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Increasing science and technology linkage in fuel cells: A cross citation analysis of papers and patents

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ABSTRACT

This study aims to explore the relationship between science and technology via analyzing cross citations between papers and patents in fuel cells. To calculate cross citation indicators, papers were retrieved from the WOS database and patent data from the USPTO during the period between 1991 and 2010, resulting in a total of 20,758 papers and 8112 patents. This study shows that there is a gradually increasing convergence between science and technology, particularly of science linkage in recent years. Papers citing patents are more time-sensitive than patents citing papers. Academic institutions are more likely to cite papers and patents published by other academic institutions.

1. Introduction

Collaboration between science and technology has been much discussed among scholars in recent years. An interactive relationship between science and technology is the key to innovation (Bhattacharya & Meyer, 2003; Cole & Eales, 1917). To encourage technological invention and seek innovative breakthroughs, experts in emerging disciplines such as nanotechnology and biotechnology integrate science and technology.

Cross citation analysis is a bibliometric method extensively used in investigating science and technology interaction. The primary assumption of cross citation analysis is that papers represent science output, patents represent technology creativity (Bassecoulard & Zitt, 2004; Meyer, 2002; Verbeek et al., 2002), and the cross citations between papers and patents illustrate knowledge exchange between science and technology (Verspagen, 2000). Although papers and patents cannot represent the whole intellectual achievement of science and technology, the general trends of basic research efforts can be gauged from the quantity of papers (Tijssen, 2004), and detailed and sufficient information about technology activities can be explored through patents (Jaffe, Fogarty, & Banks, 1998; Schmookler, 1950, 1953). Hence papers and patents can be used as proxy indicators of technological and scientific activity (Bhattacharya, Kretschmer, & Meyer, 2003). The cross citations between papers and patents which are quantitative, standardized and easily obtained, can therefore be used to reveal reliable linkage relationships between scientific and technological outcomes (Bhattacharya et al., 2003; Meyer, 2000).

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In related analysis of science and technology interaction, a great deal of researches have conducted patent citation analyses to explore contributions of science to the development of technology (Gittelman & Kogut, 2003; McMillan, Narin, & Deeds, 2000; Narin, Hamilton, & Olivastro, 1997; Schmoch, 1993; Tijssen, 2001; van Vianen, Moed, & van Raan, 1990; Verbeek et al., 2002). A few studies have paid attention to patent citations by papers (Bassecoulard & Zitt, 2004; Glänzel & Meyer, 2003; Hicks, 2000), but few have analyzed both paper citations by patents and patent citations by papers at the same time. Science linkage and technology linkage can be seen as two symmetrical dimensions of science and technology interactions. A more detailed and systematic comparative study is needed to better understand the relationship between science and technology.

With high energy conversion efficiency and pollution-free operation, fuel cells has become an emerging field in renewable energy technology. The development of fuel cells has drawn widespread attention of many researchers and developers, and it has become a useful tool for examining the interaction between science and technology. Many studies have focused on patent citations analysis in fuel cell area, including Barrett (2005), Daim, Rueda, Martin, and Gerdsri (2006), Godoe and Nygaard (2006) and Verspagen (2007). Beyond these, few studies have examined papers citing patents in this area. In light of the lack of studies in the fuel cell area, this study attempts to analyze cross citations between papers and patents by applying cross citation indicators including science linkage, technology linkage, technology cycle time and science cycle time to understand the characteristics, speed and dynamic changes of the interactions between academic research and technological innovation in the field of fuel cells.

2. Literature review

2.1. Investigating science & technology interaction by cross citation analysis

Analysing citations of patents and papers can provide a direct approach in studying interactions between science and technology. Patent citations containing prior patents and related scientific literature can also be used to explore technological development trends and evaluate the connection between scientific research and technological development; here, time lag is used to calculate predicted technological lifecycle (Albert, Avery, Narin, & McAllister, 1991; Glänzel & Meyer, 2003; Narin & Olivastro, 1988). These findings serve as indicators of academic influence on patents, evaluating the connection between technology and science while reflecting the level of dependency of technological development on academic research; in other words, the contribution of academic research to technological industry (Narin & Olivastro, 1988). Narin et al. (1997) demonstrated that science linkage on US patents doubled during the periods of 1987–1988 and 1993–1994. They also found that most of the papers cited in these patents were published by authors located in American universities or academic institutions. Tijssen (2001) revealed that in the USTPO, the more frequently patents cite papers in one country, the more interactive the relationship is between science and technology in that country. This also shows that scientific research and technological development in these particular countries are similar in terms of fields of interest. Therefore, countries which lead technological development and have strong scientific foundations tend to have higher proportions of patents citing papers (Gittelman & Kogut, 2003; McMillan et al., 2000).

Besides research into science linkage, Verbeek et al. (2002) also employed indicators such as science cycle time to evaluate the interaction between science and technology when conducting research on American patents citing papers during the period of 1992–1996. Branstetter and Ogura (2005) and van Vianen et al. (1990) revealed that the citation time lag for U.S. patents citing papers is getting shorter, at times even moving faster than academic research, showing that patents are increasingly influenced by scientific research. Study also shows that papers in the fields of chemistry and biotechnology are more likely to be cited, showing the importance of foundational scientific knowledge in patent citation in these fields (Schmoch, 1993; van Vianen et al., 1990; Verbeek et al., 2002).

The advantages of measuring science and technology interaction by patent citation have been highlighted by many researchers. According to Bhattacharya et al. (2003), Meyer (2000), patent citation analysis can objectively present the linkage between science and technology, due to the fact that patent citation extracts data that are collected for legal reasons, strengthening the credibility of those data. Theoretically patent citations are determined or added by the patent examiner, so the references reveal the patent's novelty and provide important and quantifiable background knowledge information, like the spillovers or related dimensions of the innovation, for bibliometrics analysis (Hall, Jaffe, & Trajtenberg, 2005; Narin et al., 1997).

