

The unbalanced performance and regional differences in scientific and technological collaboration in the field of solar cells

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Abstract This study attempts to explore collaborations in the field of solar cell science and technology, focusing on the productivity and citations of papers and patents at the global and country levels. This study finds that most papers and patents are collaborative efforts, however, the rate of collaboration is higher for papers. In particular, international collaboration is not common in patents. In terms of performance, international collaborations have shown the best performance overall if looking at trends that cover the 30 years from 1980 to 2009, but the performance of single-authored papers has been better in the more recent ten-year period, 2000–2009. At the country level, we found that most countries have higher rates of international collaboration with greater numbers in papers and patents. Asian countries such as Japan, Taiwan and India have significant citation performance with high ratios for domestic collaboration; the rates are even greater than the average ratio for international collaboration.

Keywords Collaboration · Solar cell · PV system · Paper · Patent

Introduction

Co-authorship signifies the collaborative relationship among authors, including the interaction and communication of basic theories and technical information (Heffner 1981). Price (1986) considered that if the collaborative papers continues growing in large

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quantity, the single-author paper will be no longer in existence by 1980. The advancement of communication tools provides better and more efficient communication for researchers to collaborate with one another. With the rapid growth of collaborative efforts, scientific communities have swiftly become more globalized. As a result, many researchers have conducted studies to investigate if collaborative papers do in fact improve the quality of research. Beaver (2001) conducted a comprehensive review of scientific collaborations and explored the reasons for collaborations, concluding that the typical size for collaborations is 2–3 persons, and that collaborations may not have any impact on the productivity of research. Avkiran (1997) looked at the papers from 14 journals of finance in the period 1987–1991 as the sample for analysis, and found no difference in quality between single-authored and collaborative papers. On the other hand, other studies have suggested that there is a correlation between collaboration and improved quality (Katz and Hicks 1997; Gupta and Karisiddappa 1998; Kim 2005; Lo 2010; Sin 2011; Sooryamoorthy 2009). Kim (2005) also found that the economic downturn has led to a quality decline in international collaborations and further identified clinical medicine as a discipline with the highest rate in international collaborations out of the eight major fields. Sooryamoorthy (2009) discovered that the impact of collaborative papers generally exceeds the impact of single-authored papers, and there is a positive relationship between number of authors and number of citations.

In the field of technology, collaborative efforts take the form of co-inventors in patents, but not many studies on such collaborations have been conducted. One of these was a study done by Meyer and Bhattacharya in 1997 on the co-inventors of thin films. It shows that patents are more influenced by patents of single authors and small teams than by patents from larger teams. In addition, collaborative patents seldom include co-inventors from different organizations. For a better understanding of the commonalities and differences between academic collaborations and technological collaborations, comparisons of papers and patents revealed that there are more collaborations than single-authored works in the case of both papers and patents (Meyer and Bhattacharya 2004). However, it is clear from the above that little research has been done on papers and patents in science and technology.

Solar cells is a key topic of research in energy technology. Since the energy crisis, and with the increasing awareness of the importance of environmental conservation, governments around the world have promoted policies of clean energy and solar energy technology. As a result, the academic and industrial sectors have devoted much effort to solar-cell-related research and technology development and consequently the number of papers and patents has been increasing in this discipline. But there has been virtually no research on collaboration solar-cell research. Larsen's study, on knowledge network hubs, measures of research impact, scientific structure, and publication output in nano-structured solar cell research through co-authorship, is the only one. In it she found that more recent multi-address papers tend to receive higher citation rates (Larsen 2008).

Other than this, very few studies have been conducted on the quality of collaborative papers and patents related to solar cells. In light of the lack of studies in this area, this study attempts to explore the collaboration environment in solar cell research from both the academic and technology perspectives over a long time frame. We first analyze data at the global level to better understand if there is a growing trend toward collaborations in papers and, if so, whether there is also a trend toward better quality through international collaborations. In addition, this paper attempts to see if any similar trend applies to the productivity of patents and whether increased collaboration really improves the quality of science and technologies. We then examine data at the country level to see if there is a

similar trend toward collaborations in papers and patents in a country, as well as for observing the variations among types of co-authorship in different regions or countries and in the quality of collaborative papers and patent.

Methodology

Method

This study utilizes bibliometric and patentometric methods to explore the collaborations in papers and patents in the discipline of solar cells. Bibliometrics and patentometrics use objective statistics to observe quantitative and qualitative performance within a research topic. Number of papers and patents often provides quantitative data while the number of citations of papers/patents reveals qualitative data (Bornmann and Daniel 2008; Cole and Cole 1971; Schmoch and Schubert 2008). However, number of citations is not equal to quality. That is, number of citations and quality were not the same even though they are related. Through analysis by the indicators, one can understand the structure of academic research and technological production capacity, as well as trends in scientific and technological development, to establish common frames of reference for further research.

Data collection

In this study, all solar cells covers solar cells, solar battery, photovoltaic and PV system, which are all used as search terms. With regard to papers, first we obtained a list of 67 academic journals in the discipline of Energy & Fuels from the JCR 2008 database as the core journals for this discipline. Papers related to solar cells were obtained from these journals. Using the Science Citation Index (SCI) as the database, we entered the keywords “Solar Cell”, “Solar Battery”, “Photovoltaic” or “PV system” in the query fields of “Title”, “Abstract”, “Author Keyword”, and “Keyword Plus” to search for related papers from 1980 to 2009. We ended up with 6,225 papers as the sample for this study.

