R* the first author's publications, *RP R* the corresponding author's publications

Results and discussion

Characteristics of publications

The 8,244 documents related to energy efficiency from the SCIE and SSCI over the past two decades were categorized into 14 types. Of the 8,244 publications, 78.8 % were journal articles, 13.5 % proceeding papers, 3.3 % reviewers, and 1.8 % editorial materials. In this paper, we only took 6,494 journal articles into consideration. It can be seen in Fig. 1 that the number of articles about energy efficiency grew moderately from 1991 to 2003; however the number of articles had been increasing significantly since 2004. Over 1,188 articles were published in 2010, almost eleven times more than the number of publications in 1991.

In language analysis, 6,199 articles accounting for 95.5 % were published in English, followed by German accounting only for 1.5 %. Obviously, English is the dominant language in energy efficiency research because more relevant journals in SCIE and SSCI are published in English.

Table 1 presents several publication characteristics of energy efficiency research during 1991–2010. Besides the progressive increase of the number of total publications per year, the numbers of authors and cited references per year increased significantly. Further, the average number of authors and cited references per article were increased from 2.4 and 14.1 in 1991 to 3.4 and 28 in 2010, respectively.

Publication distribution by countries and research organizations

A total of 6,325 articles could be used to analyze the distribution of countries and research organizations (169 articles lacked author addresses and affiliations). Of these 6,325 articles, 84.9 % were single-country publications, and only 15.1 % were international. In Table 2, the 20 most productive countries were ranked with respect to the number of journal articles, the number and the percentage of single-country articles and internationally collaborated articles, the first author and corresponding author articles, and h-index. The articles from the top 20 countries accounted for more than 95 %.

Of the top 20 countries, two were from North America, six from Asia, ten from Europe, one (Australia) from Oceania, and one (Brazil) from South America, while no

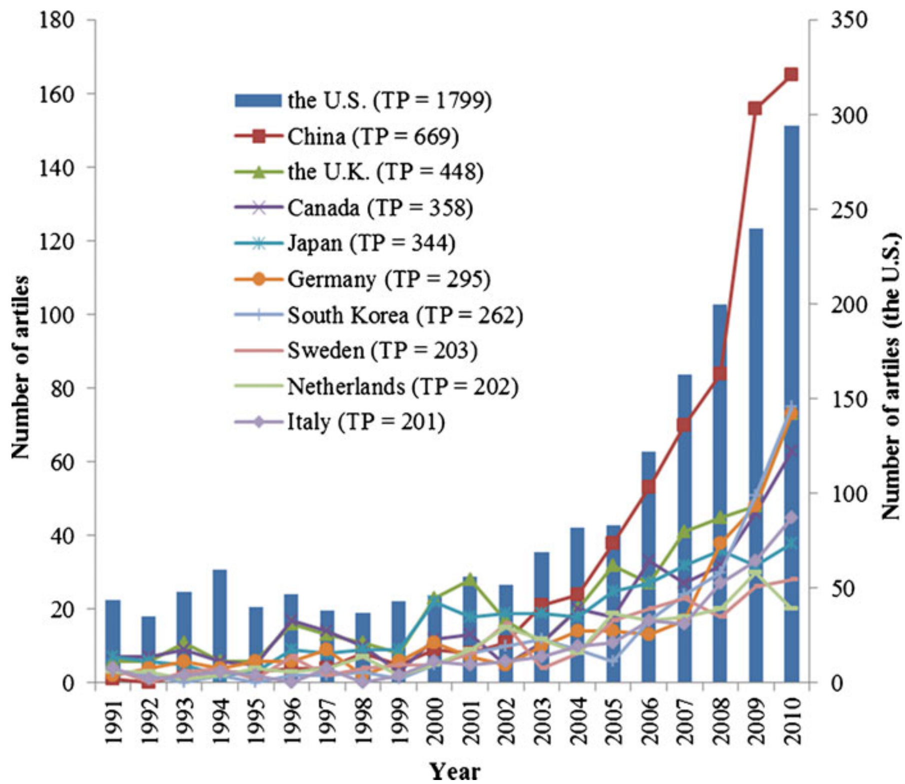

Fig. 2 Annual number of articles for 10 productive countries (1991–2010)

countries were from Africa. The USA had the largest number of total publications (1,799) including both single-country and international collaborative articles, followed by China (669) and the UK (448). China was the second to the USA in the volume of its publications, but ranked fifth by the h-index (27). This showed that the academic influence of China was relatively weaker than that of the other top 4 countries based on the h-index: the USA (69), Canada (32), the UK (32) and Japan (31). Similar to China, South Korea ranked 7th by the total number of articles, but only ranked 14th by the h-index. In contrast, the Netherlands ranked 5th by the h-index, but only ranked 9th by the total number of articles, which implied the country with higher h-index has greater influence due to more citations. It can be found from Fig. 2 that the USA has been in a leading position during 1991–2010 in terms of total publications, and the number of publications in top 10 productive countries has rapidly increased since 2003. We could come to the conclusion that the fast development of the energy efficiency research was partly driven by high productive countries. In particular, the number of China's articles increased much faster than the other top 9 countries after 2003, implying that research on energy efficiency in China has attracted much more attention in recent years.

