Scientometrics (2018) 117:667–686
https://doi.org/10.1007/s11192-018-2892-6

Mapping countries cooperation networks in photovoltaic technology development based on patent analysis

Alex Fabianne de Paulo[1] · Evandro Marcos Saidel Ribeiro[1] · Geciane Silveira Porto[1]

Received: 28 June 2017 / Published online: 31 August 2018

Abstract

Research activities on solar energy has been growing and use of patents becomes an important innovation source for many types of studies. This paper aims to analyze solar photovoltaic (PV) patents and describes its assignees cooperation profile. PV patents based on IPC Green Inventory code were selected from 1990 to 2014, filtered out co-ownership patents and use social network analysis (SNA) to find PV technology development networks. Main findings are an increase of patents assignees over the years and a general concern for develop technologies "Devices adapted for the conversion radiation energy into electrical energy", "Assemblies of a plurality of solar cells" and "Silicon; single-crystal growth". SNA enabled to identify four countries clusters that presented cooperation behavior and shared similar concerns in PV technology development. The USA, China, Spain and Korea were main countries of each cluster. Furthermore, through network statistics, it implied that a country that had more patents was not the most important on that technology development. The USA, Germany and UK were the most relevant countries in PV technologies because they were the ones with more cooperation with other countries and with the most collaborative countries overall. Thus, these countries are the largest holders and influencers in PV technologies development. Based on the structure and interaction between country clusters, it is possible to understand who cooperates or competes with whom. So, this information allows establishing strategies of partnerships, or even of competition, between countries, firms and research centers.

Keywords Cooperation networks · Patent analysis · Photovoltaic · Social network analysis

Mathematics Subject Classification 91D30

JEL Classification O13 · O32 · D85

✉ Alex Fabianne de Paulo
alexfp@usp.br

[1] School of Economics, Business Administration and Accounting at Ribeirão Preto, Universidade de São Paulo, Ribeirão Preto, São Paulo, Brazil

Introduction

The industry and business development in last years had caused drastic consequences to the environment. Gases emission has been leading a series of worldwide consequences widely discussed, as average global temperature increasing, higher temperature variation over period, the increase of frequency and intensity of extreme weather problems or the average increase on ocean level (IPCC 2014). The pollution levels reduction can bring benefits to population, for example, the increase of China newborns weight during the Olympics when there was a strong effort to reduce polluting emissions (Rich et al. 2015). The green technology concept has been discussed in academic environment to understand the main changes in Research and Development (R&D) as well as to establish policies and laws to facilitate and expand the technological development (Albino et al. 2014). Therefore, many countries have shown strong desire in containing weather problems and mitigate its consequences through green technologies development and diffusion (Hall and Helmers 2010), as the solar energy technology.

According to International Energy Agency (IEA 2014), the development and use of solar energy technologies will bring many benefits in the long term, thus generating photovoltaic (PV) energy could provide up to 25% of global electricity by 2050. It has been noticed over the past few years, an increase of growing in R&D efforts, whether in the academic or industrial environment, to obtain technologies that use the full potential available provided by solar power. One important mechanism used in R&D to improve technology development is cooperation. Technology cooperation tends to be a mechanism to find the key players and influencers to a technology type as well as it can help to accelerate technological development (Abulrub and Lee 2012). Also, strategic importance of exploring potential technology partners has been marked in recent years because of growing trend of collaborations for innovation across organizational boundaries (Petroni et al. 2012). Several studies have focused on identifying collaboration patterns, but they did not show in greater depth the relationship between assignee's countries and technologies. So, is there any cooperation to develop PV technologies and what is profile of these cooperation efforts between assignees of different countries?

Based on this question, this paper proposes to analyze cooperation profile between countries for development of PV technologies through patents analysis and relationship between countries of assignees. The contribution of this paper is to determine profile and trend of PV cooperation development and type of technology developed using Social Network Analysis techniques (SNA). So, this paper will also analyze countries assignees cooperation network and present the major clusters among those countries. It will be possible to identify geographic areas with common concerns in the development of each kind of PV technologies. This analysis will provide to R&D managers, government and interested researchers a better understanding of cooperation dynamics to develop PV technologies and allow them to establish strategies of partnerships, or even of competition, between countries, firms and research centers.

Review

During the last years emerged a new model for innovation management, Open Innovation, providing a better use and maximization of research, knowledge and technologies obtained by different organizations involved in innovation (Chesbrough 2006). This approach requires a different way of thinking and there are many ways to use it, such as simple collaborative exchanges to activities involving other companies, customers, suppliers, research institutions; importing and/or exporting ideas, technologies or patents (Porto and Costa 2013). Within the inventive process, collaboration takes on a special role to allow that technological knowledge be built together with several entities, such as countries, institutions or people. Thus, collaboration has become a central concern, not only in the scientific community, but also for managers and politicians with a greater understanding of the role played by the geographic dimension within the collaborative process (Gao et al. 2011).

Share the innovation process requires more intelligent way to use internal and external knowledges for each organization (Chesbrough 2012). Latest researches about open innovation are focused on identifying ways of enhancing the collaborative development of technologies such as crowdsourcing (Franzoni and Sauermann 2014). The benefits of capitalization through collaboration of external networks are another important dimension, which is consistently associated with open innovation (Chesbrough et al. 2006). This dimension covers all activities to acquire and maintain connections with external sources of intellectual and social capital, including individuals and organizations. It comprises the collaborative projects and the formal and informal network activities. External networks allow companies to quickly fulfill specific knowledge needs without having to spend huge amounts of time and money to develop this knowledge internally.

The company that exposes a problem and uses internal and external collaborative ways to find solutions, rewarding the best solution, brings returns for the company (Terwiesch and Xu 2008). Companies are working more frequently together with universities and public/private research centers, there is a notable increase in the technological cooperation and exchange of know-how between companies (Petroni et al. 2012). Dittrich and Duysters (2007) show a strategy based on prospection and collaboration between companies through technological cooperation networks. Which offers flexibility, speed, innovation and ability to adjust them to market changing conditions and new strategic opportunities.

Among the researches of solar energy development technologies improvements, Dong et al. (2012) through bibliometric analysis indicated an increase in publications about solar energy between years 1991 and 2010, which shows a growing interest in this subject. Lei et al. (2013) examine the technological cooperation in the solar cell industry through patents and identify the types of local, national and international collaboration, and co-ownership between organizations of the same country the main standard collaboration identified. Taking Dye-Sensitized Solar Cells (DSSCs) as an example, Wang et al. (2014a) examine the fast growth of this technology in China and investigate the increasing collaboration between China and other countries/region through bibliometric analysis and social networks exploiting the scientific collaboration patterns. Exploring through the international collaboration between countries and regions in the DSSCs industry, Wang et al. (2014b) identified the formation of three clusters, each one with its unique characteristics of international collaboration. While Guo et al. (2010) traced the nano-enhanced solar cells and thin-film R&D standard to capture main technological attributes, actors and networks, comparing the major countries and organizations involved in this technology development.

Having patents or literature information as a basis, the nodes may represent inventors, patent owners or their own patents or scientific papers. Edges may represent cooperation between the nodes. The entities position within networks has also been another attribute analyzed. It was found that entities that serve as interfaces or connections between different groups or R&D departments show increased patents production and reference frequency (Salmenkaita 2004). Thus, entities, which are positioned as intermediary's information between groups with different knowledge, will be benefit with information flows and this has a positive influence on their quantitative and qualitative production (measured by patent indicators). The centrality within a network is also associated with a higher frequency of citation of these entities (Nerkar and Paruchuri 2005).

Several studies apply SNA, such as: communications between actors (nodes) in an organizational learning network (Borgatti and Cross 2003); companies network analysis in clusters or local production arrangements (APL's) (García Macías 2002); the study of small and medium business networks (Casanueva Rocha 2003), entrepreneurship and family networks (Hsung et al. 2017) and the networks between large companies and their suppliers (Carleial 2001). These quotes show some studies that prove SNA application as an important methodology to be used in different sectors. Sternitzke et al. (2007) reinforce this, which states that it has grown researches that use SNA to deep investigate and view information from patents and literature data. Some of these studies used citation information, bibliographic coupling or indicators as measures of similarity (Leydesdorff and Vaughan 2006).

