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Industry–academia collaboration in fuel cells: a perspective from paper and patent analysis

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Abstract This study explores current collaboration trend between industry and academic institutions in fuel cells by examining collaborative papers and patents during the period 1991–2010. Papers and patents from industry–academia collaboration (IAC) are identified; the quantity, ratio, and their origins are analyzed; and the differences in performance of these collaborative documents between academic institutions and industrial institutions are contrasted. This study finds that quantities of industry–academia collaborative papers and patents increased annually in both academic institutions and industrial institutions. Countries with high production of papers and patents tend to produce more industry–academia collaborative papers and patents. Industrial institutions with high patent output and academic institutions with high paper output are active participants in IAC paper collaborations. Only a few pairs of industry–academic alliances have taken active part in IAC patent collaborations. Industry relies highly on collaboration with academia in paper publishing, but not in patenting, while academic institutions rarely rely on industry collaboration for paper or patent productivity.

Keywords Fuel cell · Paper · Patent · Industry–academia collaboration

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Introduction

Interaction between science and technology has been seen as a key pathway for innovation (Bhattacharya and Meyer 2003; Brusoni et al. 2001). Analysis of the collaboration relationship between academic institutions—including universities—and industry provide a close evaluation of the degree of mutual exchange and be one of the most direct and specific methods for investigating the interaction of science and technology (Huang et al. 2013; Noyons et al. 1994; Perkmann and Walsh 2009).

There are many forms of industry–academia collaboration (IAC), the most specific form that reflects IAC productivity is industry–academia co-authorship, including co-publication and co-applicants, where a paper or patent belongs to authors or inventors from both industry and academia at the same time. Related research on co-authorship indicates an increasing quantity of papers created by collaborations, showing collaboration has become the main producer of knowledge, and that the scale of cooperative groups is getting larger (Glänzel 2002; Kyvik 2003; Sin 2011). Citation analysis also reveals that collaborative works between academia and industry have become highly influential referenced sources and show a fundamental change in knowledge formation (Persson et al. 2004; Wuchty et al. 2007). Catalyzed by newly emerged academic disciplines, technological developments and government policies, the relationship between academic institutions and industry has intensified, and collaboration between industry and academia has become a popular new research topic among academics (Glänzel and Schubert 2004).

Most related studies evaluating the developments and outcomes of IAC are based on the analysis of papers co-published by academic institutions and industry (Calvert and Patel 2003; Katz and Martin 1997; Perkmann and Walsh 2009; Tijssen and Korevaar 1997). An upward trend in the quantity and proportion of industry–academia co-authored papers (IAC papers) has been observed in various disciplines, including membrane use for water treatment, dental materials and biomedicine (Butcher and Jeffrey 2005; Garrison et al. 1992; Lander 2013), and in various countries, including England, China, South Korea and Japan (Calvert and Patel 2003; Liang et al. 2012; Park and Leydesdorff 2010; Sun et al. 2007). Studies have shown that both academics and industry benefit from IAC relationships. Academic institutions gain more financial assistance and resources for research and development from industry, which may lead to higher research quality (Hicks and Hamilton 1999; Owen-Smith 2003; Van Looy et al. 2006). Industry, meanwhile, can keep pace with the latest scientific progress and improve corporate image and visibility (D'Este and Fontana 2007; Metcalfe 2006). However, while IAC has grown, the ratio of papers solely authored by industry has decreased rapidly. Industries have become more dependent on academic institutions for paper publication (Sun et al. 2007).

Industry–academia co-authored patents (IAC patents) are another form of IAC outcome, one which has yet to receive much attention. The fundamental driver for industry in IAC research is to obtain key knowledge and the latest developments in emerging disciplines, as key scientific discoveries can serve as the basis for future applications. Studies have revealed increasing patent collaborations between academics and industries. Stek and van Geenhuizen (2014) found from a survey of innovation collaboration in South Korea that the number of patent co-applicants by universities and enterprises increased by 214 % from 2001–2004 to 2007–2010. Bonaccorsi and Thoma (2007) found that in the field of nanotechnology, the number of patents produced by IAC was much larger than that produced by individual authors, indicating the increasing influence of academic research on technological development. Intensifying interactions between academics and industries have also been found in China (Hong 2007; Lei et al. 2012; Wang et al. 2013) and in robotics of Japan (Lechevalier et al. 2007). In addition, Kneller (2007a, b) examined collaboration between industry and universities in Japan and found that the industrial entities that are active participants in research show better performance in development.

In the twentyfirst century, the growing pressure on energy sources and the pollution of environment have become serious global problems, driving people to look for new alternative energy resources. Fuel cells—electrical devices that convert fuel energy directly into electricity through chemical reactions with oxygen or other oxidizing agents—is an emerging clean and renewable resource. With high energy conversion efficiency, pollution-free operation, and low noise and maintenance costs, fuel cell technology has been a key focus in the emerging green industry and drawn widespread attention (Steele and Heinzel 2001; Zaidi and Rauf 2009). Some reports show that academics and industries in the fuel cell field have maintained close relationships and intensively worked together with the support of governments (Breakthrough Technologies Institution 2011; Neef 2009). However, there has been little research on the interaction between academia and industry based on co-authorship analysis, with the exception of Klitkou et al. (2007), which focused solely on fuel cells in Norway. Addressing the lack of full investigations in this area, our study conducted co-authorship analysis of both papers and patents to gain a further understanding of the development and status of industry–academia collaboration in the global field of fuel cells.

