NORGES HANDELSHØYSKOLE

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Solar Photovoltaic Technology from an Innovation Perspective

A Study Using Patents as a Proxy of Innovation

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Abstract

This master thesis deals with the theme of innovation in solar photovoltaic technologies for the production of energy, and using the relevant patents between 1980 and 2010 as a proxy of the level of inventiveness, to discover what the underlying dynamics in the development of solar photovoltaic are. In addition to looking whether the innovation process has intensified or declined in the relevant time period - that is the primary research question - other interesting results of this study are going to be discussed. For example, it is interesting for corporations and individuals to discover where innovation is taking place from a geographical perspective, or the major topics that are covered by inventors as from patent applications' titles - like energy storage in solar photovoltaic. A more detailed description of the additional areas that are going to be taken care of, within the field of innovation in solar photovoltaic, is provided in the introductory part.

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Contents

1. Introduction

This document takes the form of a discussion on the topic of innovation on solar photovoltaic technologies. The aim of this study, then, is to deliver a snapshot of what the current status of the technology is, as documented through the use of patents as a proxy for the study of innovation.

1.1 The research question

My research question is – therefore – *to look at the inventions and innovations that have occurred in solar photovoltaic technology in the past thirty years and observe whether the innovation process has intensified or declined in the relevant time period*.

Other interesting aspects – complementary to the main research question that has been mentioned above and that can be drawn from patent data – are whether the inventor is a person, a corporation or an academic institution; but also whether the inventor is different from the individual/corporation that applies to the patent office in order to get protection for a given technological advance. This latter piece of information is interesting because one may infer how advances occur in the industry, whether the inventive process is triggered by corporations; or whether the creative step is left to individuals, and then corporations step in to acquire the innovations to bring them to the commercial level.

Finally, an analysis of the patent citation codes, and in particular whether newly patented innovations cite older patents in their registration document, will provide an understanding on whether new inventions build on previous inventions or not. This information will help in understanding the potential for observing sustaining radical and disruptive innovations. The relevant data, again, can be drawn from patents and will be used in the following sections of this document to unveil the underlying characteristics of the innovation process.

1.1.1 The research sub-question in the field of technology: a study of battery storage technology

While carrying out the research on the field of technology and innovation in solar photovoltaic technology, a more in-depth analysis has been carried out on battery storage technology applied to solar photovoltaic. In fact, storage of energy – especially in cases when power production and consumption occur at different stages in time - is a crucial issue that is slowing down the potential of renewable power production technologies. Solar photovoltaic doesn’t represent an exception in this regard. In addition, when looking at the most-utilized words in patent titles, the words *storage* and *battery* came up early in the list. The results from the semantic analysis, aimed at unveiling the major areas of intervention in innovation in solar photovoltaic, together with the issues regarding storage of energy, represent the major reasons behind the in-depth study of this sub-technology within the solar photovoltaic scope.

1.2 Why is the topic of innovation in solar photovoltaic technology interesting?

As stated early in this chapter, the primary objective of this paper is to see whether the number of patents regarding solar photovoltaic technology have increased or decreased over the time period between the 1980s and the year 2010. In fact, a significant increase in the pace of technological improvement – and an augmented research and development (R&D) effort - is necessary to cut down on technology costs – or to make solar PV more efficient – and allow it to compete with the traditional ways of producing energy (like the burning of fossil fuels, nuclear, etc).

In fact, climate change calls for the development of substitute technologies with respect to fossil fuels that are able to cut down on emissions, while not reducing the utility of having electricity at disposal when needed. Solar photovoltaic is one representative of such technologies, and among the ones with the highest potential. Whether the number of patents on the solar photovoltaic technology is increasing or not, the resulting trend is able to provide information that, in the end, can be used to infer whether such technologies are likely to solve the climate problem.

As it is pointed out in the OECD Patent Statistics Manual, patents do serve the purpose of unveiling innovative trends that are related to technology:

"Given that patent applications are usually filed early in the research process (Griliches, 1990), they are not only a measure of innovative output, but also an indicator of the level of innovative activity itself (Popp, 2005). Cohen et al. (2000) emphasize that there is a mutual causation between R&D and patents, and that patenting tends to stimulate R&D. Lanjouw and Mody found a strong positive correlation between patents and R&D in alternative energy for the US" (Organisation for Economic Co-operation and Development., 2009).

Beyond analyzing patents to discover the general trend of the inventive effort, it is possible to discover other information from the analysis of patents and that can be taken as complementary to the given general trend.

For instance, if the inventor is an individual but the patent applicant is a corporation, the technology can be either commercially promising, and/or can be expensive and beyond the economic possibilities of a single inventor.

Finally, whether or not inventions are revolutionary (disruptive) tells us something about whether a breakthrough in technology is likely in the future.

All these figures are of great interest for companies operating in the field, because they can obtain information on where innovation is taking place in the solar photovoltaic arena. In fact, knowing which countries are leading the technological advances may influence the companies' decision on where to establish a division that is aimed at producing solar photovoltaic cells. Another consideration of interest for companies in the field is to know who the best innovators and applicants are. In fact, thanks to this knowledge, the existing players can benchmark themselves against the top innovators or applicants, while the new entrants can use this information for more in-depth studies of why the top-innovators have reached such a position. This document will help in unveiling the general trends, but will not bring the analysis further to discover why an innovator has reached the top-positions in the ranking. In fact, this type of analysis would be highly extensive, and would go beyond the scope of this document.