Nonetheless, some researchers have expressed disagreement with this point and questioned the reliability of patent citation analysis. The central problem lies in the meaning of citation behaviour (Bornmann & Daniel, 2008). Due to the complexity of citation behaviour, we are unable to confirm the motivation of citation nor the content to which an author refers (Martyn, 1964). Some scholars doubted whether citations ultimately decided by patent examiner can truly represent actual references of inventors (Criscuolo & Verspagen, 2008). Jaffe and Trajtenberg (2002) argued that patent citations only reference novel arts or limited output and cannot reveal the complete knowledge transfer flows of patent innovation.

To our knowledge, though patent citation is not a perfect method for investigating science–technology interaction, it is still an adequate one which is available, quantitative, and standardized. Hence, we use patent citation data to uncover the relationship between science and technology.

Corresponding to science linkage which focus on patents citing papers, examining papers citing patents using technology linkage as indicator provides another channel to explore the interaction between science and technology (Glänzel & Meyer, 2003; Hicks, 2000; Lo, 2010; Yeh, Sung, Yang, Tsai, & Chen, 2013). Technology linkage uses statistical analysis to discuss papers citing patents to evaluate the impact of technological development on scientific research. This method of analysis is rarely employed, however. Glänzel and Meyer (2003) assessed the frequency and characteristics of papers citing patents, discussing the types of patents that were highly cited and the nationalities of the patent holders. The data source for papers was SCI and for patents was USPTO, covering the period of 1996–2000. The result shows that only 1.7% of all papers from SCI contain patent references, most of which are from periodicals, and nearly half of cited patents are American patents. Among different disciplines, chemistry papers cited patents most relevant to the chemistry discipline. In contrast with other citation sources, academic papers rarely cite patents. Chemistry papers are an exception, however (Bassecoulard & Zitt, 2004).

2.2. Fuel cells

In recent years, particularly since ratification of the Kyoto Protocol, threats of energy scarcity and environmental pollution, coupled with a desire to reduce CO_2 emissions, have encouraged countries around the world to seek alternative energy solutions. Fuel cells, which convert the chemical energy of fuel into electricity through electrochemical reaction, are mainly divided into six main technology types: proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) and alkaline fuel cells (AFC). Being a clean, renewable and sustainable source of energy, fuel cells have gained international recognition as one of the important green industries. In the last five years, North America and Asia, and the USA and South Korea particularly, are the leading regions in developing fuel cells for large stationary prime power applications (Fuel Cell Today, 2012b). Supported and promoted by many countries, there was a 20-fold increase in shipments of fuel cells annually between 2007 and 2010 (Fuel Cell Today, 2011).

In order to maintain international technological leadership, governments around the world have been devoting substantial resources to the fuel cell industry. Collaborative projects between academics and industry are one of the most important measures taken by governments. The European Union set up the European Hydrogen and Fuel Cell Technology Platform (HFP) in 2004 and funded the project "Coordination Action to Establish a Hydrogen and Fuel Cell ERA-NET (HY-CO)", which have facilitated intensive and successful collaboration between industry and academia (Neef, 2009). According to the report "Fuel Cell Collaboration in the United States," universities and industry in US frequently cooperate with each other under the assistance of state agencies or industry groups (Breakthrough Technologies Institution, 2011). In China, nearly all fuel cell projects funded by government involved local universities, especially top-tier universities such as Tsinghua and Tongji Universities (Fuel Cell Today, 2012a). Many universities in the US and China have set up and work closely with fuel cell start-up companies for further technological development and commercialization (Breakthrough Technologies Institution, 2011). Additionally, Huang (2013) investigated global science and technology linkage in seven energy technology fields including most of promising energy fields nowadays such as solar energy, wind power, biomass energy and so on. They found from the survey that hydrogen and fuel cells had the highest technology linkage and second highest science linkage in 2011. All the evidences suggest that the interaction of science and technology in the fuel cell field is considerably active and intense, which makes it an appropriate area for our research.

3. Methodology

A bibliometric method was employed to examine the characteristics of cross citations between papers and patents in the area of fuel cells. Note that this study regards papers as the output of scientific research and considers patents the output of technological creativity. Papers and patents are the most appropriate bases for analysing scientific study and technological creativity. However, paper and patent statistics are the only measure of formal and publicly verified output of research and inventive activities.

Based on the foundation of bibliometric studies, the analysis of patent citations was initiated by Narin's study in 1994. This study reference related studies of Narin to develop indicators regarding the linkage and cycle times of science and technology.

3.1. Databases

Patents were retrieved from Patent Full-Text and Image Database (PatFT) of the U.S. Patent and Trademark Office (USPTO). Academic periodical papers were retrieved from the SCI (Science Citation Index) and SSCI (Social Sciences Citation Index) sections of the Web of Science (WOS) database for this study.

Patents from the USPTO database can be considered the epitome of global technologies development for its market size and its position as powerhouse for key technologies development. Overseas corporations often apply for patents in the USA. The WOS database was used for its extensive collection of academic periodicals, encompassing a large proportion of academic research findings in fuel cells.

Related studies of citation analysis in the fuel cell area, such as Barrett (2005), Godoe and Nygaard (2006), Seymour, Borges, and Fernandes (2007) and Verspagen (2007), used related keywords regarding the main types of fuel cells to gather patent and paper data without standardized keywords or search queries.

In reference to these studies, we gathered patents from USPTO database containing keywords related to and can be representative of the broad topic of fuel cells, such as "Solid Oxide Fuel Cells", "Proton Exchange Membrane Fuel Cells", "Direct Methanol Fuel Cell", "Alkaline Fuel Cells", "Phosphoric Acid Fuel Cells", "Molten Carbonate Fuel Cells", "Nanomaterials for High Performance" or "Biological Fuel Cells" in the "Title", "Abstract" and "Claims" fields. Search queries for WOS also used the same keywords to search "Topic" to collect papers. A total of 8112 patents and 20,758 papers related to fuel cells during the period of 1991 and 2010 were identified.