In these 6,325 articles, 3,710 (58.7 %) articles were produced by a single-research organization and 2,615 (41.3 %) were inter-institutionally collaborative publications. Table 3 shows that among the 21 most productive research organizations, eight are from the USA, four from China, two from South Korea and one from Russia, Netherlands, India, Singapore, Taiwan, Turkey and Sweden, respectively. Although the UK, Canada, Japan, Germany, Italy, Sweden, Spain, France, Australia, Brazil, Switzerland, and Greece were among the top 20 productive countries, there were no entities in

Table 3 Top 21most productive research organizations (1991–2010) with the number of publications, and h-index etc

Research organizations	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	RP R (%)	h-index (R)
University of California, Berkeley, USA	142	1 (2.25)	1 (1.91)	1 (2.72)	1 (1.77)	1 (1.7)	23 (1)
Chinese Academy of Sciences, China	81	2 (1.28)	5 (0.86)	2 (1.87)	2 (0.96)	2 (0.97)	16 (4)
Tsinghua University, China	75	3 (1.2)	2 (1.13)	3 (1.3)	3 (0.92)	3 (0.94)	8 (17)
Hong Kong Polytechnic University, China	59	4 (0.93)	4 (1.05)	15 (0.76)	4 (0.77)	4 (0.81)	11 (14)
Russian Academy of Sciences, Russia	55	5 (0.87)	3 (1.08)	30 (0.57)	5 (0.76)	5 (0.78)	8 (17)
University of Illinois, USA	51	6 (0.81)	8 (0.57)	4 (1.15)	9 (0.47)	12 (0.41)	14 (5)
Utrecht University, Netherlands	51	6 (0.81)	6 (0.7)	7 (0.96)	6 (0.66)	6 (0.65)	17 (3)
Massachusetts Institute of Technology, USA	51	6 (0.81)	8 (0.57)	4 (1.15)	7 (0.63)	7 (0.54)	20 (2)
City University Hong Kong, China	44	9 (0.7)	11 (0.54)	8 (0.92)	8 (0.51)	7 (0.54)	13 (6)
Lund University, Sweden	43	10 (0.68)	6 (0.78)	34 (0.53)	8 (0.57)	7 (0.52)	12 (11)
Stanford University, USA	42	11 (0.66)	27 (0.32)	4 (1.15)	21 (0.33)	24 (0.32)	13 (6)
National University of Singapore, Singapore	40	12 (0.63)	8 (0.57)	18 (0.73)	14 (0.4)	14 (0.39)	10 (15)
Indian Institutes of Technology, India	39	13 (0.62)	11 (0.54)	18 (0.73)	11 (0.44)	11 (0.42)	7 (20)
Georgia Institute of Technology, USA	38	14 (0.6)	15 (0.43)	11 (0.84)	11 (0.44)	11 (0.42)	13 (6)
National Taiwan University, Taiwan	38	14 (0.6)	21 (0.38)	8 (0.92)	13 (0.43)	10 (0.44)	13 (6)
Penn State University, USA	34	16 (0.54)	17 (0.4)	18 (0.73)	21 (0.33)	21 (0.34)	13 (6)
Seoul National University, South Korea	34	16 (0.54)	34 (0.3)	10 (0.88)	21 (0.33)	17 (0.36)	8 (17)
University Maryland, USA	33	18 (0.52)	22 (0.35)	15 (0.76)	21 (0.33)	26 (0.31)	12 (11)
Korea Advanced Institute of Science and Technology, South Korea	32	19 (0.51)	15 (0.43)	28 (0.61)	17 (0.35)	15 (0.37)	7 (20)
Ege University, Turkey	32	19 (0.51)	45 (0.27)	11 (0.84)	14 (0.4)	17 (0.36)	12 (11)
Oak Ridge National Lab, USA	32	19 (0.51)	22 (0.35)	18 (0.73)	17 (0.35)	17 (0.36)	9 (16)

TP number of publications, *TP R* rank and the percentage of total publications, *SP R* single research organization publications, *CP R* international collaboration publications, *FP R* the first author's research organization publications, *RP R* the corresponding author's research organization publications

