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A bibliometric analysis of hydrogen energy literature, 1965–2005

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The present study explores the characteristics of hydrogen energy literature from 1965 to 2005 based on the database of Science Citation Index Expanded (SCIE) and its implication using the bibliometric techniques. The results of this work reveal that the literature on hydrogen energy grows exponentially with an annual growth rate of about 18% for the last decade. Most of document type is in the form of journal articles or meeting abstracts, constituting 90.17% of the total literature and English is the predominant language (94.66%). USA, Japan and China are the three biggest contributing countries on hydrogen energy literature publishing, 25.8%, 14.9%, 7.7%, respectively. The Chinese Academy of Sciences in China is the largest contributor publishing 308 papers. The journal literature on hydrogen energy does not confirm the typical S-shape for the Bradford-Zipf plot, but five core journals, i.e. *International Journal of Hydrogen Energy*, *Journal of Power Source*, *Journal of the Electrochemical Society, Solid State Ionics*, and *Electrochimica Act*, contributing about 41% can be identified. Journals with highly cited articles and most highly cited articles are also identified, in which the most highly cited article receives more than 1,000 citations.

Introduction

The global oil demand has been increased significantly recently, partially due to the economic growth of two highly populated countries, China and India. On the other hand, there is growing evidence that the world production of crude oil may reach the

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maximum early in this century [THOMAS & ZALBOWITZ, 2003 : 28]. The crude oil may be depleted within several decades. Moreover, the burning of fossil fuel inevitably releases carbon dioxide. Each liter of gasoline produced, distributed and then consumed in a vehicle releases approximately 3 kg of carbon dioxide (THOMAS & ZALBOWITZ, 2003 : 28). Indeed, the burning of fossil fuel since the industry revolution has increased the CO_2 concentration to about 360 ppm [THOMAS & ZALBOWITZ, 2003 : 28]. Carbon dioxide is one of major greenhouse gases. High concentration of greenhouse gases will cause greenhouse effect and may change the earth's climate.

To reduce dependence on fossil energy and the emission of greenhouse gases, there is growing interest pursing hydrogen energy as an alternative around the world for the recent decade. In particular, various types of fuel cells have been developed recently for transportation, stationary as well as portable power sources. Indeed, when fuel cell technologies started to demonstrate real promise for the last decade, many countries have initiated programs for the development of hydrogen production, distribution, and storage technologies [HASSAN, 2005]. In particular, USA launched a 1.2 billion FreedomCAR (Cooperative Automotive Research) Initiative in January 2002 to fund research on fuel cell cars to reduce emissions of greenhouse gases from vehicles and pursue independence of petroleum for USA [A FREE RIDE: FREEDOMCAR INITIATIVE, 2003]. In February 2003, President Bush of the USA announced a 1.7 billion fuel cell initiative, combining with the FreedomCAR initiative to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies [THE WHITE HOUSE PRESIDENT GEORGE W. BUSH, 2003]. With this initiative, "the first car driven by a child born today could be powered by fuel cells" [THE WHITE HOUSE PRESIDENT GEORGE W. BUSH, 2003]. Such aggressive programs will certainly advance science and technology related to hydrogen technology.

Indeed, to enter the era of hydrogen economy, research and development of hydrogen energy has grown very rapidly in recent decades. As a reflection, the hydrogen energy literature must also grow dramatically. The background information reveals the increasing importance of hydrogen energy and the literature review below indicates the lack of scientometric study on such bright new area. This study aims to investigate the characteristics of hydrogen energy literature from 1965 to 2005 and its implication using the bibliometric techniques, which is a statistical method of bibliography counting to evaluate and quantify the growth of literature for a particular subject.

The objectives of this study are: (1) to explore the growth of hydrogen energy literature published; (2) to determine the core journals that contain a substantial portion of journal literature on hydrogen energy; (3) to find the productivity distribution of institutions on this subject; (4) to identify major contributing countries that published hydrogen energy articles most; (5) to find the dispersion of kinds of language and

document types of the literature on hydrogen energy; (6) to reveal the characteristic of citation for the hydrogen energy literature.

Literature review

Retrieving the bibliographic data from the Science Citation Index of the Institute for Scientific Information, BRAUN & AL. [1997] measured the frequency of usage of the prefix nano- in the title of journal papers during the 1986–1995. They found that there were 4152 papers having the nano- prefix in their title and the exponential growth is clearly with doubling time of 1.6 years. In addition, nanoscale chemistry, physics, and materials sciences are leading progresses and carbon nanotubes is one of the most active subfield of research in the nanosciences. Using Braun et al's study as basis, MEYER & PERSSON [1998] further studied some characteristics of nanotechnology using bibliometric data. According to the journal's classification, they found that most nano-papers are published in the major field of natural sciences, then, followed by multidisciplinary sciences, engineering and materials sciences and life sciences, respectively. The USA, Japan and Germany are three heads of the leading countries in nano publications. Academy of Sciences of the People's Republic of China is the most productive institution. MIT comes next and followed by U.C. Berkeley and Tohoku University, Japan. Overall, American and Japanese institutions are major ones that published nano papers. In terms of patterns of collaboration, they demonstrated that some countries tend to collaborate with researchers from a variety of countries, e.g., USA; while others, e.g., Japan and China, restrict international collaboration. SCHUMMER [2004] conducted a co-author analysis of over 600 papers published in "nano journals" in 2002 and 2003 and investigated if this apparent concurrence is accompanied by new forms and degrees of multi- and inter-disciplinarity as well as of institutional and geographic research collaboration. By analyzing the patterns of research collaboration and comparing with these of classical disciplinary research, he argued that nanoscale research reveals no particular patterns and degrees of inter-disciplinarity and that its apparent multi-disciplinarity consists of different largely mono-disciplinary fields which are rather unrelated to each other and which hardly share more than the prefix "nano".