As for patents, the data was retrieved from the database of United States Patent and Trademark Office (USAPTO) by inserting the keywords “Solar Cell”, “Solar Battery”, “Photovoltaic” or “PV system” in the query fields of “Title”, “Abstract”, and “Claims.” We obtained 6,343 patents from 1980 to 2009 as the samples for this study.

Indicators

The type of authorship in papers was determined by the lists under the author bracket of the SCI database. If the bracket showed a result of one person, then the paper was considered to be a single-authored work. When the number of authors exceeds one person, the work was classified as a collaborative work. Next, the collaborative works were divided into two groups—domestic collaborations and international collaborations—by checking the addresses of the authors. If authors are from the same country, their collaborations are considered domestic. If the authors are from 2 or more countries, their collaborations are considered to be international. If a paper is written by 3 American authors, 2 Taiwanese authors and one Japanese author, then it will be recorded as one paper from the U.S., one from Taiwan and one from Japan. The calculation does not include any weighting factors. Collaborations in patents are determined by the name and country of the inventor(s).

We followed the same rules in the categorization of patents as in the categorization of papers. The patents were divided into single authors, domestic collaborations, and international collaborations. The indicators used in this study include the following: (i) number of papers/patents, (ii) number of citations of papers/patents, (iii) average number of authors per paper/patent, (iv) citations per paper/patent, (v) the Domestic Collaborative Index (DCI), (vi) the International Collaborative Index (ICI), (v) the Relative Citation Index (RCI). The formulae for DCI, ICI and RCI are as follows:

$$\text{DCI} = (D_i/N) \times 100 \quad (1)$$

where D_i is the number of domestically co-authored papers/patents, and N is the number of papers/patents.

$$\text{ICI} = (I_i/N) \times 100 \quad (2)$$

where I_i is the number of internationally co-authored papers/patents, and N is the number of papers/patents.

Meanwhile, the Relative Citation Index (RCI) is the ratio of a country's average number of citations divided by all the sampled countries' average number of citations. Thus, if a country's papers are cited with a frequency equal to the expected number, then its Relative Citation Index will be 1.0. The formula for calculating the Relative Citation Index, which is shown as (3), provides an easy way of identifying relatively frequently and relatively infrequently cited publications.

$$\text{RCI} = \left(\frac{\frac{C_i}{P_i}}{\frac{C_1}{P_1}} \right) \times 100 \quad (3)$$

where C stands for the number of citations, i for a specific institute, I for all institutes in this field; C_i means the number of citations in the field of i institute; P_i is the number of papers in the field of i institute; C_1 is the citation number for all institutes in the same field; P_1 is the number of papers from all institutes in the field.

Results

General/Global

This study examines papers and patents related to solar cells from 1980 to 2009, investigates three formats of authorship, including single authors, domestic collaborations, and international collaborations, and analyzes overall trends for the entire 30 year period as well as developments by separate 10-year periods (1980–1989, 1990–1999, 2000–2009). The following analysis is conducted from the perspectives of number of papers and patents in the field of solar cells, the number of citations of papers/patents in the field of solar cells, and the citations per paper/patent in the field of solar cells.

The average number of authors per paper/patent is shown in Table 1, grouped into domestic and international authorship. For the 30-year period 1980–2009, the average number of authors per paper is 3.77, higher than the 2.32 in patents, indicating that on average more authors work together to produce papers. There is also a gap between the average number of authors per domestic versus international collaboration in both papers (4.06 and 4.96) and patents (3.16 and 3.75). The gap is wider for international

Table 1 Average number of authors for different types of collaborations in papers and patents

	Papers			Patents		
	Domestic	International	Total	Domestic	International	Total
1980–1989	3.36	3.00	2.61	2.76	3.06	1.89
1990–1999	3.82	4.85	3.40	3.17	3.36	2.26
2000–2009	4.19	5.01	3.96	3.31	3.95	2.56
1980–2009	4.06	4.96	3.77	3.16	3.75	2.32

collaborations, while the average number of authors for international collaborations is higher than the number of authors for domestic collaborations.

Closer observation of the changes in the average number of authors at different time periods reveals that over time the average number of authors increased gradually for both domestic and international collaborations. For domestic papers, the average number rose from the initial 3.36–4.19, an increase of 0.83 over these 30 years; similarly, the average number of authors for patents rose from 2.76 to 3.31, an increase of 0.55. For international collaborations, the average number of authors for papers rose from 3.00 to 5.01, an increase of 2.01 in 30 years, while the average number for patents rose from 3.06 to 3.95, an increase of 0.89. The overall average number of authors was higher for international collaborations than for domestic collaborations, and the differential increased over the years. The average number of authors for papers was consistently higher than that for patents, and the number increased at a faster rate.

The number of papers and patents in the field of solar cells

Figure 1 shows the numbers and percentages of different types of authorship for papers and patents—single authors, domestic collaborations and international collaborations—over the past 30 years from 1980 to 2009. Fifty-five papers (0.88 %) from the initial sample were excluded from the calculations because they lacked enclosure of authors' addresses. An analysis of the remaining 6,170 papers is shown in Fig. 1a. “Domestic collaboration” is the type of authorship with the highest percentage, with the percentage reaching as high as 71.10 % (3,014 papers) for the 2000–2009 period, the most recent decade. “International collaborations” show the highest growth rate, and the percentage over 2000–2009 surpassed the percentage of single-authored papers, which is evidence for a clear growth trend. With regard to patents, as shown in Fig. 1b, during the first 10-year period (1980–1989), most of the patents were produced by single authors (754 papers, 49.74 %). The percentage of domestic collaborations in patents has gradually increased through the years (49.08–62.5 %). Though the percentage of international collaborations has also been rising (0.53–3.79 %), the figure has remained lower than that for domestic collaborations. Overall, the graph shows that authorship in patents has shifted from single authors to more collaborative efforts. However, the percentage of international collaborations has remained low, albeit gradually increasing. In sum, the authorship of patents is now dominated by domestic collaborations.

