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Technological collaboration patterns in solar cell industry based on patent inventors and assignees analysis

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Abstract This study examines technological collaboration in the solar cell industry using the information of patent assignees and inventors as defined by the United States Patent and Trademark Office. Three different collaborative types, namely local (same city), domestic (different cities of the same country), and international collaboration, are discussed. The general status of solar cell patent collaborations, transforming trends of collaborative patterns, average numbers of assignees and inventors for three collaborative types, and international collaboration countries are studied. It is found that co-invented patents and co-assigned patents have both increased in numbers during the four decades studied, and that collaboration between technology owners is very low while the collaboration between inventors is active. Domestic collaboration is the main collaborative pattern for both assignee collaboration and inventor collaboration. The other two collaborative types show contrary trends: international collaboration has slowly risen in the past decades while local collaboration has dwindled. The US has the largest number of internationally collaborative patents worldwide, though such patents account for a low portion of total US patents. In contrast, China has a small total number of patents and internationally collaborative patents, however its international collaborative shares are higher. The international collaboration patents among countries are few. A co-assigned patent analysis indicates that the main international cooperation partner of the United States is Japan. Based on an international co-invented patent analysis, the main international collaboration partners of the United States are Britain, Japan, and Germany; and the United States is also the most important collaboration partner of China.

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Introduction

With the help of information and communication technologies, knowledge-based economies emerge when people group in an intense effort to co-produce new knowledge (i.e., produce and exchange) (David and Foray 2002). Some research views the increasing collaborative inventive activities globally as natural extensions of globalization in trade and investment, while others often associate a nation's competitiveness with the accumulation of technological capabilities and the specialization on a national level. Therefore the research may advocate higher level on national collaboration but strongly oppose collaborative inventive efforts across borders, worrying that such efforts will lead to dissipation and leakage through inventive partners (Ma and Lee 2008).

At a high level of generality, the technological collaboration means that invention, the people generating these inventions and the ownership of these inventions tend to cross regional or national borders more frequently (Guellec and Van 2001). As innovation involves learning and knowledge diffusion, some scholars consider that innovative actions strongly exhibit local and specific characteristics which are shaped by regional institutions (Tappeiner et al. 2008). Amin and Cohendet (1999) suggest that extra-local knowledge is an important source of innovation and helping less-favored regions break out from their "locked-in" dilemma. Collaborative knowledge production has become a central concern in recent years, not only in the scientific community, but also for policy makers with a further understanding of the role played by geographical space in research collaboration (Gao et al. 2011).

Patent analyses are particularly appropriate for probing the geographical collaboration relationships for inventive activities. Patent data represent a valuable source of information related to technological development and collaboration. Several information fields in a patent application can yield valuable insights into inventive activities. The fields of inventors and assignees usually contain detailed address information of assignees and inventors, which are suitable for analyzing collaboration status in geographical areas. Comparing US patents granted in 1969–1972 and in 1983–1986, Cantwell reports an increasing share of patents with the owners and inventors located in different countries (Cantwell 1989). Using patent data from the eight most inventive OECD countries and two Asian economic entities (South Korea and Taiwan), Ma and Lee (2008) examined the pattern of international collaboration across countries in inventive activities and found a pattern of increasing collaboration in such activities around the world over the past two decades. In other research by Gao et al. (2011), geographic variations in intraregional, inter-regional and international knowledge exchanges involving China from 1985 to 2007 are examined using patent data from the USPTO. In addition, the technological collaboration relationship may change across different disciplines and types of research. Several studies using patent co-inventorship show that the chemistry and biotechnology work involved more international partners than the electronics and material fields. In these cases, chemistry is the scientific area which shows the highest centrality degree in patent networks (Balconi et al. 2004; Lissoni et al. 2008). A similar study by Ortega observed differences between research areas when it comes to establishing collaborative ties with local, national or international partners (Ortega 2011). The results show that there are two well defined groups: A "Bio" group, with a high international collaboration pattern but less

national participation, and a "Physicist" group, supported by a high proportion of national partners but with few international connections.

