Qualitative and quantitative analysis of solar hydrogen generation literature from 2001 to 2014

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Qualitative and Quantitative Analysis of Solar hydrogen Generation Literature From 2001 to 2014

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Abstract

Solar hydrogen generation is one of the new topics in the field of renewable energy. Recently, the rate of investigation about hydrogen generation is growing dramatically in many countries. Many studies have been done about hydrogen generation from natural resources such as wind, solar, coal etc. In this work we evaluated global scientific production of solar hydrogen generation papers from 2001 to 2014 in any journal of all the subject categories of the Science Citation Index compiled by Institute for Scientific Information (ISI), Philadelphia, USA. Solar hydrogen generation was used as keywords to search the parts of titles, abstracts, or keywords. The published output analysis showed that hydrogen generation from the sun research steadily increased over the past 14 years and the annual paper production in 2013 was about three times 2010-paper production. The number of papers considered in this research is 141 which have been published from 2001 to this date. There are clear distinctions among author keywords used in publications from the five most high-publishing countries such as USA, China, Australia, Germany and India in solar hydrogen studies. In order to evaluate this work quantitative and qualitative analysis methods were used to the development of global scientific production in a specific research field. The analytical results eventually provide several key findings and consider the overview hydrogen production according to the solar hydrogen generation.

***Keyword*:** Solar hydrogen generation, hydrogen generation, water splitting, hydrogen literature.

1. Introduction

Today's energy shortage and environment pollution are the two issues that we face in this century, and due to these reasons, the industry for producing renewable energy is growing[1]. One of the important methods of energy generations from renewable energies is solar hydrogen [2-11]. As a renewable and clean source, solar energy has gained significant attention in recent years for the high demand for low energy at a competitive cost and with zero emissions [9, 12-15]. Since solar energy is inherently variable and intermittent, one of the main obstacles to their widespread use in providing reliable electric power is the requirement to store the electrical energy[16, 17].

Using hydrogen for energy storage system is an attractive option which is surplus electric power that is obtained from a photovoltaic panel that moves to an electrolyser to generate hydrogen stored by water splitting and then, the stored hydrogen gas is supplied to a fuel cell during times of low or no sunlight to compensate the supply shortfalls[18-21].

Considerable research has been done on the different components of solar-hydrogen system for RAPS, namely the solar PV panel, electrolyser, hydrogen storage and fuel cell[3, 22, 23]. Shabaniet and Andrews considered the PEM fuel cells in experimental investigation to supply heat and power in PAPS. The economic advantages of using the fuel cell heat to improve the LPG hot water system over a 30-year appraisal period is estimated to be about 15% of the total capital cost of the solar hydrogen system. John Andrews and Xin Xu Dou studied about designing a control unit for a solar-hydrogen system for remote area power supply in 2010 in Australia, and they found that all requirements started earlier will be carried into the simulation (Matlab) to establish the best control algorithms. When they designed the optimum control, system was tested in computer. The experience system was designed to measured real performance.

An overview of experimental and demonstration systems are described in the literature. However, there is still a need for more work on the general control unit for these systems as well as reducing the total cost of the system, extending the lifespan of components, and safety assurance. Some research investigations have been done on design and test of preferred options for splitting the Photovoltaic output between final load and electrolyser as needed by the instantaneous system conditions, as well as achieve high power transmission efficiency to the combined final load and electrolyser. Figure 1 shows that solar cells absorb light from the sun. Then, they transfer it to the electrolyzer in order to split water into hydrogen and oxygen[24].

