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Photovoltaic technologies: Mapping from patent analysis

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ABSTRACT

The objective of this article is to identify the technological development of photovoltaic cells by the analysis of patents. The Derwent Innovations Index (DII) database of Thomson Derwent was used for this research. 22,682 patents were obtained. The results indicate that 1) the number of patents deposited on photovoltaic cells grows every year, 2) the main depositor countries are the United States, China, Japan, Germany and South Korea, 3) American and Japanese organizations stand out with the highest number of patent registrations, 4) the main areas of knowledge were Engineering, Instruments and Instrumentation, Energy and Fuels, Chemistry and Polymer Science, 5) the patents on photovoltaic cells are concentrated in the area of semiconductors for the conversion of solar radiation into electric energy, in the area of generators for the direct conversion of light energy into electric energy and in the area of solar panels adapted for roof structures and 6) there is a prominence of deposited patents for polymer-based photovoltaic cell technologies, carbon nanostructures, III-V compounds, cadmium telluride and amorphous silicon cells.

1. Introduction

The use of traditional fossil fuels to generate electric energy causes serious environmental problems, such as climate change, global warming, air pollution, and acid rain, among others. On the other hand, the consummation of electric energy on the planet increases using due to modern society's increasingly use of equipment and products that run on electricity. In this perspective the development of renewable energy technologies is necessary to obtain competitive prices to compete with traditional sources of energy that generate environmental pollution [1–6].

To address these problems, some nations have taken challenging measures. The United States, for example, announced its “Advanced Energy Initiative” in 2006 and outlined a daring goal to reduce imports of Middle Eastern oil by 75% by the year 2025 through the development of new and renewable energy sources. The South Korean Government, in turn, has established "The 2nd National Plan for Energy Technology Development" to improve its global competitiveness in energy technology. This plan aims to develop new and renewable energy technologies and improve energy efficiency by doubling energy-related research and development investments in the country by 2020. In addition, Japan and China have also established national energy Development of new and renewable energy technologies to reduce their dependence on fossil fuels and to foster a strategic green growth industry [7].

Photovoltaic technology has developed rapidly over the last thirty years. The main activities of photovoltaic patents began in the late 1950s and the main photovoltaic patent assignees at that time were involved in the space business [8,9].

Patent data has been widely used in technology assessment and forecasting [10–13]. The patent is a right granted to the researcher and is an outlet for scientific and technological development, revealing what organizations consider worth protecting. A collection of patents in a particular discipline may represent part of the accumulated knowledge in science and technology within that discipline. The growth of the number of patents of a given technology provides a good indication of its state of development [8]. However, care must be taken in using the quantity of patents to draw conclusions, since this quantity may have no relation to the quality and strength of the patent [14].

For alternative technologies, such as photovoltaics, research and development analysis is important for the observation and understanding of technologies in the market. Photovoltaic cell patent registrations are a valuable data set in the analysis and diffusion of PV

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technology and R&D activities. The dynamics of PV R&D activity is considered high, documented in a large increase in PV patent documents [9].

Considering the development of technologies in photovoltaic cells and the increase on production of electric energy by the solar source [3], a question arises is: how is the technological development of photovoltaic cells from the analysis of patent registration? The aim of this paper is to analyse patents related to the technologies of photovoltaic cells that were deposited between the years of 2004–2013. In this way, this paper contributes to the monitoring of photovoltaic cell technologies.

The article is organized in the following manner: Section 2 contains the literature review on photovoltaic cells technologies and patent analysis. Section 3 presents the methods as well as the detailed research procedure. Section 4 includes the analysis of the photovoltaic cells patents. Finally, the last section presents the conclusions, recommendations and suggestion for future research.

2. Literature review

The literature review covered the topics photovoltaic cell technologies and patent studies and analysis.

2.1. Photovoltaic cell technologies

The literature about photovoltaic solar cell technology considers three generations. Table 1 presents the main photovoltaic technologies: first generation (fully commercial) systems that use crystalline silicon technology in both their simple crystalline form and polycrystalline; second generation systems that are based on photovoltaic thin and generally include three major families: amorphous silicon, cadmium telluride and indium copper selenide, indium and gallium-diselenide; and the third generation ones that include organic photovoltaic cell technologies that are still under demonstration or have not yet been widely marketed, as well as new concepts in development.

Studies conclude that to increase PV participation in the renewable energy market it is necessary to raise awareness about the benefits (social, economic and environmental); Increase research and development of new technologies (to obtain cheaper and more efficient cells); Implement public policies and programs that encourage PV generation; More qualified professionals for this market. The photovoltaic industry needs to improve conditions for a reliable policy framework to ensure a return on investment, innovation and continuous research [41].

2.2. Patents as a source of technological information

Technological innovation is a fundamental condition for the success of the process related to productive systems and many companies invest in the development of technologies. However, in order to guide research activities, save time and avoid unnecessary expenses, the search for technological information available on patent bases and in specialized literature should be consulted before starting new projects [42,43].

Identifying product opportunities using patent analysis is important because it facilitates the creative process of generating new products that product developers do not tend to intuitively consider. Being able to forecast products and services that can lead the future allows for greater competition between rival companies. Providing promising technology through patent analysis is a relevant opportunity for the management and decision-making of companies and countries [44,45].

The future success of a particular technology has to be predicted before the investment decision. In this way, Altuntas, Dereli, and Kusiak (2015) propose a new method for predicting technological success based on patent data that takes into account in four aspects: technology life cycle, diffusion speed, patent strength and potential of expansion [46]. As patents result from the company's investments in basic research and applied development, patent data can be considered as a good representative of the company's genuine inventive activity [47].