Solar cells are a clean, renewable and sustainable source of green energy, and are valuable contributors to protecting our environment. A solar cell, or photovoltaic (PV) cell, is a device which converts sunlight into electricity by the photovoltaic effect. The energy crisis, along with increasing awareness of the importance of environmental conservation, also spurred global governments to promote clean energy policies and solar energy technologies. In recent years (2003–2007),total PV production grew on average by almost 50 % worldwide (Jäger-Waldau 2007). As a result, academic and industrial sectors have devoted significant effort to solar cell related research and technology development, thereby increasing the numbers of patents in this discipline. Few studies on innovation activities in solar cell industry use patent data; these studies are mostly conducted by the same research group. The researchers monitor the key technology trends in solar cell industry by combining chance discovery and survival analysis with patent data (Wang and Chiu 2010; Chiu et al. 2009, 2010). Moreover, the research for technological collaboration works in this industry is close to zero. The exception is the study of collaborations in solar cell science and technology observed by paper data and patent data where researchers found that collaboration in patents on an international scale as analyzed by co-inventorship is not active (Chen et al. 2010). In light of the lack of studies in this area, this study attempts to explore the collaboration environment in solar cell industry through patent perspective over a long time frame. The study also tries to determine through analysis of patent inventors and assignees whether both show growing trends in collaboation, and to explore the similarities and differences between inventor collaboration and assignee collaboration. In addition, this paper attempts to see if the distance of collaboration has become longer with the benefits of networking through the analysis of three collaboration types in recent years. Then, the average numbers of assignees and inventors per co-patent are calculated in serval time periods. Furthermore, the active collaborative countries or regions in the solar cell industry are explored, and the main collaboration partners of active collaborative countries are revealed.

Data and methodology

Data collection

Patents are downloaded from issued databases of the United States Patent and Trademark Office (USPTO). The USPTO is the most important such database, as the US is the center of the global economy and technological development, especially in solar cell industry, and as such the patents in the USPTO are more representative and valuable. Approximately half of the inventions of US patents are foreign-owned, and each country's invention patents in the US are roughly proportional to their country's Gross Domestic Product (GDP) (Narin 1991). Taking geographical factors into consideration, the USPTO patents provide detailed address information of assignees and inventors which are essential to analyze geopolitically-related collaboration. For other patent data sources, some have small foreign-owned patent shares, such as the State Intellectual Property Office of P.R.C. (SIPO), which has only about 8 % issued foreign-owned patents in 2011 (SIPO 2012). Some sources lack detailed address information for assignees and inventors in patent text content. For example, Espacenet database from the European Patent Office (EPO) only provides the countries of assignees and inventors but no address information. Thus, the

Table 1 Related IPC symbols of Photovoltaic (PV) filed

Photovoltaics (PV)	IPC
Devices adapted for the conversion of radiation energy into electrical energy	H01L 27/142, 31/00-31/078, H01G 9/20, H02N 6/00
Using organic materials as the active part	H01L 27/30, 51/42-51/48
Assemblies of a plurality of solar cells	H01L 25/00, 25/03, 25/16, 25/18, 31/042
Silicon; single-crystal growth	C01B 33/02, C23C 14/14, 16/24, C30B 29/06
Regulating to the maximum power available from solar cells	G05F 1/67
Electric lighting devices with, or rechargeable with, solar cells	F21L 4/00, F21S 9/03
Charging batteries	H02J 7/35
Dye-sensitised solar cells (DSSC)	H01G 9/20, H01M 14/00

Source: World Intellectual Property Organization (WIPO). IPC Green Inventory. http://www.wipo.int/classifications/ipc/en/est/

USPTO is the most appropriate source to research technological collaboration patterns in solar cell industry by patent inventors and assignee analyses.

The search queries are composed of keywords and IPC (International Patent Classification) symbols. The European Patent Office (EPO) website provides a "Find Classifications for Keywords" function, which can report the related IPC symbols for technological keywords. This study entered "solar cell" and "photovoltaic" in the dialog box, and the webpage reported that H01L031 is the important IPC symbol related to solar cells (Wang and Chiu 2010). Furthermore, the World Intellectual Property Organization (WIPO) (2012) website also provides the "IPC Green Inventory". This was developed by the IPC Committee of Experts in order to facilitate searches for patent information related to so-called "Environmentally Sound Technologies" (ESTs). Currently, ESTs are widely scattered across the IPC in numerous technical fields and presented in a hierarchical structure. Photovoltaic (PV) is one of the sub-fields in solar energy, and the related IPC symbols of this area are listed in Table 1.

Therefore, this study gathered patents which contained keywords related to and including "Solar Cell", such as "Solar Battery", "Solar module", "Photovoltaic" or "PV System" in the "Title", "Abstract" and "Claims" fields, and they are assigned the related IPC symbols. Ultimately, we retrieved 9,650 solar cell utility patents in USPTO granted patent database.