By searching the MEDLINE database for articles indexed under the publication type "Randomized Control Trial (RCT), TSAY & YANG [2005] investigate the features of RCT literature based on bibliometric methods. Their research results revealed that the literature growth rate, from 1965 to 2001, is steadily rising and follows an exponential model. From 1990 to 2001, a total of 114,850 citations dealing with RCTs were retrieved, among them the multi-center study is extensively used. Forty-two core journals were identified using Bradford's law. Generally, RCTs are found in publications concentrating on cardiovascular disease, cancer, asthma, postoperative

condition, health, and anesthetics. Focusing on books, journal publications, conference proceedings and technical reports, ACKERMANN [2005] examined the bibliometrics of the controversial scientific literature of polywater, a new kind of water, research. The data were collected from the beginning in 1962 with the first publication of the discovery of polywater and ending in 1974 with the last polywater papers. The source of publication were drawn from the *Composite Bibliography of Polywater Research Literature, 1962–1974*, compiled by the Author, and the citation source were obtained from the print version of Science Citation Index (SCI) Five and Ten Year Cumulation for 1955–1964, 1965–1969, 1970–1974, and 1975–1979. Ackermann employed four bibliometric indicators, e.g., publication (P) frequency for measuring publication pattern and output, citation per publication (CPP) for impact, uncited publications (UP) and author self-citations(SC) for their effect on P and CPP. His study showed that journal publications are with the highest publication frequency, books are with the highest citations per publication, and uncited publications and author self-citations are insignificant. Comparing to several non-controversial scientific literature, i.e., normal scientific literature, these findings may demonstrate to be common to other controversial scientific literature.

Employing bibliometric techniques, PATRA & AL. [2006], analyzed growth pattern, core journals and authors' distribution in the field of bibliometrics using data from Library and Information Science Abstracts (LISA). Bradford's law of scattering was used to identify core journals and Lotka's law was used to identify authors' productivity patterns. Their research results reveal that *Scientometrics* was the core journal in this field, authors' distribution did not follow original Lotka's law and literature growth did not show any definite pattern. Moreover, 12 most productive authors with more than 20 publications in the bibliometric field were also identified. HASSAN [2005] investigated the evolution of the knowledge structure of the field of fuel cells during the nineties using data on patents and scientific publications. He employed simultaneous mapping approach to examine deeply the cognitive structure of the field of fuel cells at the world level. The results demonstrated the heterogeneity of the field of fuel cells. It also showed that "the fuel cell field was subject to increasing cognitive linkages between science and technology and substantial cognitive interrelations among the knowledge bases of the sub-fields identified."

Methodology

For the present work, database of Science Citation Index Expanded (SCIE), a product of the Thomson Scientific, is employed to retrieve data from 1965 to 2005 for this study. Although other databases such as Applied Science and Technology ABS, Compendex, EngIndex/FS, are also available for bibliometric analysis, SCIE is adopted because it is recognized as the leading English-language supplier of services providing

access to the published information in the multidiscipline fields of science and technology. Moreover, it is the only database that offers a comprehensive citation data of the published literature.

The Web of Science SCIE database currently contains approximately 5900 world leading scholarly science and technical journals covering more than 150 disciplines from 1945 to date (ISI SCIE). For the present study the time span of the SCIE available is from 1965 to date. Generally, each record in the SCIE database contains an English-language title and descriptive abstract, together with full bibliographic information. The bibliographic information includes the journal or other publication title, the authors' name and affiliation, document type, the language of the original document, etc. Document types indexed included books and monographs, conferences, symposia, meetings, journal articles, reports, theses and dissertations.

Since fuel cells are the main vehicle for the application of hydrogen energy, in this study, the search command "hydrogen energy" or "fuel cell" or "fuel cells" are used in the topic field to retrieve most of the papers which embodied these three key words in article title or abstract. In this paper, the literature on hydrogen energy or fuel cell is referred to as hydrogen energy literature. Each relevant record was then downloaded to a compact disc. Care has been exercised to examine the data collected to assure their identity. Subsequently, the data were analyzed by Visual Fox Pro and Excel. By employing bibliometric techniques, especially literature growth model, Bradford's law and citation counting, the results of this study are analyzed and discussed.