The patent is a temporary title to an invention or utility model, granted by the State, by virtue of law, which gives the owner or his successors the right to prevent third parties, without their consent, from producing, using, place on sale, sell or import the product object of its patent and/or process or product obtained directly by process patented by it [43]. The invention is characterized by the requirements of novelty, inventive step, industrial application and descriptive sufficiency, its validity is 20 years from the date of filing. The utility model is the object of practical use, or part of it, susceptible to industrial application, which presents a new form or arrangement, involving an inventive act, which results in a functional improvement in its use or in its manufacture. It is valid for 15 years from the date of deposit [42,48]. The patent is valid only in the countries where it was requested and granted its protection. Each country is sovereign to grant or not the patent independently of the decision in other countries on corresponding patent applications [42,43].

Patent documentation is the most comprehensive of all research sources. Studies show that 70% of the technological information contained in these documents is not available in any other type of information source. According to the World Intellectual Property Organization (WIPO), the number of patent applications has grown to around 1.5 million each year, resulting in more than 500,000 patents granted. Companies in the United States, Japan and Europe increasingly use this instrument as a strategic input [42,43].

Patents promote the dissemination of knowledge and innovation. Therefore, patent documents are a rich source of technological and commercial information. They record the nature of the invention, the direction of technological development and R&D activities [49]. Besides that, the patent registers allow one to analyse the invention as to the novelty aspect: i) detect /; Detect/prevent patent infringement, ii) research technological advances in ones area, iii) identify opportunities for acquisitions and licensing, iv) avoid duplication of R&D initiatives, v) monitor competition, vi) determine the extent of protection of the invention, vii) find potential loopholes in the market, viii) identify the specialists or inventors for competitive intelligence and recruitment, and ix) to search English language equivalents to analyse patent documents published in a foreign language [50].

Patent documents, as well as patent applications, are sources of information and technological knowledge, and can be used by any company, university, research institution, government body and especially by researchers who carry out technological prospecting. Access to these documents occurs through the public or private patent databases [48]. Table 2 presents the main bases that can be consulted.

The most frequent analyses that can be done from the patents are [51]:

a) Regarding the history: in order to evaluate the behaviour of the number of patent document deposits over time, monitoring allows us to deduce the interest or not in the development of the technology of photovoltaic cells;
b) The history of deposits by a depositor country: this analysis aims to illustrate the evolution of deposits of patent documents in different countries over time in order to identify which countries are active in the research and development of this technology. To do so, the country of first filing of the patent is used, which in general is the owner of the technology;
c) The depositors: to identify both the companies and/or institutions that deposit the patent documents over time, and therefore, would be the leaders in the development of such technology;
d) The areas of knowledge: in order to identify the most prominent areas among the deposited patent documents;
e) The International Patent Classification: to order the patent documents, in order to facilitate access to the technological information contained therein.

Table 1
Photovoltaic technologies.
Source: Compiled from authors referenced in the table.

	Technology	Description	Authors
First generation	Monocrystalline silicon	They are cultivated by the Czochralski process. They have a great conversion efficiency, however, present high manufacturing costs, higher energy requirements during their life cycle, longer energy return time, and require the use of very pure materials (solar grade silicon) and perfect crystal structure.	[3,15–20]
	Polycrystalline silicon	This is becoming more attractive, compared to monocrystalline because the cost of production is lower. It is less efficient but has a better aesthetic appearance, consumes less energy during its life cycle. Requires less energy in its manufacture and the crystal structure does not have to be perfect.	[3,15–20]
Second generation	Silicon nanowires	They can allow a new way to convert solar to electric energy with high efficiency and low cost. Compared to other traditional technologies, they require less silicon to achieve the same amount of absorption. The energy losses that occur when light passes through a photovoltaic cell without being absorbed is less. They allow the use of silicon of inferior quality to solar grade silicon and can be produced with excellent electrical characteristics. These advantages can substantially reduce the cost of producing solar cells based on silicon nanowires by keeping these cells competitive.	[21]
	Amorphous silicon	The first amorphous silicon solar cell was reported by Carlson in 1976. In the market the same arose in 1981. The high expectation in this material was contained by the relatively low efficiency obtained so far and by the initial degradation induced by light. This technology diverges from crystalline silicon in the fact that the silicon atoms are located at random to one another. This randomness in the atomic structure has an important effect on the electronic properties of the material, causing a larger gap (1.7 eV) while that of the crystalline silicon is 1.1 eV.	[18,22–24]
	Cadmium telluride	One of the most promising approaches to manufacturing low cost and high efficiency involves the use of cadmium telluride. The CdTe has been known to have the ideal gap (1.45 eV) with a high coefficient of absorption of the solar spectrum being one of the most promising photovoltaic materials for thin film cells. However, the toxicity of cadmium (Cd) and environmental issues related to the use of this material pose a problem for this technology. The other potential problem is the availability of Te that can lead to scarcity of raw material thus affecting the cost of the modules.	[18,22,24–27]
	Copper indium diselenide or copper indium gallium Copper indium–gallium diselenide or copper indium gallium selenide	It contains semiconductor elements of groups I, III and VI of the periodic table, which are beneficial because of their high optical absorption coefficients and their electrical characteristics that allow device adjustment. Some of the major challenges of these technologies have been the limited ability to expand the process of high yield and low cost, and degradation under wet conditions, as it promotes changes in the properties of the material and the shortage of indium in nature.	[18,20,22,25,28]
Third generation	Organic photovoltaic cells	Almost all organic solar cells have a flat layered structure, wherein the light absorbing layer is sandwiched between two different electrodes. One of the electrodes has to be (semi) transparent and the indium tin oxide (ITO) is normally used. They are constructed from thin films (typically 100 nm) of organic semiconductors, such as polymers. They are composed of small molecules such as pentacene, polyphenylene vinylene, copper phthalocyanine (a blue or green organic pigment) and carbon-based nanostructures (fullerenes, nanotubes, graphene). Unlike traditional silicon, the manufacturing process is less expensive, since it uses low cost material and high production throughout. They have the potential to be flexible, semitransparent and manufactured in a continuous printing process, a wide coating area, easy integration into different devices, significant cost savings compared to traditional solutions, ecological and economic advantages. However, organic photovoltaic cells have limited durability and they are not yet capable of converting sunlight into electricity, with the same efficiency as silicon cells. The low efficiency is due to the low absorption of incident sunlight because organic cells have a large energy gap.	[15,18,29–35]
	Dye sensitized solar cell	These cells belong to the group of hybrid solar cells because they are formed by organic and inorganic materials. The main difference of this type of cell compared to conventional solar cells is that the functional element which is responsible for the absorption of light (the dye) is separated from the transport mechanism of the charge carriers. Thus impure raw materials and simple cell processing are allowed, which reduces the cost of the device. An important feature is stability over time. They use low-cost titanium dioxide (TiO_2) in their manufacture compared to silicon that is used in conventional solar cells. Cells based on organometallic dyes, such as ruthenium and porphyrins (zinc complexes), have shown excellent conversion efficiency from solar to electric. However, large-scale application of them is limited due to practical issues, for example, the difficulty of synthesis and purification of ruthenium and porphyrins and, especially, the issues of limited availability of ruthenium. Semiconductors of the perovskite (CH_3NH_3) PbX_3 organometallic trialkyl class, where X may be iodine, bromine or chlorine) may be used as light-collecting components in dye-sensitized solar cells to give perovskite solar cells. Because they are very thin these cells are highly flexible and transparent. The conversion of solar energy through organometallic perovskite has recently emerged as arguably the most promising of all thin-film solar cell technologies. Many efforts have been devoted to the development of metal-free organic dyes. Among them the following stand out: squaraine, coumarin, indoline, phenothiazine, triphenylamine, fluorene, thienopyrazine, carbazole and tetrahydroquinoline.	[1,15,23,29,33,36–38]