Although papers and patents only represent a minimum of the intellectual achievements of science and technology, the general trends of basic research efforts can be gauged from the quantity of papers (Tijssen 2004), and detailed information about technology inventions can be explored through patents (Jaffe et al. 1998). Therefore, papers and patents can be used as proxy indicators of technological and scientific activity (Bhattacharya and Meyer 2003). Expanding on these previous studies, this study analyzed co-authorship outcomes, including IAC papers and IAC patents, to understand the characteristics of IAC at the country level and the institution level, and to explore the relationship between academic institutions and industry in fuel cell technology.

Methodology

Bibliometric methods were employed to explore the relationship between science and technology in the fuel cell field, as well as the attributes of that relationship. IAC papers/patents are the most appropriate bases for analyzing the collaboration between scientific study and technological creativity. Note that this study regards IAC papers/patents as the output of industry–academia collaboration; However, paper and patent statistics only measure formal and publicly verified output of research and innovative activities, there are other outputs that can represent scientific and technological results.

Data sources

The data of this study include patents retrieved from Patent Full-Text and Image Database (PatFT) of the U.S. Patent and Trademark Office (USPTO), and academic periodical papers retrieved from the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) sections of the Web of Science (WOS) database. As the United States is a large market for and a powerhouse in key technologies, a large number of overseas corporations apply for patents there, making US patents the epitome of global technological development, and thus the patents retrieved from the USPTO was selected as the data source. The WOS database was used for its extensive collection of academic periodicals, encompassing a large proportion of academic research findings in fuel cells.

In reference to related studies (Barrett 2005; Godbold 2005; Huang and Yang 2013; Seymour et al. 2007), patents gathered 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 by ''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 retrieved.

To ensure the accuracy of the data collected, retrieved bibliometric data underwent authority control prior to further compilation. Papers and patents with two or more authors or assignees were filtered as co-authored, and institutions of co-authored paper authors and co-authored patent assignees were identified and categorized into two types: academia (including university, graduate school and nonprofit research institution) and industry (including companies and enterprises). Next, co-authored papers and patents were verified by the type of institutions. If co-authors of papers and patents include members of academic institutions along with industrial entities, the paper or patent is identified as an IAC paper/patent. Finally, the quantity of IAC papers/patents was counted. Each IAC paper/-patent and co-author was counted once by person—if co-authors belong to different institutions, each institution was counted once; if institutions were in different countries, each country was counted once.

Indicators

To better understand the collaborative relationship between industry and academia, this study used IAC paper/patents to calculate the industry–academia collaboration rates for papers (IACs) and patents (IACt) as indicators. The higher the IACs and IACt values are, the higher the level of IAC relationship is.

$$\mathrm{IACs} = \frac{CP}{P} \times 100\,\% \tag{1}$$

CP represents the number of IAC papers, and P represents the total number of papers.

$$\mathrm{IACt} = \frac{CT}{T} \times 100\,\% \tag{2}$$

CT represents the number of IAC patents, and T the total number of patents.

Results and discussion

This study explores the trends and characteristics of IAC in fuel cells during the period 1991–2010. The quantities of IAC papers and IAC patents—IACs and IACt—are calculated, and the main IAC countries and IAC institutions are identified and examined to compare the differences in IAC outcomes between industry and academia.

Analysis of IAC papers

Number of IAC papers

As Table 1 indicated, among the 20,758 papers in fuel cells obtained for this study, there are 1658 IAC papers, with IACs being 7.99 %. The IACs rate in the fuel cell field is considerably lower than the 17 % obtained by the IAC study by Butcher and Jeffrey (2005) in the field of membrane use for water treatment. Among the 3213 institutions with papers published, there approximately 40 % have IAC papers.

All 1658 IAC papers were published by authors in 52 countries. As shown in Table 2, the top ten countries with the highest numbers of IAC papers also published highest quantity of papers overall, with Switzerland being the only exception. The top three countries—the United States, Japan and Korea—published 1184 IAC papers in total, accounting for 71 % of all IAC papers. Most of the top ten countries, with the exception of China, have higher IACs than the overall IACs (7.99 %); Japan shows the highest IACs with 16.69 %, indicating a high tendency of industry-academia collaboration. China though ranks 6th in the number of IAC papers, it shows the lowest IACs among the top ten countries, even lower than the overall IACs.

Table 3 shows the analysis of IAC papers of academia and industry. The IACs rate in academia is quite low, indicating that academic institutions rarely published papers resulting from IAC. The IACs rate for industry, however, is up to 70.43 %, showing its high dependency on IAC. Among all 684 industrial institutions that published papers, 85.53 % published IAC papers. This indicates that most of the industrial institutions published research papers were collaborations with academic institutions, meaning IAC is an very important channel for industry to publish papers. Conversely, less than 30 % of the academic institutions with published papers have collaborated with industry, showing a low collaboration relationship for academia in paper publication.