To ensure the accuracy of the data collected, retrieved bibliometric data underwent authority control prior to further compilation. Next, the quantity of citations of papers citing patents and patents citing papers, including citation numbers and cited frequency of papers and patents, was counted. The number of citations is counted as one when the same citation is referenced repeatedly in the same paper or patent.

The citations of patents citing papers were collected from "Other Reference" on patents' front pages, for references difficult to gather from the texts (Narin et al., 1997). Note that this study did not remove repetitions in cited papers of patents as the USPTO database classifies all non-patent citations as "Other References" without employing a standardized format. Analysis of the cited papers of patents was based on their cited frequency.

3.2. Indicators

To compare the differences in paper and patent citation, we applied related indicators symmetrically to show the relationships within and between papers and patents. Most indicators were explained by Narin (1994), Narin (1995) and various co-authors (Narin, Albert, Kroll, & Hicks, 2000; Narin & Breitzman, 1995; Narin et al., 1997; Narin & Olivastro, 1988). These indicators are also referenced by other related research to reveal paper–paper and patent–patent relationships.

Breitzman and Narin (2001) proposed technology cycle time, which calculates patent citation time lag, to evaluate the speed of technological innovation. Verbeek et al. (2002) used science cycle time as an indicator to calculate the time lag of paper cited time and evaluate the immediate impact of research on technological innovation. Science linkage of patents, an indicator that evaluates the connection between patents citing patents via calculating the number of papers cited for each patent, is was also employed to discuss the interaction between science and technology (Branstetter & Ogura, 2005; Narin & Olivastro, 1998; Verbeek et al., 2002).

Most of the indexes based on the aforementioned studies are related to traditional linkages within papers or patents. To conduct analysis of cross citation relationships between papers and patents, this study developed following indicators:

3.2.1. Science linkage (SL)

A higher SL value indicates a higher number of papers cited by patents on average (Narin & Olivastro, 1998).

$$SL_i = \frac{\sum Rt_i}{Pt} \tag{1}$$

Rt_i represents the number of papers cited by patent i, and Pt represents the total number of patents.

3.2.2. Technology linkage (TL)

Referenced to the meaning of SL, the higher value of TL indicates a higher frequency of patents cited by papers on average.

$$TL_i = \frac{\sum Rs_i}{Ps} \tag{2}$$

Rs_i represents the number of patents cited by paper i, and Ps represents the total number of papers.

3.2.3. Technology cycle time

Technology cycle time (TCT) consists of the technology cycle time of papers (TCTs) and of patents (TCTt). The lower the TCT value is, the more novel the cited patent is, indicating higher innovation potential (Narin et al., 2000).

$$TCTs = \frac{\sum Ts_i}{Ps} \tag{3}$$

Ts_i represents the median age of patents cited by paper i, and Ps represents the total number of papers with patent citations. Here, if the paper only cites one patent, the median age of patents cited by this paper will be the age of this patent. If the paper cites two or more patents, the median age will be that of all the cited patents. More specifically, a patent/paper's age is the length of time between the citing one's publish date and cited one's publish date.

$$TCTt = \frac{\sum Tt_i}{Pt} \tag{4}$$

Tt_i represents the median age of patents cited by patent i, and Pt represents the total number of patents with patent citations. Here, the computation method for the median age of patents cited by patents is the same as that of median age of patents cited by papers.

3.2.4. Science cycle time

The lower the SCT value is, the more recently published the scientific results are (Verbeek et al., 2002). SCT consists of SCTs and SCTt. SCTs is the cycle time for papers citing papers and SCTt is the cycle time for patents citing papers' age.

$$\text{SCTs} = \frac{\sum \text{Ss}_i}{\text{Ps}} \quad (5)$$

Ss_i represents the median age of the papers cited by paper *i*, and Ps represents the total number of papers with paper citations. Here, the computation method for the median age of papers cited by papers is the same as that of median age of patents cited by papers.

$$\text{SCTt} = \frac{\sum \text{St}_i}{\text{Pt}} \quad (6)$$

St_i represents the median age of papers cited by patent *i*, and Pt represents the total number of patents with paper citations. Here, the computation method for the median age of papers cited by patents is the same as that of median age of patents cited by papers.

The higher the value of the first and second indicator indicates higher linkage between science and technology. Conversely, the lower the value of the third and fourth indicator means the more rapid the interaction between science and technology.

3.3. Hypothesis

As indicated in the previous section, empirical studies by Narin et al. (1997) and Tijssen (2001) have demonstrated the increase in citations from patents to scientific research. Thus we suggest that the science linkage in the field of fuel cells will increase annually. As for technology linkage, although no clear evidence in literature shows a growth trend, we still speculate that TL will increase annually as there is more academic and technology interaction in the field of fuel cells around the world. Thus the hypotheses of this study (seen below) are that SL and TL will increase annually. The hypotheses will be tested with the Pearson correlation coefficient (r).

Hypothesis 1. The science linkage (SL) increased yearly.

Hypothesis 2. The technology linkage (TL) increased yearly.

3.4. Limitations

The interaction between science and technology is extremely complicated. We are fully aware of and understand that there are some unavoidable limitations when analysing the characteristics of science and technology interaction by cross citations of papers and patents.

First of all, while bibliographic reference can only capture the "direct" linkage between science and technology with "indirect" linkages such as human mobility, educational process are ignored, and the cross citations between papers and patents may underestimate the dependence involved in science and technology (Verbeek et al., 2002). Thus, the interpretations of citation analysis results could be limited and may not be able to fully reveal the interaction between science and technology.