(*continued on next page*)

Table 1 (*continued*)

Technology	Description	Authors
III-V compound	Cells based on these compounds, such as GaAs, InP (indium phosphide) and GaSb (gallium antimonide) have direct bandgaps of energy, ie they emit only light as a way to release the energy absorbed at the passage of the electron Of the valence band for the conduction band, present high coefficients of optical absorption, high cost of production, better resistance to irradiation, better weight / power ratio in space applications.	[17,39,40]

The use of patent classification as a tool to organize and search for patent information has been used in state-of-the-art research in a particular scientific or technological field and its innovations [52]. The classification is a feature within patent documents, which was established by the Strasbourg Agreement in 1971. Information on the International Patent Classification, also known as IPC, is published by the World Intellectual Property Organization. The classification has a hierarchical structure of five levels, composed by section, class, subclass, group and subgroup. The hierarchy contains a total of eight sections, more than 120 classes, more than 600 subclasses, and about 70,000 groups. Each group can be further divided into major groups and subgroups, where 10% of the groups (about 7000) are major groups [53]. Fig. 1 is an example of the IPC code.

The IPC code can be seen as a topical tag for the content of the patent document. Therefore, it is possible to determine the similarity theme of two patents based on the similarity of their IPC codes. Patent documents are more similar when they have more *prefixes* in common in their IPC codes. For example, given three patents with IPC codes H01L27/18, H01L27/00 and H01L31/00, the first two patents are more similar than the last two [53].

3. Research method

Considering the objective, this research can be characterized as descriptive [54] resulting in a description of the evolution of photovoltaic technologies. As to the research approach, it is quantitative [55], since it was necessary to quantify the variables analyzed according to a defined objective for the analysis of the information and description of the results.

The research procedure included five stages, according to Fig. 2. In the first stage, the database and the patent search strategy were defined. From these definitions, the second, third and fourth stages were followed, which consisted in the capture, treatment and analysis of patents, respectively. Finally, in the fifth stage, considerations were made about the research.

The Derwent Innovations Index (DII) database was chosen to capture patents because of the worldwide coverage characteristics in patent documents. This patent search and analysis system features patent information extracted from 40 patent-issuing agencies around the world organized into three categories, or sections: Chemical, Engineering and Electrical and Electronic. It also presents references and citations received from six major patent-issuing bodies (PCT-Patent Cooperation Treaty, United States, Europe, Germany, Great Britain, Japan) since 1973.

The search strategy was based on the association of keywords related to photovoltaic cells in the topical field (TS), considering the International Patent Classification of the WIPO. The search was carried out with the keywords in the English language (language used in the base), corresponding to: TS = (photovoltaic module or photovoltaic panel or photovoltaic cell). The symbol * was used as a wildcard in order to retrieve radical variants of the word cell, and operator OR was used to retrieve abstracts that presented any of the words between this operator. The time span of the retrieved documents was from 2004–2013. The database queried returns a result of only published patents. Patents filed for publication must go through an evaluation process that can take months to years. Thus, since there is a delay between the filing and the publication, it was decided not to include in the search for patents the years 2014–2016 to guarantee the research a closer approximation to reality.

The documents were exported in.txt file, with all fields provided by the DII database (inventor, title, abstract, patent number, international patent classification, etc.). In order for the retrieved documents to be processed and analyzed, they were imported into the Excel software, which made it possible to organize the data, as well as the graphic representation related to the countries, inventors, depositors and international patent classification, per year of deposit.