The growth of hydrogen energy literature published

As indicated earlier, the SCIE database, from 1965 to 2005, is available during the course of this study. For this time span, the SCIE contains 14,449 items on hydrogen energy. Table 1 shows the distribution of the number of literature published and the cumulated number every five years.

Table 1. Five-year production of the hydrogen energy literature, 1965–2005

Year	1965–69	70–74	75–79	80–84	85–89	90–94	95–99	2000–04	2005
Article	320	172	235	363	363	1014	2718	6815	2449
Cumulate	320	492	727	1090	1453	2467	5185	12000	14449

The fuel cell was invented by Sir William Grove in 1839. In 1960s, it was applied mainly for space power and the Department of Energy of the USA has been funding research and development of fuel cell technology since 1984 [THOMAS & ZALBOWITZ, 2003]. Before 1980, the number of SCIE papers on hydrogen energy published each year was from 24 to 76. The year of 1990 to 1994 was the period of significant publication on hydrogen energy based on the SCIE as the number of articles published

on hydrogen energy was tripled than the previous period of 1985 to 1989. It was nearly tripled for the next 5-year period and tripled again for the further next 5-year period, i.e. for 2000 to 2005. It is interesting to note that in early 2002, the Bush government of the United States of America [U. S. DEPARTMENT OF ENERGY, 2006] launched the FreedomCAR initiative. Since 1990, extensive studies on hydrogen energy have been conducted all over the world and the fuel cell papers increased sharply. The number reached 2449 in 2005. Indeed, the literature on hydrogen energy grows exponentially for the last decade as demonstrated in Figure 1, which illustrates that the cumulative literature on hydrogen energy may be fitted relatively well by an exponential fit as $y = 482+12e^{0.176(x-1965)}$. The annual growth rate is around 18%. This suggests that hydrogen energy is indeed a fast developing subject.

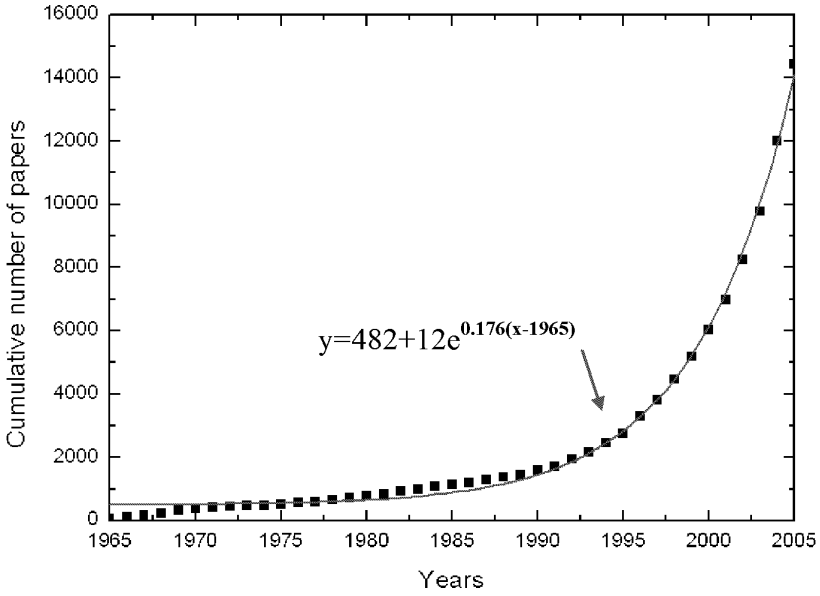

Figure 1. Cumulate growth of the hydrogen energy literature,1965–2005

Some characteristics of hydrogen energy literature

Table 2 illustrates the distribution of document type in hydrogen energy literature. As common in many subjects, the single most prevalent form of publication is the research article, which contributes 84.93% of the total literature. The second largest form of hydrogen energy publication is meeting abstracts, which covers 5.23%,

significantly lower than that for journal literature. Other minor documents include news, reviews, editorial material, note, etc. Most of document type on hydrogen energy that collected in the SCIE is in the form of journal articles or meeting abstracts, constituting 90.17% of the total literature. This reflects the collection policy of the SCIE. The major source materials for the SCIE database are scientific and technical journals and some conference publications published throughout the world over a wide range of languages.