There has been an increase in the number of institutions from academia and industry participating in IAC since 2004, as shown in Fig. 1. The coefficients of determination (R^2) for institutions from academia and industry reached 0.97 and 0.95 respectively, meaning that the numbers of both academia and industry institutions participating in paper collaboration are increasing exponentially. Comparing the annual distribution of IAC paper institutions quantities from academia and industry, the number of academic institutions with IAC papers is higher than the number of industrial institutions in every year from 1991 to 2010, and the gap between the two widens over the years. The ratio between number of academic institutions to industrial institutions with IAC papers in 1991 was 1:1; by 2010, the ratio had become 1:1.5. As such, we see a more rapid growth rate in the number of academic institutions than industry institution that participate in IAC relationships.

Table 1 Number of IAC papers and institutions

IAC papers	1658
Total papers	20,758
IACs	7.99 %
IAC paper institutions	1270
Total paper institutions	3213
%	39.53

Table 2 Top ten countries with the highest numbers of IAC papers

Ranking	Country	Number of IAC papers	Total number of papers	IACs (%)	Ranking in total papers
1	United States	**588**	**5072**	**11.59**	1
2	Japan	**424**	**2540**	**16.69**	3
3	Korea	**172**	1613	10.66	4
4	Canada	153	1225	12.49	5
5	Germany	129	1198	10.77	6
6	China	100	**3801**	2.63	2
7	France	88	809	10.88	8
8	Britain	77	829	9.29	7
9	Italy	62	686	9.04	9
10	Switzerland	33	276	**11.96**	17

Bold: top three countries

Table 3 IAC papers institutions in industry and academia

	Academia	Industry
IAC papers	1658	1658
Total papers	19,313	2354
IACs	8.58 %	70.43 %
IAC institutions	685	585
Total institutions	2529	684
%	27.09	85.53

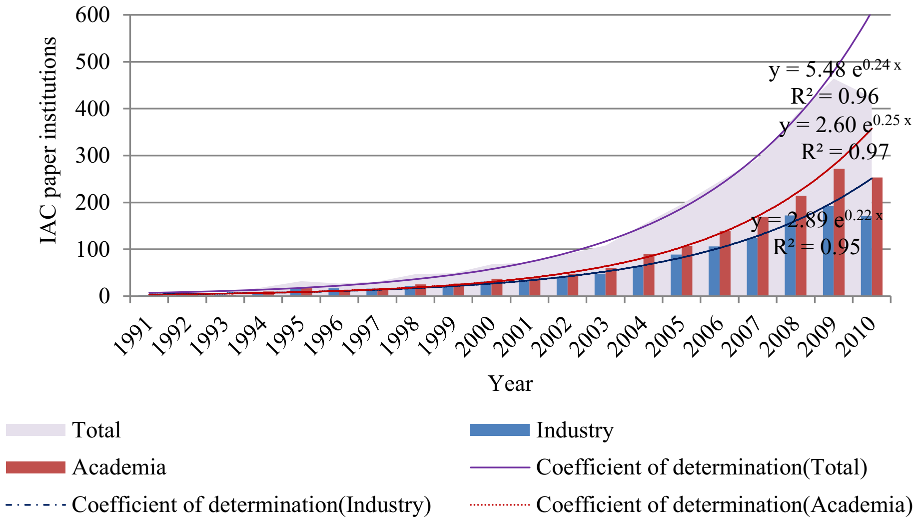

Fig. 1 Annual distribution of the IAC papers institutions numbers during 1991–2010

Along with the increase of IAC paper institutions both in academia and industry, there is a rapid 330 % growth in the quantity of IAC papers from 2004 to 2010, as shown in Fig. 2. The number of IAC papers reached 303 in 2010, over 150 times greater than 1991. Overall, the number of IAC papers increased exponentially, with coefficient of determination R^2 reaching 0.97. It is noted that both of the number of IAC papers and the number of involved institutions increased sharply since 2004. This may indicate that a higher number of institutions participating in collaboration has stimulated the growth of IAC papers.

Compared with the number of IAC papers, the growth trend in collaboration rate for papers (IACs) is fairly different. In academia, IACs increased gradually in the earlier years, increasing from 5.56 % in 1991 to 12.66 % in 1999. Nevertheless, it shows a slow downward trend since 1999, dropping to 8 % in 2010. Overall IACs showed similar growth pattern to that of academic institutions. IACs for industry is different, showing a rapid increase from 12.50 % in 1991 to 84.17 % in 2010, indicating that IAC papers have become a key pathway to knowledge formation. The increase in IAC rate shows that there is more dependence on academic institutions by industry, which is consistent with the study on coauthored works between universities and industries in Japan by Sun et al. (2007), in which the number of papers published by industry alone decreased drastically while the number of IAC papers increased. Industry in Japan has also become more likely to collaborate with academic institutions.

Main institutions of IAC papers

As shown in Table 4, there are 25 institutions with more than 20 IAC papers, among which 10 are industrial institutions (given in bold) and 15 are academic institutions.