4. Patent analysis

Among the possible analyses that can be done from the patent documents, to reach the objective of this research, the following topics were analyzed: evolution of the quantity of patents deposited per year;

Table 2
Bases of technological information.
Source: (Adapted from [48]).

Public bases		
National Institute of Industrial Property	www.inpi.gov.br	Patents deposited in Brazil.
European Patent Office	www.epo.org	Patents worldwide, possibility of printing the original document.
World Intellectual Property Organization	www.wipo.int/	Bibliographic information, summary and design of patent applications filed via PCT, published as of January 1998.
United States Patent and Trademark Office	www.uspto.gov/	Search all US patents granted since 1975.
Japan Patent Office	www.jpo.go.jp/	Search of bibliographic data of patent applications in Japan.
Free Patents on line	www.freepatentsonline.com	Free service containing US patents and European patents.
Google Patents	www.google.com/patents	Free service containing US patents or patents that have been deposited at the USPTO US office.
Trade bases		
Derwent World Patent Index		Derwent Innovations Index is a powerful patent research tool combining Derwent World Patents Index®, Patents Citation Index ™ and Chemistry Resource.
DIALOG		Recommended mainly for interested in products / processes / compounds and chemical compositions, contains: abstracts and bibliographical data of the documents considered relevant; Containing additional information for better understanding by the user.

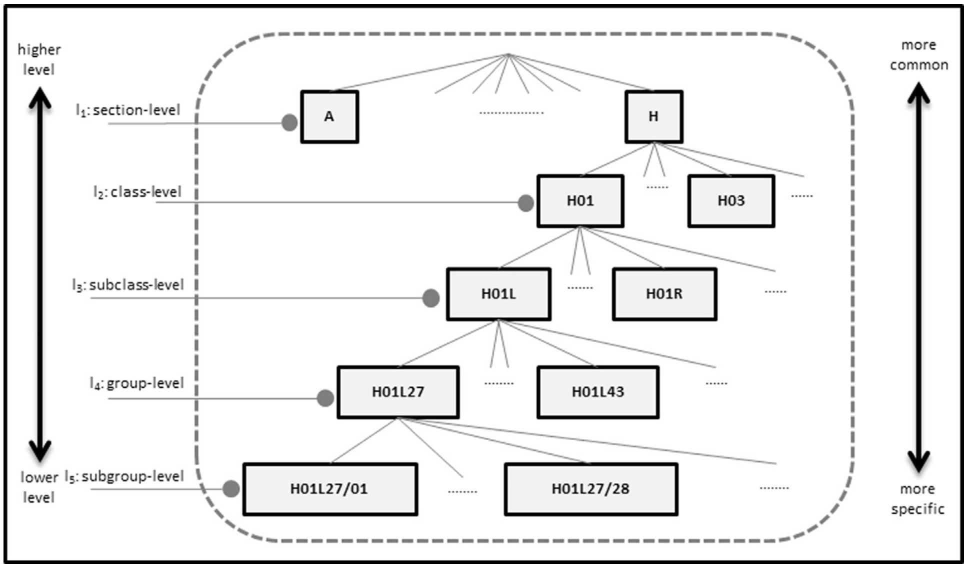

Fig. 1. Hierarchical tree IPC.
Source: [53].

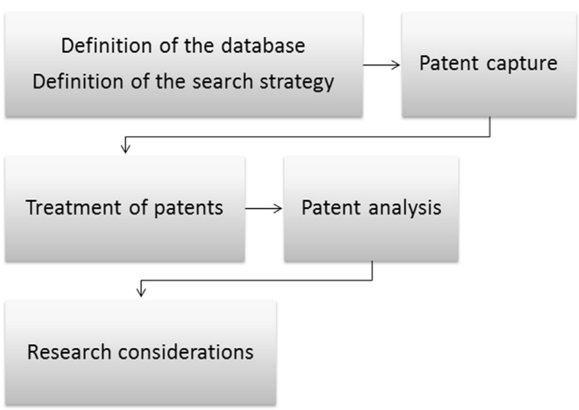

Fig. 2. Stages of the research.

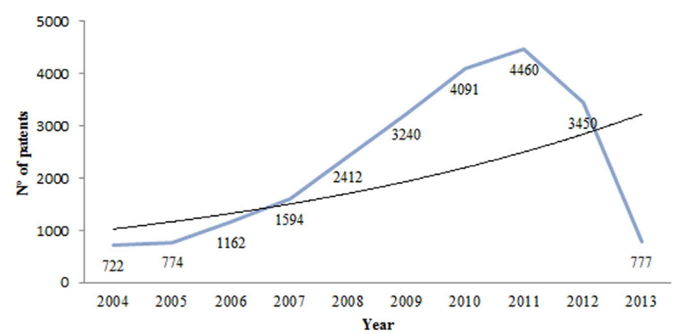

Fig. 3. Chronological distribution of patent deposits made between 2004 and 2013.

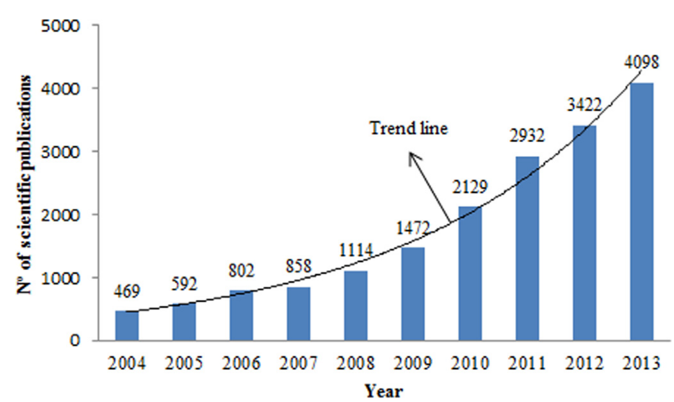

Fig. 4. Number of scientific publications per year in the period 2004–2013.

main countries and depositors/institutions; main inventors and areas of knowledge; and technological information through international patent classification.