Secondly, though this study regards papers as the output of scientific research and patents as the output of technological creativity, there are also other outputs that can represent scientific and technological results. It should be noted that our research adopts a patent-orientated strategy rather than a secrecy strategy. In the fuel cell area, many inventions are not patented because of secrecy strategies to protect inventions (OECD, 2006), which is one of the limitations in our research.

Thirdly, because information in "other references" in patents citations is sometimes incomplete, this study can only gather paper citations with recognizable sources, and exclude others like technology reports or books. Lastly, the patent examination time between different countries may influence the time of patent information disclosure and knowledge communication. Therefore, this study only collected patents from the USPTO and did not compare cited times between US patents and others, such as EPO patents.

Finally, our study measures science–technology interaction based on the number of cross citations without considering the total number of references. There is the possibility that the total number of references by papers and the number of patent references are on the same growing trend. Longitudinal analysis of the relative dynamic changes in the number of cross citations remains an interesting subject for further investigation.

4. Results and discussion

This study examines the correlation between science and technology in fuel cells, using citations of 20,758 papers and 8112 patents between 1991 and 2010. The findings reveal the characteristics of cross citation between papers and patents; identifies the major sources of inter-citations; and calculates the rate, linkage and citation time lag of cross citations between science and technology.

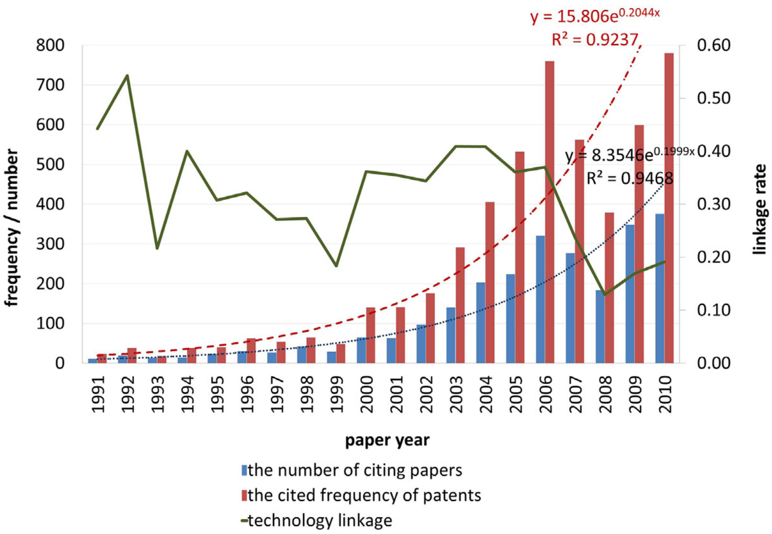

Fig. 1. Distributions of the number of citing papers, the cited frequency of patents and the technology linkage by paper year.

4.1. Analysis of papers citing patents

4.1.1. Number of papers citing patents and technology linkage

Among the 20,758 papers collected there are 2505 papers citing patents, accounting for 12.06% of all papers. The total cited frequency of patents is 5151, each paper citing 2.06 patents on average. Across all 20,758 papers, each paper only cites 0.25 patents on average – in other words, the technology linkage for fuel cells is 0.25. The percentage of papers citing patents once is 60.56%, and 96% of papers cite patents frequencies less than 5. Only 7 papers cited patents more than 20 times.

The change in the number of citing papers, the cited frequency of patents and technology linkage are shown in Fig. 1. There is an evident growth in both the number of citing papers and the cited frequency of patents, each with coefficients of determination (R^2) reaching 0.95 and 0.92 respectively. Among the 26 papers citing patents more than 10 times, 23 were published after 2006, showing a high patent citation tendency in recent years.

Fig. 1 also shows the technology linkage (TL) ranging from 0.13 to 0.54 during the period from 1991 to 2010. TL remained high, at 0.4, from 2000 to 2006, but dropped between 2007 and 2008. The average number of cited frequency for patents in one paper remained at about 2 from 2000 to 2008, indicating that the cited frequency of patents in every paper remained stable. As the total quantity of citing papers and cited frequency of patents dropped from 2007 to 2008, this resulted in a downward slope in the technology linkage value. It was not until after 2009 when the number of citing papers and cited frequency of patents increased again and enhanced the technology linkage.

4.1.2. Time lag between citing papers and cited patents

After elimination of repeated and unverified data in the total cited patents, 2916 cited patents remained. As shown in Fig. 2, the distribution of these cited patents spans from 1891 to 2009, a time difference of 118 years. Before 2004, the number of cited patents and cited frequency of patents increased annually. More than half of the cumulative number of cited patents was published after 1999, and most of these cited patents – 244 – were published in 2004. The cumulative cited frequency of patents surpassed half of the total after 1997 and the cited frequency of patents in 2004 reached the peak of 322. Major reference patents for papers cited came between 1999 and 2004.

Fig. 3 examines the citation time lag for papers and cited patents. Citation time lag between two and three years accounted for the highest proportion of cited frequency at more than 8% of the total of 5067. Citation time lag between four and five years accounted for more than 7% of all cited frequency of patents. The cumulative percentage of citation time lag of less than eight years was 53.41%. Therefore, scientific research is likely to be influenced by technological development within an eight-year timespan, and particularly within a time lag of two to five years. This illustrates the tendency for papers tend to cite patents published within a time lag of 8 years.

4.1.3. The technology cycle time and science cycle time of papers

The more recently the cited patents were published, the lower the TCTs values are, showing immediate interaction between citing papers and cited patents. This study further examines technology cycle time of papers (TCTs) and the science cycle time of papers (SCTs). TCTs is calculated from the average of the median of the time lag for all papers with patent citations.