Looking at the statistics for types of authorship of papers and patents, the percentage of single-authored papers and patents are both in decline (31.08–11.44 % and 49.74–33.72 %). The rate of decline for papers is higher than for patents. Although the percentage of single-authored patents is in decline, the total number of patents by single

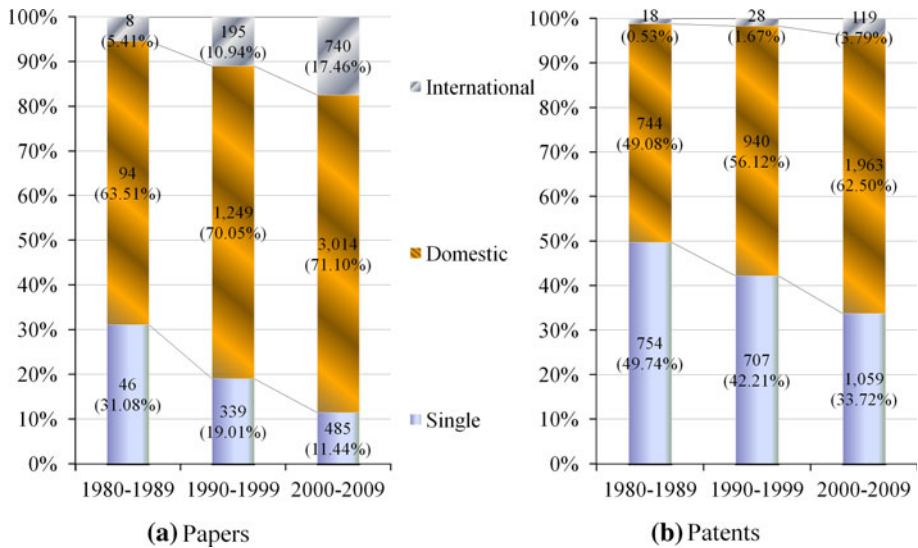


Fig. 1 Authorship types for papers and patents over time (1980–2009). **a** Papers, **b** Patents

authors accounts for more than one-third of total patents even in 2000–2009. Price (1986) assumed that the single-authored papers will be no longer in existence; however, it has not occurred. In both papers and patents, the percentages of domestic collaborations are continually increasing. By the period 2000–2009, domestic collaborations have become the predominant format of both papers and patents, with 71.10 % (3,014 papers) of total papers and 62.50 % (1,963 papers) of total patents. International collaboration also shows increases over time for both papers and patents. The percentage of papers by international collaboration reaches a high of 17.46 % (740 papers) in 2000–2009, which is 6.02 % higher than the percentage of single-authored papers (11.44 %). However, the percentage of international collaborations in patents for the same period only reaches 3.79 %, which shows that the trend in this area is weak.

Citations of papers and patents in the field of solar cells

In this study, we use the same method of calculation for citations of papers and for citations of patents. “Citations” refers to the number of times the paper has been cited since its publication or the number of times the patent has been cited since its approval. For example, the number of “citations” for 2006 refers to the number of times that papers/patents published or approved in 2006 have been cited. Following the same rule, the number of citations for 2007 refers to the number of citations from 2007 and onward of papers/patents published or approved in 2007.

Figure 2 shows the number of citations of papers and patents with different types of authorships. Papers from domestic collaborations have the highest percentage of citations (36,070 papers; 69.79 %). International collaborations rank second in terms of percentage of citations (8,498 papers; 16.44 %); single-authored papers have the lowest percentage (7,119 papers; 13.77 %). For patents, as with papers, domestic collaborations have the highest proportion of citations (34,850 papers; 38.51 %). Single-authored patents have second highest proportion, while international collaborations have the lowest proportion, at 1.77 % (1,034 papers).

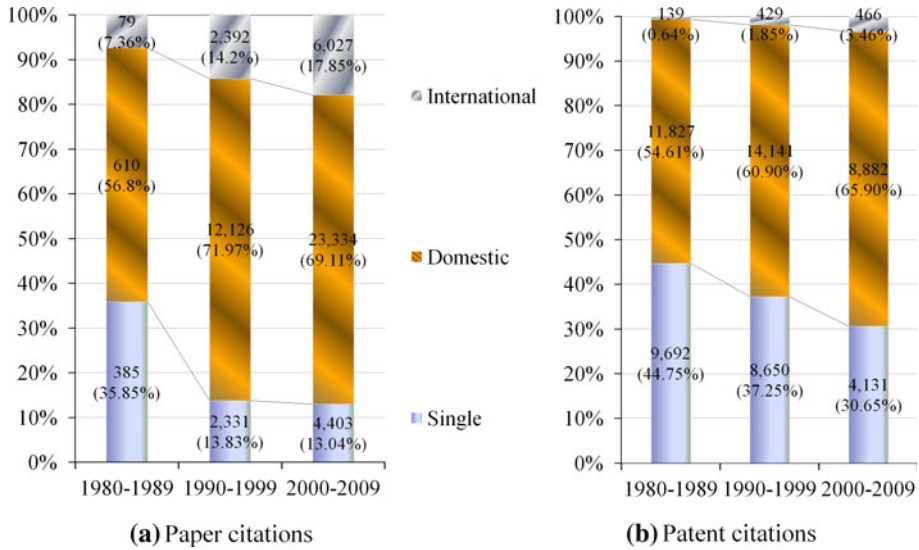


Fig. 2 Changes in paper citations and patent citations for three types of authorship. **a** Paper citations, **b** Patent citations