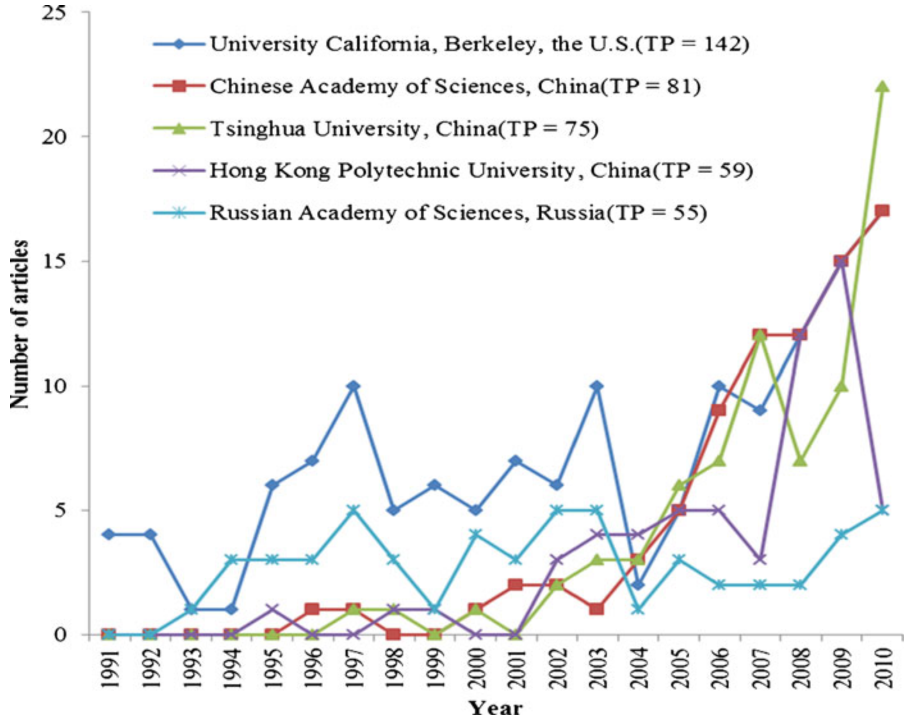

Fig. 3 Annual number of articles for top 5 productive research organizations (1991–2010)

the top 20 productive research organizations from these countries We found that the University of California at Berkeley ranked highest with 142 articles, followed by the Chinese Academy of Sciences (81) and Tsinghua

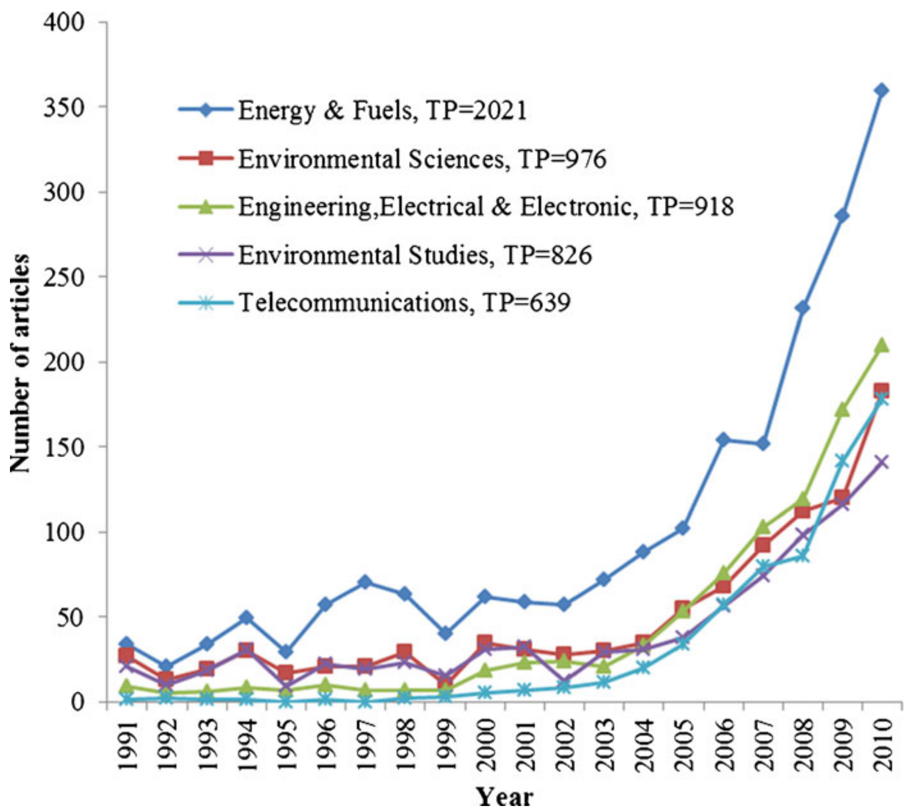

Fig. 4 Annual number of articles for top 5 subject categories (1991–2010)