1.3 The methodology in brief

The first element to be studied, in order to reduce such a vast field of research, was to find the code that was best at describing the solar photovoltaic technologies in the European Patent Office's (ESPACENET) database. Because of certain restrictions on the ability to download the results excel-sheets (imposed by the same portal), it was necessary to further narrow down the search scope to make sure of being able to extract all the data in the output set, and not just a part of it. For more details, please refer to Chapter 4 which deals with the methodology applied in making these restrictions.

Once all the results have been extracted, and combined into a single Excel file, the next step was to search for duplicate records to perform a clean-up. Then, the analysis was carried out - to discover the innovation trend in solar photovoltaic – through the use of filters and Excel pivot tables.

So when it came to find out what are the major areas of innovation, together with a study based on the sub-classification codes (as always, assigned by the European Patent Office website), a semantic analysis was performed. The semantic analysis, in the form of Tag Clouds, was based on the words included in titles of patents. The tool adopted for this purpose – freely available on the Web and named Wordle - counts the number of times a word is found in a text, and draws up a ranking of the most-cited words. This tool has permitted to highlight how the theme of energy storage is central to the sphere of innovations in solar photovoltaic. For further information and limitations of this methodology, please refer to sections 4.2 and 5.1.

Before going into details, however, a discussion of the fundamentals of energy production using solar photovoltaic is provided in the next chapter.

2. Description of the solar photovoltaic technology

In this section of the document, the *solar photovoltaic* (Solar PV) technology will be described. The motivation behind this explanatory introduction lies in the fact that an understanding of how solar PV works is basic for the later sections of this document. A general description of the main components for power generation will be provided, as patents - taken as a proxy for studying the processes of innovation - will often refer to these different components or materials used in the manufacturing of solar cells. The reason why innovation is so important when looking at green technologies – and in this specific case, when solar PV is considered – is that changes in the materials, the way the components are manufactured or the inclusion of additional features may drive substantial performance or cost improvements.

For this section, due to the complexity of topic and the moving towards other disciplines like Physics, there is often reference to the work of David Coley entitled "Energy and Climate Change" (Coley, 2008). In particular, in this book, Coley describes the basic principles of how solar panels work.

The principle behind Solar photovoltaic (solar PV) technology was developed by Einstein, which earned him the Nobel Prize in Physics in 1921. Solar PV is based on the use of two semi-conductors – it can be germanium and silicon, but an evolution in the materials used has occurred. One major condition for these materials is that they need to be "poor" conductors of electricity, but not insulators – i.e. not items that resist electric charge flows. Another feature of these constituents is the number of electrons – four - in the outer layer of their atomic structure. This feature allows them to establish bonds among themselves, hence permitting the arising of a crystalline lattice.

Thus, there are no free electrons within the lattice to carry the electric current because all the four valence electrons - or the electrons of an atom that can form chemical connections with other atoms - are used in the bonding. Then, in order to make the crystal a conductor of electric current, light of short-enough wave length (characterized by higher energy contents) or heat has to strike the crystal and free the previously mentioned valence electrons. The next step now is to create a device that generates a difference in potential in the crystal so as to force the electrons to move in the same direction. The doping of the crystal is a technique that makes possible what has been mentioned as an aim in the previous sentence.

The doping of the crystal requires the existence of two types of semiconductors, i.e. the n-type and p-type (depending on whether positive –p –, or negative – n –). To produce the n-type it is necessary to introduce an element that has five atoms on the outer shell (phosphorus is a common n-type material); so that these atoms tie with four other neighbors and leave an electron free. Since these latter electrons are not tied to others, it is much less energy-consuming to separate them from their atoms. Through the production of p-type semiconductors, to continue, the aim is to create “holes” to make the free electrons move so that the previously mentioned free electrons can occupy those slots. A usual p-type semiconductor is the one with only three outer electrons (e.g. boron).

Then the p-type semiconductor and the n-type are put in contact so as to create an electric field, and make the free electrons of the n-type material fill the holes in the p-type materials. Once the two semi-conductor materials are brought into contact, the electrical neutrality (i.e. the zero-sum of the electric charges of the atoms that make it up) of the materials taken separately fails, as the sum of the number of electrons is not equal to the number of neutrons in the atoms of the two materials any more. In fact, the electrons move towards the juncture between the two semiconductors, leaving behind a positive charge, and creating a negative charge in the p-type material. The negative charge creates an electric field that prevents other electrons from passing the juncture to fill the holes in the p-type material. The result is the creation of a diode because we have a tool that does not allow the movement of electrons in one direction, but permits the flow in the other. Any electrons that are freed from the light that hits the solar cell near the junction are attracted to the positive part of the field, and pass the junction to the n-type material. Finally, connecting together the two sides of the p-type and n-type material away from the junction, the electrons return to their respective materials. This process generates a current.

The image on the next page shows – visually – the structure of a solar cell that produces power through solar photovoltaic.