Table 2. Distribution of document type of the hydrogen energy literature, 1965–2005

Document type	No. of articles	%	Cum. %
Article	12272	84.93	84.93
Meeting Abstract	756	5.23	90.16
News Item	419	2.90	93.06
Review	352	2.44	95.50
Editorial Material	237	1.64	97.14
Letter	168	1.16	98.30
Note	145	1.00	99.31
Book Review	38	0.26	99.57
Correction	22	0.15	99.72
Discussion	12	0.08	99.80
Correction, Addition	8	0.06	99.86
Reprint	7	0.05	99.91
Bibliography	5	0.03	99.94
Abstract of Published Item	4	0.03	99.97
Biographical–Item	3	0.02	99.99
Item about an Individual	1	0.01	100.00
Total	14449	100.00	

Table 3. Language distribution of the hydrogen energy literature, 1965–2005

Rank	Language	No. of articles	%	Cum. %
1	English	13677	94.66	94.66
2	Japanese	309	2.14	96.80
3	Chinese	184	1.27	98.07
4	German	175	1.21	99.28
5	French	42	0.29	99.57
6	Polish	16	0.11	99.68
7	Spanish	12	0.08	99.76
8	Portuguese	7	0.05	99.81
9	Rumanian	7	0.05	99.86
10	Russian	6	0.04	99.90
11	Italian	4	0.03	99.93
12	Swedish	3	0.02	99.95
13	Korean	2	0.01	99.96
14	Czech	2	0.01	99.97
15	Hungarian	1	0.01	99.98
16	Slovak	1	0.01	99.99
17	Slovene	1	0.01	100.00
	Total	14449	100.00	

One interesting observation is the growing number of languages in which hydrogen energy literature is being communicated. As one might expect, English is the predominant language of articles on hydrogen energy. As shown in Table 3 English language articles constitute 94.66% of the total. There are only 5.34% non-English-language articles. This may be due to the fact that the UK and the USA are the predominant countries of publication and the SCIE is an American-Based database. Moreover, English is the official language for most international conferences. In addition to English, the hydrogen energy literature is also published in 16 different languages as also shown in Table 3. Among them Japanese and Chinese are the second and third largest contributing languages.

Country and institution productivity

Table 4 illustrates the distribution of countries contributing to hydrogen energy literature. The table is ranked by the number of articles each country contributing hydrogen energy journal literature. It should be noted that an article may be authored by many authors in several different institutions. Therefore, the sum of article published by each institution may be larger than the total number of article. It can be seen that the largest contributor, USA has 522 institutions published 4335 (25.8%) journal articles.

Table 4. Institution productivity distribution of hydrogen energy literature, 1965–2005

Rank	Country	Article, (%)	Inst.	Rank	Country	Article, (%)	Inst.
1	USA	4335 (25.8)	522	17	Brazil	171 (1.0)	36
2	Japan	2502 (14.9)	316	18	Singapore	154 (0.9)	7
3	Peoples R China	1299 (7.7)	148	19	Australia	154 (0.9)	25
4	Germany	1202 (7.2)	249	20	Denmark	151 (0.9)	20
5	South Korea	875 (5.2)	90	21	Mexico	132 (0.8)	27
6	England	726 (4.3)	131	22	Poland	122 (0.7)	33
7	Canada	683 (4.1)	83	23	Greece	119 (0.7)	9
8	Italy	553 (3.3)	83	24	Finland	99 (0.6)	7
9	France	486 (2.9)	115	25	Turkey	97 (0.6)	19
10	India	421 (2.5)	80	26	Portugal	96 (0.6)	12
11	Russia	282 (1.7)	66	27	Norway	80 (0.5)	18
12	Spain	272 (1.6)	40	28	Ukraine	79 (0.5)	26
13	Sweden	247 (1.5)	22	29	Belgium	66 (0.4)	18
14	Taiwan	228 (1.4)	44	30	Argentina	63 (0.4)	20
15	Switzerland	213 (1.3)	28		Others	683 (4.1)	204
16	Netherlands	192 (1.1)	34	Total		16782*	2532

* An article may be authored by many authors in several different institutions, therefore, the sum of article published by each institution may be larger than the total number of article.

The Japan and China come next, ranked the second and the third, respectively, contributing 2502 (14.9%) and 1299 (7.7%) SCIE articles on hydrogen energy. The subsequent countries include Germany (4th), South Korea (5th), England (6th), etc.

Thirty most productive institutions are shown in Table 5. It should be noted that an institution may be a single institute or may consist of several institutes. Among them, there are 17 institutions contributing more than 100 papers on hydrogen energy all over the world. The Chinese Academy of Sciences in the Peoples Republic of China is the largest contributor publishing 308 SCIE papers on the subject. The Pennsylvania State University in the USA is the second contributor publishing 223 papers. The University of California in USA, the National Institute of Advanced Industrial Science and Technology, AIST in Japan, Kernforschung Anlage Julich in Germany and the University of London Imperial College of Science, Technology and Medicine in England, ranked third to sixth, contribute 191, 188, 165, and 142 articles, respectively.