Table 4 Top 20 most productive journals (1991–2010) with the number of publications, IF, and h-index etc

Journal name	TP	Percent	R	IF (2010)	h-Index (R)
Energy Policy	578	8.9	1	2.629	31 (1)
Energy and Buildings	202	3.1	2	2.046	21 (3)
Energy	196	3.0	3	3.597	22 (2)
Energy Conversion and Management	125	1.9	4	2.072	18 (5)
Applied Energy	95	1.5	5	3.915	14 (8)
Applied Thermal Engineering	93	1.4	6	1.826	13 (10)
International Journal of Hydrogen Energy	77	1.2	7	4.057	18 (5)
International Journal of Energy Research	74	1.1	8	1.86	13 (10)
Building and Environment	68	1.0	9	2.131	13 (10)
Journal of Power Sources	61	0.94	10	4.29	19 (4)
Computer Communications	55	0.85	11	0.816	10 (18)
Journal of Cleaner Production	55	0.85	11	2.43	14 (8)
IEEE Transactions On Wireless Communications	54	0.83	13	2.152	12 (13)
Renewable Energy	54	0.83	13	2.58	11 (14)
Energy Economics	50	0.77	15	#N/A	18 (5)
Energy Efficiency	50	0.77	16	2.466	7 (19)
IEEE Transactions On Mobile Computing	44	0.68	17	2.381	11 (14)
International Journal of Refrigeration-Revue Internationale Du Froid	41	0.63	17	1.439	11 (14)
Building Research and Information	39	0.60	19	#N/A	11 (14)
IEICE Transactions On Communications	39	0.60	20	0.301	4 (20)

TP number of publications, *R* rank, *Percent* the percentage of the journal's publications, *IF* impact factor

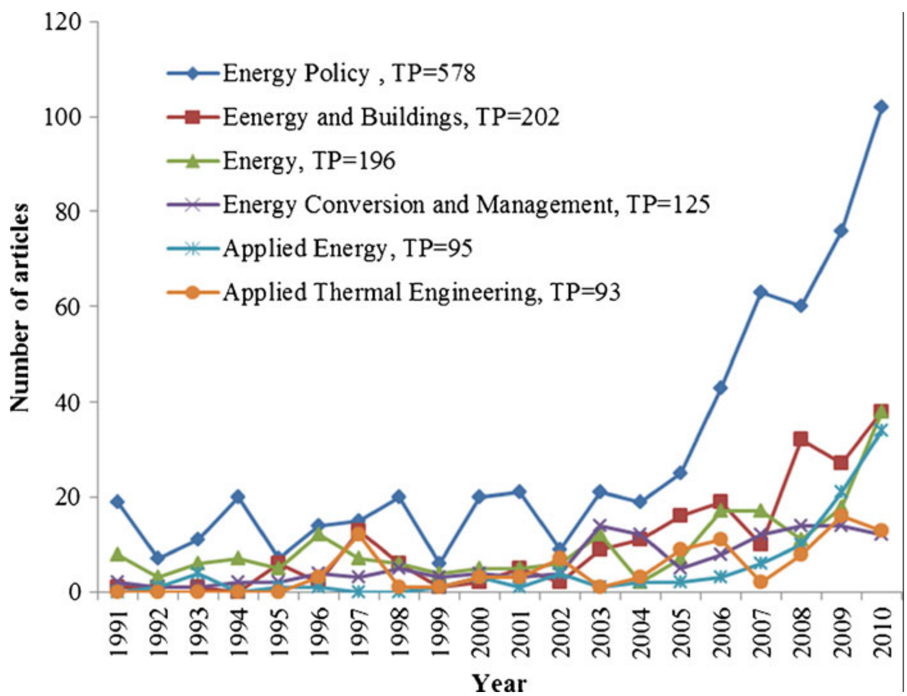

Fig. 5 Annual number of articles for top 6 productive journals (1991–2010)

University (76). It is worth noting that, the Chinese Academy of Sciences, Russian Academy of Sciences, and Indian Institute of Technology, ranking 2nd, 5th, and 12th respectively, are integrated research entities consisting of many relatively independent research organizations distributed throughout their own countries. We also found that the University of California at Berkeley still ranked first with h-index (23), followed by Massachusetts Institute of Technology (20) and Utrecht University, Netherlands (17). It is notable that Tsinghua University in China, Hong Kong Polytechnic University and Russian Academy of Sciences ranked 3rd, 4th and 5th by total publications, but ranked 17th, 14th and 17th by h-index, respectively. The research organizations with higher h-indexes have greater scientific level.