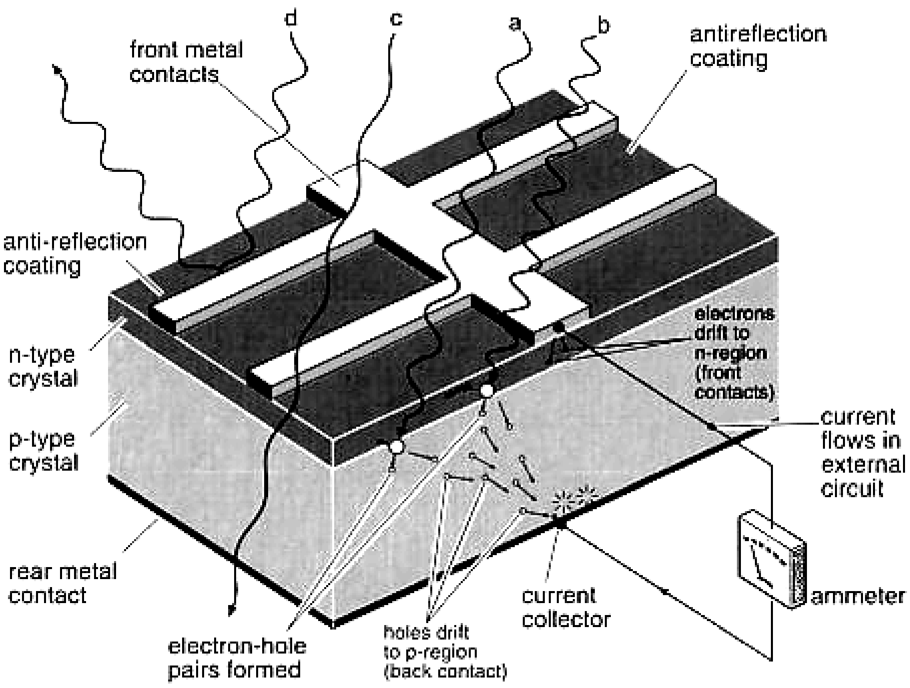


Figure 1 Schematic of a Solar Cell (Coley, 2008)

In addition, to understand what the operation of solar PV is, a mention of the issue of efficiency of solar cells is crucial. To start, one needs to focus on the quantum nature of light. Given the frequencies in sunlight, each proton – when hitting the surface of a solar cell - either frees one electron or none (the release of more than one electron is rare).

"*The energy -* E_{rad} *- in joules of an individual proton is given by:*

$$E_{rad} = \frac{hc}{\lambda} = 2 * 10^{-25}/\lambda$$

Where h *is the Planck's constant (*$6.626 * \ 10^{-34} Js$*),* [c and λ are respectively the speed and wavelength of light]" (Coley, 2008).

This law establishes how much energy is required to release an electron (or the energy *band gap*), and the amount varies depending on the type of semi-conductor employed. Furthermore, as outlined by Coley, the application of this formula - given the quantum nature of light – has some interesting implications to take into account:

The first proposition is that the use of silicon as one of the two semi-conductors implies that *"almost one quarter of the solar spectrum cannot promote electrons* *in a free state. Such radiation will simply warm the cell. Because we are dealing with a quantized phenomenon, more energetic photons can still only promote a single electron unless they have enough energy to release exactly two electrons. For sunlight, this equates to a loss of one third of the incident energy"* (Coley, 2008).

Secondly – and following from the previous statement - *"The maximum theoretical efficiency is 42 per cent [but] because the semiconductors are indeed semi-conductors, they have a relatively high resistance; therefore any current flowing through them will suffer losses. In addition, there [is some loss] at the juncture and at the terminals. All in all, the maximum theoretical efficiency will be under 23 per cent, and in a working cell even less due to heating effects, reflections from the upper surface and blocking of sunlight caused by the terminals, which are in the form of a fine grid"* (Coley, 2008).

Back to the efficiency of the solar cell, one way to improve it is to reduce the band gap, or select a semiconductor material for which the electrons require less energy to become free. Unfortunately, however, the band gap determines the voltage produced by the cell as well, so there is a trade-off. Or rather "*although a lower band gap will increase the current produced by the cell, the voltage produced will drop, and as power is the product of the current and voltage, the power produced by the cell will fall*" (Coley, 2008).

The proposed solution to this problem of efficiency comes from the use of different semiconductors with different band gaps in a multi-junction cell structure. In this way different materials would target different radiations of the solar spectrum. The proposed added materials are copper indium diselenide, cadmium telluride or gallium arsenide.

Other attempts to improve efficiency include the making of transparent grid terminals or the addition of an antireflective coating between the glass cover and the contact grid.

Next, another issue is how to make these solar PV less expensive. One method is the use of polycrystalline - or amorphous – instead of a pure mono-crystalline solar cell.

According to a Report from Datamonitor in 2010, "*Crystalline PV is the largest installed technology and therefore the largest produced solar PV technology globally, accounting for as much as 87.3% of global solar PV production in 2010*. [In addition,] *driven by the high power generation efficiency offered by the technology compared to the other commercially available solar technologies, global annual production volume of single-crystalline PV* [–the major representative in Crystalline PV- type technology-] *grew at a CAGR of 67.5% during 2005–2010 to reach 9,032MW (9GW) in 2010 from 684MW in 2005*" (Datamonitor, 2010).

As stated in the introduction to this section, the details of PV solar cells, the materials and the description of operations will be useful once the focus in the document shifts towards the analysis of the innovation process using patents. In fact, the relevant patents will refer - to the above mentioned - elements that characterize the solar cells.

3. Patents and innovation

A theoretical framework

Inventions in green technologies are getting an increased consideration both in economic studies (Braun et al., 2010; Johnstone et al., 2010; Glachant et al., 2009) and in policy-makers' discussions. At the same time, a question on how to measure these innovations both from a methodological point of view - and a request of what are the desired outcomes of the analysis - remain. As innovation in general cannot be directly subject to quantitative analysis, there is need to find a tangible indicator, or a proxy, of innovation that expresses this concept. To reach this end, "*the most frequently used measure of the outcome of innovative activity are patent data, which have the key strength that they allow the mapping of technology domains, which makes them particularly suited for [a] technology-specific study*" (F. G. Braun, Hooper, Wand, & Zloczysti, 2011).