Table 5. The most productive institutions of the hydrogen energy literature, 1965–2005

Rank	Institution	Country	Article
1	Chinese Academy of Sciences	P. R. China	308
2	The Pennsylvania State University	USA	223
3	University of California	USA	191
4	National Institute of Advanced Industrial Science and Technology, AIST	Japan	188
5	Kernforschung Anlage Julich GMBH	Germany	165
6	University of London Imperial College of Science, Technology and Medicine	England	142
7	Consejo Superior de Investigactiones Cientificas, CSIC	Spain	128
8	University of Illinois	USA	127
9	Royal Institute of Technology, KTH	Sweden	123
10	Russian Academy of Sciences	Russia	109
11	Tohoku University	Japan	107
12	Korea Institute of Science and Technology	South Korea	106
13	Tokyo Institute of Technology	Japan	104
14	Max Planck Inst	Germany	103
15	Pacific Northwest National Laboratory	USA	101
16	Argonne National Laboratory	USA	100
17	University of Tokyo	Japan	100
18	Case Western Reserve University	USA	97
19	Los Alamos National Laboratory	USA	94
20	Nanyang Technological University	Singapore	93
21	Indian Institute of Technology	India	88
22	Georgia Institute of Technology	USA	87
23	University Connecticut	USA	87
24	Yamanashi University	Japan	83
25	University of Science and Technology of China	P. R. China	81
26	Seoul National University	South Korea	80
27	Zhejiang University	P. R. China	78
28	Tsing Hua University	P. R. China	77
29	University of South Carolina	USA	77
29	Yokohama National University	Japan	77

Bradford law and journal literature

As discussed previously, the journal article is the single most prevalent form of publication. In total, there are 901 journals published 14290 hydrogen energy articles. Among them 344 journals publish only one article. The BRADFORD'S [1953] law has been widely employed to study journal literature distribution. BROOKES [1973] created the Bradford-Zipf's S graph and explained the initial concave curve of the Bradford distribution as representation of the higher density of the nuclear zone. Journals in the nuclear zone constitute the core journals. Figure 2 illustrates the Bradford-Zipf plot – the cumulative number of papers for each journal against the logarithm of its ranks – for journal literature of hydrogen energy. Clearly, the figure does not demonstrate the typical S-shape for the Bradford-Zipf plot. However, the approximately linear portion appears after the journal ranks of about 5. The top 5 journals located within the initial concave curve portion of the Bradford-Zipf plot may be considered as the core journals (contributing 5862 about 41% of the total) in hydrogen energy literature. The other literature is dispersing to 896 journals.

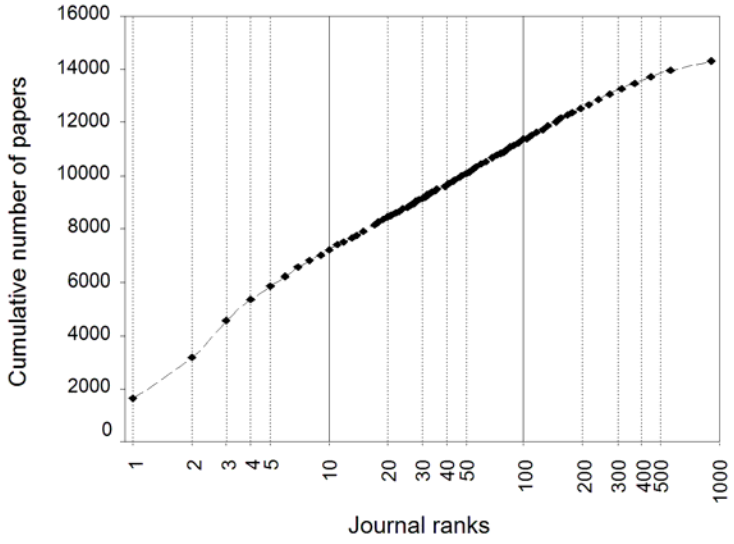

Figure 2. The Bradford-Zipf plot of hydrogen energy journal literature, 1965–2005

Table 6 provides the ranking list of journals and number of articles published by these five core journals and other more productive ones. It should be noted that the comparison of journal productivity on hydrogen energy in the present study is

disregarded the age of a journal. Some journals, such as *Electrochemistry*, published in 1933, is quite old, while others, such as *Electrochemistry Communications*, published in 1999, is relatively young. The annual production rate of the five top most productive journals will be further discussed in the following paragraph.

In order to avoid making the ranking table too long, the top 20 journals were taken as the cut off number. Thus, Table 6 lists 20 titles which have at least published 84 articles on hydrogen energy. To look more deeply into the nature of the top 20 journals, Table 6 was generated. In this table, the top 20 journals are ranked in descending order of the number of published articles. The table also lists initial publication date, frequency of publication and subject field, taken from *Journal Citation Reports*, 2005 (science edition) [JOURNAL CITATION REPORTS, 2005] and Ulrich's on Disc [ULRICH'S PERIODICAL DIRECTORY, 2005].

With no surprise, *International Journal of Hydrogen Energy*, *Journal of Power Source* and *Journal of the Electrochemical Society* are the three largest contributors to the journal literature on hydrogen energy, as the key words of their title are hydrogen energy, energy and fuel, or electrochemistry related. Moreover, the five core journals are either energy & fuels or electrochemistry related, except *Solid State Ionics* is related to physical chemistry, physics and condensed matter. *Journal of Electrochemical Society*, published in 1947, is the oldest among the core journals.