Inventor collaboration and assignee collaboration

The USPTO patent data provide detailed address information of assignees and inventors, therefore we can obtain the name of the country or city where the assignees or inventors are located. Patent inventors are the creators of innovation, so inventors' addresses represent the locations of inventive activity. As assignees are generally associated with patent and commercial rights, which are opposed to innovative aspects of patents, the assignees' addresses point out that the intended agent and the location for deployment and commercialization of intellectual property rights accrue to the patent while filing the application (Ma et al. 2009). Because the main aim of filing a patent is to ensure the right adscription of the patent and protect the invention in order to obtain the best economic benefit, the patent collaboration relationship not only considers the invention but also rights

and potential market income. It is clear that inventor collaboration and assignee collaboration represent two dimensions of geographical collaboration; the former reflects the collaboration of inventive activity, and the latter represents the economic collaboration produced by innovation.

Collaborative relationships can be observed from the number of inventors or assignees on patents. Multiple inventors mean that several inventors collaborated to complete an invention for which the patent application is filed. Similar to multiple inventors, it is possible to assign a given patent to multiple assignees. Empirical evidence suggests that some inventions from multinational companies' (MNC's) subsidiary locations are either jointly (with the subsidiary) or exclusively assigned to the MNC's headquarters for certain strategic reasons (Etemal and Dulude 1987). The former brings a growth in co-assignment, while the latter results in non-matching countries of the residence between inventors and assignees. Multiple assignees represent potential economical collaboration for realizing patents' commercial benefits.

One thing needs to be noticed that there may be no assignee declared in patent applications. It is possible to leave the assignee field blank according to the permission of patent office (i.e., "no assignee"). The Patent Law of America only dictates that the individual inventor can file for a patent and corporation can obtain patent rights through transference. Therefore, an applicant with no intended location for commercialization of the filed patent, or patent applications that protect intellectual property but have no commercial benefits may result in no assignee being named.

Three collaborative types

In terms of the address information of inventors and assignees, each collaborative patent can be classified into one of three collaborative types: local collaboration, domestic collaboration, and international collaboration.

- Local Collaboration (LC): inventors or assignees are from the same city.
- Domestic Collaboration (DC): inventors or assignees are from different cities but in the same country.
- International Collaboration (IC): inventors or assignees are from two or more countries.

Collaborative patents are classified according to collaborative type, following the "maximum distance principle". If a patent belongs to more than one collaborative type, the priority rule will be shown as IC > DC > LC. For instance, if a patent is applied for by three companies, one in Tokyo, Japan, another one in Osaka, Japan, and a third located in Washington DC, USA, according to the "maximum distance principle", this patent is considered as an international collaboration patent by co-assignee analysis.

Measurement of collaboration

An important but controversial issue in collaboration analysis is to assign the credit for a collaborative patent to its partner countries (or cities). If a patent is produced by four inventors, two in Germany, one in Japan, and one in the USA, it can be easily seen that three international collaboration linkages and one domestic collaboration linkage are involved:

[Germany, USA] [Germany, Japan] [Japan, USA] [Germany, Germany].

Since the primary concern of this study is not simply on collaborative patents in solar cell industry but also on the collaboration environments involved, we have adopted the 'whole count' method in preference to 'fractional counting'. In the whole count method, a

link between any two countries would be counted as 1; whereas it would be counted as 1/4 in the fractional counting method. We assume that a link between any two countries is always seen as single unit, which does not vary with the number of countries involved in a collaborative patent. When we calculate the patent number of each collaborative country for this patent, it is recorded as one patent by Germany, one by Japan and one by the USA. That is, the calculation does not include weighting factor.

Results

General status of solar cell patent collaboration

This study examines the patents in the solar cell industry, investigates the two collaborative dimensions including patent assignees and inventors, and analyzes the overall trends as well as the developments in four 10-year periods (1971–1980, 1981–1990, 1991–2000, and 2001–2010). The following is the analysis of the perspectives of collaborative numbers for patents, and the collaborative percentages in two collaborative dimensions.

Table 2 shows that patent collaboration among assignees is very few, only 229 patents, with 2.8 % of the total patents collaborated upon by assignees. The low share of co-assigned patents indicates that the exclusive degree of technology owners in solar cell industry is high. In contrast, the number of cooperative patents by patent inventors is large, and 5,927 patents (61.5 %) are collaborative patents as analyzed by inventors. The large number and share of co-invented patents show that technology collaboration in the solar cell industry is necessary and active.

Closer investigation into the change in collaborative patents reveals that collaborative patent numbers have increased gradually for both assignee and inventor collaboration. This shows that invention has shifted from single inventors or organizations to more collaborative efforts. For patent assignees, the collaborative share has increased from 0.9 to 2.8 %, an increase of 1.9 % in the 40 years; the collaborative share for inventors has grown from 45.8 to 67.7 % with an increase of 21.9 %. It indicates that patent inventor collaboration has been more active than assignee collaboration in the solar cell industry. In the samples, 1,481 patents without assignees are excluded from the calculation.