Of the 2505 papers with patent citations, 45 were eliminated due to inability to calculate median citation time lag. In the other 2460 papers, the highest median of citation time lag is 158 years for papers citing patents. The highest median of

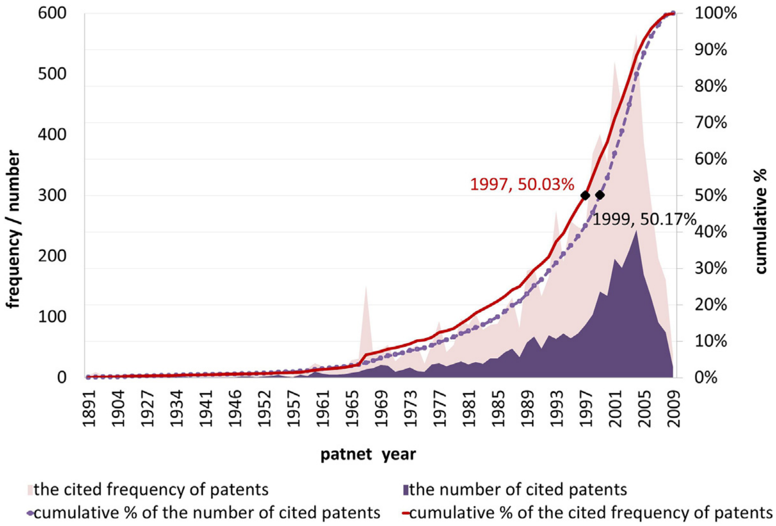

Fig. 2. Distribution of the number of cited patents and the cited frequency of patents by patent year.

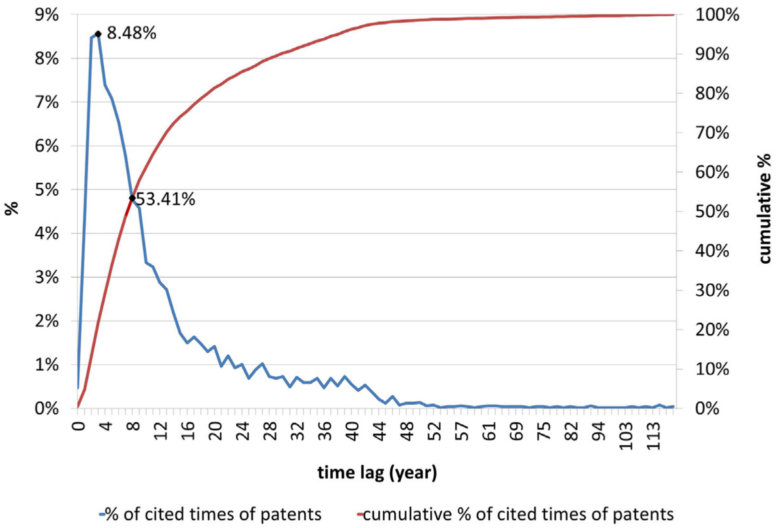

Fig. 3. Time lag between citing papers and cited patents.

papers citing papers is 51 years, indicating that papers citing patents have larger citation time lag than papers citing papers. While TCTs is 12.93 years and SCTs is 6.25 years, the citation time lag for papers citing papers is shorter than that of papers citing patents.

4.1.4. Analysis of highly cited patents

Table 1 illustrates the top 20 cited patents of all 2999 cited patents collected. American patents dominated with 18 patents, while France and the EU both obtained one patent each. The highest cited patent, "Pechini method," was invented by Maggio Pechini for Sprague Electric Co. in 1967. The patent remains an important reference for fuel cell technology. The second most cited patent was invented by Ian Raistrick from the United States Department of Energy in 1989, and had been cited 46 times. Besides the two patents mentioned, the other 18 highly cited patents were published in 1990–1999.

Among these 20 highly cited patents (including 1 joint invention), 12 patents are the property of industrial organizations, eight of research institutions and one of a university. The Los Alamos National Laboratory from the United States obtained four of these top 20 patents, and Mahlon S. Wilson invented three of the four patents. Prototech Company and United Technologies Corporation in the United States and Hoechst Aktiengesellschaft in Germany each possess ownership of two highly cited patents.

Table 1
Top 20 highest cited patents.

Patent number	Patent year	Inventor	Institute/assignee	Cited times
US 3330697	1967	Pechini; Maggio P.	Sprague Electric Co.	111
US 4876115[a]	1989	Raistrick; Ian D.	The United States Department of Energy (US)	46
US 5919583	1999	Grot; Walther Gustav | Rajendran; Govindarajulu	E. I. du Pont de Nemours and Company (US)	41
US 5211984[a]	1993	Wilson; Mahlon S.	Los Alamos National Laboratory (US)	40
US 3992331	1976	Petrow; Henry G. | Allen; Robert J.	Prototech Company (US)	32
US 5547551	1996	Bahar; Bamdad | Hobson; Alex R. | Kolde; Jeffrey A. | Zuckerbrod; David	W. L. Gore & Associates, Inc. (US)	30
US 4044193	1977	Petrow; Henry G. (US) | Allen; Robert J. (US)	Prototech Company (US)	29
US 4248941	1981	Louis; George A. (US) | Lee; John M. (US) | Maricle; Donald L. (US) | Trocciola; John C. (US)	United Technologies Corporation (US)	27
EP 00574791	1993	Helmer-Metzmann Freddy | Osan Frank | Schneller Arnold | Ritter Helmut Prof | Ledjeff Konstantin | Nolte Roland | Thorwirth Ralf	Hoechst Aktiengesellschaft (DE)	26
US 5422411	1995	Wei; Jinzhu (CA) | Stone; Charles (CA) | Steck; Alfred E. (CA)	Ballard Power Systems Inc. (CA)	24
US 4910099[a]	1990	Gottesfeld; Shimshon (US)	Los Alamos National Laboratory (US)[b]	23
US 6248467[a]	2001	Wilson; Mahlon S. (US) | Busick; Deanna N. (US)	Los Alamos National Laboratory (US)	22
US 5438082	1995	Helmer-Metzmann; Freddy (DE) | Osan; Frank (DE) | Schneller; Arnold (DE) | Ritter; Helmut (DE) | Ledjeff; Konstantin (DE) | Nolte; Roland (DE) | Thorwirth; Ralf (DE)	Hoechst Aktiengesellschaft (DE)	22
US 5234777[a]	1993	Wilson; Mahlon S. (US)	Los Alamos National Laboratory (US)	19
US 5468574	1995	Ehrenberg; Scott G. (US) | Serpico; Joseph (US) | Wnek; Gary E. (US) | Rider; Jeffrey N. (US)	Dais Corporation (US)	18
US 5525436[a]	1996	Savinell; Robert F. (US) | Litt; Morton H. (US)	Case Western Reserve University (US)	17
US 4677092	1987	Luczak; Francis J. (US) | Landsman; Douglas A. (US)	International Fuel Cells Corporation (US)	17
US 4316944	1982	Landsman; Douglas A. (US) | Luczak; Francis J. (US)	United Technologies Corporation (US)	17
FR 2748485[a]	1997	Faure Sylvain (FR) | Pineri Michel (FR) | Aldebert Pierre (FR) | Mercier Regis (FR) | Billion Bernard (FR)	Centre National De La Recherche Scientifique (C.N.R.S.) (FR) | Atomic Energy And Alternative Energies Commission (FR)	16
US 6430966[a]	2002	Meinhardt; Kerry D. (US) | Vienna; John D. (US) | Armstrong; Timothy R. (US) | Pederson; Larry R. (US)	Battelle Memorial Institute (US)	15