The ten industrial institutions published 314 IAC papers, which accounts for 18.93 % of the 1658 IAC papers. Most of these institutions are from the electronics,

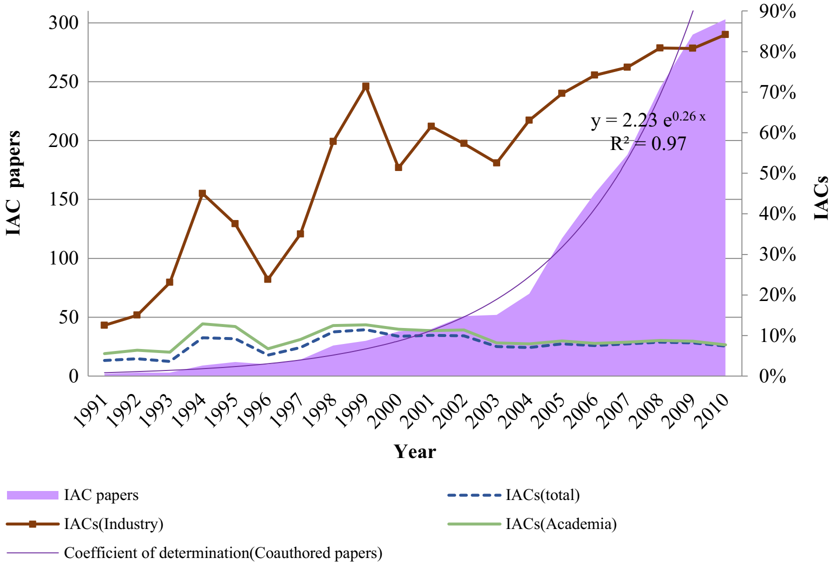

Fig. 2 Annual distribution of IAC papers and IACs

Table 4 Institutions with more than 20 IAC papers

Ranking in number of IAC papers	Academic institutions	Number of IAC papers	Number of Total papers	IACs (%)	Country
1	*Chinese Academy of Science**	*76*	*1064*	*7.14*	*China*
2	**Ballard Power Systems Inc. ****	**54**	**72**	**75.00**	**Canada**
3	*French National Centre for Scientific Research**	*42*	*395*	*10.63*	*France*
4	*Pennsylvania State University—University Park**	*38*	*293*	*12.97*	*United States*
5	**General Motors Co.****	**36**	**73**	**49.32**	**United States**
6	**Toyota Motor Co.****	**35**	**53**	**66.04**	**Japan**
7	**Samsung Advanced Institute of Technology**	**34**	**64**	**53.13**	**Korea**
8	**Hyundai Motor Company****	**32**	**41**	**78.05**	**Korea**
8	*Tokyo Institute of Technology**	*32*	*177*	*18.08*	*Japan*
10	*Tohoku University**	*30*	*139*	*21.58*	*Japan*
11	**Nissan Co.****	**29**	**34**	**85.29**	**Japan**
11	*The University of British Columbia**	*29*	*96*	*30.21*	*Canada*
11	*National Research Council of Canada**	*29*	*246*	*11.79*	*Canada*
14	*Kyushu University**	*28*	*124*	*22.58*	*Japan*
14	*The University of Tokyo**	*28*	*148*	*18.92*	*Japan*
16	**Hitachi, Ltd.****	**27**	**46**	**58.70**	**Japan**
17	**Samsung Electronics Co., Ltd.**	**24**	**35**	**68.57**	**Korea**
17	*Korea Advanced Institute of Science and Technology**	*24*	*165*	*14.55*	*Korea*
19	*Kyoto University**	*23*	*136*	*16.91*	*Japan*
20	**United Technologies Corporation****	**22**	**32**	**68.75**	**United States**
20	*The University Of Yamanashi**	*22*	*118*	*18.64*	*Japan*
20	*Royal Institute of Technology**	*22*	*166*	*13.25*	*Denmark*
23	*Jülich Research Centre**	*21*	*270*	*7.78*	*Germany*
24	**3M Company****	**20**	**23**	**86.96**	**United States**
24	*Virginia Polytechnic Institute and State University*	*20*	*90*	*22.22*	*United States*

Industrial institutions are given in bold, and academic institutions are given in italics. Top 50 institutions by highest numbers of papers are labeled with * and top 50 institutions by highest numbers patents with **

telecommunications or automobile industries, and eight are ranked in the top 50 institutions with highest numbers of patents (see note, Table 4), indicating that industries with high patent productivity tend to also have more IAC papers. Additionally, the ten industrial institution, with the exception of General Motors Co., all have IACs higher than 50 %, which suggest that these institutions highly dependent on IAC for scientific research and paper output. Concerning the nationality of the ten industries, three each are from Japan, United States, and Korea, and one is from Canada. These countries have also published high numbers of IAC papers, as seen in Table 2.

The 15 academic institutions holding more than 20 IAC papers consist of 8 universities and 7 research institutions, and have a total of 464 IAC papers, accounting for 27.99 % of the 1658 IAC papers. These 15 academic institutions consist of 6 from Japan; 2 each from the United States and Canada; and 1 each from China, Denmark, France, Germany and Korea. Again, most of these countries are also listed in Table 2, showing the highest numbers of IAC papers. Among the 15 academic institutions, all except Virginia Polytechnic Institute and State University are ranked in the top 50 with the highest numbers of papers (see note, Table 4). It is indicated that academic institutions with high paper outcomes, such as the Chinese Academy of Science, the French National Centre for Scientific Research and Pennsylvania State University—University Park, are particularly identified as primary partners for industry to collaborate with.