Patents are rich in the data they convey. A summary of the different pieces of information that they deliver is given in the list below:

- Information on inventors and applicants;
- Technical explanations of the creation;
- The technological classification;
- The protection coverage and the timing of the invention.

In the following sub-sections, first an analysis of the main advantages, then a list of some drawbacks from using patents as a proxy of innovation is provided.

3.1 Advantages from the Use of Patents as a Proxy of Innovation

Patent data as statistical indicators of innovation have triggered attention by scholars (Schmookler, 1950), and are used as a proxy to measure the rate of technical change in different nation states, areas, institutions (such as universities), business segments and corporations.

One first major advantage of patents is that they rely on a common legal framework. This factor makes them comparable through time and countries. In addition, there is some requirement to be matched in order to file a patent. These necessities about a candidate product - or process - to be eligible for patenting are the following:

- Novelty
- The involvement of an inventive step
- The patented product - or process - can be used for some industrial application

Based on the definition of patentable products – or processes – patents are strictly bound to the concepts of novelty and invention.

Patenting requires the revelation of the causal innovation that grant the owner the exclusive rights and protection over the use or sale of an underlying manufactured good or process. In addition, patents represent legal titles with a temporary duration. Then, the patent scheme allows the appropriation of the advances from the invention for the inventor. This arrangement represents itself one of the ultimate incentives for inventors to invest in research.

Patent documents are published 18 months after application no matter when the patent for the underlying invention is granted (Braun et al., 2011).

Finally, the patent data used in this analysis is mainly analyzed looking at *patent application* dates. In fact, there could be some difference in the time that it takes for the different national patent offices to grant a patent to the respective inventor. Instead, patent application dates are those closest to the actual date when the innovation took place, and - for the purposes of this study – it qualifies as more relevant information.

3.2 Limitations and Drawbacks from the Use of Patents to Study the Innovation Dynamics

There exist also some drawbacks - or limitations - which are typical of this approach of using patents for studying the innovative dynamics of solar photovoltaic technology. One of such limits is the number of patents that could reach a significant value of an economic nature. In fact, only few of the submitted patents would be so innovative to qualify for being of high economic value. This leads to the consequence that the distribution of the value of patents is highly skewed to the right (Braun et al., 2011).

Another factor to be considered is that not all inventions are patented. In fact, some companies prefer to adopt a different strategy to keep their inventions away from competitors. For example, the keeping of these inventions as secret can help in protecting them by not publishing the details and specifications for innovative products. This way, other companies in different geographical contexts from those used by the innovative could not benefit from the patent-disclosed information.

4. Methodology

4.1 Using patents to assess innovations

The methodology applied in this study will be presented in this section of the document. As explained above, this work focuses on solar photovoltaic related patents. For this technology, the aim is to study the dynamics of innovation through the study of patents. To perform this analysis, reference is made to the website of the European Patent Office (ESPACENET), instead of the patent offices of individual states. ESPACENET, in particular, was developed by the European Patent Office (EPO) together with the member states belonging to the European Patent Organization. The choice of taking a broader perspective, rather than looking at the individual states' patent offices, was made for two reasons.

The first, and foremost, concerns the assumption that the inventor of new technological improvements has the incentive to protect them at a more international level, while for the less innovative improvements it would not have such an inducement. In this study, the aim is to observe the dynamics of changes for those inventions that have been registered on the European Patent Office database by their inventor. In fact, the more patents spread on a geographical basis in terms of areas of IPR protection, the more their cost increase. So it is plausible to assume that inventors may decide to take upon themselves more expensive coverage if they discover a truly innovative product. Another reason is that, in some cases duplicate entries had to be deleted from the European dataset. In fact, it could happen that the same patent was registered both with the National database code and with the international level code (with the WO – for World – and EP – for the European Patent Office). Given all these considerations, since the aim was not to take into account double entries and to find where innovation takes place, the patents referring to the WO code and EP code have been removed from the dataset. The existence of duplicate entries would have had an impact on the results of this analysis, and this is why a choice has been made on the dropping of the WO- and EP-coded ones.

In addition, this study focuses primarily on patents with application dates between 1980 and 2010.

Next, the patents' application date is central this study, rather than the publication date, the second being the date when the invention is covered by a patent for the first time. The patents applications, as opposed to the publication date, are dated on the basis of when the initial application has been submitted to the patent office, or the date that is closest to the date when the inventive step has taken place.

Before analyzing the patents, the data were subject to clean up and transformation. Then, the analysis was conducted in two steps. Initially, the dynamics of innovation for solar photovoltaic technology has been presented. In particular, in the beginning of the study, the aim was to understand whether the number of applications has increased – or it has reduced - over the years, together with the impact of the different countries on the general trend. In fact, the next step is to understand which country is awarded with the leading position when it comes to innovation in solar photovoltaic technology, and whether the ranking of countries has changed over the years.

Next stage was to discover the main fields that have been subject to innovation during the considered time period. In fact, it was interesting to look at nations and see who are leading in the different innovation field. To do this, the first step was to use the secondary codes of patent classification by ESPACENET for inventions in the sub-fields of innovations in solar photovoltaic technology (primary and secondary codes will be better explained in the Results chapter).

Finally, in order to better understand the major advance grounds - and add a new level of information on the topic in this study - an analysis was carried out using a word tagging tool.