[a] Patents of research institutions.
[b] Inventors' institutions.

4.2. Analysis of patents citing papers

This study analyzed the numbers and times of papers cited by a total 8112 patents from the period of 1991 to 2010. There are 9686 citations of papers across 1999 patents, meaning that 24.64% of patents cite papers. This shows that nearly one quarter of technological invention in the field of fuel cells refers to scientific research.

4.2.1. Number of cited papers and science linkage

Among the 1999 patents citing papers, there are 9686 times that papers have been cited in total, reaching an average of 4.85 cited frequency per patent. The average cited frequency of papers for the total 8112 patents (including patents without paper citations) reached 1.19. That means the science linkage in fuel cells is 1.19. A closer examination of the 1999 patents with paper citations reveals that more than half (53.88%) of these patents have only one or two paper citations, and 260 patents, only 13.01%, with more than 10 paper citations. Table 2 shows 19 patents with more than 40 paper citations. The one with the highest number of paper citations is published in 2006 by Polyfuel, Inc., a leading manufacturer of fuel cells in United States; the second was co-invented by Pennsylvania State University and Ion Power, Inc. in 2010. It is noteworthy that 11 of the 19 patents in Table 2 are properties of academic institutions in the United States – seven are owned by the University of Illinois – Urbana Champaign, and Pennsylvania State University, the University of Oklahoma, Ohio University, and the University of Tennessee own one patent each. In 1980, the US federal government passed the Bayh-Dole Act, which gave universities the right to retain, exploit and transfer the property rights of inventions deriving from federally funded research, and greatly accelerated university patenting in the US (Henderson, Jaffe, & Trajtenberg, 1998; Mowery & Sampat, 2005). Our results show that patents with high numbers of paper citations tend to be owned by academic institutions. Academic institutions seem be more likely to refer to papers in patent innovations. Czarnitzki, Hussinger, and Schneider (2009) also confirmed that academic patents invented by German professors are more basic and have more non-patent references than non-academic patents randomly selected from EPO.

Table 2
Patents with more than 40 paper citations.

Patent number	Patent year	Institute/assignee	Number of paper citations
US 7094490	2006	Polyfuel, Inc.	78
US 7709113	2010	Pennsylvania State University|Ion Power, Inc.	76
US 7132188	2006	University of Illinois – Urbana Champaign	58
US 7785728	2010	University of Illinois – Urbana Champaign	57
US 7183017	2007	Hoku Scientific, Inc. – A Delaware Corp.	55
US 7008971	2006	Hoku Scientific, Inc.	54
US 7279247	2007	University of Illinois – Urbana Champaign	53
US 7282282	2007	University of Oklahoma	53
US 7811689	2010	University of Illinois – Urbana Champaign	52
US 7740974	2010	Abbott Diabetes Care Inc.	52
US 7569297	2009	University of Illinois – Urbana Champaign	51
US 7635530	2009	University of Illinois – Urbana Champaign	49
US 7368190	2008	University of Illinois – Urbana Champaign	48
US 7682724	2010	Monsanto Technology LLC	48
US 7651797	2010	Abbott Diabetes Care Inc.	48
US 7803264	2010	Ohio University	47
US 7619036	2009	University of Tennessee	46
US 7732080	2010	U Chicago Argonne, LLC	45
US 7521097	2009	Nano Gram Corporation	40

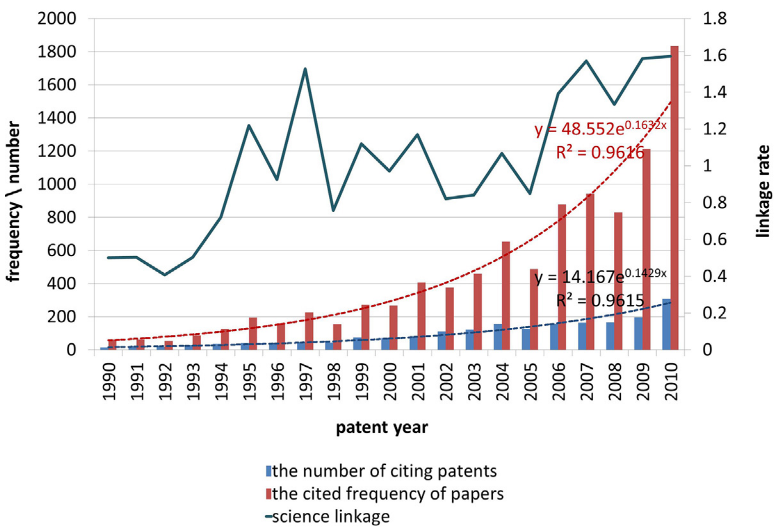

Fig. 4. Distribution of the number of citing patents, the cited frequency of papers and the science linkage by patent year.