Table 2 Numbers and percentages of co-assigned patents and co-invented patents

	Assignee			Inventor		
	Collaboration	Single	Total	Collaboration	Single	Total
1971–1980	7 (0.9)*	757 (99.1)	764 (100)	428 (45.8)	506 (54.2)	934 (100)
1981–1990	29 (2.0)	1,401 (98.0)	1,430 (100)	925 (53)	819 (47)	1,744 (100)
1991–2000	70 (2.9)	2,361 (97.1)	2,431 (100)	1,816 (62.8)	1,077 (37.2)	2,893 (100)
2001–2010	123 (3.5)	3,416 (96.5)	3,539 (100)	2,758 (67.7)	1,316 (32.3)	4,074 (100)
Total	229 (2.8)	7,935 (97.2)	8,164 (100)	5,927 (61.5)	3,718 (38.5)	9,645 (100)

* The numbers in brackets mean the ratio of collaboration patents or single patents to total patents in certain periods

Changing trends of collaborative pattern

For collaborative patents, three collaborative types: local collaboration (LC), domestic collaboration (DC), and international collaboration (IC) are studied by the analyses of assignees and inventors. The percentages of co-assigned patents for three collaborative types with the total number of co-assigned patents during the 1971–2010 periods are shown in Fig. 1.

The numbers of co-assigned patents in each collaborative type with the total number of co-assigned patents in four periods are shown in Table 3.

The results show that the proportion of LC patents has declined 1971–2010 while the proportion of DC patents increased year by year. The proportion of IC patents shows a rapid growing trend in the most recent 10 years, which means the distance of assignee collaboration has become longer. From Table 3, it is clear that the numbers of co-assigned patents of domestic collaborations and international collaborations have increased in the past four 10-year periods, but that of local collaborations has decreased slightly in recent 10 years. Moreover, local collaboration and domestic collaboration are the main collaborative types of assignees in previous 20 years (1971–1990), whereas domestic collaboration is the only predominant type of co-assigned patent in the later 20 years. In the first 10-year period (1971–1980), there were several local collaborations and domestic collaborations, but no international collaboration. The number of domestic collaboration patents increased rapidly and was larger than that of local collaborations in the following three 10-year periods. The number of international collaboration patents has increased extensively and has become an important collaborative type in the recent 10 years. However, local collaboration is to the contrary, with 25 co-assigned patents in 2001–2010, which is lower than the 26 in 1991–2000.

Similarly, the percentages and numbers of co-invented patents for different collaborative types in the four periods are shown in Fig. 2 and Table 4 respectively. The results

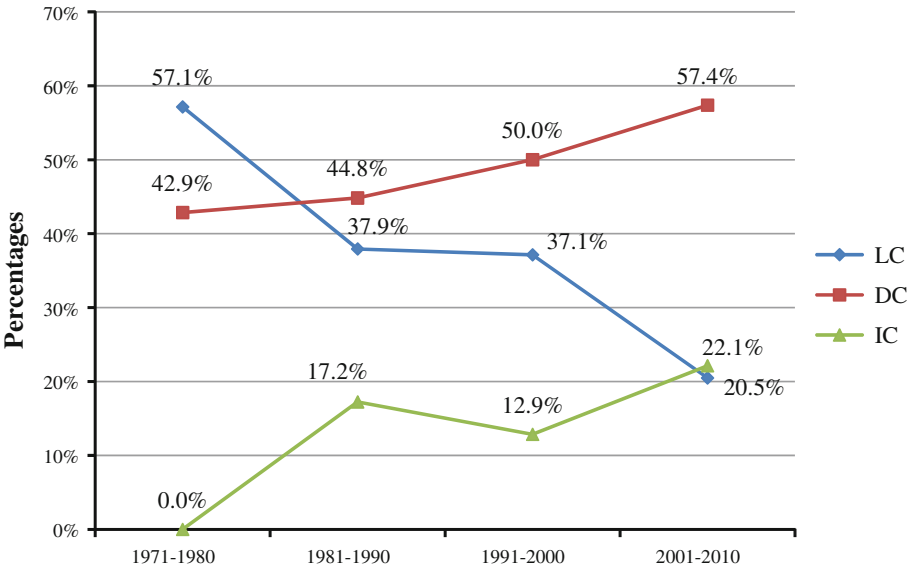

Fig. 1 Percentages of three collaborative types of co-assigned patents

Table 3 Numbers of co-assigned patents of three collaborative types

	LC (%)	DC (%)	IC (%)	Total (%)
1971–1980	4 (57.1)*	3 (42.9)	0 (0.0)	7 (100)
1981–1990	11 (37.9)	13 (44.8)	5 (17.2)	29 (100)
1991–2000	26 (37.1)	35 (50)	9 (12.9)	70 (100)
2001–2010	25 (20.5)	70 (57.4)	27 (22.1)	122 (100)
Total	66 (28.9)	121 (53.1)	41 (18.0)	228 (100)