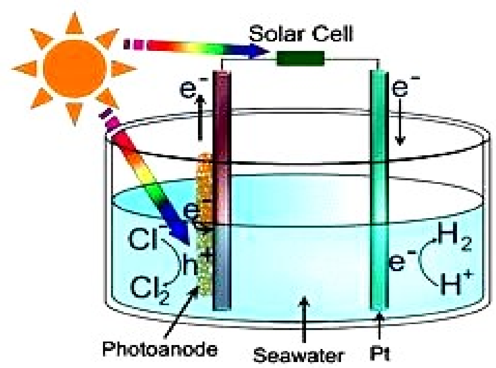

Fig 1. Solar cell inserts electric to the electrolyzer

In this paper, we consider solar hydrogen literature. Since, hydrogen is a relatively broad term, it can refer to a number of different technologies, processes, and methods. It has many applications related to energy, smart grid, energy management, energy policy, telecommunications, and business. For this reason, hydrogen applications can be the foundation for many location-enabled services that rely on analysis, visualization and dissemination of results for collaborative decision-making. The aims of this paper is to analysis qualities and quantities of the researches done during the last two decade.

2. Methodology and materials

All documents used in this study were accessed from the database of the Science Citation Index (SCI), obtained by subscription from the ISI, Web of Science, Philadelphia, PA, USA. In this study, we only focus on papers published after 2001, because there was less data regarding solar hydrogen before that year. To shed the light on solar hydrogen trends and contributions, quantitative analysis and qualitative analysis are conducted in this research.

2.1 Quantitative analysis

For the quantitative analysis, the SCI are systematically searched for solar hydrogen-related materials published from 2001 to April 2014. Selected documents included ''Solar hydrogen generation'' in the title, abstract, or keywords. Analyzed parameters included authorship, patterns of international collaboration, journal, language, document type, research address, number of times cited, and reprint author's address. Citation analysis was based primarily on the impact factor as defined by the Journal Citation Reports (JCR) and on Citations per Publications (CPP), which are used to assess the impact of a journal relative to the entire field. It is defined as the ratio of the number of citations the publication has received to since it is published.

2.2 Qualitative analysis

For qualitative analysis the historical method was used. The historical method proposes that historical phenomena can be rich and complex; we can gain a better understanding by reviewing and investigating the times, places and contexts in which events occur and develop. The historical method was employed in investigating the initiation and development of solar hydrogen as documented in publications in the SCI from 2001 to April 2014. For a longitudinal literature review, we employed historical review method to explore solar hydrogen technological trend. Based on this review, we forecast possible future developments.

3. Result and discussion

3.1 Number of publication and citation among year

According to the data obtained from ISI Web of Knowledge as presented in figure 2, it shows the number of publications about solar hydrogen generation in a period of 15 years. From the figure 2, it is concluded that the research about this topic have just been published from 2000. Therefore, it is observed that research in solar hydrogen is extensively new topic. In addition, there were fewer than 6 paper published before 2006 and only after 2008 this research became a hot topic among researchers. Obviously, in 2013 there was rapid increase in number of publications and citations. Although in 2008 the number of publications was fewer than 2007, however, the citation trend shown in figure 3 indicates that the number of citations is very close to the one in 2007. Thus, the promising future of solar hydrogen is guaranteed.