Fig. 4 shows the number of patents citing papers and the cited frequency of papers experiencing exponential growth between 1991 and 2010. The coefficient of determination (R^2) reached 0.96. This means more and more patents have referred to papers, and cited frequency of papers has also increased. In addition, science linkage rapidly increased from 0.5 to 1.22 from 1991 to 1995, experiencing most rapid growth. Though it remained stagnant at between 0.8 and 1.1, after 2006, the science linkage increased to more than 1.3. Additionally, the average number of cited papers in each patent showed an upward growth from three or four papers per patent in 2005 to more than five papers per patent after 2006.

All the above indicate that patents published in recent years tend to cite a greater number of papers. As shown in Table 2, all of the 19 highly cited patents were published after 2006, with eight published in 2010. These figures prove that technology development in recent years has referred to scientific research extensively.

4.2.2. Time lag between citing patents and cited papers

An upward trend in the number of patent citing papers and patent citing papers in the field of fuel cells has been shown. The time lag of patents citing papers is discussed in the following paragraphs.

In total, papers have been cited 9686 times among the 1999 patents. Excluding unverified citations, this study collected the data of 9675 incidences of cited patents to analyze. The earliest paper, one on inorganic chemistry, was published by W.F. Giggenbach in 1874, leaving a period of 135 years between that and the latest paper, which was published in 2009. As shown in Fig. 5, the cumulative cited frequency of papers published after 1996 accounts for more than 50% of all the cited frequency, with the cited frequency peaking from 2000 to 2002, with reaching more than 600 paper citation times annually. Papers published after 2003 showed a downward trend in terms of cited frequency. The results above show that papers

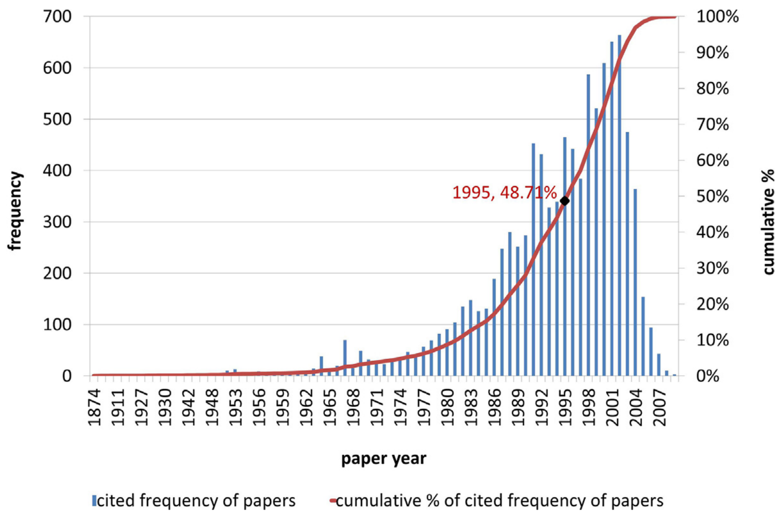

Fig. 5. Distribution of the cited frequency of papers by paper year.

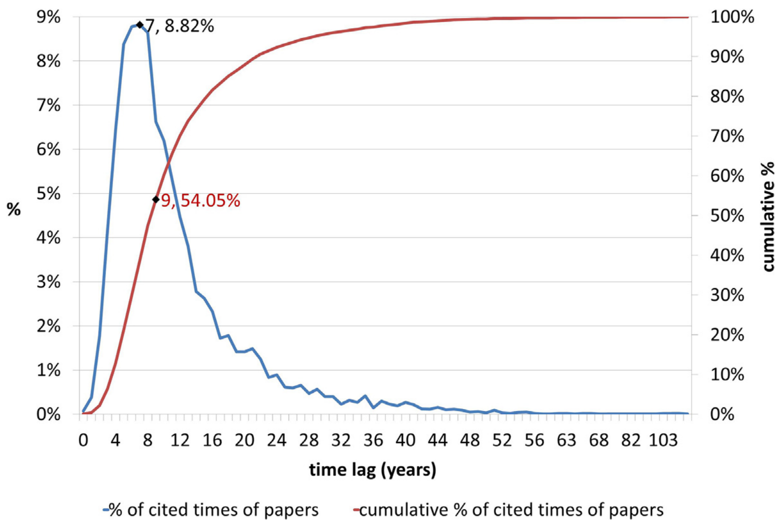

Fig. 6. Time lag between citing patents and cited papers.

published between 1996 and 2002 were important reference points for patents, and mean technological innovation in fuel cells has been influenced much by papers with a seven- to 13-year time lag.

Fig. 6 shows that, of all 9675 cited frequencies of papers, citation time lag between five and eight years each accounted for more than 8%, while citation time lag of four, nine and 10 years also exceeded 6% each. Overall, the cumulative cited frequency of papers with time lag less than nine years accounted for 54.05% of all cited frequency. This indicates that patents tend to cite papers published within a nine-year time lag, and particularly those published within a time lag of five to eight years. In comparison, papers tend to cite patents published within two to three years. From this study, we see that patents citing papers seem not to be as time sensitive as papers citing patents.

4.2.3. *The science cycle time and technology cycle time of patents*

Fig. 6 shows that the time lag for patents citing papers is usually within nine years. The difference between the time lag of patents citing papers and that of patents citing patents can be calculated from science cycle time of patents (SCTt) and technology cycle time of patents (TCTt).