As shown in previous literature review, there are several researches that assessing cooperation in PV and use SNA as part of methodology. However, such studies do not outline a comprehensive cooperation profile on development of PV technological innovations. Firstly, Dong et al. (2012) and Wang et al. (2014a, b) use data from academic publications of Web of Science rather than technological innovations as patents. Academic publication data are important for assessing knowledge flow and research interests. But present manuscript proposes to analyze effective cooperation in the PV technology development. Secondly, the other studies use patent databases restricted to a region as Guo et al. (2010) which uses patents only from PATSTAT, an EPO's (European Patent Office) database and Lei et al. (2013) which bases its analysis only on USPTO (United States Patent and Trademark Office) patents. The relevance of these two patent offices is indisputable, but using patents applied in just one office or another restricts cooperation analyzes because PV patents may be applied in many other patent offices around the world. Third, previous studies are limited to a specific type of PV technology such as "thin-film solar cells" or "dye-sensitized solar cells." Except for Lei et al. (2013), which is more comprehensive and uses the International Patent Classification (IPC), other authors select PV technologies based on terms related to this theme. Thus, present paper differs from the others by using data from several patent offices, as well as selecting PV patents with IPCs pointed out by Green Inventory (WIPO 2015). Furthermore, this paper outlines the cooperation for PV technologies development, point related clusters of countries and types of technologies interest of each cluster.

Data and methodology

To understand the cooperation profile predominantly used in the photovoltaic technology development, the first step was to build a solar energy patents database from 1990 to 2014 based on IPC Green Inventory (IPC-GI) photovoltaic classified by the World Intellectual Property Organization (WIPO 2015), which makes this classification appropriate for researches on green technologies (Porto and Kannebley 2012). Table 1 shows the chosen IPC codes for this database.

Figure 1 show a synthesis of methodology used on this paper. Data were collected through the *Derwent Innovation* (DI) database, which has data from the major world patent offices and allows simultaneous access for the information of patent authorities. The

Table 1 Alternative energy production: IPCs photovoltaic solar energy. *Source*: Adapted from IPC *Green Inventory* (WIPO 2015)

Description of photovoltaic technology (PV)	IPC list
Devices adapted for the conversion of radiation energy into electrical energy	H01L 27/142, 31/00-31/078; H01G 9/20; H02N 6/00; H01L 27/30, 51/42-51/48
Assemblies of plurality of solar cell	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 cell	G05F 1/67
Electric lighting devices with, or rechargeable with, solar cells	F21L 4/00; F21S 9/03
Charging batteries	H02J 7/35
Dye-sensitized solar cells (DSSC)	H01G 9/20; H01M 14/00

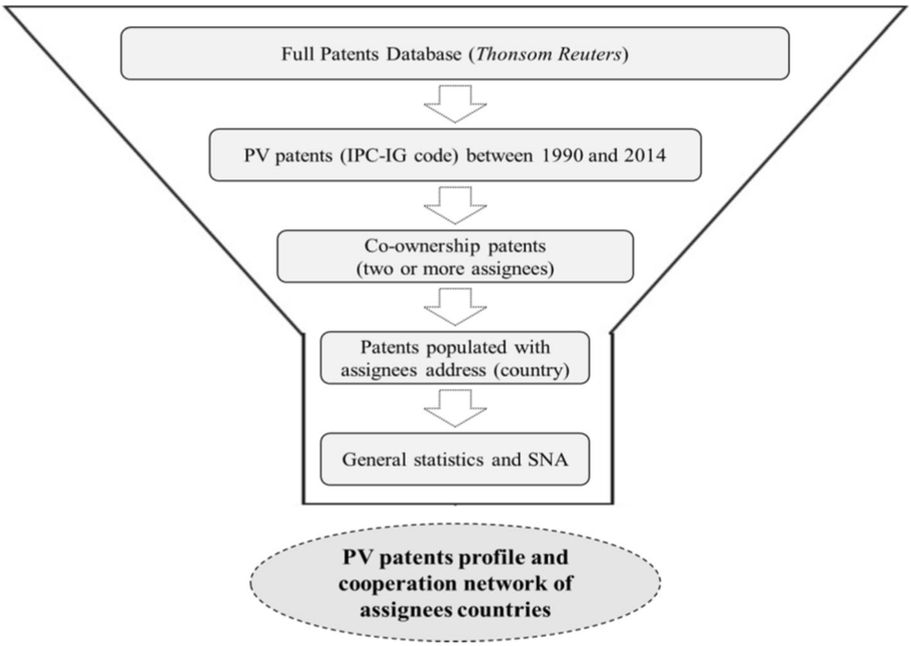

Fig. 1 Methodology synthesis

searches were done on this base from the selected IPC-IG patent codes to identify all the applications from 1990 to 2014. These data were exported and reorganized using Microsoft Excel spreadsheets. The analyzed data refers to the following fields found on patents: publication number, IPC code, publication year, assignee name and assignee address (country). All applications (publication number) were used but not INPADOC family patent codes. This paper doesn't consider data relating to inventors because the objective is to analyze the relations of co-ownership between countries of organizations that hold rights of PV patents. Evaluating patents from the perspective of those who effectively own the technology allows to analyze issues related to the interests of market protection as well as strategies of competition between organizations. Moreover, most of patent databases present some restrictions in filling of address and country data, either to assignees or inventors. Only the American patent database provided by USPTO has some more detailed address information for assignees and inventors. As this study choose for a broader approach, permeating several other patenting entities which would allow a global analysis on PV cooperation, data on assignees' countries are more consistent for the database collected.

There is no doubt that collaborations among different types of organizations (i.e. university, research institute or enterprise) are very important for open innovation literature because it could reveal more profound results if cooperation between different kinds of organizations. So, present analyzes were made by grouping countries of assignees and point out a macro vision on technological cooperation and there are no specific discussions whether assignees are universities, research institutes or companies. The results and discussions in this line are object of further studies by the authors.

Since the objective was to study cooperation, patents with more than one assignee were adopted as a cooperation proxy. Thus, the patent with a single assignee can be assumed to be developed exclusively by their assignee without any cooperation between organizations (assignee). Figure 2 shows the evolution of patent applications regarding the number of assignees over the analyzed period. It is observed that throughout the 1990s the patents were required mostly with a just one assignee. This situation was changed in the early 2000s, being in the same proportions between patents with one or more than one assignee. After 2010 there has being found again a trend in developing innovations resulting from internal effort and not from cooperation with other entities. Despite this conclusion, the period 2010–2014 had 44% of patents filed by two or more assignees, which was lower than the average of 53% between 2005 and 2009. However, in absolute values, the most recent period between 2010 and 2014 produced 7746 photovoltaic patents, equivalent to 33.5% more patents compared to 5-year period 2005–2009.