If citations of papers are a reflection of quality and the number of papers is viewed as the reflection of quantity, the two numbers can be used for a comparative analysis. Looking first at papers from domestic collaborations, the percentage of citations of papers is higher than that of papers only in one period. For papers from international collaborations, the percentage of citations is higher than the percentage of total papers for all periods. These results demonstrate that papers from international collaborations are of high quality, but this is not necessarily the case for domestic collaborations. Patents from domestic collaborations demonstrate high quality performance; patents from single-authors are lower in quality; patents of international collaborations only show better quality in the period 1990–1999.

Comparing papers and patents produced by domestic collaboration, they show different performance. Figure 2a shows that for the first two decades of this study, the percentage of citations of papers from domestic collaborations rose (from 56.8 to 71.97 %), but that percentage figure dropped (69.11 %) in 2000–2009. However, the percentages of citations from domestic collaboration papers was invariably higher than the percentages of citations from international collaboration papers. In Fig. 2b, citations of domestic-collaboration patents have been increasing over time as a percentage of the total, with the percentage of citations accounted for by domestic-collaboration patents exceeding the percentage of total patents accounted for by domestic-collaboration patents in all three periods. Citations of international-collaboration papers and patents have both risen as a percentage of total citations. The proportion of citations of international-collaboration papers is larger in all three time periods than the proportion of international-collaboration patent citations. However, while overall citations of patents from international collaborations are increasing as a percentage of total patent citations, their percentage is still lower than for either domestic-collaboration or single-author patents.

Citations per paper/patent in the field of solar cells

Citations per paper/patent help to evaluate the use or impact of papers/patents. The citations per paper/patent in the field of solar cells from 1980 to 2009 are listed in Table 2. Over our

Table 2 Citations per paper/patent by different types of authorship

	Papers			Total	Patents			
	Single author	Collaboration			Single author	Collaboration		Total
		Domestic	International			Domestic	International	
1980–1989	8.37	6.49	9.88	7.26	12.85	15.90	7.72	14.29
1990–1999	6.88	9.71	12.27	9.45	12.23	15.04	15.32	13.86
2000–2009	9.08	7.74	8.14	7.97	3.90	4.52	3.92	4.29
1980–2009	8.18	8.28	9.01	8.38	8.92	9.56	6.27	9.22

thirty-year period, citations per patent are 9.22, which is slightly higher than the 8.38 citations per paper. Papers from international collaborations have the highest citations per paper with a rate of 9.01, followed by 8.28 in domestic collaborations, and 8.18 in single-authored papers. Regarding patents, domestic collaborations have the highest citations per patent with a rate of 9.56, followed by single-authored patents with 8.92, and patents from international collaborations with only 6.27. Overall, citations per patent are higher in all categories than the citations per paper with the exception of international collaborations.

For this study we also conducted analysis of variance (ANOVA) on papers and patents by single authors, domestic collaborations, and international collaborations. The results are all statistically insignificant ($F(2,6) = 1.545, p = .287 > .05$; $F(2,6) = .200, p = .824 > .05$). Taken together with the above, our results show that collaborations seem to improve the quality of papers and patents, but the impact is not significant.

Country level

The performance in the field of solar cells for paper numbers and patent numbers is seen through country level, Fig. 3 shows the paper and patent trends of the top five countries. In papers, USA has large amount of papers, but the increasing trend has been slowed. The amounts of papers for Japan and Germany rank number two and number three respectively, the increasing trends have been growing; as well as the rest countries have positive growth in increasing trends. In patents, USA also has large amount of patents, but the trend had decreased in 1990–1999 and had increased in 2000–2009. Japan has the second largest amount of patents, and it has kept increasing in the three decades. Taiwan ranks third in the amount of patents, the trend had been slowly growing in 1990–1999 and had started increasing in 2000–2009; and the rest countries have similar trends as Taiwan.

This study further looks at 20 countries that are in the top 15 in terms of number of papers, number of paper citations, number of patents and number of patent citations. The selected countries are Australia, Belgium, Canada, Switzerland, China, Germany, Denmark, Spain, France, the UK, Israel, India, Italy, Japan, South Korea, Mexico, Netherlands, Sweden, Taiwan and the USA. Egypt is removed due to the lack of patents although Egypt is the top 15 in terms of number of papers. The papers and patents from the above countries show significant performance in terms of both quality and quantity. In this section we analyze paper and patent collaboration by country in the field of solar cells.