Analysis of IAC patents

Number of IAC patents

Table 5 shows that there are 62 IAC patents identified from the 8112 patents selected, with IACt being 0.76 %. These 62 IAC patents were owned by 62 institutions, accounting for 5.59 % of the total 1109 institutions with patents. Overall, compared to IAC papers, the number of IAC patents, the quantity of institutions with IAC patents, and IACt are relatively low.

As Table 6 illustrates, the 62 IAC patents are produced from 11 different countries—the United States has the highest number, with 40 IAC patents; Japan has 32; and Korea and Germany each have 6. All 11 countries, with the exceptions of the Netherlands and Saudi Arabia, are listed in the top ten countries with the highest quantity of patents. It means that countries with high patent outcomes also have higher numbers of IAC patents. In addition, among the top five countries with the highest number of patents, Korea has the highest IACt.

Table 7 shows that IACt for industry is low as 0.87 %; though IACt for academic institutions is relatively higher, it is also below 8 %. This shows that IAC is not the main route for industry nor academic institutions in patent production. Among the 62 IAC patent institutions, 32 are industrial, accounting for 3.44 % of the total—much lower than the 16.67 % of academic IAC patent institutions. Generally, it is not common for academic institutions and industries to produce patents from IAC.

As shown in Fig. 3, prior to 2001, few institutions produced IAC patents. The number of institutions increased gradually and reached 42 in 2010. The numbers of IAC patent institutions from industry and from academia are similar, indicating an even distribution in a 1:1 rate of collaboration relationship between the two types of institutions.

As illustrated in Fig. 4, there were virtually no IAC patents produced prior to 2002. The number of IAC patents grew from 1 in 2001 to 21 in 2010. This trend is generally

Table 5 Number of IAC patents and institutions

IAC patents	62
Total patents	8112
IACt	0.76 %
IAC patents institutions	62
Total patents institutions	1109
%	5.59

Table 6 Countries with IAC patents

Country	Number of IAC patents	Number of total patents	IACt (%)	Ranking in total number of patents
United States	40	3937	1.02	1
Japan	32	2357	1.36	2
Korea	6	286	2.10	5
Germany	6	571	1.05	3
Canada	4	385	1.04	4
France	4	111	3.60	7
Israel	3	58	5.17	8
Italy	1	58	1.72	8
Netherlands	1	29	3.45	13
Britain	1	127	0.79	6
Saudi Arabia	1	3	33.33	23

Table 7 IAC patents institutions in industry and academia

	Academia	Industry
IAC patents	62	62
Total patents	801	7101
IACt	7.74 %	0.87 %
IAC institutions	30	32
Total institutions	180	929
%	16.67	3.44

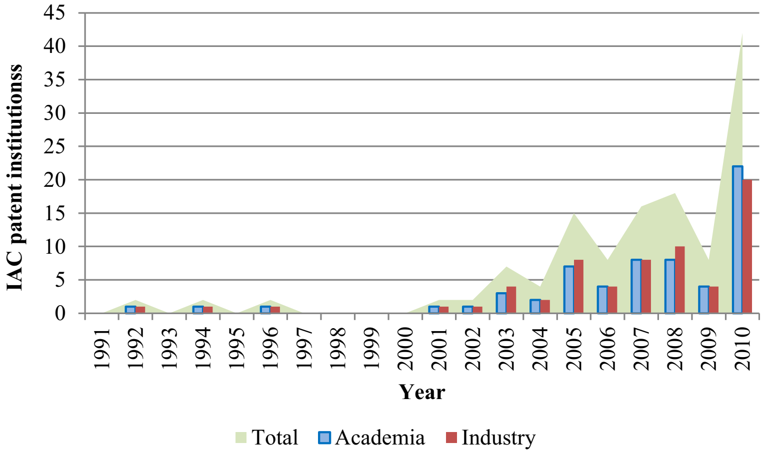

Fig. 3 Annual distribution of the IAC patents institutions numbers during 1991–2010

consistent with the number of institutions that have produced IAC patents. The IACt for industry and the overall IACt are relatively low, with the highest point being 2 % in 2010. The number of IAC patents from the academic sector is also low, and most of IAC patents are filed after 2003. In 2010, the number of coauthored patents reached its peak of 20. The IACt for academic institutions is around 10 % for most of the years. In 2010, the IACt has increased to 18.58 %, indicating one-fifth of the patents are from IAC.

Overall, the number of IAC patents and the number of involved institutions are low, but there has been an increasing tendency toward cooperation over the years, particularly for academic institutions with lower numbers of patents. Collaboration with industry provides opportunities for these institutions to obtain patents.