In Fig. 3, the trends of article quantities in the top 5 productive research organizations during 20 years were revealed. The annual number of articles of Russian Academy of Sciences fluctuated from 1991 to 2010, while annual volume of articles published by the University of California at Berkeley, Chinese Academy of Sciences and Tsinghua University surged after 2003. The number of articles of Hong Kong Polytechnic University increased markedly in 2007 and then decreased sharply in 2010.

Subject categories and journals

Except for 6 articles without information relating to their subject categories, 6,488 articles about energy efficiency were divided into 178 subject categories in SCIE and SSCI. The five most frequent subject categories based on the number of total publications (Fig. 4) are Energy & Fuels (2,021), Environmental Sciences (976), Engineering, Electrical & Electronic (918), Environmental Studies (826), and Telecommunications (639). The numbers of articles in these five subject categories soared during the period from 2004 to 2010, especially in Energy & Fuels which has been the research area of energy efficiency based on articles published from 1991 to 2010.

Of 6,494 articles, more than 30 % are from 20 journals (Table 4). *Energy Policy* (578, 8.9 %) was the most productive journal, followed by *Energy and Buildings* (202, 3.1 %), and *Energy* (196, 3.0 %); *Energy Policy* had the highest h-index score (31). Interestingly, the *Journal of Power Sources* ranked 10th by the number of articles, but had the highest IF (4.29) and its h-index (19) was fourth highest among these 20 journals. It shows that the *Journal of Power Sources* is a core journal with a large influence on energy efficiency research.

Table 5 Top 10 most cited articles about energy efficiency, from the published date to May 2012

Title (Author)	Journal (published time)	Citations	Citations per year
A water and heat management model for proton-exchange-membrane fuel-cells (Nguyen, TV; White, RE)	Journal of the Electrochemical Society (1993.1)	587	30.23
Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc *sensor networks* (Younis, O; Fahmy, S)	IEEE Transactions on Mobile Computing (2004.10)	493	64.30
Wide-band reflective polarizers from cholesteric polymer networks with a pitch gradient (Broer, DJ; Lub, J et al.)	Nature (1995.11)	324	19.54
An iodine/triiodide reduction electrocatalyst for aqueous and organic media (Papageorgiou, N; Maier, Wf; Gratzel, M)	Journal of the Electrochemical Society (1997.3)	304	19.93
Data gathering algorithms in sensor networks using energy metrics (Lindsey, S; Raghavendra, C et al.)	IEEE Transactions on Parallel and Distributed Systems (2002.9)	267	27.38
Energy-efficiency of mimo and cooperative mimo techniques in sensor networks (Cui, SG; Goldsmith, AJ; Bahai, A)	IEEE Journal on Selected Areas in Communications (2004.8)	261	33.32
Production of synthesis gas (Rostrupnielsen, JR)	Catalysis Today (1993.12)	254	13.73
A thermally self-sustained micro solid-oxide fuel-cell stack with high power density (Shao, ZP; Haile, SM et al.)	Nature (2005.6)	253	36.14
Self-humidifying polymer electrolyte membranes for fuel cells (Watanabe, M; Uchida, H et al.)	Journal of the Electrochemical Society (1996.12)	246	15.87
Balancing transport and physical layers in wireless multihop networks: jointly optimal congestion control and power control (Chiang, M)	IEEE Journal on Selected Areas in Communications (2005.1)	242	32.63

Figure 5 showed the trends of article quantities in the top 6 journals. The number of articles published by *Energy Policy* grew rapidly after 2005, while the upward trend of the other five journals tended to begin more recently.

Highly cited articles

Among 6,494 scientific articles about energy efficiency published during 1991–2010, 74 articles accounting for 1.1 % were cited more than 100 times, 144 accounting for 2.2 % were cited 50–99 times, and 388 accounting for 6.0 % were cited 25–49 times until May 2012. Table 5 lists the top 10 most cited articles. Seven of these had first authors from the USA, and four articles were published in chemistry-oriented journals.

"A water and heat management model for proton-exchange-membrane fuel-cells", authored by Nguyen and White both from University of South Carolina, was cited 587 times and was published in *Journal of the Electrochemical Society* in 1993. This paper, in contrast to the previous one-dimensional transport of the reactants and products in the electrodes, developed a two dimensional heat and mass transfer model for proton exchange membrane (PEM) fuel cells to evaluate the efficiencies and effects of various design and operating parameters on the performance of a PEM fuel cell (Nguyen and White, 1993). It demonstrated the important roles played by water and heat management in maintaining high performance of polymer electrolyte fuel cells (Wang 2004).