4.2 Text-mining techniques – Wordle – to gain better insight on the area of innovation

Patent investigations centered on systematized information such as filing dates, inventors, applicants, or citations, is the state of the art methodology (Archibugi & Pianta, 1996; Be'de'carrax & Huot, 1994; Ernst, 1997; Lai & Wu, 2005). These structured data can be analyzed by database management tools such as OLAP (On-Line Analytical Processing) modules, bibliometric methods, or data mining techniques. Lately, there has been attention in the application of text mining techniques to support the task of patent analysis.

Moreover, the aggregate of patent records is growing fast worldwide, generating the necessity for an automatic categorization method to take the place of slow and labor-intensive manual classification. Since precise patent categorization is important when looking for relevant existing patents in a given field, patent cataloguing is a central task. Kim and Choi claim that since "*patent documents are structural documents with their own characteristics distinguished from general documents, these unique traits should be considered in the patent categorization process.* [One of the exclusive characteristics of patents is the fact that they are] *structured by claims, purposes, effects, embodiments of the invention, and so on*" (Kim & Choi, 2007).

The proposed methodology is the following: "*After selecting one of the fields among the ones titled* claim, purpose *and* application *field* [in this analysis the "title" field is the basis for this analysis], *a semantic analysis of these fields is completed, instead of comparing all the text in a patent to find the similar ones*" (Kim & Choi, 2007).

Then, Kim and Choi claim that the patent records can be identified by means of user-defined tags [or words that the inventor indicates in the patent application to help in classifying the patent] for clustering them into several semantic elements [or words], and allow for patent categorization (Kim & Choi, 2007).

In this paper, instead of making use of the inventor-defined tags for patent classification and clustering (as suggested by Kim and Choi), but similar to the scholars' methodology a word tag tool that counts and rank words by the number of times they occur is employed - Wordle. The reason why such a decision has been taken is technical. In fact, patent tags are not included in the Excel file that can be extracted from the European Patent Office's Database. This means that, in order to perform such an analysis – and given the extensive number of patents - , one should go and fetch the inventor-indicated tags for each of the 1666 patents.

Another point in favor of text mining techniques is the one provided by Lin, Lin and Tseng, who show the advantages of using of the previously mentioned tools for patent analysis. In particular, they have produced a software code to carry out operations that are comparable to those performed by Wordle – but it is able to analyze word pairs, rather than single keywords.

Again, one of the major advantages that are described by the authors of this paper resides in the fact that such text mining tools allow for efficiency gains in analyzing big quantities of data in few minutes, and thanks to computing capabilities.

"*As an example,* [relating to the authors' dataset, but giving the idea] *for the 381,375 documents in the NTCIR-4 Chinese collection (469 MB of texts), it takes only 133 min on a notebook computer with a 1.7 GHz CPU, 512 Mega RAM, and 4500 RPM hard disk for indexing, keyword extraction, and term association computation*" (Tseng, Juang, & Chen, 2004 from Tseng, C.-J. Lin, & Y.-I. Lin, 2007).

To conclude, the scholars that have been mentioned in the previous paragraph claim that, when judged against more traditional methods, text mapping technologies, like keyword extraction, increases the efficiency in a considerable way, while maintaining adequate effectiveness (Tseng et al., 2007).

4.2.1 **Drawbacks from the use of Wordle as a text mining tool**

There are two main drawbacks in the methodology that has been applied over keyword referencing. In fact, this analysis was carried out by looking at observations of single words, instead of pairs as suggested by Tseng et al. This decision was taken to simplify the problem, and because the algorithm developed by researchers was too complex to build and run as a program for the average user who has no programming capabilities. One reason that led Tseng et al to look at word-pairs is to better understand the context of use for the given word pair. The sample of reference – and when looking at the specific domain of battery and storage for photovoltaic energy storage – has been controlled to check that there were no instances of use of the given words in a different context than the desired one. The analysis could be then performed on single words, rather than on couples, because the use of ESPACENET classification codes has narrowed down what technologies are patented, or the what type of technology is protected (i.e.

solar photovoltaic). In a way, this factor has given the possibility for the study of single words, rather than pairs. If this was not the case, the dataset would be populated by more “diverse” patents, thus the problem of assigning patents to different contexts of innovation would have been more challenging. The mentioned issue combines with the impossibility to adopt a methodology to fully avoid the occurrence of patents that – given the fact that they include in the title the researched words – are mistakenly assigned to a context of innovation that they do not belong to.

Finally, another simplification of the given methodology refers to the use of the words that compose patents’ title for the analysis using the word-tag tool. In fact, Tseng et al suggest the use of the title, and other information like the patents’ abstracts. Unfortunately, the patents’ abstract information is not available in the Excel results, thus making it impossible to carry out such an analysis using abstract descriptions.

Again, given the fact that the patent area of innovation – solar photovoltaic – was narrowed down from the very beginning when gathering the data, this simplification would not affect the analysis results.

4.3 Complementary Analysis on Innovation

Through the use of this instrument - Wordle - it was possible to map those that were the most commonly used words in patents’ titles, with the respective counts of the number of times a given word was used. With this methodology, then, it was possible to map – and better than just using the patents’ sub-citation codes - the main areas of innovation. Another decision was taken at this step, or to narrow down the analysis to a particular aspect of innovation on the technology of solar photovoltaic. The mentioned aspect is the use of batteries for energy storage in solar photovoltaic systems. To carry out this investigation, a study of patents that included the word Battery, then one of those containing the word Storage, and – to finalize - one of those patents containing both words (Battery and Storage) has been performed. In fact, it is possible that, in patents’ titles, one of the two words is missing, still having them referring to batteries for energy storage (and energy produced via a photovoltaic system that is object of the patent). This is the reason behind the study of the three cases that have been previously mentioned.