Main institutions for IAC patents

Among the 62 institutions which produced IAC patents, 43 institutions (69.35 %) produced only one patent each, and 8 institutions produced two patents (12.90 %). There are 11 institutions that produced three or more patents, as shown in Table 8, including 6 academic institutions and 5 enterprises. Most of these institutions are located in the United States, with the rest in Japan and Korea. Among these institutions, only Stanford University and Honda Motor Co., Ltd. produced more than ten IAC patents in collaboration. The two institutions maintain a close relationship, and nearly all of their IAC patents are contributed by collaboration with each other. Stanford University produced 17 IAC patents with IACt up to 85 %, 16 of which were co-invented with Honda Motor Co., Ltd. Pennsylvania State University and Panasonic Corporation, which rank third and fourth, have also collaborated to produce six patents; the IACt for Pennsylvania State University was 70 %. Enterprises with higher numbers of IAC patents, including Honda, Panasonic, Toyota, Samsung, and Nissan are also ranked in the top 50 institutions with the highest number of patents even though their IAC patent numbers are low, with the highest IACt being merely 13.33 %.

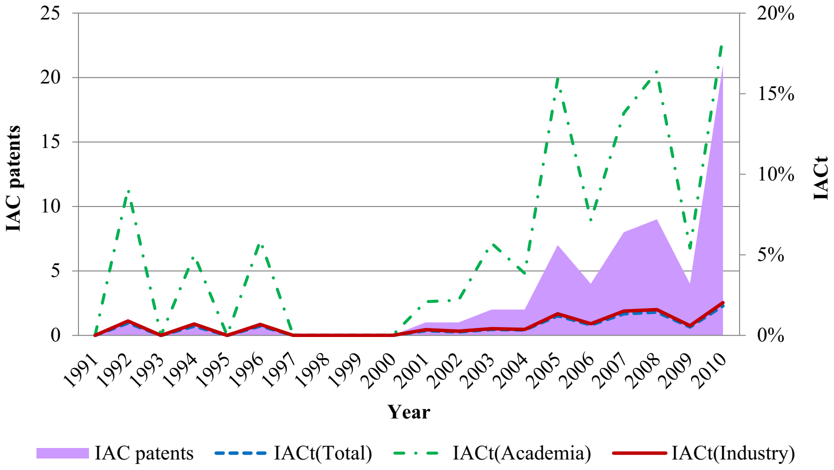

Fig. 4 Annual distribution of IAC patents and IACt

Table 8 Institutions with more than three IAC patents

Ranking in number of IAC patens	Institutions	Number of IAC patents	Number of Total patents	IACt (%)	Country
1	*Stanford University*	*17*	*20*	*85.00*	*United States*
2	**Honda Motor Co., Ltd.****	**16**	**487**	**3.29**	**Japan**
3	**Panasonic Corporation****	**7**	**248**	**2.82**	**Japan**
4	*Pennsylvania State University—University Park*	*7*	*10*	*70.00*	*United States*
5	**Hyundai Motor Company****	**4**	**30**	**13.33**	**Korea**
6	**Delphi Technologies, Inc. ****	**3**	**115**	**2.61**	**United States**
7	**Fuel Cell Energy, Inc. ****	**3**	**41**	**7.32**	**United States**
8	*US Department Of Energy***	*3*	*40*	*7.50*	*United States*
9	*Battelle Memorial Institute*	*3*	*29*	*10.34*	*United States*
10	*Korea Institute of Science And Technology*	*3*	*18*	*16.67*	*Korea*
11	*National Institute of Advanced Industrial Science And Technology*	*3*	*12*	*25.00*	*Japan*

Industrial institutions are given in bold, while academic institutions are given in italics. Top 50 institutions by highest numbers of patents are labeled with **

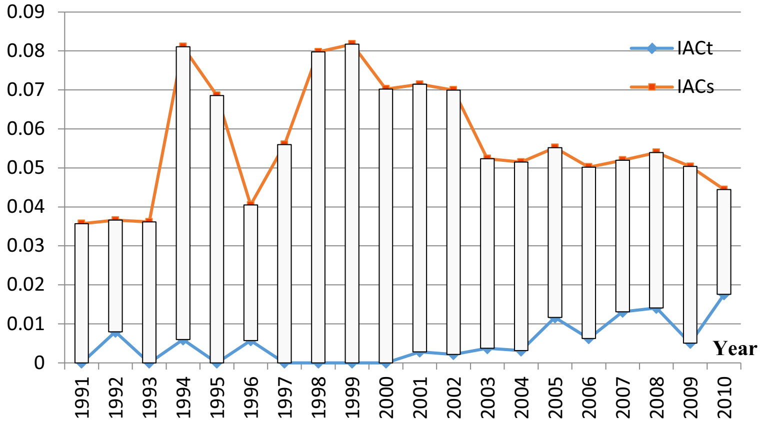

Fig. 5 Annual distribution of IACs and IACt in fuel cells

Discussion

Increasing trend of industry–academia collaboration

The result reveals an increasing trend of industry–academia collaboration both in publication and innovation. More institutions are getting involved and taking active part in industry–academia cooperation. The number of IAC papers reached 303 in 2010, which is nearly 150 times greater than 1991. The number of IAC patents has grown from 1 in 2003 to 21 in 2010. However, the overall number of IAC papers and IAC patents remains low, without much impact on the overall figures. Also, the growth trend in the number of IAC papers from academic institutions has slowed down. Overall, the total numbers of IAC papers and IAC patents have increased annually, but are not as rapidly as anticipated. There is still much room for industry–academic cooperation to grow.