* The numbers in brackets mean the ratio of this kind of co-assigned patents to total co-assigned patents in certain periods

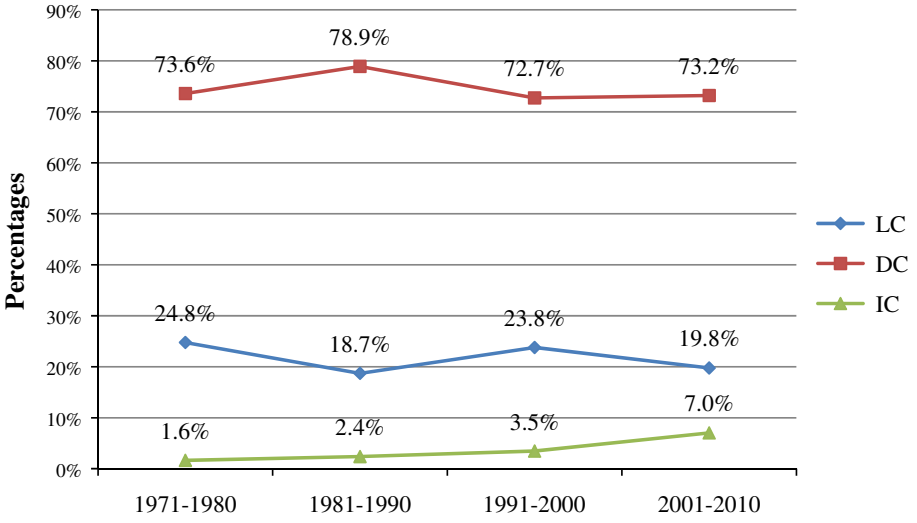

Fig. 2 Percentage of three collaborative types of co-invented patents

reveal that domestic collaboration has been the predominant type of inventor collaboration throughout the 40 years, with an average percentage of 74.6 %, larger than that of co-assigned patents. The percentages in Fig. 2 show that domestic collaborations have shown the highest percentage of the three collaborative types, and the percentage has been steady during the four periods. The percentage of local collaboration patents has declined from 24.8 % (1971–1980) to 19.8 % (2001–2010), a decline of 5 %, while the percentage of international collaboration patents has risen from 1.6 % (1971–1980) to 7 % (2001–2010), a rise of 5.4 %. From Table 4, it is clear that the number of domestic collaboration patents have increased rapidly, especially in the most recent 10 years. For local collaboration and international collaboration, though the patent numbers have always been much lower than that of domestic collaboration in the four periods, they have still gradually increased. In general, the result shows that local collaboration on co-invented patents in solar cell industry is in a decline; however, international collaboration is increasing. It is similar with the transferring trend of assignee collaboration.

Table 4 Numbers of co-invented patent percentages of three collaborative types

	LC (%)	DC (%)	IC (%)	Total (%)
1971–1980	106 (24.8)*	315 (73.6)	7 (1.6)	428 (100)
1981–1990	173 (18.7)	730 (78.9)	22 (2.4)	925 (100)
1991–2000	432 (23.8)	1,321 (72.7)	63 (3.5)	1,816 (100)
2001–2010	545 (19.8)	2,019 (73.2)	194 (7.0)	2,758 (100)
Total	1,256 (21.2)	4,385 (74.0)	286 (4.8)	5,927 (100)

* The numbers in brackets mean the ratio of this kind of co-invented patents to total co-invented patents in certain periods

Average numbers of assignees and inventors for three collaborative types

Table 5 lists the average number of assignees and inventors per co-patent in the solar cell industry; grouped into three collaborative types. The total counts in Table 5 include patents without collaboration. The figures show that average number of inventors is larger than that of assignees in each period. Because the shares of collaborative patents (Table 2) are very low for co-assigned patents, most patents have single assignee and the total counts of average assignee are close to 1 in all periods. On the contrary, the shares of collaborative patents for co-invented patents are much larger than that of co-assigned patents. The percentages have increased continuously for four periods; therefore the total counts of average inventor in Table 5 point to clear characteristics for collaborations. The trend also shows a rapid growth in collaboration of inventors. Similarly, gaps exist between the average number of assignees (2.09, 2.26 and 2.02) and inventors (2.87, 3.31 and 3.95) of local, domestic and international collaborations. The gap is wider in international collaborations. For assignees, the domestic collaboration number is higher than local collaboration and international collaboration numbers, with international collaboration the lowest. It is perhaps limited by the exclusive characteristic of patent rights. For inventors, the international collaboration number is the highest and much larger than that of local or domestic collaboration. It indicates that the invention in the solar cell industry needs collaboration between several inventors, especially inventors from different countries.