The next step, then, was to analyze the entire data set to find who the main inventors and applicants are. A second level of analysis on this ground was to understand whether those players were the same for each patent and see, then, whether they were mainly companies, individual inventors or academic institutions.

Finally, the patents in the dataset have been analyzed to see if innovation was more of a sustaining type, or more of a disruptive type based on citations that could be drawn from patent data. The two types of innovations could be defined – using Christensen work – in the following way:

- Sustaining innovations occur when "*new technologies foster improved product performance*" (Christensen, 1997). In particular, "*some sustaining technologies can be discontinuous in character, while others are of an incremental nature*" (Christensen, 1997).
- On the other hand, disruptive technologies "*bring to a market a very different value proposition than had been available previously. Generally, disruptive technologies underperform established products in mainstream markets*" (Christensen, 1997).

This latter type of analysis will be the last one before the concluding chapter that is aimed at summarizing the findings.

Before exposing the analysis results at the roots of this document, on the next page it is possible to see an excerpt of the first patents that have been reported from ESPACENET following a search using the parameters described above (and reported in the first line of the picture as well). The results in the excerpt refer to the year 2010.

Approximately 370 results found in the Worldwide database. power OR energy AND photovoltaic in the title or abstract | 2010 as the publication date | Y02E10/50 as the European Classification								
Displaying publications 1 - 30 as of 2011-07-17.								
Title	Publication number	Publication date	Inventor(s)	Applicant(s)	International classification	European classification	Application number	Date of application
Photovoltaic power generation equipment having sealing device	KR20100009731 (U)	2010-10-05			H01L31/042		KR20090003451U	20090325
PHOTOVOLTAIC POWER GENERATING APPARATUS BEING FEASIBLE FOR CONTROLING TILT ANGLE	KR20100002091 (U)	2010-03-02			F24J2/38 H01L31/042		KR20080011009U	20080819
Mount for solar cell module, and photovoltaic power generation system using the mount	AU2009312092 (A1)	2010-05-14	SAGAYAMA KENICHI	SHARP KK	E04D13/18 H01L31/042	H01L31/042B F24J2/52	AU20090312092	20091104
SOLAR MODULE ARRANGEMENT AND ROOF ARRANGEMENT	CA2733984 (A1)	2010-02-18	DUDAS MIRKO [FR]	DUDAS MIRKO [FR]	H01L31/042	F24J2/38 F24J2/54C4 H01L31/042 H01L31/042B	CA20092733984	20090812
PHOTOVOLTAIC SOLAR MODULE.	MX2010010579 (A)	2010-11-05	SEIDLITZ DANIEL	BAYER MATERIALS	H01L31/042 H01L31/048	H01L31/042B	MX20100010579	20100927

Figure 2 A snapshot of the first Patents displayed on Excel when running the described search (year 2010). Source: ESPACENET

5. Results

5.1 A side note on the applied methodology

Thanks to the initiative of "*a joint study by the United Nations Environment Programme (UNEP), the European Patent Office (EPO) and the International Centre for Trade and Sustainable Development (ICTSD)*" («EPO - Classification scheme», S.d.) - aiming at grouping all the innovations in the energy sector under the same dedicated reference code, and different from that used previously for the same patents - the dataset used for the analysis will be composed of patents that belong to the solar photovoltaic field. In fact, the three actors that have been just mentioned, have undertaken a project aimed at developing a better classification code for green technologies. This new classification will be used throughout this document.

In fact, Patents are classified in Patent Office's databases using codes that allow the distinguishing of the innovation area for the underlying invention. Such codes are composed of a series of letters and numbers to give a more precise description of the field of innovation, and allow those who are interested in a specific class of patents to return simple and effective results in a search. An example is the following code, which is also the code employed for the analysis in the solar photovoltaic technology – subject of this study:

Y02E10/50

In detail, Y02 is the class that refers to clean energy technology, and consists of two subclasses, i.e. Y02C (which refer to "*greenhouse gases- capture and storage/sequestration or disposal*" («EPO - Classification scheme».)) and Y02E (which is headed by "*greenhouse gases - emissions reduction technologies related to energy generation, transmission or distribution"* («EPO - Classification scheme»))

Once the class Y02E has been chosen, the tree-structure allows for the choice of sub-classification options to narrow down the scope of the search. These codes and sub-codes are provided in the table below – and referring to the code adopted in the analysis - with the summary and description of each of them as taken from the ESPACENET website. For a full reference, please see the Appendix number 1.

Y02E		
Classification Code	**Description**	**Comment**
10/00	Energy generation through renewable energy sources	Geothermal, hydro, oceanic, solar (PV and thermal), wind
	Subclassification Code	
	10/48	Mechanical power, e.g. thermal updraft
	10/50	**Photovoltaic (PV) energy**
	10/52	PV systems with concentrators
	10/54	Material technologies
	10/54B	CuInSe2 material PV cells
	(continues...)	

Table 1 The table shows the Classification and Sub Classification codes for Solar Photovoltaic Technology in Espacenet

Next, after having discussed about the classification codes, a first limitation of this study concerns the scope of the analysis. In fact, a constraint set by the ESPACENET web portal is a limit over the downloadable number of patents that are displayed as a search results. For this reason, I have considered the patent classification code Y02E10/50 only (described, generically, as photovoltaic energy in the table above). This is because the restriction in the search area would reduce the number of results, and permit to download the full dataset.