From the search strategy established in section three, 23,775 documents were retrieved from the period 2004–2013. However, since the patent analysis is being done based on the year of filing, not the publication, 1093 patents were excluded from 1991 to 2003. As a result, there were 22,682 patents deposited in the period 2004–2013.

As can be seen in Fig. 3, the number of patents deposited per year has been increasing exponentially. It is also observed that there was a growth of approximately 327% in the total number of patent applications between the first and last three years, from approximately 2658 (2004–2006) to 8687 (2011–2013).

This increase in the number of deposits may be the result of global investment policies in programs for the development of renewable energy. The tendency of the innovation indicator 'patent quantity' corroborates with the indicator 'number of scientific publications' showing a trend of exponential growth. It was confirmed by the search in Web of Science database with the key words: "photovoltaic module * or photovoltaic panel * or photovoltaic cell". The search resulted in 17,888 publications from 2004 to 2013, as shown in Fig. 4.

Fig. 5 identifies the leading countries in the filing of patent applications from 2004 to 2013. The first positions are occupied by the United States, China, Japan, Germany and South Korea with 6473, 5605, 3094, 2097, 1126 patents deposited, respectively. The growing number of deposits of patent documents on photovoltaic cells in these countries is due, among other reasons, to the fact that they have a culture of patenting their research results.

The number of scientific publications corroborates with the number of patents in terms of representativeness per country, since, through Fig. 6, it can be observed that of the 17,888 publications, the United States, China, Japan, South Korea and Germany were the main countries that published on photovoltaic cells in the period 2004–2013.

The evolution of the total number of patent documents on photovoltaic cells per country in the period from 2004 to 2013 is shown in

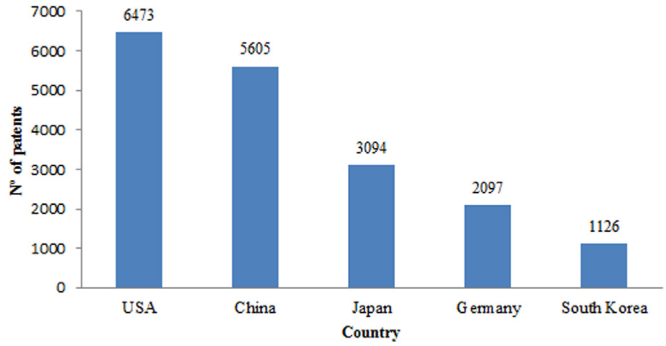

Fig. 5. Number of patents per depositor country in the period from 2004 to 2013.

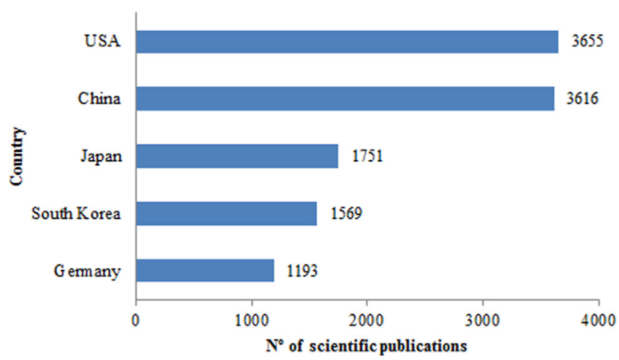

Fig. 6. Number of scientific publications of the five major countries in the period 2004–2013.

Fig. 7. It can be seen that the first two positions are occupied by the United States and China respectively, followed by Japan, Germany and South Korea.

The increase in the number of patent deposits on photovoltaic cells in these countries is driven, in particular, by the government's incentives for renewable energy and energy efficiency policies. Some incentives are the reduction of corporate income tax, subsidies to operators of renewable energy projects to offset their costs, as well as lines of financing [56]. Countries such as China and Germany have used the feed-in tariff (FIT), while Japan, South Korea and the United States have taken advantage of the RPS (Renewable Portfolio Standard) [4].

The United States, through the Investment Tax Credit (ITC), foresees tax deductions equivalent to 30% of the costs of renewable generation projects [57]. In Germany, the KfW development bank finances renewable energy works. In China, it was launched in 2009 for installations with capacity over 50 kW, the solar photovoltaic energy payment program, which provides subsidy of US $ 2.93/W of photovoltaic solar energy generated [58].

There are also incentives to use renewable energy in residences, such as the net-metering system. In California (USA), the net metering program was established in 1996 and allows electricity consumers to install renewable energy generation equipment in their homes and to receive the energy they generate. Japan in turn has the "Subsidy for Residential PV systems". In China, for example, there is the Township Electrification Program, which aims to bring electricity to rural areas through solar photovoltaic and wind technologies [58].

These incentives also favor the achievement of targets such as those related to the reduction of greenhouse gas emissions since the main activity contributing to the high emission of greenhouse gases is the production of electricity and heat by burning Fossil fuels [58]. According to the latest WMO review in the year 2015, such emissions have achieved rates of 400 ppm of CO_2, 1845 ppb of CH_4 and 328 ppb of N_2O [59].

In China, besides the feed-in tariff and the Township Electrification Program, there are programs that stimulate technological innovation and patent filing, especially in areas considered a priority by the Chinese, such as solar energy. The China Intellectual Property Service published its "National Patent Development Strategy (2011–2020)". Chinese policy has introduced several incentives, including cash bonuses, excellent infrastructure for researchers and tax breaks for patent-producing companies, while also stimulating innovative entrepreneurs for that market [46on an individual basis [60].