Analysis of this study shows differences between IAC scientific collaboration and IAC technological collaboration. The quantities of IAC papers and IAC paper institutions are both higher than of IAC patents and IAC patent institutions. Also, as shown in Fig. 5, the annual IACs rates are shown to be higher than annual IACt values from 1991 to 2010. This result is consistent with the findings of Huang et al. (2013) and Meyer and Bhattacharya (2004), who made investigations of paper and patent collaborations in the area of thin films and solar cells respectively and found collaboration rates higher for papers than patents. According to Lissoni and Montobbio (2008) and Meyer and Bhattacharya (2004), inventors and institutions are more cautious about patent collaboration, as it involves sharing property rights and economic interests. This is the reason patent collaborations are rarer than paper collaborations.

It is worth mentioning that the gap between IACs rate and IACt rate is reducing from 1998. Figure 5 shows that from 1998 to 2002, the annual IACs rate are all maintained more than 7 %, then the rate dropped to 5 % in 2003, and has continued to decrease since. We speculate that the decreasing trend of IACs is due to the sharply growing number of total papers. On the other side, IACt rates have increased gradually since 2002, showing inventors are becoming more open to industry–academia cooperation. This accords with the trend of intensifying technological collaborations between academics and industry around the world (Hong 2007; Lechevalier et al. 2007; Lei et al. 2012; Stek and van Geenhuizen 2014).

Active participants in collaboration

We notice that countries with higher outputs of papers and patents tend to produce more IAC papers and IAC patents. Table 9 presents countries which are listed in both the top ten of IAC papers and IAC patents. As indicated, among the top ten countries with highest numbers of IAC patents, eight countries are also listed in the top ten countries with highest

Table 9 Countries listed as in both top ten of IAC papers and IAC patents

Country	Ranking in total number of papers	IACs (%)	Ranking in total number of patents	IACt (%)
United States	1	11.59	1	1.02
Japan	3	16.69	2	1.36
Korea	4	10.66	5	2.10
Canada	5	12.49	4	1.04
Germany	6	10.77	3	1.05
France	8	10.88	7	3.60
Britain	7	9.29	6	0.79
Italy	9	9.04	8	1.72

numbers of IAC papers, illustrating that industry–academia collaboration tends to occur in both scientific and technological research at the same time in a given country. Additionally, all of these active participants also have high outcomes of papers and patents and are listed in top ten by totals. These statistics show that the countries with high numbers of papers and patents tend to produce more IAC patents/papers and have higher IAC rates.

The situation of participating institutions is more complicated. As Table 8 shows, there are only 11 institutions holding three or more IAC patents, 3 of which are also listed in the top institutions with more than 20 IAC papers. Thus there is no obvious tendency for institutions to engage in paper and patent collaboration simultaneously. Among the ten industrial institutions with more than 20 papers, eight are ranked in top 50 with the highest patents, which suggests that enterprises with strong technical strength are usually active seekers of advanced science and collaborative opportunities with academia. Among the 15 academic institutions with more than 20 IAC papers, 14 of them are included in the 50 most productive institutions by publications. It can be inferred that academic institutions of high academic performance are primary partners of enterprises, which has also been confirmed in the studies of Abramo et al. (2009) and Wen and Kobayashi (2001). As for industry–academic patent collaboration, we did not identify many active institutional participants except for those who have established close long-term cooperative relationships. This is consistent with Hagedoorn et al. (2003), which focused on joint patenting between companies and suggested that relational trust and joint patent experience have a significant effect on joint patenting by alliance partners.

Different collaboration patterns of industrial and academic institutions

Industrial institutions and academic institutions exhibit distinctive collaboration patterns in our research. Industrial institutions rely heavily on academics to have scientific papers, but rarely depend on academics for patent granting. As is stated in previous section, both the number of industrial institutions with IAC papers and the number of IAC papers increased dramatically after 2005. At the same time, the IACs of institutions increased annually and was over 70 % after 2005, as shown in Fig. 6, indicating that most papers from institutions are co-published with academic institutions with highly dependent IAC relationships. Obviously, industries in the fuel cell field have actively sought collaboration with