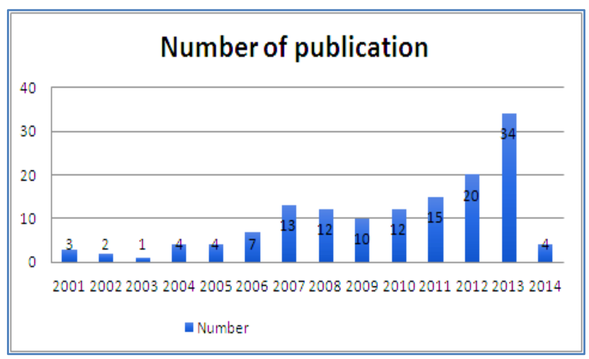

Fig 2. Number of paper published among year is displays

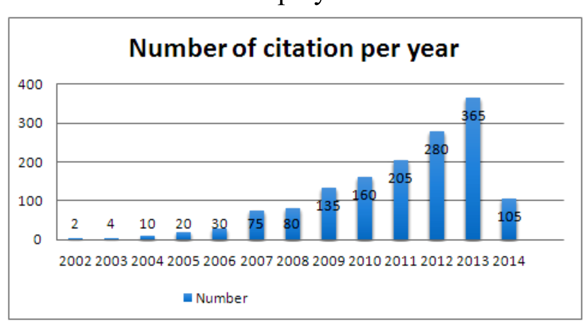

Fig 3, Number of citation among year is displays

The total citation count was obtained from SCI, web of science, on April 20, 2014. When the SCI search process for this study was conducted, the total number of times that a particular paper had been cited by all journals listed in the database was shown. The title of the most highly cited paper published in this area since 2001 is "Estimating Photo-electrochemical hydrogen generation". Materials-related aspects by Bak, T, received by International Journal of Hydrogen Energy 2002, which has been cited for 549 times. Among the top 10 most cited papers, the USA contributed 4 of them, followed by Australia, which produced 2 articles and China, Armenia, Switzerland and Israel with 1 articles each. It is worth mentioning that papers related to Energy had a relatively higher number of citations than many other scientific fields. Nevertheless, there still exist a biasness on citation analysis due to differences of the publication year. It must be pointed out that the number of citations in single article was highly correlated with the length of time since its publication. As it can be seen in figure. 3, the average number of times that the paper receives citations increases as the time goes on since its publication. Therefore, average number of citation per year was used to compare the papers in different years.

From 2005 to 2014, the annual number of Citation articles according to figure 4 the scatter plot was growing at a stable rate. The fit produced a high determination coefficient from the collected data (R2 = 0.8717). The best fit to forecast solar hydrogen generation was found to be:

y=37.868x-75861 (1)

Where y is the article number and x is the number of years since 2001. Extrapolating from the model, the number of articles about forest ecology in the following years could be forecasted.

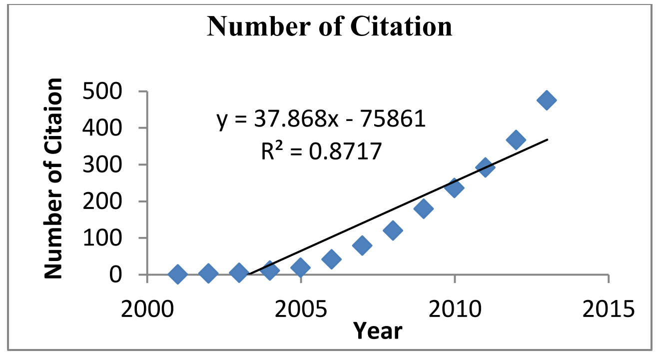

Fig 4. Scatter plot for solar hydrogen citation are displays

3.2 Distribution by source titles, research area and web of science categories

According to table 1, most of the papers in this field are published in International Journal of Hydrogen Energy, which has ranked 16 in categories of energy fuel, with 32 papers. Following by abstracts the best publisher in field is American Chemical Society with nine papers. According to the fourth column of table 1, Energy fuel with 73 papers, followed by Chemistry with 70 and electrochemistry with 41 are the three best categories.

According to distribution by web of science categories, Energy fuel, chemistry, and electrochemistry are the three categories, which publish most of the papers, followed by chemistry and material. Figure 5, shows more than 70 % of those papers published in those three categories.