Besides accumulated citations, the average annual citations for the top 10 articles were calculated in Table 5 as well. "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks", authored by Younis and Fahm both from

Table 6 Top 21 frequency of author keywords (1991–2010)

Author keywords	TP	91-10 R (%)	91-95 R (%)	96-00 R (%)	01-05 R (%)	06-10 R (%)
Energy efficiency	1,709	1 (35)	1 (29.7)	1 (34.8)	1 (31.7)	1 (35)
Wireless sensor networks	288	2 (6)	0	0	12 (1.3)	2 (8.3)
Energy	158	3 (3.2)	2 (3.3)	2 (4.3)	2 (3.7)	3 (2.9)
Sensor networks	103	4 (2.1)	0	0	5 (1.7)	4 (2.6)
Renewable energy	86	5 (1.8)	16 (1.3)	4 (1.9)	3 (2.4)	7 (1.6)
Energy consumption	84	6 (1.7)	6 (2.5)	9 (1.4)	13 (1.2)	6 (1.9)
Efficiency	83	7 (1.7)	3 (2.9)	3 (2.2)	5 (1.7)	8 (1.5)
Performance	76	8 (1.6)	99 (0.4)	40 (0.7)	47 (0.5)	5 (2)
Energy conservation	66	9 (1.4)	3 (2.9)	4 (1.9)	8 (1.5)	16 (1.1)
Simulation	65	10 (1.3)	11 (1.7)	7 (1.7)	8 (1.5)	13 (1.2)
Energy policy	65	10 (1.3)	8 (2.1)	16 (1.2)	10 (1.4)	12 (1.3)
China	59	12 (1.2)	99 (0.4)	23 (1)	13 (1.2)	11 (1.3)
Climate change	55	13 (1.1)	33 (0.8)	190 (0.2)	4 (2.2)	21 (0.9)
Energy	55	13 (1.1)	0	9 (1.4)	23 (1)	13 (1.2)
Hydrogen	54	15 (1.1)	99 (0.4)	69 (0.5)	65 (0.4)	9 (1.4)
Optimization	52	16 (1.1)	33 (0.8)	9 (1.4)	13 (1.2)	19 (1)
Energy saving	49	17 (1)	16 (1.3)	0	23 (1)	16 (1.1)
Biomass	48	18 (1)	0	40 (0.7)	7 (1.6)	22 (0.9)
Design	46	19 (0.9)	16 (1.3)	23 (1)	107 (0.3)	18 (1.1)
Sustainability	44	20 (0.9)	33 (0.8)	40 (0.7)	13 (1.2)	23 (0.9)
Sustainable development	44	20 (0.9)	0	9 (1.4)	10 (1.4)	25 (0.8)

TP number of publications; *91-10 R* (%) rank and the percentage of number of publications including the author keyword during 1991–2010; *91-95 R (%)* rank and the percentage of number of publications including the author keyword during 1991–1995; *96-00 R (%)*rank and the percentage of number of publications including the author keyword during 1996–2000; *01-05 R (%)* rank and the percentage of number of publications including the author keyword during 2001–2005; *06-10 R (%)* rank and the percentage of number of publications including the author keyword during 2006–2010

Purdue University, had the highest average annual citations and was published in *IEEE Transactions on Mobile Computing* in 2004 In this paper, a novel hybrid energy-efficient distributed clustering approach, that periodically selected cluster heads according to a hybrid of the node residual energy and a secondary parameter, was proposed for long-lived ad hoc sensor networks. Compared with previous studies, the key feature of this approach was that it exploited the availability of multiple transmission power levels at sensor nodes, which was proved effective in prolonging the network lifetime and supporting scalable data aggregation (Younis and Fahmy, 2004).

Title words and keywords

Statistical analysis of author keywords, keywords plus, and title words can be used to identify directions in science (Garfield 1990a, b), which is proved a useful way to explore the development of science and technology. Bibliometric analysis of author keywords in a specific period has been used more frequently in recently years to identify the research trends (Ho 2007; Chiu and Ho 2007). The title of an article calls for much deliberation from authors and can provide important information to readers (Fu 2010). Title words provide far more detail than keywords in describing the article's contents with greater depth and variety (Garfield 1990a, b).