Moreover, one-way ANOVA analysis is also conducted by SPSS software to test the significance of the average number trends of average assignees and inventors for three collaborative types. The results reveal that the average numbers of inventors have gradually increased for collaborations ($F(2,9) = 6.420$, $p = 0.019 < 0.05$), while the average numbers of assignees have not significantly changed ($F(2,9) = 1.397$, $p = 0.296 > 0.05$).

Table 5 Average number of assignees and inventors for three collaborative types

	Assignees				Inventors			
	LC	DC	IC	Total	LC	DC	IC	Total
1971–1980	2.75	2.00	0*	1.01	2.29	2.77	3.29	1.76
1981–1990	2.18	2.08	2.20	1.02	2.76	2.99	3.36	2.04
1991–2000	2.00	2.20	2.00	1.03	2.91	3.41	3.62	2.44
2001–2010	2.04	2.33	2.00	1.04	2.98	3.43	4.15	2.62
Total	2.09	2.26	2.02	1.03	2.87	3.31	3.95	2.38

* The number of zero means there is no international collaboration patent during this period

For local collaborative patents, the average of assignees in 1971–1980 has the largest number, 2.75. The number has decreased in the next two periods, and has slightly risen in recent 10 years, while that of inventors in four periods has increased from the initial 2.29 to 2.98. For domestic collaborative patents, the average number of assignees has increased from 2 to 2.33; the average number of inventors has also increased from 3.29 to 4.15. For international collaborative patents, the average numbers of assignees have not evidently changed, while inventors have increased rapidly.

International collaboration countries in the solar cell industry

Research has suggested that the upcoming increasing technological globalization is inevitable (Archibugi and Pianta 1996). The most fundamental activities in a company's value chain—the innovation and inventive activities—will naturally jump on the bandwagon of globalization and involve more and more international collaborative efforts in order to maintain global competitiveness (Ma and Lee 2008). To analyze the international collaboration pattern of solar cell patents, the top 10 countries are selected by number of international co-patents, total number of patents and percentage of international co-patents respectively, and the results are shown in Tables 6 and 7. It is necessary to highlight that some countries may be in one of top 10 countries groups but not in the other groups of top 10 countries, and those countries need to be appended in other group list. For example, based on the numbers of international co-assigned patents, Korea ranks the 14th. Thus is not selected in the top 10 countries, as shown in Table 6. However, Korea is in the top 10 countries of total number of patents, so it is also appended to the list.

It can be seen from Table 6 that the total international co-assigned patent numbers of these countries are small in this industry. The United States has the highest numbers of solar cell patents and international co-assigned patents of all the countries and regions, but the percentage of international co-assigned patents for all the patents is low and out of the

Table 6 International collaboration of co-assigned patents in solar cell industry

Country	Number of international co-assigned patents		Total number of patents		International collaborative share (ICS)*	
	Number	Rank	Number	Rank	Percentage	Rank
United States	34	1	4,316	1	0.79	11
Japan	16	2	2,049	2	0.78	12
France	5	3	170	6	2.94	6
Britain	4	4	94	8	4.26	5
Canada	4	4	67	9	5.97	2
China	4	4	12	18	33.33	1
Germany	4	4	677	3	0.59	13
Taiwan	4	4	307	4	1.30	9
Belgium	2	9	37	14	5.41	4
Austria	1	10	18	17	5.56	3
Italy	1	10	47	12	2.13	7
The Netherlands	1	10	53	10	1.89	8
Switzerland	1	10	95	7	1.05	10
Korea	0	14	179	5	0.00	14

* The ICS is the proportion of international collaboration patents to all the patents in a country

Table 7 International collaboration on co-invented patents in the solar cell industry

Country	Number of international co-invented patents		Total number of patents		International collaborative share (ICS)*	
	Number	Rank	Number	Rank	Percentage	Rank
United States	181	1	5,407	1	3.35	25
Germany	84	2	776	3	10.82	19
Britain	57	3	210	5	27.10	8
Japan	39	4	2,113	2	1.85	27
France	37	5	207	6	17.87	12
Austria	23	6	48	15	47.90	3
Switzerland	22	7	110	9	20.00	11
Belgium	14	8	49	14	28.60	7
Taiwan	14	8	360	4	3.89	24
Canada	13	10	128	8	10.16	20
China	13	10	35	16	37.10	5
Australia	12	12	70	10	17.14	14
Singapore	7	15	28	18	25.00	9
Korea	5	16	194	7	2.58	26
Thailand	2	20	8	24	25.00	9
Philippines	2	20	5	26	40.00	4
Mexico	1	24	3	27	33.30	6
Poland	1	24	2	33	50.00	1
Hungary	1	24	2	33	50.00	1