For further analysis related to open innovation and the creation of cooperation networks between assignees countries, it was used only the photovoltaic patents data in co-ownership, which were analyzed by SNA techniques that allowed an understanding of innovative processes, because it is a commonly method used to analyze information flow of patents and the inter-relationship between entities as states Sternitzke et al. (2008). According to Wasserman and Faust (1994), the fundamental difference of SNA to other researches is

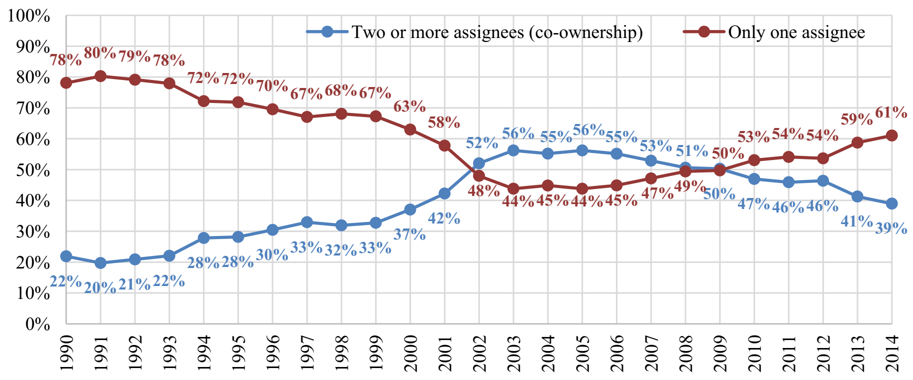

Fig. 2 Historical view of PV patents with and without co-ownership

that the emphasis is not on the attributes (characteristics) of the actors, but links between edges; that is, the observation unit is composed by the set of actors and their edges. SNA allows identify entities connection and/or companies within their technology environment, which means that actors can be recognized as hubs in network cooperation, or as bridges between the different subnets. Identify the strength of cooperation between nodes is another point analyzed in this paper. The proximity between two nodes of a network means they can be technology related. For instance, if two assignees are nearby each other, and they do not cooperate with each other, it might indicate that they are involved in a high technological competition. However, if they cooperate between themselves, they can possibly develop new technologies using complementary skills (Sternitzke et al. 2008).

It was chosen Gephi (Bastian et al. 2009) as a tool to build, visualize and analyze PV patents networks because it is an open-source software with a friendly interface and its allow agile and accurate analyses based on SNA theory. Gephi combines built-in functionalities and flexible architecture to handle all types of networks. One novelty to use Gephi for cooperation analysis is the use of modularity function (Blondel et al. 2008) to identify countries collaboration cluster for PV development. It is allowing a quick visualization of main communities' e their relation in the whole PV cooperation network. Addition SNA statistics as degree, strength, pagerank and clustering coefficient (Jackson 2008) were used, to facilitate analysis and findings of this paper. The level indicator measures the amount of countries that are connected in each node. Strength of a tie is a probably linear combination of reciprocal services which characterize the tie. The clustering coefficient refers to a network node tends to group and form communities (Newman 2010).

A complementary analysis is also done using Salton's measure. This indicator is used to define the relative strength of mutual collaboration link between two countries (Glänzel 2001; Zhou and Glänzel 2010). It can be calculated by the number of joint patents divided by the square root of the product of the number of total patents of two countries.

Results and discussions

Next sections present the results that identify assignees countries and technologies profiles. In addition, they aimed an analysis of cooperation networks for photovoltaic technologies development.

Technologies and assignees countries profile

It was identified 163,659 photovoltaic patents between 1990 and 2014. As we proposed to verify cooperation relationship using assignee countries, we had to pick out those patents that had two or more assignees (co-ownership) and they had "Assignee Address" field filled in. Therefore, we got 20,013 patents and these were patent universe analyzed (Table 2).

Over 25 years analyzed, it was verified an average increase of patents amount (15.2%) assignees (10.1%) and countries of the assignees (22.7%). The growth of patents (#PP) is quite irregular over the years, but it remains stable over the last 5 years (2010–2014), around 20% growth per year. In 1990, only nine countries cooperate on photovoltaics patents development but this scenario changes in 2014 where it can be found 49 countries with co-ownership patents (#CT). Finally, in the early 90s, patents assignee rate (#PAR) was almost 1:2 (1.89 patents per assignee) and it was concentrated in a few assignees. This

Table 2 Distribution of patents, assignees and countries of assignees

Year	#PT	#CT	#AT	#PCR	#PAR	#ACR	#PP (%)	#CP (%)	#AP (%)
1990	161	9	85	17.89	1.89	9.44	–	–	–
1991	172	9	118	19.11	1.46	13.11	6.8	0.0	38.8
1992	155	9	113	17.22	1.37	12.56	− 9.9	0.0	− 4.2
1993	168	8	117	21.00	1.44	14.63	8.4	− 11.1	3.5
1994	207	7	158	29.57	1.31	22.57	23.2	− 12.5	35.0
1995	174	9	147	19.33	1.18	16.33	− 15.9	28.6	− 7.0
1996	215	8	205	26.88	1.05	25.63	23.6	− 11.1	39.5
1997	223	10	140	22.30	1.59	14.00	3.7	25.0	− 31.7
1998	244	12	176	20.33	1.39	14.67	9.4	20.0	25.7
1999	244	10	195	24.40	1.25	19.50	0.0	− 16.7	10.8
2000	249	9	189	27.67	1.32	21.00	2.0	− 10.0	− 3.1
2001	291	15	264	19.40	1.10	17.60	16.9	66.7	39.7
2002	395	14	303	28.21	1.30	21.64	35.7	− 6.7	14.8
2003	401	17	340	23.59	1.18	20.00	1.5	21.4	12.2
2004	456	19	406	24.00	1.12	21.37	13.7	11.8	19.4
2005	455	24	366	18.96	1.24	15.25	− 0.2	26.3	− 9.9
2006	421	16	312	26.31	1.35	19.50	− 7.5	− 33.3	− 14.8
2007	816	30	756	27.20	1.08	25.20	93.8	87.5	142.3
2008	1246	32	1279	38.94	0.97	39.97	52.7	6.7	69.2
2009	1330	28	1370	47.50	0.97	48.93	6.7	− 12.5	7.1
2010	1597	37	1762	43.16	0.91	47.62	20.1	32.1	28.6
2011	2006	35	2227	57.31	0.90	63.63	25.6	− 5.4	26.4
2012	2314	44	2657	52.59	0.87	60.39	15.4	25.7	19.3
2013	2767	47	4348	58.87	0.64	92.51	19.6	6.8	63.6
2014	3306	49	5156	67.47	0.64	105.22	19.5	4.3	18.6
Total	20,013	507	23,189	39.47	0.86	45.74			

Legend: #YEAR: patent publication year; #PT: total of patents (two or more assignees); #CT: total of assignees countries; #AT: total of assignees; #PCR: rate of patent for assignee country; #PAR: rate of patent for assignee; #ACR: rate of assignee by country; #PP: growth percentage of patents compared to previous year; #CP: growth percentage of countries compared to previous year; #AP: growth percentage of assignees compared to previous year

rate decreasing over the years suggesting that there were more cooperation and co-ownership such that patents assignee rate becomes 0.64 in 2014. To prove this in Table 2, growth percentage of assignees (#AP) is much higher than the patents (#PP).

When type of technology is analyzed, Fig. 3 shows that around 70% of patents were about "Devices adapted for the conversion of radiation energy into electrical energy" (33%), "Assemblies of a plurality of solar cells" (20%) and "Silicon; single-crystal growth" (17%).

Figure 4 illustrates that before 2007, photovoltaic technologies development had low growth and it was focused on "Assemblies of a plurality of solar cells" and "Silicon; single-crystal growth". Patents about "Devices adapted for the conversion of radiation energy into electrical energy" and "Dye-sensitized solar cells (DSSC)" grown continuously over the years and got more focus since 2007.