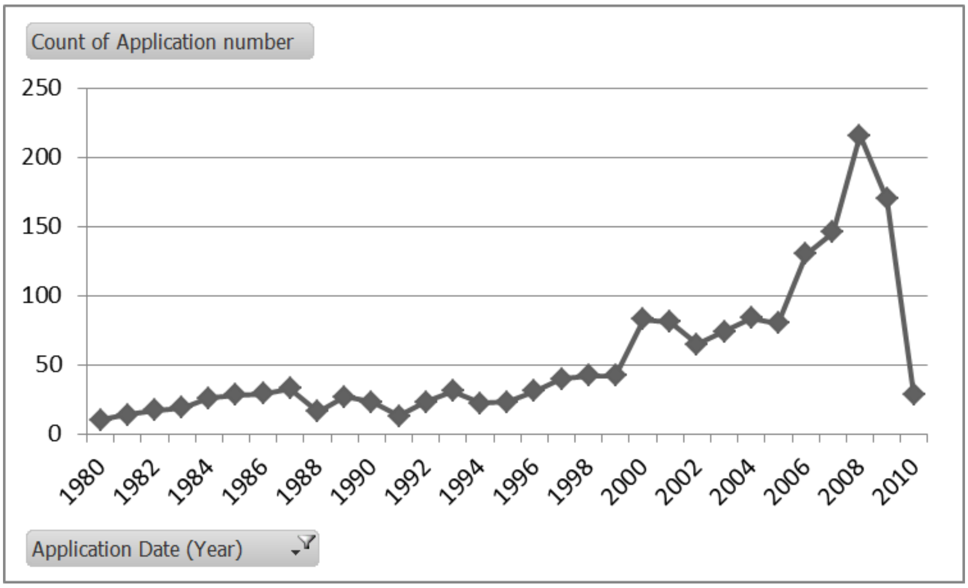
Subsequently, given the limit of 500 patents, the same research was carried out for each year, and narrowing the results down with a Boolean search to show only the patents with:

- The word ***energy*** or ***power*** in at least one of the *title* and/or *abstract* fields
- The word ***photovoltaic*** in at least one of the *title* and *abstract* fields

Once this step was complete, the patents were filtered to eliminate those with a publication number beginning with WO (as of World Intellectual Property Organization) and EP (European Patent Office) for the reasons expressed in the methodology section – or to avoid double counting of the same invention. Consequently, the total number of patents resulting after the cleanup is 1.666 titles.

5.2 Innovation in Solar Photovoltaic: Trend

After merging the files, a first analysis was intended to go and see if an increase - or decrease - has occurred over the years regarding the innovative effort on solar photovoltaic technology. Therefore, the aim was to observe, from year to year, the absolute numbers of registered patents to get a feeling of the inventive pattern. The results – following the guidelines that have been described in the methodology part on choosing the application dates – are shown in the graph below[1].



Graph 1 Number of Patents in the Search Results by Application Date (Year)

[1] For a full reference, please see the Appendix 2

From the graph above it is possible to see that, with the exception of 2009-2010, patent applications have scored a significant growth in the studied field of solar photovoltaic, and especially from the mid-1990s. Assuming that the sharp decline in 2010 is due to the long-tail effect of the economic crisis, but potentially also to delays in registering patents, and defining V_{Year} as the final number of applications made on that year, the Compound Annual Growth Rate (CAGR) in the number of patent applications from the year 1979 to the year 2009 is defined as follows:

$$CAGR_{1979,2009} = \left[\frac{V_{2009}}{V_{1980}}\right]^{\frac{1}{\#\ years}} - 1 = \left[\frac{170}{10}\right]^{\frac{1}{29}} - 1 = .104 = 10.4\%$$

Therefore, the CAGR of patent applications over the twenty-nine-year period from the 1980s to the end of 2009 is about ten-and-a-half percent. This means that virtually every year - from 1979 to 2009 - the total number of patents that have been submitted to the different nations' patent offices has increased by 10% when compared to the patent applications of the previous year.

From the analysis so far, it is possible to see that the trend has been of a great upside in patents applications. Possible reasons that led to this increase are the rise in oil prices – and influenced by the very much questioned scarcity in fossil fuels reserves - as well as the introduction of a market for green certificates and the Kyoto Protocol. All these factors have led to greater public interest in green energy, thus raising the interest of innovators.

Dechezlepretre et al have covered this aspect in their study of 2008 named "Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data". Citing the authors:

"*What about the dynamics of innovation? General figures suggest a strong influence of the Kyoto Protocol in the recent period. While innovation in climate change technologies and innovation in all technologies were growing at the same pace until the mid-nineties, the former is now developing much faster*"(Antoine Dechezlepretre, Matthieu Glachant, Ivan Hascic, Johnstone, & Meniere, 2008).

This results outlined in the previous sentence are confirmed in the study that has just been carried out on patent data for solar photovoltaic technology. It seems that an increase in the innovative effort has been observed in the past ten years, thus confirming the expectations of dealing with a sector – the one of solar photovoltaic – that is in rapid growth.

5.3 Innovation in Solar Photovoltaic: the Leading Countries

In this subsection the aim of the analysis is to observe what nations are the most-cited when it comes to national referencing codes in patent publications. In addition to counting the number of registered patents for each country, it is interesting to observe the dynamics of innovation in the time period of the analysis. For the purposes of this study, therefore, first a table showing the nations that are the most cited will be presented. Then, for the top-five, the development over the time period in the number of applications will be presented.