Rates of collaboration

Table 3 shows the rankings of these 20 countries for papers and patents rankings, including their percentage share of the total and their rate of collaborations. The USA ranks first in

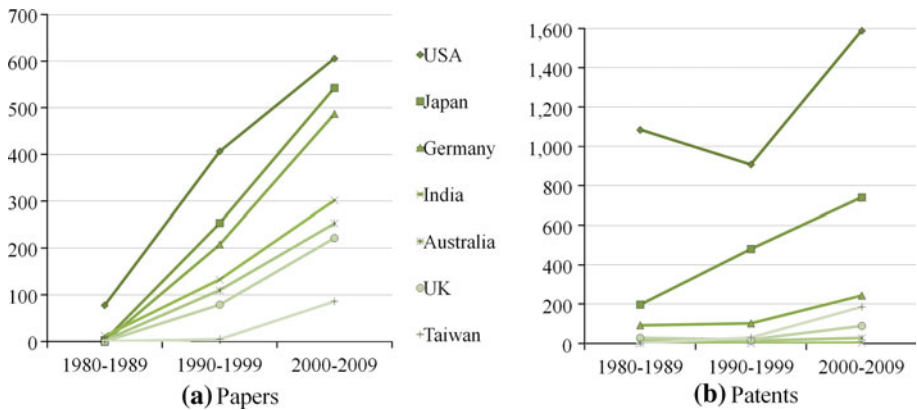


Fig. 3 The trends of papers and patents of top 5 countries in the field of solar cells. **a** Papers, **b** Patents

the number of papers and patents, followed by Japan and Germany. The USA, Japan and Germany account for 85.84 % of the total number of patents. However, they account for only 41.91 % of the total number of papers, which means the concentration of patents is higher than that of papers (Huang, Lee and Chen 2010).

As for rates of collaboration in papers, the 20 countries have been divided into three levels according to the country's collaboration rate. Taiwan, Spain, China, South Korea and France are included in the first level with paper collaboration rates higher than 95 %. These are all Asian countries or non-English speaking countries in Europe. All of these countries except Taiwan are ranked from the sixth to 11th places in terms of number of papers; Taiwan is ranked 21st. The second level includes Belgium, India, Sweden, Germany, Japan, Switzerland and Netherlands, with paper collaboration rates between 90 and 95 %. Again, these are all Asian countries or non-English speaking countries in Europe. Japan, Germany and India are ranked from second to fourth places respectively in the rankings of the numbers of papers, the rankings of the rest of countries in the second level are scattered, all behind number 10. The third level includes Italy, Mexico, UK, Israel, Canada, the USA and Australia, with paper collaboration rates between 80 and 90 %; four of the seven are English-speaking countries, the exceptions being Italy, Mexico and Israel. The USA, Australia and UK are respectively ranked first, fourth and seventh for number of papers; the remainder are below 10th place in terms of number of papers. The rates of paper collaboration in Denmark below 80 %. Overall, the rates of paper collaboration are higher in Asian and non-English speaking countries; however, the rates of paper collaboration has no direct relationship with the numbers of papers.

For patents, India is exceptional, as it has only three patents in the field of solar cells, all of which are collaborative papers and cause its patent collaboration rate to be 100 %. The next 17 countries are color-coded, as was done for papers, into three levels: The first level includes Belgium, Japan, China and Taiwan, all from Asia or Europe, with collaboration rates higher than 70 %. The UK, South Korea, Germany, Switzerland, Mexico, France, Australia and Sweden are categorized in the second level with patent collaboration rates between 60 and 70 %. These eight countries are geographically scattered, in Asia (1), non-English speaking Europe (4), non-English speaking North America (1), and English speaking countries (2). Spain, Canada, Israel, USA, and Italy are gathered in the third level with patent collaboration rates between 50 and 60 %; these countries are from non-English

Table 3 Rankings for numbers of papers and patents in the field of solar cells and rates of collaboration

Country	Papers			Patents		
	Rank	Share (%)	Collaboration %	Rank	Share (%)	Collaboration %
Taiwan	21	1.47	97.80	4	3.43	73.73
Spain	6	5.01	96.44	18	0.27	58.82
China	8	3.61	96.41	19	0.19	75.00
South Korea	11	2.82	95.98	11	0.69	68.18
France	9	3.57	95.00	6	1.93	63.11
Belgium	20	1.51	93.55	15	0.49	80.65
India	4	7.24	92.62	25	0.05	100.00
Sweden	16	1.91	92.37	16	0.36	60.87
Germany	3	11.26	92.23	3	6.90	67.96
Japan	2	12.97	92.13	2	22.39	77.15
Switzerland	13	2.30	91.55	7	1.34	67.06
Netherlands	12	2.61	91.30	13	0.62	48.72
Italy	10	3.13	87.05	12	0.63	50.00
Mexico	14	2.09	86.05	25	0.05	66.67
UK	7	4.88	85.38	5	2.15	69.85
Israel	21	1.47	84.62	10	0.71	57.78
Canada	17	1.75	84.26	8	1.22	58.44
USA	1	17.68	82.31	1	56.55	52.89
Australia	5	5.93	80.87	9	0.84	62.26
Denmark	25	1.04	68.75	20	0.14	22.22

speaking Europe (3) or are English speaking countries (2). The remainder of the 21 countries in our sample have patent collaboration rates lower than 50 %: the Netherlands and Denmark.

Our next step in this study is to compare the three levels respectively in paper collaboration and patent collaboration as shown in Table 3. Taiwan and China are in the Level 1 group for both categories, with high rates of both paper and patent collaboration; South Korea, France, and Spain have high rates of paper collaboration, however, their rates of patent collaboration are lower. India is the exception among countries that fall into Level 2 for number of papers, as it has a higher rate of patent collaboration than its paper collaboration (owing to having only three patents, all of which are collaborative). Sweden, Germany, and Switzerland have rates of paper collaboration close to their rates of patent collaboration. Belgium, Japan, and Netherlands have high rates of paper collaboration (Level 1), but lower rates of patent collaboration (Level 2 or below). Among countries in Level 3 for number of papers, Mexico, the UK, and Australia have higher rates of patent collaboration than rates of paper collaboration. Italy, Israel, Canada, USA and Denmark have similar rates of paper and patent collaboration.