Figure 3 illustrates the annual production of the top five most productive journals on hydrogen energy. The annual production of the *Journal of Power Sources*, the second most productive one and with publication frequency of 24 issues annually, rises exponentially for the past decade with some fluctuations. In 1995, it published about 60 papers on hydrogen energy and it reached 336 in 2005. On the other hand, cumulatively the most productive one and with publication frequency of 15 issues per year, *International Journal of Hydrogen Energy* shows a quantum jump for the year 1997. For that particular year, it published 115 papers on hydrogen energy, which is much larger than the previous years, about or less than 20 papers. From 1997 to 2005, its production on hydrogen energy increased relatively slowly to the level of 160 to 170 papers annually. The third most productive journal, *Journal of the Electrochemical Society*, a relatively old and monthly journal, demonstrated relatively high annual productions of about 20 papers on hydrogen energy from 1965 to 1970 and about 40 papers with some peaks and valleys from 1978 to 1992. After 1992, it increases slowly from about 40 to 140 papers in 2005. Both *Solid State Ionics* and *Eletrochimica Acta* demonstrate an exponential growth in annual production from 1990 with a much smaller growth rate than that for the *Journal of Power Sources* for the last decade.

Table 6. Top 20 hydrogen energy journals published more than 84 articles, 1965–2005

Rank	Journal name	No. of articles	Publication frequency	Publication date	JCR subject categories
1	*International Journal of Hydrogen Energy*	1648	15/Y	1976	ENERGY & FUELS ; ENVIRONMENTAL SCIENCES ; PHYSICS, ATOMIC, MOLECULAR & CHEMICAL
2	*Journal of Power Sources*	1533	24/Y	1976	ELECTROCHEMISTRY ; ENERGY & FUELS
3	*Journal of the Electrochemical Society*	1383	Monthly	1947	ELECTROCHEMISTRY ; MATERIALS SCIENCE, COATINGS & FILMS
4	*Solid State Ionics*	803	40/Y	1980	CHEMISTRY, PHYSICAL ; PHYSICS, CONDENSED MATTER
5	*Electrochimica Acta*	495	28/Y	1959	ELECTROCHEMISTRY
6	*Abstracts of Papers of the American Chemical Society*	352	Semi-annually	1937	
7	*Electrochemistry*	339	Monthly	1933	ELECTROCHEMISTRY
8	*Journal of Applied Electrochemistry*	250	Monthly	1971	ELECTROCHEMISTRY
9	*Journal of Electroanalytical Chemistry*	222	26/Y	1960	CHEMISTRY, ANALYTICAL ; ELECTROCHEMISTRY
10	*Electrochemical and Solid State Letters*	185	Monthly	1998	ELECTROCHEMISTRY ; MATERIALS SCIENCE, MULTIDISCIPLINARY
11	*Journal of Physical Chemistry B*	175	Weekly	1896	CHEMISTRY, PHYSICAL
12	*Journal of Membrane Science*	136	40/Y	1977	ENGINEERING, CHEMICAL ; POLYMER SCIENCE
13	*Applied Catalysis A – General*	128	38/Y	1981	CHEMISTRY, PHYSICAL ; ENVIRONMENTAL SCIENCES
14	*Journal of Materials Science*	128	24/Y	1966	MATERIALS SCIENCE, MULTIDISCIPLINARY
15	*Journal of the European Ceramic Society*	124	16/Y	1985	MATERIALS SCIENCE, CERAMICS
16	*Catalysis Today*	118	40/Y	1987	CHEMISTRY, APPLIED ; CHEMISTRY, PHYSICAL ; ENGINEERING, CHEMICAL
17	*Journal of New Materials for Electrochemical Systems*	118	Quarterly	1998	ELECTROCHEMISTRY ; MATERIALS SCIENCE, MULTIDISCIPLINARY
18	*Electrochemistry Communications*	114	12/Y	1999	ELECTROCHEMISTRY
19	*Journal of the American Ceramic Society*	99	Monthly	1899	MATERIALS SCIENCE, CERAMICS
20	*Energy Conversion and Management*	84	20/Y	1961	THERMODYNAMICS ; ENERGY & FUELS ; MECHANICS ; PHYSICS, NUCLEAR