Our calculation reveals that the median of the time lag for individual patents and their paper citations can be as long as 81 years, while the highest median of time lag for an individual patent and its patent citations is 34 years, showing a large discrepancy of nearly 50 years between the two. After calculation, the SCTt is 10.67 years and the TCTt is 9.09 years, showing a difference of less than two years. This shows that though patents citing patents has a more rapid time cycle, the time cycle of patents citing papers is not far behind. This indicates that patents are relatively time sensitive to both papers and patents.

Table 3
Cross citation between papers and patents.

Papers citing patents	No. of citing papers (1)	Total No. of papers (2)	% (1)/(2)	No. of cited patents (3)	Average No. of cited patents (3)/(1)	Technology linkage (3)/(2)
	2505	20,758	12.06%	5151	2.06	0.25
Patents citing papers	No. of citing patents (1)	Total No. of patents (2)	% (1)/(2)	No. of cited papers (3)	Average No. of cited papers (3)/(1)	Science linkage (3)/(2)
	1999	8112	24.64%	9686	4.85	1.19

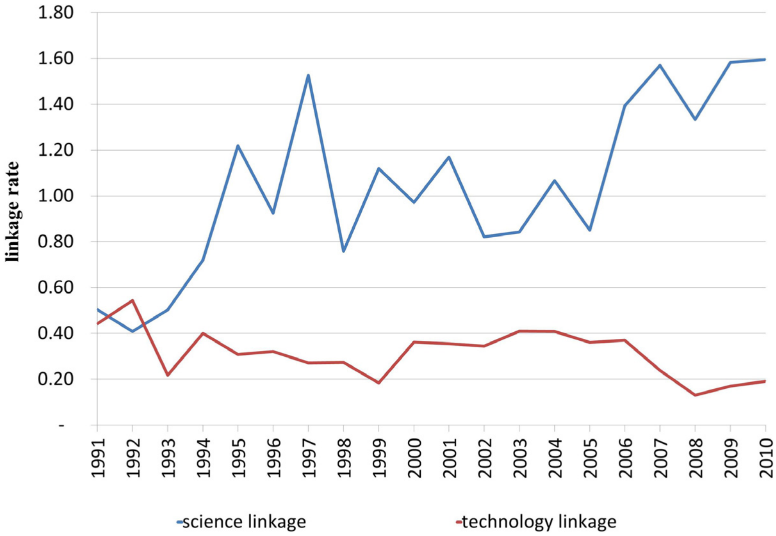

Fig. 7. Science linkage and technology linkage by year.

4.3. Discussion

Based on the results of the above analysis, of the 20,782 papers in fuel cells, 12.06% included patent citations, and total number of patents cited is 5151. So every paper cites 0.25 patents on average, meaning that the TL is 0.25. Of the 8112 patents in fuel cells, 24.64% included a total of 9686 cited papers, so each patent cites on average 1.19 papers, and the SL is 1.19. In comparison, the linkage of patents to papers seems much higher than the linkage of papers to patents. These results are in line with observations made by Glänzel and Meyer (2003), Bassecoulard and Zitt (2004) and others: in papers, the number of patent citations is far lower than other types of citations (Table 3).

As indicated in Fig. 7, observation of the annual change in science linkage and technology linkage shows that when science linkage showed an upward trend, technology linkage dropped slightly. Particularly after 2006, the tendencies of the two linkages reverse direction. Since 2006, the average number of cited papers in patents has increased, with large numbers of patents citing high numbers of papers being published or supported by academic institutions after 2006. Hence, the high number of cited papers in patents by academic institutions resulted in the rise of science linkage. Conversely, though an increase of cited patents in papers since 2006 is seen, the number has not increased at a rate that is proportional to the total number of papers published, resulting in a drop in technology linkage.

Regarding the test of Hypothesis 1, the Pearson correlation coefficient (r) of SL and the time (year) is 0.73, $p < 0.05$, showing that SL is increasing annually, while the Pearson correlation coefficient (r) of Hypothesis 2 is −0.48, $p > 0.05$, showing no significant evidence that TL increased annually.

Most of the patents cited by papers were published within eight years, with majority within two to three years. The papers cited by patents were published within a timespan of nine years, with the highest proportion at a time lag of five to eight years. In contrast, the time lag of papers citing patents is slightly shorter than that of patents citing papers, meaning patent citation in papers is more time sensitive than paper citation in patents.

Additionally, comparing science cycle time and technology cycle time of papers and patents, we find that the TCTs is 12.84 years and the SCTs is 6.15 years, and the TCTt is 9.09 years and the SCTt is 10.67 years. We can see that interaction within papers and within patents is much timelier than that between papers and patents, meaning that intersections between science and technology take a longer time than inter-science or inter-technology intersections.

5. Conclusion

The resulting data indicates that the numbers of cross citations between papers and patents are not particularly high, but are gradually increasing. Rapid rises in both citing and cited numbers of papers and patents have been witnessed after 2003. The average number of paper citations in each patent increased annually after 2006, indicating a growing number of cross references between patents and papers.

The result also shows that SL of patents is higher than TL of papers, but both TL and SL reveal that cross citations between patents and papers are still not important sources of references. From the test results, this study has found that while science linkage increased annually at a rapid rate, technology linkage did not show an increasing trend.

It is noted that papers citing patents are more time-sensitive than patents citing papers. The results of science cycle time and technology cycle time for patents and papers show lower time sensitivity in cross citations between papers and patents than in papers citing papers or patents citing patents. This indicates that interaction within papers or patents is relatively more timely than cross interaction between papers and patents. Also, the time lag between papers and their patent citations is three to five years shorter than that between patents and their paper citations.

Further comparative analysis illustrates that highly cited patents in papers tend to be patents from the United States, most of which are issued by industrial institutions. However, patents by academic institutions, particularly by large US research institutions, are still the main source of citations by papers. As for patents with high paper references, most of these are published by academic institutions in the United States. Therefore we suggest that papers and patents published by academic institutions tend to cite more from other academic organizations. The same specific citation tendency was not found in papers and patents published by industrial institutions.

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