Based on the above analysis, countries can be divided into three types depending upon the rates of paper and patent collaboration, as shown in Table 4: (1) Countries whose level of paper collaboration is higher than their level of patent collaboration, which are South Korea, France, Spain, Belgium, Japan and the Netherlands. (2) Countries whose level of paper collaboration is the same as its level for patent collaboration, which are Taiwan,

Table 4 The distribution of countries' levels in terms of rates of paper collaboration and rates of patent collaboration

Papers	Patents		
	Level 1 >70 %	Level 2 >60 %, <70 %	Level 3 <60 %
Level 1 >95 %	Taiwan	South Korea	Spain
Level 2 >90 %, <95 %	China	France	
	India	Sweden	Belgium
		Germany	Japan
		Switzerland	Netherlands
Level 3 <90 %	–		Italy
		Mexico	Israel
		UK	Canada
		Australia	USA
			Denmark

China, Sweden, Germany, Switzerland, Italy, Israel, Canada, USA, and Denmark. (3) Countries whose level of patent collaboration is higher than its level of paper collaboration, which are India, Mexico, the UK and Australia.

Next we will further analyze the dissimilarity of domestic and international collaboration rates.

Domestic collaboration rates and international collaboration rates

The performance of each country in terms of rates of domestic collaboration and international collaboration is shown in Fig. 4. Domestic collaboration rates are presented along horizontal coordinates and international collaboration rates are shown along vertical coordinates; the dotted line denotes the average rates of domestic collaboration and international collaboration.

In terms of papers, South Korea, India and Japan, all Asian countries, have significant performance with higher-than-average rates in both domestic collaboration and international collaboration, as shown in Fig. 4a; Taiwan is an exceptional case, being the only sample with a higher-than-average rate in domestic collaboration for papers but lower-than-average rate in international collaboration. The remaining countries have domestic collaboration rates for papers lower than the worldwide average; however, their international collaboration rates are higher than average rate. In sum, Asian leaders South Korea, India and Japan have higher-than-average rates of both domestic and international collaboration; however, for Taiwan the international collaboration rate for papers is lower than average.

Country performance in terms of rates of domestic patent collaboration and international patent collaboration is shown in Fig. 4b. In Taiwan and Belgium the rates of both domestic patent collaboration and international patent collaboration are higher than the average rates worldwide. The rate of domestic patent collaboration in Japan and South Korea are higher than average; however, their rates of international patent collaboration are lower than average. The Netherlands has lower rates of both domestic patent collaboration and international patent collaboration than average. The remaining countries have

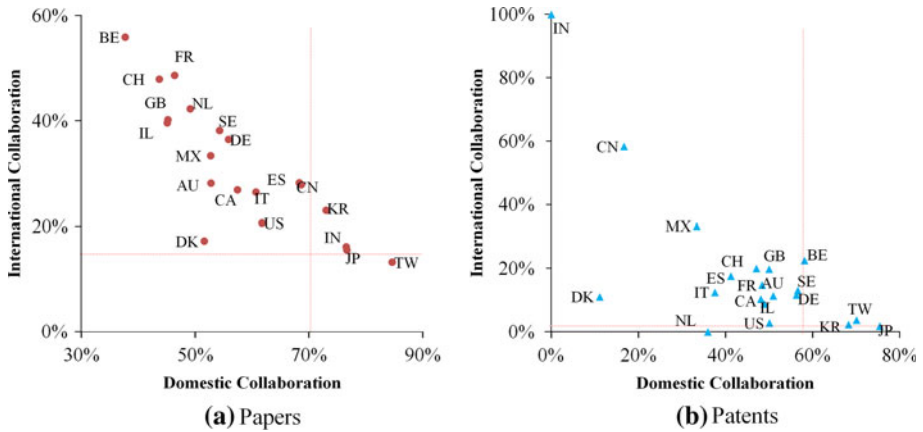


Fig. 4 Country performance in paper and patent collaborations. **a** Papers, **b** Patents

higher-than-average international collaboration rates, but their domestic collaboration rates are lower than the average rate for all countries.

Comparing Fig. 4a with Fig. 4b, most countries with high rates in paper and patent collaboration have higher rates in international collaboration. However, the Netherlands has lower-than-average rates of international collaboration and domestic collaboration in science and technology. The Netherlands also has a low rate of international and domestic patent collaboration. Taiwan has a high rate of domestic paper collaboration but a low rate of international paper collaboration. Japan and South Korea have high rates of domestic patent collaboration but low rates of international patent collaboration. The rates of both domestic and international paper collaboration in Japan, India and South Korea are high, and the rates of both domestic and international patent collaboration in Taiwan and Belgium are high. Therefore, we conclude that the rates of domestic collaboration of science and technology in Japan, Taiwan and South Korea are high, even higher than the rates of international collaboration.

Citations of collaborative papers and patents in each country

The rates of citations of papers and patents produced through domestic and international collaboration are shown in Fig. 5a. India, Japan and South Korea have citations rates for domestic and international collaboration that are higher than the average rates worldwide. Denmark and Taiwan have high citation rates for works of domestic collaboration but low rates for works from international collaboration. The remaining countries have higher citation rates for international collaborations than the average; but the citation rates for domestic collaborations are lower than the average.