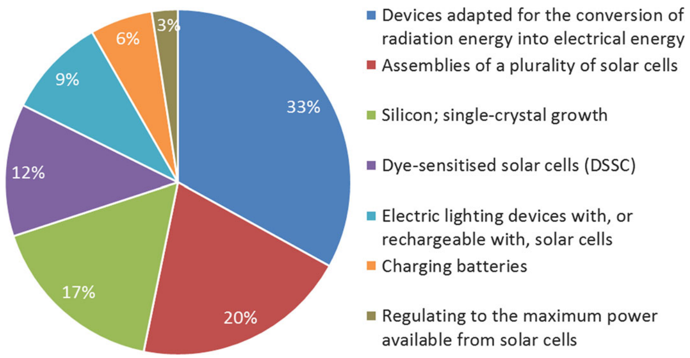

Fig. 3 Distribution of PV patents

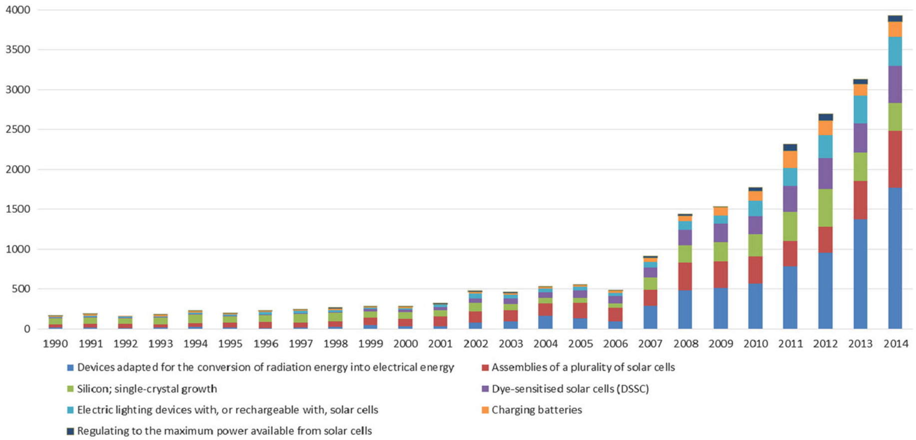

Fig. 4 Growth of PV patents over 1990–2014

Figure 5 shows distribution of patents among top 10 countries with the highest amount of patents. Assignees from these countries accumulate 91% of PV patents and Japan, USA, China and Germany were the countries that more produce photovoltaics technologies.

Figure 6 explores patents production by country over the period and it points a significant patents growth after 2006. Japan and USA led this growth over 2006 and China got a relevant position after 2008. Germany remains light growth over period and Korea showed great production of PV technologies after 2012.

Figure 7 shows various technologies types developed on top 10 assignees countries where we can see that countries have common technological preferences. The USA, Germany and UK have more focus on "Devices adapted for the conversion of radiation energy into electrical energy". Already Japan, Taiwan and the Netherlands have the most relevant research in "Assemblies of a plurality of solar cells". Japan and UK have significant technological efforts in "Dye-sensitized solar cells (DSSC)". About "Silicon; single-crystal growth" technology, France and Japan are the most important patent producer. China surpasses other countries in "Electric lighting devices with, or rechargeable with, solar cells" and the Netherlands in "Regulating to the maximum power available form solar cells". Overall, Japan and Netherlands are the countries that permeate

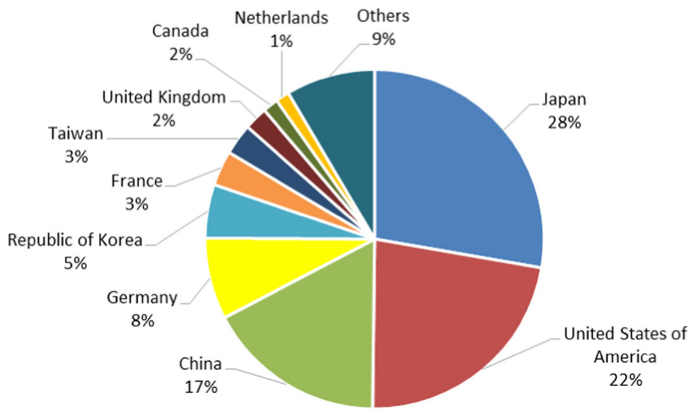

Fig. 5 Top 10 (amount) countries of PV patents assignees

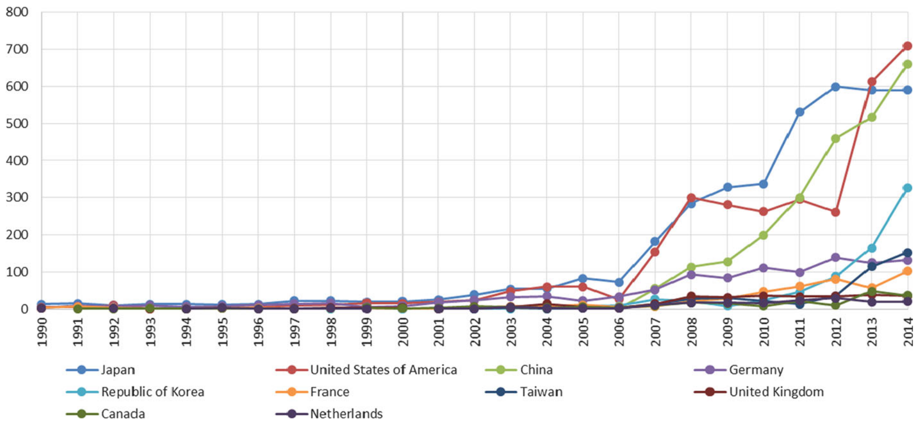

Fig. 6 Evolution of PV patents by top 10 assignees countries

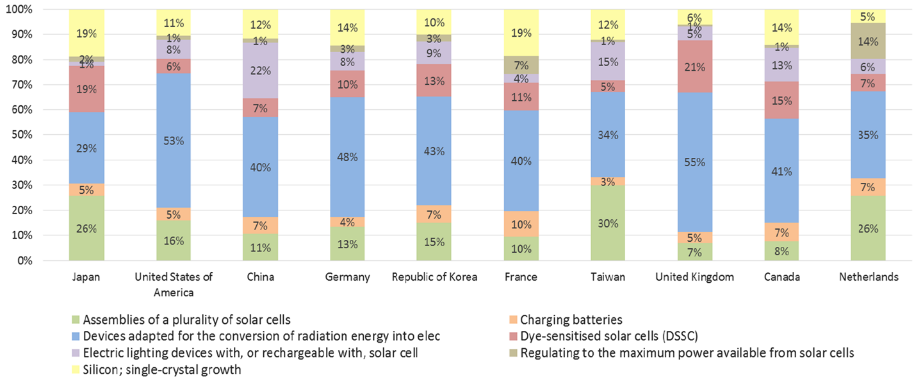

Fig. 7 PV technologies developed by top 10 assignees countries

expressively all kinds of technologies about solar photovoltaics. However, the Dutch technological effort to produce patents is much lower than the Japanese is.

Based on time evolution of amount of PV patents, assignees and co-ownership, it is possible to draw a cooperation trend line for the next years after data collected (Fig. 8). In graph (i), it observes two curves with average variation of patents and assignees by year. These variables and data are obtained from Table 2. Based on these historical curves, it is possible to identify polynomial functions that best fit the curves of variables #PP and #AP. For #PP curve, function is $y = 2E - 06x^5 - 0.0001x^4 + 0.0031x^3 - 0.0333x^2 + 0.1459x - 0.1488$ and $R^2 = 0.199$. For #AP curve, function is $y = 2E - 06x^5 - 0.0002x^4 + 0.0046x^3 - 0.0484x^2 + 0.1924x - 0.0848$ with $R^2 = 0.1364$. A projection to next 5 years through these polynomial functions can be observed in the line dotted and called "Polynomial (#PP)" and "Polynomial (#AP)" on this graph legend. Such trend curves point to an upward curve in number of patents and assignees. For co-ownership curve shown in Graph (ii), it obtained the function $y = -4E - 08x^6 + 5E - 06x^5 - 0.0002x^4 + 0.0029x^3 - 0.0196x^2 + 0.0644x + 0.1499$ and $R^2 = 0.955$. The use of this function points to a projection of increase in the cooperation percentage in 5 years as shown on this graph.