* The ICS is the proportion of international collaboration patents to all the patents in a country

top 10. In contrast, the total number of patents in China is very low, but the percentage of international co-assigned patents is the highest with 4 international co-assigned patents, which ranks the country among the top 10. As a large-scale developing country, China has strengthened international collaboration in almost all technological fields since successful opening-up and economic reform policies implemented in 1978. It is clear that most of the countries with high technological intensity in the solar cell industry also have more international collaboration efforts, but the percentage of international collaborations are very low, except for China. Due to the exclusive nature of patent rights, the collaboration of patent assignees has been low, especially for assignees from different countries. Therefore, the number for international co-assigned patents is small.

Table 7 shows that the United States, Japan and Germany, the top 3 inventor countries with high total patent numbers, are same as the top assignee countries. The United States also has the highest international co-invented patent number, while the percentage of international co-invented patents is low and is out of the top 10. Poland and Hungary both have the highest international collaboration share of patents with a percentage of 50, followed by Austria and the Philippines. China also has higher international collaboration share, 37.1 %, with 13 co-invented patents. Analysis shows that the international collaborative share is higher in small countries and in countries with low technological intensity.

In general, the international collaboration patent numbers and shares of inventor countries are much higher than that of assignee countries. The high technological intensity countries and high international collaboration countries are not only similar for assignee

analysis but also for inventor analysis, however, the top 10 international collaboration share countries have much difference between co-assigned patents and co-invented patents. Assignee countries with high international collaborative share are mostly high total patent countries, while the inventor countries are in the opposite situation. It needs to be noticed that China has higher international collaborative share in co-assigned patents and co-invented patents.

Main international collaboration partners

In order to further understand the international collaboration relationships among main countries in solar cell industry, the main international collaboration partners of higher international collaboration countries and the co-patent numbers are showed in Figs. 3 and 4.

In these figures, the different symbols represent different levels of co-patent counts. And the size of the symbols reflects the magnitude of international co-patent counts among the countries within the same category. There are five levels of international co-patent numbers of countries, thus five symbols in all. Triangle is the first level. Countries marked by the triangle have the largest number of international co-patents. By order, these symbols are triangle, black square, bigger circle, white square, and the smaller circle.

Figure 3 shows that international collaborations of solar cell patents among countries are really rare. Only the collaboration between the United States and Japan is prominent. The United States has the most frequent collaborations with Japan in solar cell industry. The sixteen patents among the co-operation of the United States and Japan account for half of the total international co-assigned patents of the United States. For Japan, the co-patents with the United States are the total international co-patents. It means that the United States is the most important collaboration partners of Japan, and vice versa. China has the highest International Collaborative Share (ICS) value for co-assigned patents (see Table 6), and has two international collaboration partners: the United States and Taiwan. The result partly accords with the discovery in the study of Lei et al. (2012). According to patent assignee analysis, they found that the most important partner of China was Taiwan, especially in the fields of Electrical and Electronic machinery (E&E) and Computer and Communication (C&C).

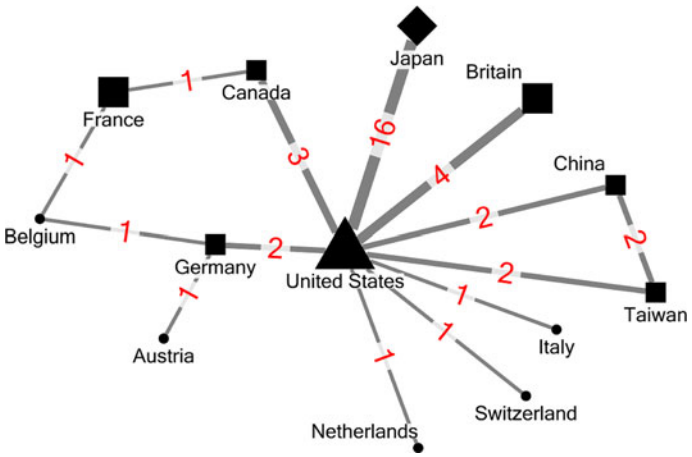

Fig. 3 Main international collaboration partners of top 10 co-assigned patent countries