Figure 5b shows the patent citation rates for each country’s domestic and international collaborations. Belgium and Japan have greater rates of patent citations both in domestic and international collaborations than the worldwide average ratios. Taiwan has higher citation rates for domestic collaborations than the worldwide average; however, their citation rates for international collaborations are lower than the average rates worldwide. South Korea and the USA have lower-than-average citation rates for both domestic and international collaborations. The remaining countries have higher-than-average rates of patent citations for international collaborations, but lower-than-average citation rates for domestic collaborations.

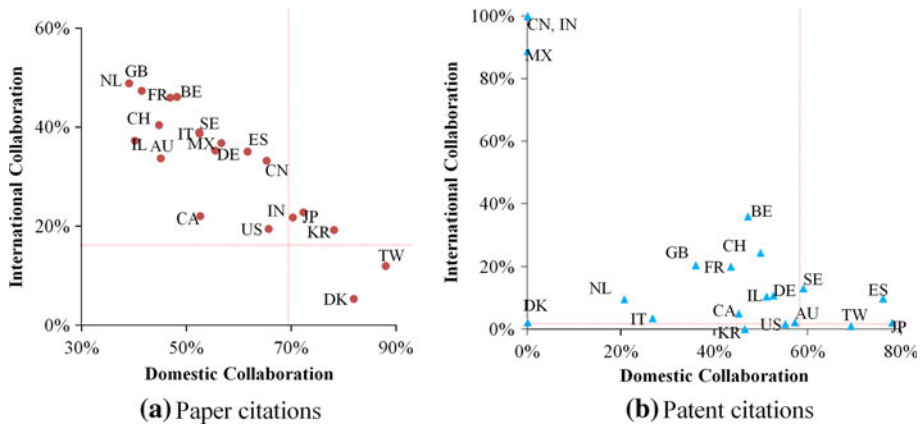


Fig. 5 Citation rates of papers and patents from domestic collaboration and international collaboration, by country. **a** Paper citations, **b** Patent citations

Comparing Fig. 5a with Fig. 5b, most countries with high citation rates for paper and patent collaborations have higher rates for international collaborations. The USA and South Korea have low citation rates for international and domestic patent collaborations. South Korea, Japan and India have high citation rates for domestic paper collaborations but low rates for international collaborations; Taiwan has similar conditions for patent citations. The citation rates for both domestic and international paper collaborations are high in Taiwan and Denmark, and the citation rates for both domestic and international patent collaboration are high in Japan and Spain. Therefore, we conclude that the citation rates for domestic collaborations in science and technology are high in Japan and Taiwan, even higher than the rates for international collaborations. South Korea especially has a high citation rate for domestic paper collaborations and the USA has a high citation rate for international paper collaborations. However, their citation rates for domestic and international patent collaboration tend to be lower.

RCI in each country

The Relative Citation Index, also known as the RCI, stands for the ratio of a country’s average citation rate (per paper/patent) to the world’s average citation rate. RCI is helpful in presenting the diversity of relative paper performance in individual countries and in the world; it also varies in a power law relationship with the size of a country’s paper numbers and patent numbers. Figure 6a indicates that the ratios of paper RCI in Switzerland, Sweden, Germany, the USA, and Australia in both domestic and international collaboration are greater than one, which means that the five countries have significant performance in these two types of collaboration. The ratios of paper RCI in Denmark and Sweden are greater than one only in domestic collaboration; the ratios of paper RCI in Netherland, Japan, UK and Italy are greater than one only in international collaboration. The RCI of most countries’ papers is higher in domestic collaboration than in international collaboration. Only the Netherlands, Japan, UK, Italy, China, Spain and India, countries located in Asia and Europe, have better RCI performance in international collaboration; the result suggests that those countries raise paper quality through international collaboration.

Figure 6b illustrates that only the USA has a ratio for patent RCI of USA in both domestic and international collaboration of greater than 1, which shows that USA has outstanding performance in both types of collaboration. The ratios of patent RCI in Spain are greater than one only in domestic collaboration; the ratios of patent RCI in Japan, Sweden, Switzerland, Israel, France, UK, Belgium and Mexico are greater than one only in international collaboration. Most countries' patents performance shows a higher RCI in international collaboration than in domestic collaboration. Only the RCI of the USA, Spain, Australia, Canada, Taiwan, Italy and South Korea show better performance in domestic collaboration; the result suggests that those countries have a certain significant level of patent quality in domestic collaboration.

Comparing the paper and patent RCI for each country, most countries have better RCI performance for papers through international collaboration, but better RCI performance for patents through domestic collaboration. The USA, Canada, Taiwan, South Korea, Mexico, and Denmark—countries from North America, Asia and Europe—have better performance for both paper and patent RCI in domestic collaboration than international collaboration. Japan, the UK, the Netherlands, China, India—countries concentrated in Asia and Europe—have better paper and patent RCI in international collaboration than domestic collaboration. Sweden, Switzerland, Israel, France, Germany, Belgium—almost all European countries—have better RCI performance in domestic-collaboration papers than in international-collaboration ones; but with a more significant RCI performance in patents from international collaboration. Spain, Australia and Italy—countries from Europe and Oceania—show better RCI performance for papers in international collaboration but better RCI performance for patents in domestic collaboration.