It is known that evolution in quantity of patents and assignees can point to an increase in relation of patents co-ownership. This can be verified by third curve with the percentage of

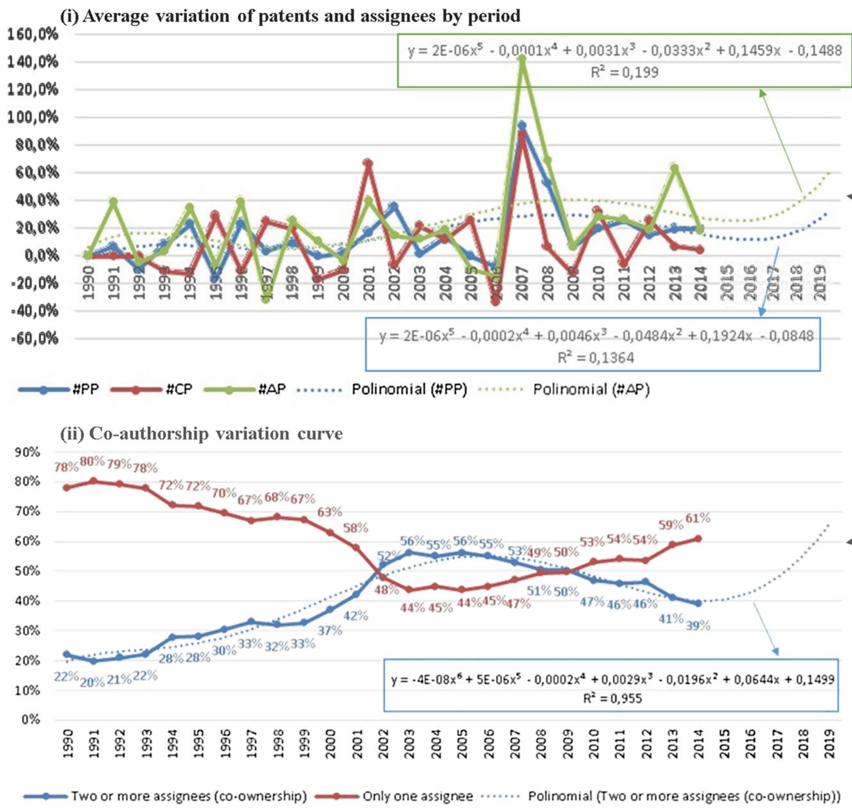

Fig. 8 PV cooperation trend

co-ownership. In summary, it can be noted that three curves present similar formats and projections and point to a positive evolution in collaboration for development of PV technologies.

Cooperation network analysis

Gephi software was used to plotting the cooperation network and a bipartite network whose nodes were composed of two categories of data: patents and assignees countries. The *OpenOrd* network layout algorithm was used to build this network (Fig. 9) where blue nodes are patents and yellows nodes are the countries of assignees. On this bipartite network, countries nodes are always linked in a patent node. Nodes size has been considered by the nodes centrality in the network that were set to highlight nodes with higher amount of edges.

For a better analysis and visualization, the bipartite network has been simplified so that patents were represented by edges and countries, by nodes. Thus, the network has been modified to be able the analysis countries cooperation and they will be linked by co-ownership patents. *Fruchterman Reingold* algorithm allowed obtaining the cooperation network between assignees countries (Fig. 9). When considering modularity statistics, it can be found clusters of countries, which implies that these countries have more cooperation links for some types of patents. In Fig. 10, the nodes are marked in accordance with modularity. It is possible verify on this network that the US, Japan, Germany and England maintains reciprocal technological effort and in less frequent level with France, Switzerland and Canada; while China cooperate more often with US and Taiwan.

For further analysis, the four main communities were isolated as showed on Fig. 11. Cluster (i) has 1.024 cooperation patents and is polarized on Korea that represents 82% of patent from this group. The main technologies developed in this cluster are "Devices adapted for the conversion of radiation energy into electrical energy" (42%) and

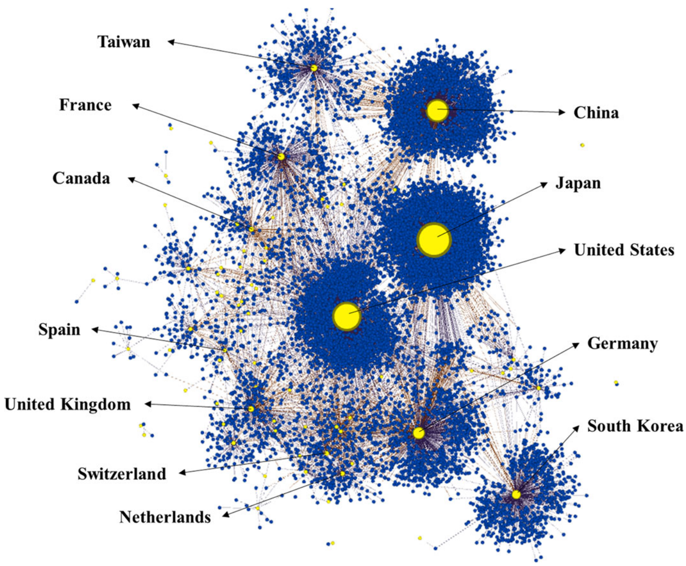

Fig. 9 Bipartite network of PV patents and countries of the assignees

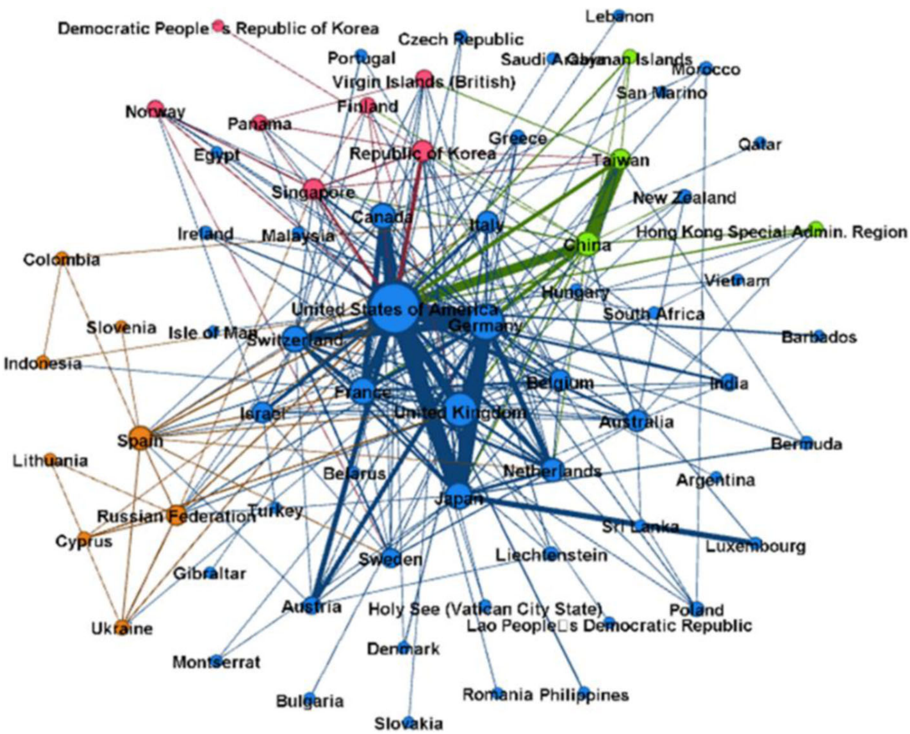

Fig. 10 Clusters of assignees countries according cooperation relationship

"Assemblies of a plurality of solar cells" (18%). The cooperation occurs in greater intensity between Korea–Singapore and Singapore–Norway. There is no triangulation in this cluster and cooperation occurs only between two countries.

The cluster (ii) is composed by four countries: China, Hong Kong, Taiwan and Cayman Islands and covers a universe of 3485 co-ownership patents. China is the main actor of this group and get 86% of patents, followed by Taiwan with 13% of patents. Most cooperation technologies in this group are "Devices adapted for the conversion of radiation energy into electrical energy" (39%) and "Assemblies of a plurality of solar cells" (13%). China focus 21% of its efforts on "Electric lighting devices with, or rechargeable with, solar cells" but cooperates only internally (within the country) without co-ownership of other countries of its group.

Cluster (iii) has 157 only cooperation patents, with 61% of these are Spanish assignees and 18% Russian. There is a greater concern in this group to cooperate for "Devices adapted for the conversion of radiation energy into electrical energy" (53%).

The cluster (iv) it is the most complex and relevant of PV network studies here. Complex by the amount nodes and edges of this subnet and relevant because it concentrates the highest amount of cooperation besides connects all other clusters. It has 75% photovoltaics patents and USA, Germany, UK and Japan are main nodes of this community. While there have been isolated for further analysis, these communities are connected (Fig. 10). In the cluster (iv), the USA cooperates both with Korea and Singapore (i), China and Taiwan (ii) and Spain (iii). In this same way, Germany (iv) cooperates with China (ii) and UK (iv) with Spain (iii).