Among 4,481 articles containing author keywords collected from the SCIE and SSCI, there were total 12,775 keywords listed by authors, in which 10,284 (80.3 %) author keywords were mentioned only once, 1,276 (10 %) author keywords twice, and 457 (3.6 %) keywords three times. The large number of once-only author keywords suggests a lack of continuity in research and a wide disparity in research foci (Chuang et al. 2007). The number of keywords used for more than

Table 7 Top 20 frequency of title words (1991-2010)

Title words	TP	91-10 R (%)	91-95 R (%)	96-00 R (%)	01-05 R (%)	06-10 R (%)
Energy	2,518	1 (38.8)	1 (32.4)	1 (40.8)	1 (37.2)	1 (39.8)
Efficiency	1,254	2 (19.3)	2 (22.4)	2 (21.7)	2 (17.9)	2 (18.9)
Network(s)	695	3 (10.7)	280 (0.4)	90 (1.1)	4 (5.8)	3 (15.6)
System(s)	657	4 (10.1)	3 (5.9)	3 (7.3)	3 (10.3)	4 (11.2)
Wireless	483	5 (7.4)	0	162 (0.7)	8 (3.9)	6 (11)
Sensor	469	6 (7.2)	0	866 (0.1)	21 (2.5)	5 (11.2)
Performance	349	7 (5.4)	4 (3.3)	4 (4.6)	5 (4.8)	7 (6)
building(s)	320	8 (4.9)	6 (3.1)	5 (3.7)	10 (3.3)	8 (5.9)
Power	268	9 (4.1)	80 (0.9)	5 (3.7)	12 (3.2)	9 (5)
Control	244	10 (3.8)	80 (0.9)	9 (3.1)	6 (4.1)	11 (4.2)
Heat	240	11 (3.7)	80 (0.9)	11 (2.9)	6 (4.1)	12 (4.1)
Energy efficient	237	12 (3.6)	45 (1.3)	40 (1.6)	14 (3)	10 (4.6)
Production	227	13 (3.5)	15 (2)	10 (3)	12 (3.2)	14 (3.9)
Design	224	14 (3.4)	11 (2.4)	11 (2.9)	15 (2.8)	14 (3.9)
Efficient	212	15 (3.3)	11 (2.4)	27 (2)	28 (2.2)	13 (4)
Effect	161	16 (2.5)	4 (3.3)	20 (2.4)	25 (2.4)	23 (2.4)
Case	160	17 (2.5)	80 (0.9)	8 (3.5)	29 (2.1)	19 (2.6)
Development	159	18 (2.4)	9 (2.7)	11 (2.9)	9 (3.8)	39 (1.9)
Evaluation	157	19 (2.4)	20 (1.8)	62 (1.3)	27 (2.3)	18 (2.8)
Thermal	151	20 (2.3)	25 (1.6)	48 (1.4)	18 (2.5)	20 (2.5)

TP number of publications; *91-10 R (%)* rank and the percentage of number of publications including the author keyword during 1991–2010; *91-95 R (%)* rank and the percentage of number of publications including the author keyword during 1991–1995; *96-00 R (%)* rank and the percentage of number of publications including the author keyword during 1996–2000; *01-05 R (%)*rank and the percentage of number of publications including the author keyword during 2001–2005; *06-10 R(%)* rank and the percentage of number of publications including the author keyword during 2006–2010 three times was merely 758 (5.9 %), which showed that the popular research topics in energy efficiency were focusing on a small field (Fu 2010). Table 6 lists the top 21 frequent author keywords in energy efficiency oriented research to accurately measure their quantity fluctuations, using 5-year intervals from 1991 to 2010. Energy efficiency appeared most frequently in the whole 20 years, which can be attributed to the searching term "energy efficiency". Excluding "energy" and "efficiency", "wireless sensor networks" (288, 6 %), "sensor networks" (103, 2.1 %), and "renewable energy" (86, 1.8 %) in Table 6 appeared in author keywords most frequently (Table 6). Obviously, the research about wireless sensor networks and sensor networks for green communication to improve energy efficiency has received more attention in recent years. By analyzing top 21 frequent author keywords, we found that the emerging research fields of energy efficiency focused on green communication (wireless sensor networks, sensor networks; 391, 8.73 %), energy sustainability (energy consumption, energy conservation, climate change, energy saving sustainability, and sustainable development; 342, 7.63 %), and renewable energy (exergy, hydrogen, biomass; 157, 3.5 %). It also should be noted that China was the only country name in the top 21 author keywords, which indicated that the research of China's energy efficiency occupied more and more attention.

After eliminating the preposition, such as "in", "at", "on" and other meaningless words in the analysis of title words, the 20 single words used most frequently are revealed in Table 7 and analyzed again in 5-year periods. To some extent, this analysis of title words was analogous with the analysis of author keywords. Excluding the searching word "energy" and "efficiency", the top 3 words were "network(s)", "system(s)", "wireless" corresponded to the author keywords "wireless sensor network(s)" and "sensor networks",

Table 8 The top 20 frequency of keywords plus (1991–2010)