It is also probable that technological development in these five countries accompanied the economic growth rate that occurred in the period from 2004–2013, in which there was an increase of 133%, 114%, 160%, 141% and 124%, respectively of the gross domestic product (GDP) of the United States, China, Japan, Germany and South Korea. In the year 2004 the United States, China, Japan, Germany and South Korea invested respectively 2.5%, 2.3%, 3.0%, 2.4% and 2.5% of their GDP in research and development. Over the years there has been a variation in the share of GDP in R&D in these countries. In the year 2013, the United States, China, Japan, Germany and South Korea presented investments of 2.7%, 3.0%, 3.3%, 2.8%, 4.1% respectively [61].

Fig. 7 also shows that the data for 2012 and 2013 presented a decrease compared to previous years. This fact is characterized by the difference between the filing date and the date of publication in the database, since in order to be published the deposited patent needs to be examined. However, the number of analysts in the examination centers and the number of applications that are in the queue are disproportionate, resulting in the delay of publication and consequent decrease in the number of published patents.

Among the nine major institutions with the largest number of deposits, as shown in Fig. 8, it is noted that 4 are American and 3 Japanese. This fact corroborates the predominance of the United States and Asian countries as the main depositor countries. Occupying the first position in the ranking, with 469 patents deposited, is the American company Du Pont, which is focused on developing innovative and economically viable solutions for the world's energy needs in various technologies, including photovoltaic. It also develops electronic, sports, pharmaceutical and food materials [62]. In second place is Sharp (410

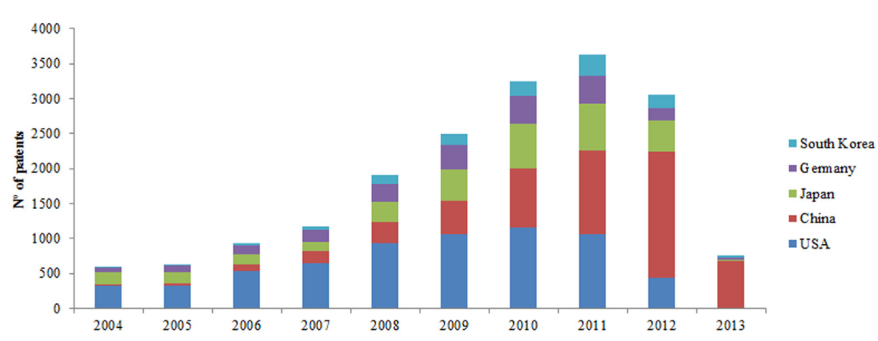

Fig. 7. Historical/geographical distribution of patent deposits from 2004–2013.

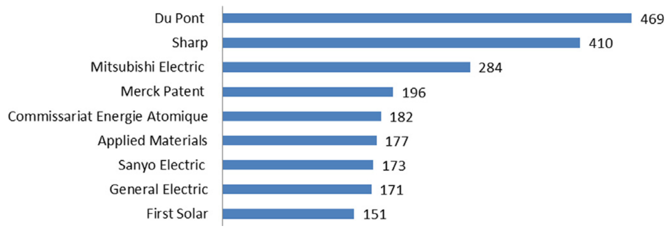

Fig. 8. Main depositors from 2004–2013.

patents), a Japanese company with more than 55 years of experience in solar technology, which was included in the list of level 1 solar companies in May 2015 and therefore represents financial stability. It markets, in addition to photovoltaic materials, printers, cell phones, televisions, etc. [63].

Mitsubishi Electric, which ranks third (284 patents), is a Japanese company that manufactures and sells electrical equipment for home, trade and industrial use. With over 80 years of experience delivering reliable and high quality products to corporate customers and general consumers around the world, Mitsubishi Electric Corporation is a recognized world leader in the manufacturing, marketing and sale of consumer electronics used in processing and communication, spatial development and satellite communication, consumer electronics, industrial technology, energy, transportation and construction equipment [64].

The fourth position is occupied by the Merck Patent Gesellschaft mit Beschränkter Haftung, with 196 patents. Merck Patent GmbH is an intellectual property of the holding company of Merck KGaA Germany and patent protection is a must for companies such as Merck that are based on innovation [65]. Commissariat Energie Atomique, the French research institution in the fields of atomic energy and renewable energy, ranks fifth with 182 patents. It participates in the development of the solar industry in France and in silicon technology, its research focuses on materials; in cells and improving their performance; in solar modules and their optimization. The R&D platform focuses on materials, with special attention to the development of high performance silicon and competitive price; photovoltaic cell technology and yield increase; and solar modules and optimization. Applied research takes place in PV experimental facilities and in real-size small scale solar power plants [66].

The American semiconductor company, Applied Materials, ranks sixth (177 patents) and has been innovating to meet customer demand, focusing on improving wafer surface quality, cell junction quality, cell passivation quality and metallization of economic accuracy [67]. The seventh position is occupied by Sanyo Electric (173 patents), one of the largest Japanese electronics industries, with more than 324 offices and factories around the world. Sanyo is part of the Panasonic Group and is responsible for the manufacturing process of HIT (Heterojunction with Intrinsic Thin layer) [68].

General Electric (a US multinational service and technology company) with 171 patents is in eighth position. GE Renewable Energy works with power generation and storage in hydroelectric power plants, wind and land-based wind turbines, solar panels, and innovative technologies such as biomass and tidal power [69]. In the ninth position, with 151 patents, is First Solar, a US company one of the largest manufacturers of photovoltaic solar modules with production units in the United States, Malaysia, Germany and Pakistan. First Solar's US patent-based competitive advantage may become increasingly relevant as Chinese manufacturers expand into US markets as it may have a strong defense capacity for its domestic market [70].