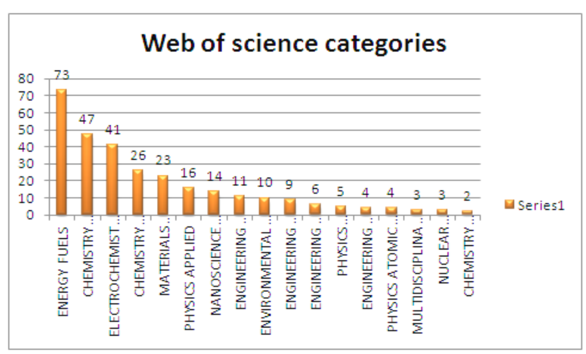

Fig 5 Distribution by web of science categories

Table.1 Distribution by source titles and Research area

Source Titles	**N**	**% of 141**	**Research Areas**	**N**	**% of 141**
International journal of hydrogen energy	32	22.6	Energy Fuels	73	51.77
Abstracts of papers of the American chemical society	9	6.38	Chemistry	70	49.64
Journal of power sources	5	3.54	Electrochemistry	41	29.07
Solar energy	5	3.54	Engineering	29	20.56
AIP conference proceedings	4	2.83	Materials Science	25	17.73
Energy environmental science	4	2.83	Physics	21	14.89
Applied physics letters	3	2.12	Science Technology Other Topics	17	12.05
International journal of energy research	3	2.12	Environmental Sciences Ecology	10	7.092
Journal of physical chemistry c	3	2.12	Nuclear Science Technology	3	2.12
ESA Special Publications	2	1.41	Construction Building Technology	2 1.41	

N: Number of Publications

3.3 Top ten papers in solar hydrogen generation

The most frequently cited articles for the period between 2003 to 2014 are presented in table 2. Five of the most frequently cited articles were published in International Journal of Hydrogen Energy. Six of the most frequently cited articles (among them the top six listings) originated in the USA and Australia, and one each in, China, Armenia, Switzerland, and Israel respectively. The two articles with the most citations (549 and 135) come from International Journal of Hydrogen Energy and Nano letter. An interesting aspect, presented as the fourth column in Table 2, is the average number of citations per year (AC). Although this observation is not consistent, it appears that the number of citations per year tends to increase with the number of years since publication. Pointing to a possible snowball effect when it comes to the acceptance of novel research results published papers involved international collaborations. A summary of the 10 most frequently cited articles revealed that six papers originated in the United States, and four were published in International Journal of Hydrogen Energy, which has one of the highest impact factors in the category of energy. The three journals with the most articles in this category were Solar Energy, Energy & Environmental Science and Journal of Power Sources.

3.4 Distribution by document type and language

The majority of publications on solar hydrogen generation research is done in English. One interesting finding is the increase in solar hydrogen generation research since 2010; it is clear that Solar Hydrogen Generation or Solar Hydrogen Power study is becoming ever more important around world. According to figure 6, it is clear more than 97 (68%) of papers published is articles, followed by 35(24.8%) proceedings paper**,** abstract with 6 %, amd review with 2 %.

Table 2. Top high citation papers in field solar hydrogen generation

Author	Title	J	C	NC	AC
Bak, T[2]	Photo electrochemical hydrogen generation from water using solar energy. materials-related aspects	International journal of hydrogen energy	Australia	549	42.23
Hensel [20]	Synergistic effect of cdse quantum dot sensitization and nitrogen doping of TIO2 nanostructures for photo electrochemical solar hydrogen generation	Nano letters	USA	135	27
Aroutiounian[21]	Metal oxide photo electrodes for hydrogen generation using solar radiation driven water splitting	Solar energy	Armenia	134	13.4
Raja[22]	Photo electrochemical hydrogen generation using band-gap modified nanotubular titanium oxide in solar light	Journal of power sources	USA	71	7.89
Raja[23]	Determination of photo conversion efficiency of nanotubular titanium oxide photo electrochemical cell for solar hydrogen generation	Journal of power sources	USA	66	7.33
Gibson[24]	Optimization of solar powered hydrogen production using photovoltaic electrolysis devices	International journal of hydrogen energy	USA	56	8
Licht[25]	Over 18% solar energy conversion to generation of hydrogen fuel; theory and experiment for efficient solar water splitting	International journal of hydrogen energy	Israel	54	3.86
Luo[26]	Solar hydrogen generation from seawater with a modified BIVO4 photoanode	Energy & environmental science	China	53	13.25
Z'Graggen [27]	Hydrogen Production By Steam Gasification of Petroleum Coke Using Concentrated Solar Power - II - Reactor Design, Testing, and Modeling	International journal of hydrogen energy	Switzerland	51	5.67
Paul[28]	Optimal Coupling of PV Arrays To PEM Electrolysers In Solar-Hydrogen Systems For Remote Area Power Supply	International journal of hydrogen energy	Australia	42	6