Keywords plus	TP	91-10 R (%)	91-95 R (%)	96-00 R (%)	01-05 R (%)	06-10 R (%)
systems	287	1 (7.5)	4 (3.1)	3 (3.8)	2 (6.2)	1 (8.8)
Performance	282	2 (7.3)	11 (1.5)	2 (4.9)	1 (6.4)	2 (8.4)
Energy	164	3 (4.3)	1 (5.6)	1 (5.8)	3 (3.9)	6 (4.1)
Design	152	4 (4)	35 (1)	18 (1.4)	4 (3.3)	3 (4.7)
Model	146	5 (3.8)	11 (1.5)	13 (1.7)	5 (2.8)	4 (4.6)
Energy efficiency	132	6 (3.4)	9 (2.1)	25 (1.2)	8 (2.4)	5 (4.2)
Efficiency	122	7 (3.2)	5 (2.6)	5 (2.3)	6 (2.7)	8 (3.5)
Consumption	122	7 (3.2)	11 (1.5)	7 (2)	15 (1.7)	7 (3.9)
Optimization	98	9 (2.6)	35 (1)	78 (0.6)	23 (1.4)	9 (3.3)
Emissions	79	10 (2.1)	103 (0.5)	4 (2.6)	26 (1.3)	11 (2.3)
Simulation	78	11 (2)	103 (0.5)	25 (1.2)	21 (1.5)	10 (2.4)
Policy	75	12 (2)	5 (2.6)	13 (1.7)	23 (1.4)	13 (2.1)
Growth	73	13 (1.9)	3 (3.6)	7 (2)	15 (1.7)	14 (1.8)
Management	67	14 (1.7)	35 (1)	192 (0.3)	37 (1)	12 (2.2)
Water	62	15 (1.6)	11 (1.5)	7 (2)	11 (1.9)	18 (1.5)
Temperature	62	15 (1.6)	11 (1.5)	192 (0.3)	14 (1.8)	15 (1.7)
Power	59	17 (1.5)	0	192 (0.3)	11 (1.9)	16 (1.7)
Oxidation	58	18 (1.5)	5 (2.6)	25 (1.2)	11 (1.9)	21 (1.3)
Decomposition	54	19 (1.4)	0	7 (2)	8 (2.4)	28 (1.1)
Conversion	53	20 (1.4)	35 (1)	5 (2.3)	7 (2.6)	46 (0.9)

TP number of publications; *91-10 R (%)* rank and the percentage of number of publications including the keyword plus during 1991–2010; *91-95 R (%)* rank and the percentage of number of publications including the keyword plus during 1991–1995; *96-00 R (%)* rank and the percentage of number of publications including the keyword plus during 1996-2000; *01-05 R (%)* rank and the percentage of number of publications including the keyword plus during 2001–2005; *06-10 R (%)* rank and the percentage of number of publications including the keyword plus during 2006–2010 which indicated that the wireless sensor network was popular topic of energy efficiency in the last decade. Three related terms "power", "heat", "thermal" appeared 659 times in total, which showed that the efficiency of thermal energy received much attention during these 20 years. "Building(s)" (320, 4.9 %) appeared in the top 20 title words, but not in the top 20 author keywords, although the latter included the related term, "design," suggesting that the energy efficiency in buildings received considerable coverage from 1991 to 2010.

The top 20 frequency of "keywords plus" as well as its rank and percentage in different periods are shown in Table 8. "Energy", "efficiency", "energy efficiency", and "design" appeared in author keywords, title words, and keywords plus list at the same time. Some words such as "emissions", "growth", "management", "model", "oxidation", "temperature", and "water" only presented in keywords plus list describing the broad content in energy efficiency articles.

Conclusions

Based on the databases of SCI and SSCI, this paper studied the characteristics of the energy efficiency literature from 1991 to 2010 using bibliometric techniques, elucidating an expanding and shifting focus. The total 8,244 publications were divided into 14 document types. Of the articles, 95.5 % were published in English, while other 20 languages were used only in 295 articles. This reflects the fact that the study of energy efficiency has become more extensive and global over the past two decades. In this research arena, the USA has been not only the most productive country, but also most influential country based on having the highest h-index. Correspondingly, UC Berkeley produced the most single country and internationally collaborative articles, and it also had the highest h-index. The results indicated that the top three most active subject categories of energy efficiency research were "energy and fuels", "environmental sciences", and "electrical and electronic engineering". In this timeframe, *Energy Policy* has been the most productive journal, and the most highly cited article is entitled "A water and heat management model for proton-exchange-membrane fuel-cells," authored by Nguyen and White (1993) and published in the *Journal of the Electrochemical Society*. Based on a statistical analysis of title words and keywords, three hotspots of energy efficiency research are identified: green communication, renewable energy, and energy sustainability. Green communication and renewable energy research in particular, has developed rapidly in recent years. In the future, these two energy efficiency topics are likely to continue to progress, while unforeseeable hotspots may also emerge.

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