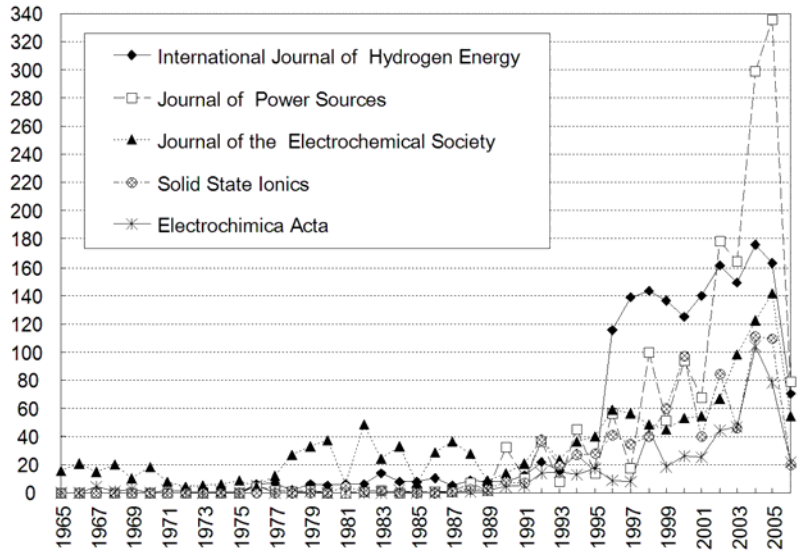

Figure 3. Top 5 hydrogen energy journals annual production, 1965–2005

Journals with highly cited articles

Journals with highly cited articles are also of significant interest. Table 7 shows, by the first quarter of 2006, there are 13 journals with at least two articles cited more than 100 times. *Journal of the Electrochemical Society* has 29 articles cited more than 100 times. *Solid State Ionics,* comes next and followed by *Nature*, *Electrochimica Acta,* and *Journal of Membrane Science* with 15, 8, 8, 7 highly-cited articles, respectively.

Table 7. Hydrogen energy journals with two articles cited more than 100 times, 1965–May 2006

Rank	Journal	No. articles
1	*Journal of the Electrochemical Society*	29
2	*Solid State Ionics*	15
3	*Nature*	8
4	*Electrochimica Acta*	8
5	*Journal of Membrane Science*	7
6	*Journal of Power Sources*	5
7	*Journal of Electroanalytical Chemistry*	5
8	*Science*	4
9	*Langmuir*	3
10	*Journal of Solid State Chemistry*	2
11	*Journal of Physical Chemistry*	2
12	*Applied Catalysis A – General*	2
13	*AICHE Journal*	2

Table 8 lists the 15 most highly cited articles with title, author name, journal's name and article type, ranked by cited rate until the first quarter of 2006. It can be seen that the most highly cited article is entitled "Storage of hydrogen in single-walled carbon nanotubes", authored by Dillon et al. and published in *Nature*. The times cited for this particular paper is as high as 1078. The second most highly cited paper with cited number of 963 was published as a review article, published in *Journal of the American Ceramic Society* entitled "Ceramic fuel-cells" authored by N.Q. Minh. Table 8 illustrates that among the 15 most highly cited articles, 11 are original research articles and four are review papers. Four of them were published in *Nature* and 7 out of them are in chemistry-oriented, especially electro-chemistry, journals. It is interesting to note that review papers are written by single or two authors, while original research articles are usually team works by at least three authors. This suggests the importance of team works for original research on fuel cell as it is a multi-disciplinary subject.

Table 8. Most highly cited articles of hydrogen energy, 1965 – May 2006

	Title	Author	*Journal/PY*	Type	Times cited
1	Storage of hydrogen in single-walled carbon nanotubes	Dillon, AC; Jones, KM; Bekkedahl, TA; Kiang, CH; Bethune, DS; Heben, MJ	*Nature* (1997)	Article	1078
2	Ceramic fuel-cells	Minh, NQ	*Journal of the American Ceramic Society* (1993)	Review	963
3	The oxidation of small organic-molecules- a survey of recent fuel-cell related research	Parsons, R; Vandernoot, T	*Journal of Electroanalytical Chemistry* (1988)	Review	573
4	Carbon nanotubule membranes for electrochemical energy storage and production	Che, GL; Lakshmi, BB; Fisher, ER; Martin, CR	*Nature* (1998)	Article	476
5	Proton conductivity: Materials and applications	Kreuer, KD	*Chemistry of Materials* (1996)	Review	395
6	Polymer electrolyte fuel-cell model	Springer, TE; Zawodzinski, TA; Gottesfeld, S	*Journal of the Electrochemical Society* (1991)	Article	359

Table 8. (cont.)

	Title	Author	*Journal/PY*	Type	Times cited
7	Ordered nanoporous arrays of carbon supporting high dispersions of platinum nanoparticles	Joo, SH; Choi, SJ; Oh, I; Kwak, J; Liu, Z; Terasaki, O; Ryoo, R	*Nature* (2001)	Article	303
8	Preparation of Cu nanoclusters within dendrimer templates	Zhao, MQ; Sun, L; Crooks, RM	*Journal of the American Chemical Society* (1998)	Article	297
9	Combinatorial electrochemistry: A highly parallel, optical screening method for discovery of better electrocatalysts	Reddington, E; Sapienza, A; Gurau, B; Viswanathan, R; Sarangapani, S; Smotkin, ES; Mallouk, TE	*Science* (1998)	Article	297
10	A mathematical model of the solid-polymer-electrolyte fuel-cell	Bernardi, DM; Verbrugge, MW	*Journal of the Electrochemical Society* (1992)	Article	287
11	On the development of proton conducting polymer membranes for hydrogen and methanol hydrogen energys	Kreuer, KD	*Journal of Membrane Science* (2001)	Article	271
12	Effective energy function for proteins in solution	Lazaridis, T; Karplus, M	*Proteins – Structure Function and Genetics* (1999)	Review	269
13	Water-uptake by and transport through Nafion ® 117 membranes	Zawodzinski, TA; Derouin, C; Radzinski, S; Sherman, RJ; Smith, VT; Springer, TE; Gottesfeld, S	*Journal of the Electrochemical Society* (1993)	Article	268
14	Thin-film catalyst layers for polymer electrolyte fuel-cell electrodes	Wilson, MS; Gottesfeld, S	*Journal of Applied Eletrochemistry* (1992)	Article	261
15	Materials for fuel-cell technologies	Steele, BCH; Heinzel, A	*Nature* (1997)	Article	246