J: Journal, ***C*** : Country, ***NC*** : Number of citation, ***AC*** : Average citation

3.5 Distribution by countries and organization

Table 3 shows USA is at the top with 42 (20.20 %), followed by China, with 16(15.33%). Australia ranks third, with 13 (6.13%). Germany, India, Japan, Spain, England, South Korea **and** Switzerland, were also among the top ten countries publishing solar hydrogen generation articles. Listing publications by organization name, in third column table3, shows that the United States Department Of Energy Doe With 10 articles, University of California System with 7 articles, at the top institution, followed by Chinese Academy Of Sciences, Royal Melbourne Institute Of Technology RMIT, are the top four solar hydrogen research institutions that have published the most articles on solar hydrogen power during 2001 to 2014.

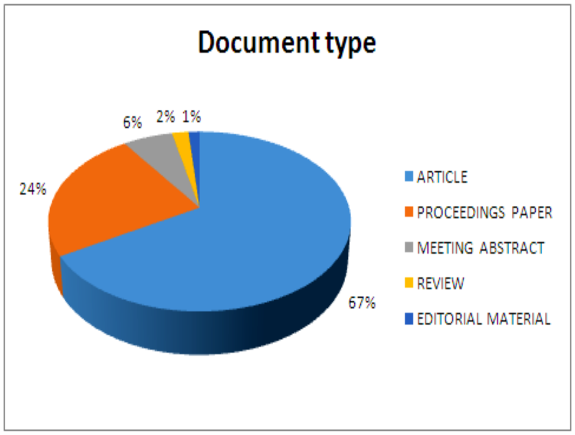

Fig 6. Type of document in ISI web of knowledge

3.6 Distribution by author, frequency author keyword and funding agencies

According to the table 4, there are 67 authors in the world who participated in publications related to solar hydrogen generation research area. The first 10 authors are listed in table 4 with the number of publication in this area. Prof, Roeb and Sattler with 6 publication in solar hydrogen generation from Germany has most of the papers, following by Andrews from Australia with 5 papers. Behind them kanmani, Li Y and Licht are the five top author in this area.

In the third column of table 4, it is shown that the top funding agencies which funded the investigations on solar hydrogen generation. National Natural Science Foundation Of China with 8 papers is the first among funding agencies followed by NSF with 5 paper is ranked second, and Natural Basic Science Program China with 3 papers are the top three funding agencies in field of solar hydrogen.

Table.3. Distribution by country/territory and institution name

Countries/	N	Organizations-Enhanced	N
USA	42	United States Department Of Energy Doe	10
China	16	University Of California System	7
Australia	13	Chinese Academy Of Sciences	6
Germany	12	Royal Melbourne Institute Of Technology RMIT	5
India	10	University Of California Santa Cruz	5
Japan	10	University Of New South Wales	5
Spain	9	Anna University	4
England	7	Anna University Chennai	4
South Korea	6	Argonne National Laboratory	4
Switzerland	5	National Taiwan University	4

In Table 5, author keywords that appeared in the articles from 2001 to 2014 were counted with intervals of 5 years. Among all 107-author keywords used, 72 (71%) keywords appeared only once, 23(21%) keywords were used twice, and 8 (7%) keywords appeared three times. The large number of one-time-used keywords probably indicates a lack of continuity in research and a wide disparity in research focuses. The most frequently used keyword for all periods was "Solar hydrogen" as it was also a keyword used in this research. During the entire study period, Hydrogen, Solar energy and Water splitting are always the most frequently used author keywords, which indicates that these title are invariable hotspots in the field of solar hydrogen production research. Furthermore, it is worth noticing that limited research has been done before on Photocatalysis, Hydrogen production, and PEM electrolyser. However articles on these aspects have obviously increased in recent years. The number of papers and percentage of which author keywords including solar hydrogen and hydrogen etc.