Discussion and conclusion

This study examines papers and patents in the field of solar cells from 1980 to 2009 and tries to find out if there is a growing trend toward collaboration, and if so, we also analyze citations of papers to see if there is a trend toward better quality through international collaborations. In addition, this paper attempts to see if the trend applies to the productivity of patents, and whether more collaboration efforts would improve the quality of science and technology. To gain further understanding of similarities and differences between collaboration results in different countries, this paper also examines different types of

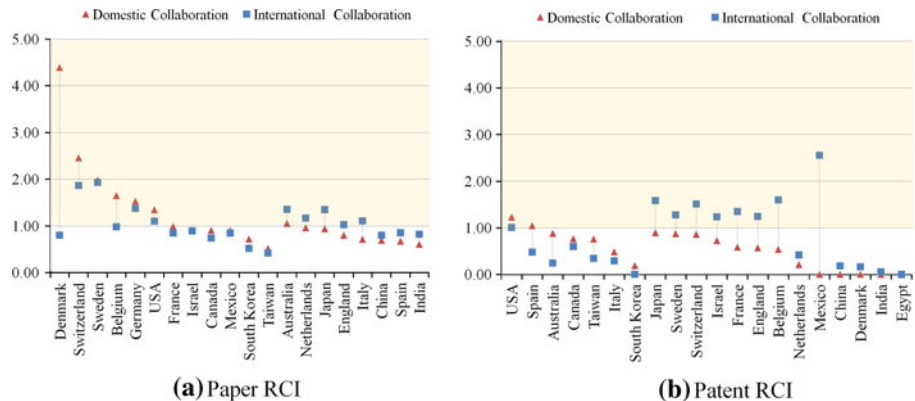


Fig. 6 The RCI of papers and patents, by country. **a** Paper RCI, **b** Patent RCI

collaborations by region and the quality of paper and patent collaborations are further analyzed at the country level.

The average number of authors in international collaborations not only has increased over time, it is now higher than the average number of authors in domestic collaborations. The percentage of collaborations in papers is higher than in patents, and the rate of international collaborations has rapidly grown. However, there are not many patents from international collaborations, and single-authored patents remain very important.

Performance as measured by paper and patent citations follow a similar trend to the number of papers and patents, but there are slight differences. While the papers of international collaborations show high quality in general, single-authored papers also demonstrate better quality in the most recent of our three 10-year time periods (i.e. 2000–2009). For patents, patents of domestic collaborations show high quality in general, while the quality of single-authored patents has gradually worsened.

For citations per paper, the quality of papers of international collaborations is the highest among all categories; single-authored papers also show high quality for 2000–2009. For citations per patent, patents of domestic collaborations have the best quality. However, over the 2000–2009 period, the relative performance in terms of citations and citations per paper/patent, as well as the shifting trends toward collaborations, may be affected by the short citation window in which many papers and patents have not been cited.

As for the part of this paper that deals with performance by country, the output of papers and patents in the field of solar cells is centered in a few countries, especially the USA, Japan and Germany. We grouped our sample countries into three levels on the basis of the rates of paper collaboration and patent collaboration. (1) The countries with a rate of paper collaboration higher than their rate of patent collaboration are South Korea, France, Spain, Belgium, Japan and the Netherlands. (2) The countries with a rate of paper collaboration close to their rate of patent collaboration are Taiwan, China, Sweden, Germany, Switzerland, Italy, Israel, Canada, the USA and Denmark.

Regarding international and domestic collaboration in each country, it can be found that most of the countries with higher rates of international collaboration are among the countries with greater numbers of papers and patents. The rates of international and domestic patent collaboration in the Netherlands are, however, relatively low. Taiwan has a higher rate of domestic paper collaboration but a lower rate in international collaboration; Japan and South Korea have better ratios of domestic patent collaboration but lower rates of international patent collaboration. Japan, India and South Korea have high rates of paper performance from both domestic and international collaboration. The conclusion is that Asian countries such as Japan, Taiwan and South Korea have significant performance in science and technology in terms of their high rates of domestic collaboration; these rates are even greater than the average rate of international collaboration.

Looking at citation performance by country, most countries have high ratio of paper and patent citations for international collaborations. However, USA and South Korea have low rates of citations for patents from international and domestic collaboration. South Korea, Japan and India have high rates of citations for papers from domestic collaboration but low rates for international collaboration; Taiwan is in the same condition in its performance with respect to patent citations. Taiwan and Denmark have high rates of citations for papers from both domestic and international collaboration; Japan and Spain have high rates of citations for patents from both domestic and international collaboration. South Korea has a high rate of citations for papers from international and domestic collaboration and the USA has a high rate of citations for papers from international collaboration; however, the patent citations of the two countries are low for both international and domestic collaborations.

Looking at the RCI performance of papers and patents by country, most countries have better performance in international collaboration when it comes to papers, but better performance in domestic collaboration when it comes to patents. The countries with high ratios of paper and patent RCI for domestic collaboration are concentrated in North America, Asia and Europe. The countries with higher ratios of paper and patent RCI for international collaboration than for domestic collaboration are centered on Asia and Europe. Most countries from Asia and Europe have great performance in terms of paper RCI for domestic collaborations; the countries with better performance in terms of patent RCI for international collaborations are mainly located in Europe. The countries with better performance in terms of patent RCI for international collaboration and with better performance in terms of patent RCI for domestic collaboration are mainly located in Europe and Oceania.

It is important to note that while this paper supports the above findings, the findings may not be conclusive since the conclusions are reached only from looking at papers and patents in the field of solar cells. The conclusions may not apply to basic science, applied science, social science or other disciplines. Extra caution should be taken in interpretation to avoid bias.

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