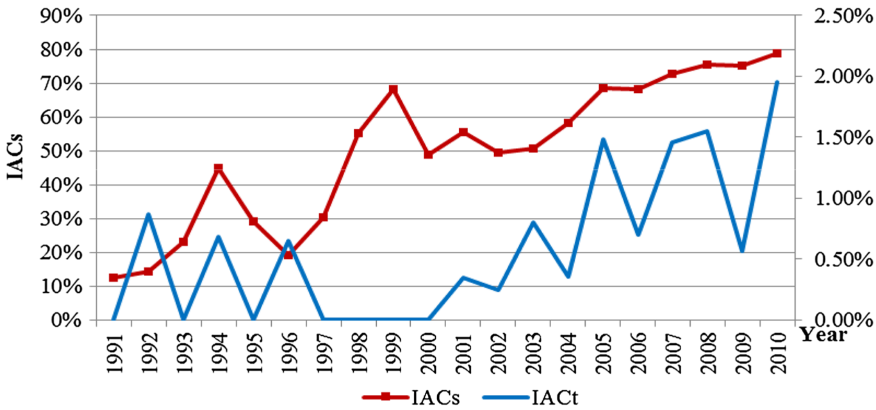

Fig. 6 Annual distribution of IACs and IACt of industrial institution

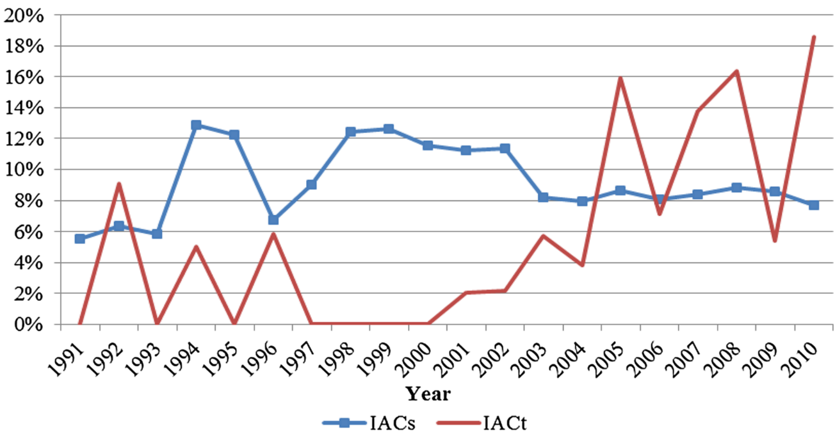

Fig. 7 Annual distribution of IACs and IACt of academic institutions

academic institutions in scientific research. As for technological cooperation, the IACt rate remained considerably low though it has seen a slight increase over time from 1991 to 2010. Due to the competitive nature of patents, most patents are patented under single assignees (Hicks and Narin 2000), which has influenced the IAC relationship of patent production in the field of fuel cells. This study's analysis shows that enterprises in fuel cells tend to produce patents independently, while it is common for enterprises to cooperate with academic institutions for paper publication, showing different types of IAC interactions.

Academic institutions, on the other hand, have a low reliance on industries in both paper publication and patent granting. Despite the increasing number of academic institutions involved in IAC and IAC papers/patents, the IACs and IACt of academic institutions are not high. As shown in Fig. 7, the IACs of academia remained over 10 % from 1998 to 2002, but decreased to and remained around 8 % from 2003, dropping more dramatically in 2010. Since scientific research is one of the major missions of academic institutions, it is fairly understandable that academic institutions have high independence in paper publications. The IACt of academia has been growing since 2000 and reached more than 18 % in 2010. In our knowledge-based society, universities have been given the responsibility of supporting industrial innovation and economic advancement (Etzkowitz 2003; Etzkowitz and Leydesdorff 2000). The transformation of universities towards entrepreneurial institutions has been captured by numerous studies (Hicks and Narin 2000; Mowery and Sampat 2001; Renault 2003). Therefore, it is not surprising that academic institutions in fuel cells have become more open and been taking active part in collaboration with industry.

Conclusion

This study analyzed the collaborative papers and patents between industrial and academic institutions in the area of fuel cells from 1991 to 2010 to explore the trends in collaboration. The annual numbers of institutions engaged in IAC collaborations and IAC papers/patents were examined to see if there is an intensifying interaction between academic and industry in full cells. Active countries and institutions were identified to discover what kind of participants are more enthusiastic about cross-institutional cooperation. In addition, we compared the numbers and ratios of IAC papers/patents of academic and industrial institutions to better understand their similarities and differences in collaboration patterns.

The numbers of IAC papers, IAC patents and IAC institutions of both industries and academia increased annually in fuel cells, showing academics and industry are becoming more closely related in this field. However, the growth of IACs has been less than expected and the overall number and ratio of IACt stayed low. The amount and ratio of IAC papers are higher than that of patents.

Eight countries—the United States, Japan, Korea, Canada, Germany, France, Britain and Italy—are listed in both the top ten countries by highest numbers of both IAC papers and IAC patents, and all show IACt and IACs higher than the average. All of these countries are among top ten countries with the most papers and patents, indicating productive countries in science and technology are more likely to engage in IAC. At the organizational level, we discovered that enterprises with high technology competiveness tend to be active participants in publication collaboration, and academic institutions with high paper output are more commonly selected as collaborating partners. On the other hand, active IAC patent collaborations mostly happen between a few pairs of alliances.

Comparative analysis of academic and industrial institutions illustrates different collaboration patterns between the two institutions. Industrial institutions are increasingly and heavily dependent on IAC to have papers, but tend to be reluctant to share patent rights with academics, considering the value placed on intellectual property protection. Meanwhile, academic institutions do not rely on IAC for papers or patents. The overall IACt rate for academics is relatively higher than for industry, and has continued growing in recent years, suggesting the development of academic enterprise. We assume that in the fuel cell area, industry–academic cooperation in technology is spreading, although it is less common than scientific research cooperation.

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