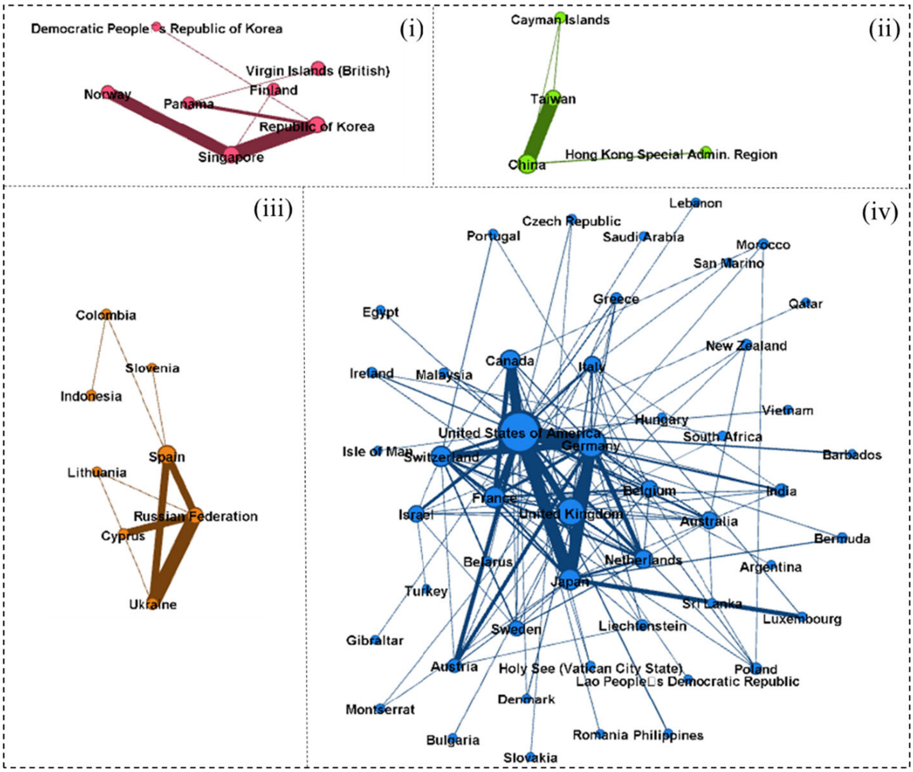

Fig. 11 Cooperation clusters for PV technologies

In Fig. 12, looking for patent co-ownership between countries of cluster (iii) and clusters (i) and (ii), it can be showed that cooperation is almost null and only an interaction between Russia–Singapore and any other interaction between the countries of cluster (iii) and clusters (i) and (ii). Thus, any link between these groups occur through cluster (iv) which will be discussed soon to follow. Because they have a common interest in patents on "Devices adapted for the conversion of radiation energy into electrical energy", possibly countries of group (iii) compete with countries of groups (i) and (ii) to development such technologies, whereas the members of groups (i) and (ii) cooperate.

Due to the size of the cluster (iv), it was decided to calculate again the modularity of this community, obtaining two new cluster (Fig. 13). Light blue cluster has France, Canada and Switzerland as main countries of this group. Already red cluster has the USA, Japan, Germany and UK as the main network nodes. Both clusters have common concern in the patents development of "Devices adapted for the conversion of radiation energy into electrical energy". However, it was identified that the light blue community has also focused on patents about "Assemblies of a plurality of solar cells" and the red community on "Silicon; single-crystal growth". Another important issue about the cluster (iv) are triangulations between countries like the USA ↔ Germany ↔ Japan, USA ↔ Germany ↔ UK and USA ↔ France ↔ Canada. Using *Fruchterman Reingold* layout algorithm (Fig. 12) to visualize community (iv), it possible see that the countries with the highest cooperation level remain at the center of the network and they have thicker edges

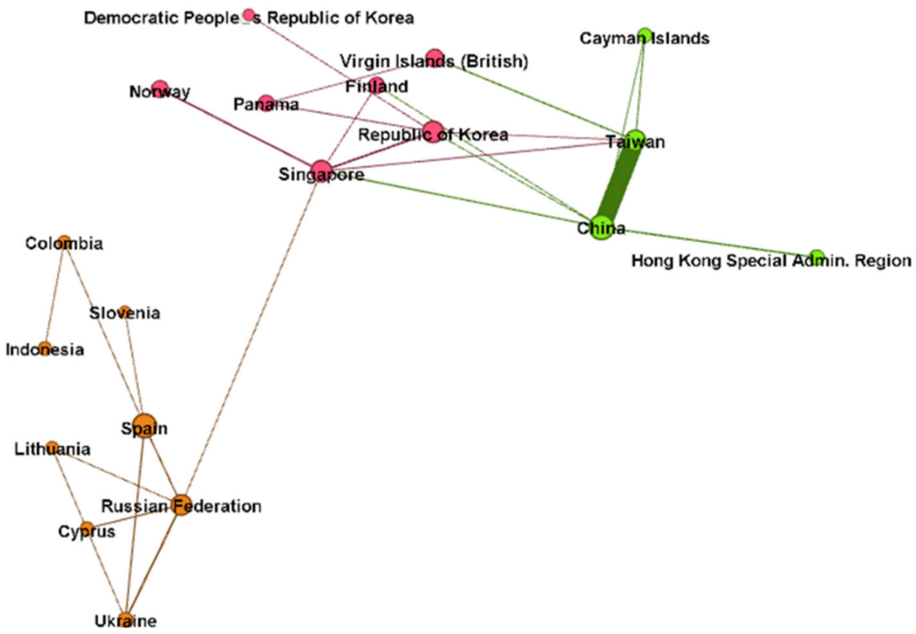

Fig. 12 Network formed with the main community exclusion (cluster iv)

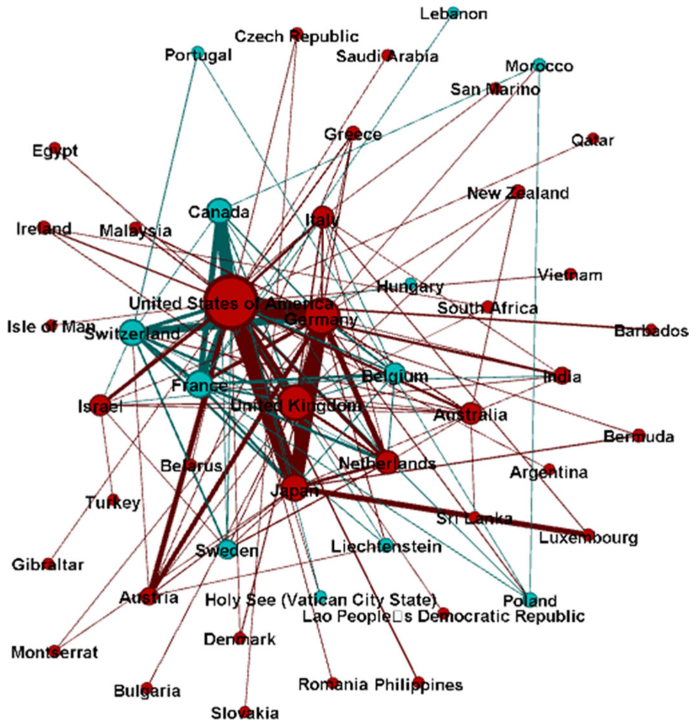

Fig. 13 Cooperation subnets of cluster (iv)

(number of patents). It brings us to conclude that these countries have a high cooperation level (co-ownership) to photovoltaic technologies development.

A relevant node in the network can be obtained by function called *Page Rank* (Page et al. 1999), which assesses how one node 'X' is relevant by analyzing the quantity and quality of the other nodes that bind to this node 'X'. In general, the node 'X' will have a high *Page Rank* value if there are many other nodes connected to 'X' and if important nodes also linked to 'X'. Figure 14 shows a cooperation network of 10 countries with higher *Page Rank* statistic.