Table 4. Top ten author and funding agencies in solar hydrogen generation

Authors	N	Funding Agencies	N
Roeb M[3, 25-30]	6	National Natural Science Foundation Of China	8
Sattler C[25, 26, 30-34]	6	NSF	5
Andrews J[35-38]	5	National Basic Research Program Of China 973 Program	3
Kanmani S[39-41]	4	National High Technology Research And Development Program 863	3
Li Y[42, 43]	4	National Key Technology Rd Program	3
Licht S[44-46]	4	Fundamental Research Funds For The Central Universities	2
Noglik A[31]	4	MEST	2
Pitz-Paal R[32]	4	National Basic Research Program Of China	2
Priya R[40, 41, 47]	4	National Dong HWA University	2
Romero M[48]	4	National Science Council Of The Republic Of China Taiwan	2

This indicates that 'information systems attracted more and more attention during the past 14 years, indicating that these words may be a potential new focus in the future. On the contrary, it is surprising to find that there are several popular titles in the past such as Photocatalysis etc. that are becoming gradually less significant as noted during our 10-year study period.

3.7 Review the first 10 top papers in field of solar hydrogen generation.

According to table 6 (see Online Supplement), there are four papers that try to improve efficiency of photo-electrochemical cells by using different material type, three researches on control current and voltage to get maximum power and other papers review the researches done in this field. The result of these 10 top paper shows that in order to improve efficiency of the generation, materials and control the losses on the process must be up to dated. One of the interesting paper, which published in 2008, consider solar hydrogen generation for vehicles with total citation 56 and average citation 8 for each year, which published in USA and number of citation each year dramatically increase. In first column table 6 (see Online Supplement), it is show that 6 paper of 10 top paper published after 2006, in other word, it is clear how this topic become hot topic in this area.

Table 5 frequency keyword by author

Frequency Keyword	N	2000/ 2005	2005/ 2010	2011/ 2014
Solar hydrogen	25	1	4	20
Hydrogen	24	2	6	16
Solar energy	19	2	5	12
Water splitting	18	1	4	13
Hydrogen generation	15	2	4	9
Electrolyzer	13	2	5	6
Photoelectrochemical	13	1	4	8
PEM electrolyser	11	2	4	5
Photocatalysis	10	2	4	4
Hydrogen production	9	1	3	5

4. Conclusion

In this work on solar hydrogen -related papers dealing with the SCI, we obtained some significant points on the global research performance throughout the period from 2001 to 2014. In total, 4681 articles were published in 1918 journals listed in 202 subject categories established by ISI. The solar hydrogen generation presented an upward trend as the paper production increased exponentially in the last 14 years, and the annual paper production in 2013 was about three times that of the paper production in 2010. As the flagship journal of the solar hydrogen generation related field, International journal of hydrogen energy published the most articles. Approximately 22% of the articles that refer to solar hydrogen generation reside in the 10 core journals, whereby the remainder resides in the other 1908 journals. With the study of national research publications in the last 15 years, the increasing trend in the number of countries worldwide participating in this research can be easily observed. To a certain extent, large numbers of research papers from a country are correlated with the high activity and academic level of the country. It was notable that USA and China, contributing the most independent and international collaborative articles, had the most frequent international partners. Articles with international co-authorship, shows higher visibility than others over the years. The use of several author keywords such as 'solar hydrogen, 'hydrogen 'and 'solar energy dramatically increased since 2007, which became the focus in the last few years, and might be a new research direction in the future. There are clear distinctions among author keywords used in publications from the five most productive countries in solar hydrogen research. Quantitative and qualitative analysis used to the development of global scientific production in a specific research field. As solar hydrogen generation has always been thought to be widely useful to energy saving, more efforts should be taken to further studies in these fields.

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