In order to identify the trends in areas of knowledge, as shown in Fig. 9, the number of registrations by knowledge area indicator was analyzed. It is observed that, of the 23 areas of knowledge analyzed by Derwent, there is a concentration in the Engineering area, with 23,475 patent documents, Instruments and Instrumentation (20,928 documents), Energy and Fuels (13,644 documents), Chemistry (10,390 Documents) and Polymers Science (5878 documents). It should be noted that a patent might involve more than one area of knowledge, which justifies the total number of publications per area of knowledge to be higher than the number of patents in the period 2004–2013 (23,775 patents).

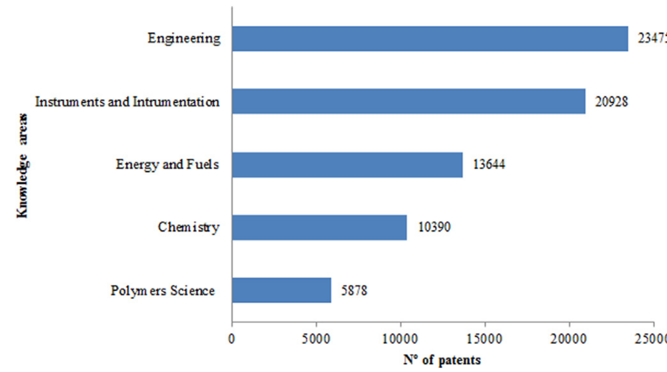

Fig. 9. Knowledge areas of photovoltaic technology.

As for the International Patent Classification – CIP, in the area of concentration of technology, only those groups with 100 or more incidences in which the documents found were considered. Among the three most representative subclasses of the CIP identified in the published documents, the highest concentration of requests (77.95%) is related to subclass H01L (subgroups: H01L-031/042, H01L-031/18, H01L-031/04, H01L-031/052, H01L-031/048, H01L-031/00, H01L-031/05, H01L-031/0224). Also noteworthy is the concentration of documents in subclass H02N (subgroup: H02N-006/00), which contributes with 8.24% of occurrences, followed by the subclass E04D (subgroup: E04D-013/18), with 4.82%. Fig. 10 illustrates such a distribution and Table 3 presents the details, for each technology concentration area, of the main classifications identified.

It can be seen from Fig. 10 and Table 3 that patents on photovoltaic cells are concentrated in the area of semiconductors (H01L-031/00), for the conversion of solar radiation into electrical energy, in an attempt to reduce costs and increase the efficiency of such conversion, in the area of generators for the direct conversion of light energy into electric energy (H02N-006/00), as well as in the area of solar panels adapted for roof structures (E04D-013/00).

Of the 22,682 patents deposited in the analyzed period, 78 were of monocrystalline silicon, 194 of multicrystalline silicon (polycrystalline), 464 of amorphous silicon, 211 of cadmium telluride, 39 of indium copper selenide, 58 of copper, indium and gallium diselenete, 1073 Organic photovoltaic cells (based on polymers - carbon nanostructure such as graphene, carbon nanotube and fullerene), 80 of dye-sensitized cells, 16 of silicon nanowires and 112 of compounds III-V, as observed in Fig. 11.

After years of photovoltaic market domination by crystalline silicon-

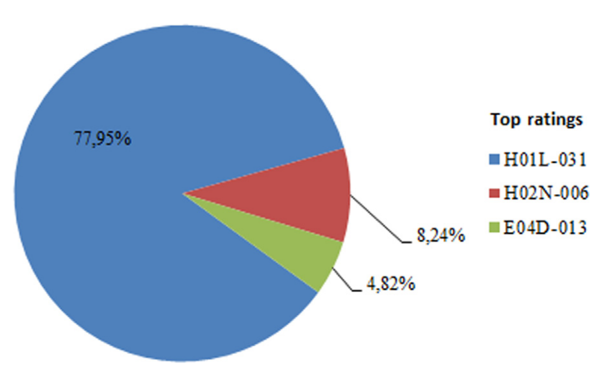

Fig. 10. Participation of the main classifications.

Table 3
Main classifications.

Section: H - Electricity	
Class: H01 - Basic electrical elements.	
Subclass: H01L - Semiconductor devices; Electrical appliances, solid state devices.	
Main group: H01L – 031/00	Description: Semiconductor devices sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and specially adapted, either for the conversion of the energy of such radiation into electrical energy or for the control of electric energy through Such radiation; Processes or apparatus specially adapted for the manufacture or treatment thereof or parts thereof.
Subclass: H01L – 031/042	Description: Photovoltaic modules or matrices of individual PV cells.
Subgroup: H01L – 031/18	Description: Cooling of PV cells.
Subgroup: H01L – 031/04	Description: Adapted photovoltaic conversion devices.
Subgroup: H01L – 031/052	Description: Cooling means directly associated with or integrated with the photovoltaic cell.
Subgroup: H01L – 031/048	Description: Encapsulation of modules.
Subgroup: H01L – 031/05	Description: Electrical interconnection between the photovoltaic cells inside the PV module, for example, serial connection of photovoltaic cells (electrodes; electrical interconnection of thin film solar cells, formed in a common substrate; particular structures for the electrical interconnection of solar cells of adjacent thin film in the module; electrical interconnection means specially adapted to electrically connect two or more photovoltaic modules).
Subgroup: H01L – 031/0224	Description: Electrodes.
Class: H02 - Generation, conversion or distribution of electricity.	
Subclass: H02N - Electric machines	
Obs: transferred to H02S - The generation of electrical energy through the conversion of infrared radiation, visible light or ultraviolet light, for example using photovoltaic modules (solar collectors, obtaining electricity from radioactive sources, sensitive devices Inorganic semiconductor light, thermoelectric devices, pyroelectric devices, light-sensitive organic semiconductor devices).	
Main group: H02N – 006/00	Description: PV plants; Combinations of PV power systems with other systems for the generation of electric energy.
Obs: transferred to H02S – 010/00	
Section: E – Fixed constructions	
Class: E04 - Construction	
Subclass: E04D - Roofing	
Main group: E04D – 013/00	Description: Support structures of photovoltaic modules specially adapted for roof structures. Description: Solar panels (supporting structures of photovoltaic modules specially adapted for roof structures).
Subgroup: E04D – 013/18	Description: Support structures of photovoltaic modules specially adapted for roof structures. Description: Solar panels (supporting structures of photovoltaic modules specially adapted for roof structures).