Using the Salton's measure, Table 3 shows the relative strength of the collaborative relationships among top 10 ten assignees shown in Fig. 14. The use of this indicator complements the analysis of network co-ownership because it takes the patent size of two collaborated countries into account. The colors in the table represent the strength of cooperation between two countries, with green cells representing the strongest relationships and red one, weakest or no cooperation. The yellow and orange colors can be understood as a cooperative relationship with medium force. Thus, it is observed that the strongest cooperation relations between these countries are: Canada–France and Canada–United States, Switzerland–Germany, Germany–Japan and Germany–United States, and Japan–United States. The proportion of collaborative patents between these countries is relatively high when compared to total of patents produced by them, which characterizes such countries as strong partnerships for development of PV technologies.

More than quantity of patents, Page Rank analysis points to the most important network nodes. The USA, Germany, UK and France are the most important countries in the photovoltaic collaboration network as these countries have several links with other countries and they have important countries linked to them. Although they are key countries in their respective clusters, China and Spain has low influence on overall network. Table 4 describes some other indicators obtained from cooperation network of photovoltaic solar energy for the top 10 countries according to *PageRank* function.

The network statistics analysis above complements the descriptive statistics on the assignees countries and allows a broader view of the importance of each country (node) on the network. Undoubtedly, amount of patents is important, but when the focus is study of cooperation in technological development, statistics as *Page Rank* and clustering coefficient are suitable to show the influence of a country over other countries. As an example,

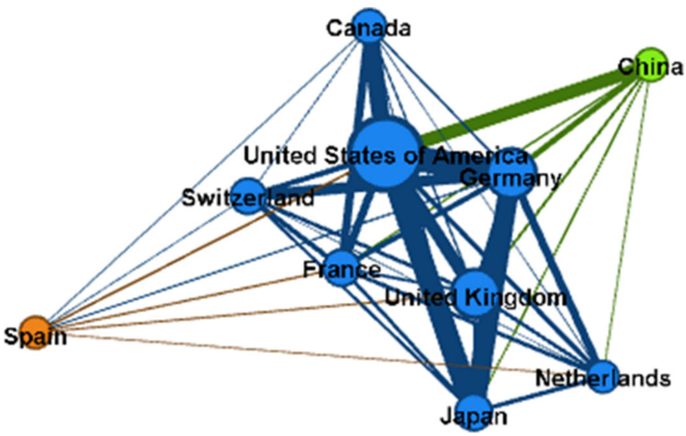

Fig. 14 Top 10 PV development countries based on page rank

Table 3 Strength of mutual collaboration based on Salton's measure. (Color table online)

	Canada	Switzerland	China	Germany	Spain	France	United Kingdom	Japan	Netherlands	United States
Canada	–	0.052	0.000	0.166	0.060	1.224	0.218	0.031	0.050	1.233
Switzerland	–	–	0.176	1.239	0.066	0.029	0.595	0.156	0.054	0.328
China	–	–	–	0.353	0.000	0.093	0.152	0.063	0.039	0.719
Germany	–	–	–	–	0.117	0.479	0.743	1.196	0.864	1.585
Spain	–	–	–	–	–	0.172	0.153	0.000	0.864	0.105
France	–	–	–	–	–	–	0.320	0.181	0.546	0.511
United Kingdom	–	–	–	–	–	–	–	0.138	0.536	0.860
Japan	–	–	–	–	–	–	–	–	0.233	1.088
Netherlands	–	–	–	–	–	–	–	–	–	0.292
United States	–	–	–	–	–	–	–	–	–	–

Table 4 SNA statistics from top 10 countries of PV cooperation network. (Color table online)

Assignee country	Page rank	Degree	Strength of ties	Clustering coefficient	Patents amount
United States	0.1141	50	675	0.125	3201
Germany	0.0552	30	435	0.280	1102
United Kingdom	0.0538	29	180	0.303	317
France	0.0356	19	169	0.450	473
Japan	0.0345	19	288	0.444	3946
Switzerland	0.0340	18	139	0.458	160
Canada	0.0311	17	130	0.449	211
Spain	0.0291	15	35	0.467	68
China	0.0288	16	203	0.525	2442
Netherlands	0.0265	15	107	0.638	185

we can see the cases of Japan and China: are among the top three patent assignees, but on the other hand, they have *Page Rank* and clustering coefficient well below to other countries like the USA and Germany.

Conclusions

It is being consensus nowadays the importance of the search for alternative energy that are clean (non-polluting) and renewable (sustainable). Regarding the electricity generation, it is clear the nations concerns to explore the generation power capacity through solar irradiation. In this context, photovoltaic technologies have gained attention from research centers and companies and have been increasingly subject of many studies. To collaborate in this field, patent data and Social Network Analysis methodology were used to support the results and discussions that show PV patents profile and trace cooperation network of assignees countries.

In the period between 1990 and 2014 it was realized an average growth in patents amount, assignees and countries of 15.2%, 10.1% and 22.7%, respectively. However, the patents growth has been irregular over the years and stabilized in 20% from 2011. Other important issue concerns the rate of patents per assignees in the 90 years was 1.89 patents per assignees and decreased to 0.64 in 2014. It appears that there are more assignee and more cooperation (co-ownership) after 2011. About the technological areas often developed, 33% are patents on "Devices adapted for the conversion of radiation energy into electrical energy", 20% "Assemblies of a plurality of solar cells" and 17% "Silicon; single-crystal growth". Patents about "Devices adapted for the conversion of radiation energy into electrical energy" continuously grown over the years, but gained greater focus from 2007. "Dye-sensitized solar cells (DSSC)" technologies had more relevance from 2011. When analyzing the assignees countries that more produces patents, there is an increase from 2007, being spearheaded by Japan and USA, and in 2008 by China. Germany also has a growth over period, but remained stable from 2010. It is interesting to note the case of Korea that from 2012 showed large increase in patenting of photovoltaic technology.

By exploring the cooperation network between assignee countries, it was identified that there are four cooperation clusters, with the following characteristics: (1) technological focus on "Devices adapted for the conversion of radiation energy into electrical energy" (42%) and "Assemblies of a plurality of solar cells" (18%), led by Korea; (2) China is the pivot and West Asian countries, has the technologies with greater focus in "Devices adapted for the conversion of radiation energy into electrical energy" (39%) and "Assemblies of a plurality of solar cells" (13%); (3) expressiveness community (smaller size), it has Spain as anchor and technological areas that there are more cooperate "Devices adapted for the conversion of radiation energy into electrical energy" (53%).

An important fact is that the cooperation between cluster of Spain (iii) and China cluster (ii) and Korea cluster (i) is practically null. Any interaction between these groups is done through cluster (iv). The cluster (iv) concentrates the largest amounts of co-ownership patents and intermediates links between other communities. In this cluster, there are countries like France, Canada, Switzerland, USA, Japan, Germany and UK. There are various cooperation interests inside this cluster: in most countries, there is an interest in developing "Devices adapted for the conversion of radiation energy into electrical energy". However, there is a focus on subgroup also in "Assemblies of a plurality of solar cells" and another subgroup that develops technologies for "Silicon; single-crystal growth".

It is observed that in all clusters there is a common interest in patent about "Devices adapted for the conversion of radiation energy into electrical energy". This type of patent encompasses technologies aimed at PV panels that, due to the exponential growth of demand for PV power generation, become a common object of technological interest. The four clusters composition presented here clearly shows the relationships of common interests and partnerships between countries, or competition insight, in PV development. This is the case of China that develops such innovations with a low cooperative relationship with other relevant countries. In practice, countries like Japan, Germany US and UK end up being competitors of the Chinese in the development of this type of technology.