Figure 4 illustrates the time evolution of cited times for the top 5 most cited articles. The paper written by Dillon, et al., which is an original research article, the cited times increased sharply from 6 for the publication year 1997 to 203 in 2002 and falls to about 170 times from 2003 to 2005. The citation rate growth for the paper by Che, et al. in 1998 shows a mild increase rate from 4 times in 1998 to about 90 in 2004 and 2005. The cited times for the three review articles seem to increase slowly with time or remain approximately steady. The paper by Minh, N.Q. shows a slow increase pattern from 30 in 1995, the second year after publication, to 137 in 2005, and there is no signal of slowing down. The review articles by Parson & Vandernoot and Kreuer, respectively, display a more steady trend. For the former, the average annual cited rate is around 35 and it is about 40 for the later.

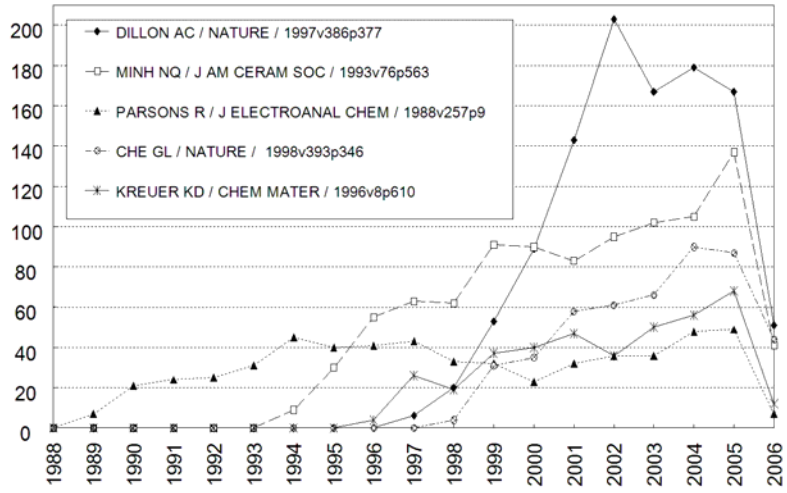

Figure 4. Cited times distribution for top 5 highly cited paper, 1989–May 2006

Conclusions and summary

The present work studies the characteristics of hydrogen energy literature from 1965 to 2005 based on the database of Science Citation Index Expanded (SCIE) and its implication using the bibliometric techniques. The study reveals that the literature on hydrogen energy grows exponentially for the last decade. This reflects the extensive worldwide study on the science and technology on hydrogen energy to pursue hydrogen

energy as a major alternative energy for fossil ones. The study also finds that most of document type is in the form of research articles or meeting abstracts, constituting 90.17% of the total literature and English is the predominant language (94.66%). USA, Japan and China are the three biggest contributing countries on hydrogen energy literature publishing, 25.8%, 14.9%, 7.7%, respectively. The Chinese Academy of Sciences in China is the largest single institution publishing 308 papers.

The present study also indicates that the journal literature on hydrogen energy does not confirm the typical S-shape for the Bradford-Zipf plot. Five core journals, namely *International Journal of Hydrogen Energy*, *Journal of Power Source*, *Journal of the Electrochemical Society, Solid State Ionics*, and *Electrochimica Acta* contributes about 41% of total journal literature on hydrogen energy. Among them, *Journal of the Electrochemical Society*, with 29 articles cited more than 100 times, is the journal contributing most to highly cited papers. On the other hand, the most highly cited article entitled "Storage of hydrogen in single-walled carbon nanotubes", authored by Dillon et al. and published in *Nature* had been cited 1078 times by the first quarter of 2006. The cited rate for the most highly-cited original papers tends to grow rapidly for the last decade, while it is more stable for the most highly-cited review papers.

It is well-known that descriptions of almost all new technologies can be found in patents. Information in patents is usually up-to-date and often never published in any other form. It is, therefore, also an important information source for an important field with current interest, such as hydrogen energy. The citation analysis in this study is mainly a metric approach. On the other hand, citation context analysis determines the most frequent pattern of usage by examining the passages where documents are cited, and providing a representation of the collective state of knowledge in a field. Future studies covering these two issues for a comprehensive insight on hydrogen energy and its literature are highly desirable and currently undergoing.

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