based solar cells, this technology has been facing competition in the technology market. It is observed in Fig. 11 that there is a prominence of deposited patents for photovoltaic cell technologies considered to be emerging based on organic polymers, carbon nanostructures (graphene, carbon nanotubes, fullerene), compounds III-V, as well as cells of cadmium telluride and amorphous silicon. This prominence is due to the search for technologies that aim to reduce costs and increase efficiency in a sustainable way. One example is the case of organic photovoltaic cells that offer the long-term potential of achieving the goal of PV technology that is economically viable for large-scale power generation [15], since organic semiconductors are a less expensive alternative to inorganic semiconductors, such as silicon. In addition, the organic molecules can be processed by simpler techniques, which are not suitable for the crystalline inorganic semiconductors [31,32].

Table 4 shows the relationship between the main countries, depositor companies and photovoltaic cell technologies.

Based on Table 4, among the patents deposited by Japanese companies (Sharp, Mitsubishi Electric, Sanyo Electric), there is a predominance of amorphous silicon technology. With regard to American companies there is a diversification of the patent technologies deposited. General Electric and First Solar had mainly patent deposits on cadmium telluride, while Du Pont and Applied Materials on dye-sensitized solar cell and amorphous silicon, respectively. The German company Merck Patent has predominance of patents deposited on organic photovoltaic cell. France's Commissariat Energie Atomique has deposited patents relating to organic photovoltaic cells and amorphous silicon cells.

Table 4
Relationship matrix between country/depositor/technology.

Main depositor	Country	Technology
Du Pont	USA	Dye-sensitized solar cell
Sharp	Japan	Amorphous silicon
Mitsubishi Electric	Japan	Amorphous silicon
Merck Patent	Germany	Organic photovoltaic cell
Commissariat Energie Atomique	France	Organic photovoltaic cell/ Amorphous silicon
Applied Materials	USA	Amorphous silicon
Sanyo Electric	Japan	Amorphous silicon
General Electric	USA	Cadmium telluride
First Solar	USA	Cadmium telluride

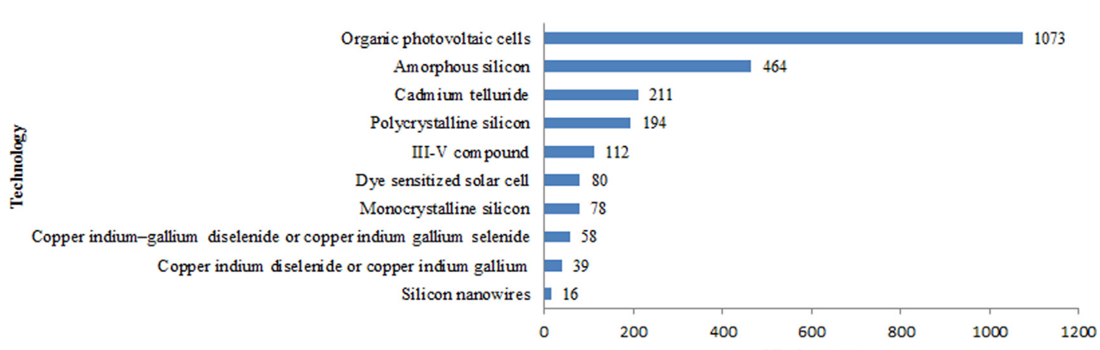

Fig. 11. Number of patents per technology.

5. Conclusion

This study conducted a patent analysis to mapping the development of photovoltaic technologies. To do so, the Derwent Innovations Index database was used to identify patents. This research concluded that the number of patents deposited on photovoltaic cells grows each year and that the main depositor countries are the United States, China, Japan, Germany and South Korea. The most important institutions / companies were the American and Japanese ones, and the main areas of knowledge were Engineering, Instruments and Instrumentation, Energy and Fuels, Chemistry and Polymer Science.

It was also verified that patents on photovoltaic cells are concentrated in the area of semiconductors for the conversion of solar radiation into electric energy, in the area of generators for the direct conversion of light energy into electric energy and in the area of solar panels adapted for roof structures. There is also a prominence of patents deposited for polymer-based photovoltaic cell technologies, carbon nanostructures, III-V compounds, cadmium telluride and amorphous silicon cells.

Patent analysis of photovoltaic cells has been based on the assumption that a patent is a good example for identify the technological knowledge developed by the community that researches photovoltaic cells. However, not all developers file patents for their inventions. Despite these limitations, patent analysis has still been able to highlight key trends in development of technologies to photovoltaic cells. For future research it is suggested a study of the relationship between the level of patent registration of a country and their degree of industrialization and commercialization of photovoltaic solar cells.

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