Finally, the *Page Rank* function of SNA allowed concluding that a country that had more patents was not the most important on that technology development, as Japan, for example. The USA, Germany and UK were the most relevant countries in collaboration network for the PV technologies because they were the ones with more cooperation with other countries and with the most collaborative countries. Although they are key countries in their communities, China and Spain showed little influence on the overall network. Thus, USA, Germany and UK are the largest holders and influencers in the development of

PV technologies. So, based on the structure and interaction between country clusters, it is possible to understand what country cooperates or competes with which. This information allows governments, firms and research centers to think about collaboration strategies, or even of competition, as well as it supports the discussion about public policies to improve development of PV technologies. It is worth mentioning that this analysis points to a rise in the field of PV intellectual property, and there are no inferences regarding the production process of PV technologies or even the market performance of each country. Thus, this means that such countries, through their broad network and flow of exchange of technological knowledge, have more dominance over the development of PV technologies.

As future work, other SNA dimensions, as the temporal dimension (dynamic network), can be exploited to identify the cooperation evolution and to search technological routes by IPC groups. Finally, it can be achieved some multiple cases studies to deepen the conclusions got here and consolidate this research about PV technologies development.

Acknowledgements The authors are grateful to FAPESP (Foundation for Research Support of the State of São Paulo) that allowed access to Derwent Innovation database by research project assistance (Grants 2012/22686-9). Many thanks to researchers of IngTec (FEARP/USP) due several discussions about this paper subject. Authors are especially grateful to anonymous reviewers for their extremely useful suggestions to improve the quality of this manuscript.

References

Abulrub, A. H. G., & Lee, J. (2012). Open innovation management: Challenges and prospects. *Procedia-Social and Behavioral Sciences, 41,* 130–138.

Albino, V., Ardito, L., Dangelico, R. M., & Petruzzelli, A. M. (2014). Understanding the development trends of low-carbon energy technologies: A patent analysis. *Applied Energy, 135,* 836–854.

Bastian, M., Heymann, S., & Jacomy, M. (2009). Gephi: An open source software for exploring and manipulating networks. *ICWSM, 8,* 361–362.

Blondel, V. D., Guillaume, J. L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment, 2008*(10), P10008.

Borgatti, S. P., & Cross, R. (2003). A relational view of information seeking and learning in social networks. *Management Science, 49*(4), 432–445.

Carleial, L. M. (2001). *Redes Industriais de Subcontratação: um enfoque de sistema nacional de inovação*. São Paulo: Hucitec.

Casanueva Rocha, C. (2003). Relaciones estratégicas entre PYMES: contraste de hipótesis empresariales mediante ARS. *Redes - revista hispana para el análisis de redes sociales*, *4*(4), 1–27.

Chesbrough, H. W. (2006). *Open innovation: The new imperative for creating and profiting from technology*. Boston: Harvard Business Press.

Chesbrough, H. W. (2012). Open innovation: Where we've been and where we're going. *Research-Technology Management, 55*(4), 20–27.

Chesbrough, H. W., Vanhaverbeke, W., & West, J. (Eds.). (2006). *Open innovation: Researching a new paradigm*. Oxford: Oxford University Press.

Dittrich, K., & Duysters, G. (2007). Networking as a means to strategy change: The case of open innovation in mobile telephony. *Journal of Product Innovation Management, 24*(6), 510–521.

Dong, B., Xu, G., Luo, X., Cai, Y., & Gao, W. (2012). A bibliometric analysis of solar power research from 1991 to 2010. *Scientometrics, 93*(3), 1101–1117.

Franzoni, C., & Sauermann, H. (2014). Crowd science: The organization of scientific research in open collaborative projects. *Research Policy, 43*(1), 1–20.

Gao, X., Guan, J., & Rousseau, R. (2011). Mapping collaborative knowledge production in China using patent co-inventorships. *Scientometrics, 88*(2), 343–362.

García Macías, A. (2002). Redes sociales y "clusters" empresariales. *Redes - Revista hispana para el análisis de redes sociales*, 1(6), 1–20.

Glänzel, W. (2001). National characteristics in international scientific co-authorship relations. *Scientometrics, 51*(1), 69–115.

Guo, Y., Huang, L., & Porter, A. L. (2010). The research profiling method applied to nano-enhanced, thin-film solar cells. *R&D Management, 40*(2), 195–208.
Hall, B. H., & Helmers, C. (2010). *The role of patent protection in (clean/green) technology transfer (No. w16323)*. Cambridge: National Bureau of Economic Research.
IEA—International Energy Agency. (2012). *Energy technology perspectives 2014—Executive summary*. http://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives_ES.pdf. Accessed 26 December 2014.
IPCC. (2014). *AR5—Fifth assessment report, synthesis report*. http://www.ipcc.ch/report/ar5/wg1/. Accessed 15 November 2014.
Jackson, M. O. (2008). *Social and economic networks*. Princeton: Princeton University Press.
Lei, X. P., et al. (2013). Technological collaboration patterns in solar cell industry based on patent inventors and assignees analysis. *Scientometrics, 96*(2), 427–441.
Leydesdorff, L., & Vaughan, L. (2006). Co-occurrence matrices and their applications in information science: Extending ACA to the web environment. *Journal of the American Society for Information Science and Technology, 57*(12), 1616–1628.
Hsung, R. M., Fu, Y. C., & Lin, N. (2017). The position generator: Measurement techniques for investigations of social capital. In *Social capital* (pp. 57–81). Routledge.
Nerkar, A., & Paruchuri, S. (2005). Evolution of R&D capabilities: The role of knowledge networks within a firm. *Management Science, 51*(5), 771–785.
Newman, M. (2010). *Networks: An introduction*. Oxford: Oxford University Press.
Page, L., Brin, S., Motwani, R., & Winograd, T. (1999). *The PageRank citation ranking: Bringing order to the Web*. Technical Report 1999–0120, Computer Science Department, Stanford University. http://ilpubs.stanford.edu:8090/422/1/1999-66.pdf. Accessed 17 January 2017.
Petroni, G., Venturini, K., & Verbano, C. (2012). Open innovation and new issues in R&D organization and personnel management. *The International Journal of Human Resource Management, 23*(1), 147–173.
Porto, G. S., & Costa, P. R. D. (2013). Abordagens da inovação. In G. S. Porto (Ed.), *Gestão da Inovação e Empreendedorismo, Cap. 4* (pp. 45–77). Rio de Janeiro: Elsevier.
Porto, G., & Kannebley, S., Jr. (2012). *Subprojeto 3—Rotas tecnológicas e sistemas de inovação produto 03—Estrutura SASTec. Faculdade de Economia, Administração e Contabilidade de Ribeirão Preto*. Ribeirão Preto, SP: Universidade de São Paulo.
Rich, D. Q., et al. (2015). Differences in birth weight associated with the 2008 Beijing Olympic air pollution reduction: Results from a natural experiment. *Environmental Health Perspectives, 123*(9), 880.
Salmenkaita, J. P. (2004). Intangible capital in industrial research: Effects of network position on individual inventive productivity. In: *Strategy in Transition* (Vol. 223).
Sternitzke, C., Bartkowski, A., & Schramm, R. (2008). Visualizing patent statistics by means of social network analysis tools. *World Patent Information, 30*(2), 115–131.
Sternitzke, C., Bartkowski, A., Schwanbeck, H., & Schramm, R. (2007). Patent and literature statistics—The case of optoelectronics. *World Patent Information, 29*(4), 327–338.
Terwiesch, C., & Xu, Y. (2008). Innovation contests, open innovation, and multiagent problem solving. *Management Science, 54*(9), 1529–1543.
Wang, X., et al. (2014a). Collaboration network and pattern analysis: case study of dye-sensitized solar cells. *Scientometrics, 98*(3), 1745–1762.
Wang, X., et al. (2014b). International collaboration activity index: Case study of dye-sensitized solar cells. *Journal of Informetrics, 8*(4), 854–862.
Wasserman, S., & Faust, K. (1994). *Social network analysis: Methods and applications*. Cambridge: Cambridge University Press.
WIPO. (2015). World Intellectual Property Organization. IPC Green Inventory. http://www.wipo.int/classifications/ipc/en/est/. Accessed 20 December 2015.
Zhou, P., & Glänzel, W. (2010). In-depth analysis on China's international cooperation in science. *Scientometrics, 82*(3), 597–612.