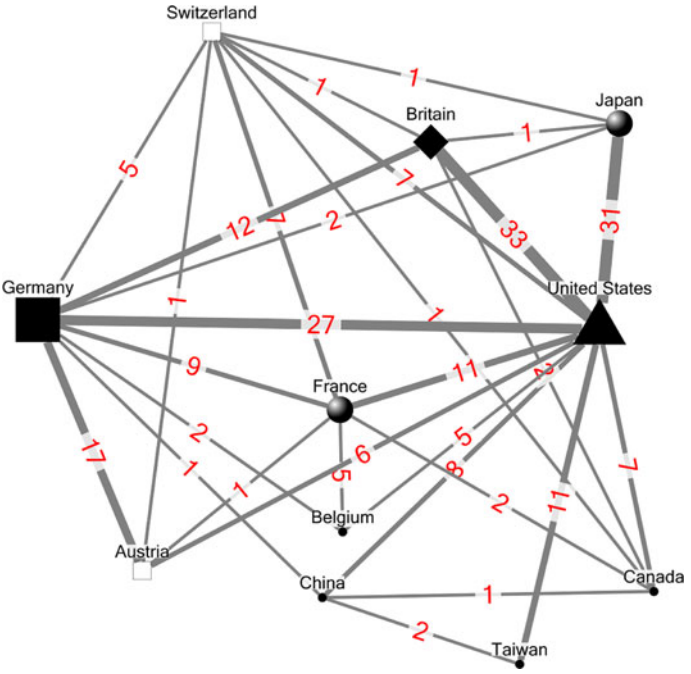

Fig. 4 Main international collaboration partners of the top 10 co-invented patent countries

Figure 4 explores the main international collaboration partners of the top 10 co-invented patent countries. It is clear that the United States has the largest number of international collaboration patents, and Germany ranks as the second. The main international collaboration partners of the United States are Britain, Japan, and Germany. Similarly, the United States is the most important collaboration partners of Britain, Japan, and Germany, and the most important collaboration partners for France, Taiwan and China. It means the innovation ability of the United States in solar cell industry is prominent and other countries would like to cooperate with it to improve their invention. It also reveals that language differences are not the holdback of patent collaborations among countries in solar cell industry. Besides the United States, Austria and Britain are also important collaboration partners of Germany. Japan conducted more collaborations with the United States than with any other countries. Taiwan and China have similar status. It is noteworthy that Austria has the closest collaboration with Germany. The co-patent numbers of Austria and Germany are larger than those of Austria with the United States. Similarly, France has more co-patents with Germany, Switzerland and Belgium except for the United States. It means that countries' regions might be one of the factors that caused the result shown in international collaboration.

Conclusion

This study is intended to examine the technological collaboration status in the solar cell industry by patent analysis. Two collaborative dimensions, patent assignees and inventors, are investigated. The research herein has drawn the following conclusions.

Patent collaboration among assignees in the solar cell industry is very uncommon, while collaboration among inventors is active. Counts of co-assigned patents and co-invented patents have both gradually increased over four 10-year periods. The percentage of co-invented patents has improved fast, but co-invented patents' share of the whole entity did not increase significantly.

For collaborative patents, three collaborative types—local collaboration (LC), domestic collaboration (DC), and international collaboration (IC)—are studied. Domestic collaboration has always been the predominant type of assignee collaboration and inventor collaboration over the forty-year period, but the co-assigned patent percentages have always been lower than the co-invented patent percentages. The local collaboration percentages of co-assigned patents and co-invented patents both show a descending trend, while the international collaborations of assignees and inventors have strengthened.

The average numbers of assignees and inventors per co-patent in the solar cell industry are also explored. The average number of assignees per patent is 1.03, lower than 2.38 for inventors. The average numbers of assignees are lower than those of inventors across all three collaborative types. The average assignee number per co-patent of domestic collaboration is higher than that of local collaboration and international collaboration in recent 20 years, and the number of international collaborations is the lowest. For inventors, the number of international collaboration is the highest and much larger than that of local and domestic collaboration in all periods. The average numbers of inventors have gradually increased for collaborations, while the average numbers of assignees have not evidently changed.

The main international collaboration countries for solar cell patents are selected by international co-patent numbers. The United States is the most active country in assignee collaboration and inventor collaboration, but its international collaborative share (ICS) is very low. It indicates strong invention ability for the solar cell industry in the United States. The international collaborative share of co-invented patents is higher in small countries and in countries with low technological intensity. China has higher international collaborative share for co-assigned patents and co-invented patents.

In order to learn the international collaborations among countries in solar cell industry, main international collaboration partners of higher international collaboration countries were explored. From the perspective of an international co-assigned patent analysis, the collaboration between the United States and Japan is more obvious than that of any other two countries. For international co-invented patent analysis, the main international collaboration partners of the United States are Britain, Japan, and Germany; and the United States is also the most important collaboration partner of China. It is also found that language differences are not the holdback of patent collaboration among countries in solar cell industry, but the regions in which those countries are located might be possible influential factors.

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