5.3.1 A Static Perspective

Let me start from the analysis of the most cited nations in the patents that interest solar photovoltaic technology. From the specified dataset, the most-cited countries are presented in the table, and with the respective count of total applications:

Country Codes	**Total number of Patent Applications over the Time Period**	**Percentage over the Total Number (1.666) of Patents in the Dataset**
JP	726	43.58%
US	372	22.33%
CN	222	13.33%
DE	115	6.90%
KR	108	6.48%
Total	1543	92.62%

Table 2 Total Number Of Patent Applications Over The Time Period

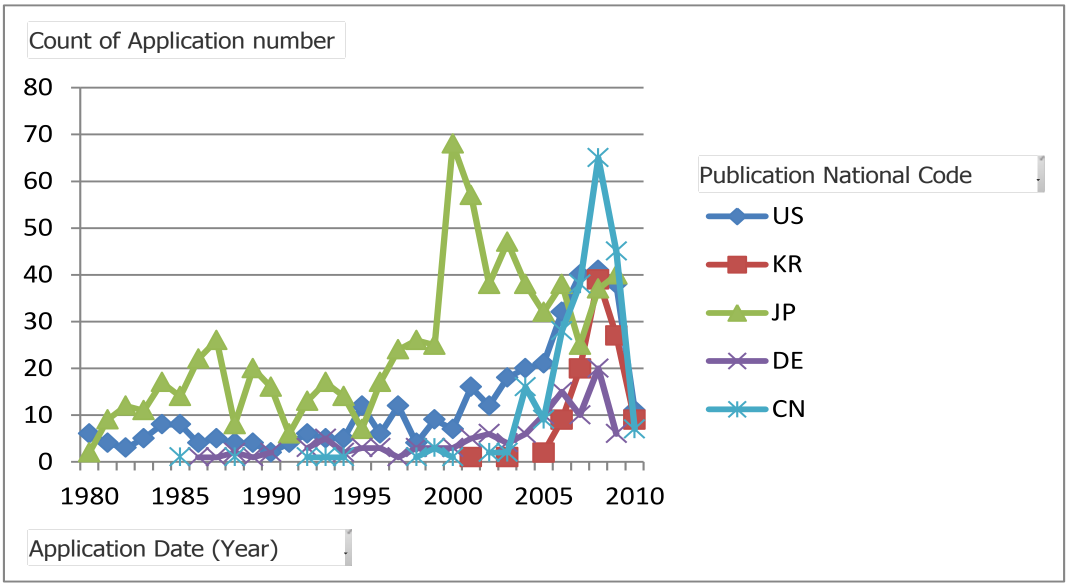
It is interesting to note that the top-five most cited countries following the counting of patents' publication national codes are Japan, the United States, China, Germany and South Korea. In particular, even more significant is to note that the top-five account for more than ninety percent (92.62% of total applications) in the dataset.

This means that – potentially – the areas where innovation takes place are concentrated geographically in the just-mentioned countries. This fact is not surprising, or the evidence that innovation in solar photovoltaic technology is localized and concentrated in the previously mentioned countries, in a way contrasting with the reach of the climate issue that has a global reach.

In order to observe the numbers of the full dataset of this study - see Appendix number 3; while the list of country codes and their association with Nations is provided in Appendix 4.

5.3.2 A Dynamic Perspective

In the following page, then, the development in the number of patent applications referring to each of the National Codes is given. Looking at the chart, and following the previous information from a static perspective, it is possible to see the important role played by Japan for the Solar Photovoltaic Technology over the period from the 1980s until 2007. In 2007, then, China took over as the leader in the number of patent applications and referring to Solar Photovoltaic Technology.



Graph 2 Count of Patents Applications/Nation. The Top Five Countries represented in the dataset (Application Number Period: 1980 - 2010)

Finally, in this section, I have looked at the Compound Annual Growth Rates (and using the same formula as before) for the different countries over the time period. To conduct this research, a time-interval of five years has been adopted. The results are the following:

Compound Annual Growth Rate (Patent Application/Nation for each Time Period_Top Five Nations by Number of Applications)						
Count of Applic	**US**	**KR**	**JP**	**DE**	**CN**	**Total**
1980 - 1985	5.92%	0.00%	47.58%	0.00%	0.00%	23.52%
1985 - 1990	-24.21%	0.00%	2.71%	0.00%	-100.00%	-2.76%
1990 - 1995	43.10%	0.00%	-15.24%	8.45%	0.00%	1.92%
1995 - 2000	-10.22%	0.00%	57.57%	0.00%	0.00%	29.13%
2000 - 2005	24.57%	0.00%	-13.99%	27.23%	55.18%	-1.30%
2005 - 2010	-12.13%	35.10%	-100.00%	-100.00%	-4.90%	-18.26%

Graph 3 Compound Annual Growth Rates for the top-5 most-cited countries - 5-year periods (Application Number Period: 1980-2010)

From the analysis that has just been carried out using the Compound Annual Growth Rate (CAGR), it is possible to see that - in Japan - the period of greatest stimulus, when it comes to innovation in solar photovoltaic technology, has occurred in the five years between 1980 and 1985, as well as between 1995 and 2000. In the period between 2005 and 2010, however, it is possible to notice that new applications for patents were null in Japan and Germany. Looking at the numbers, there is a possibility of missing data for 2010 in these two latter states and that can be due to delays in registration. From the way the CAGR is formulated, in case of missing data, the period-coefficient would go to zero (-100%) in case the number of patent applications (in this case) for the most recent year in the observation period is zero. This is because this index takes into account the initial and the final value for each interval. It is worthwhile to note the innovation push that has occurred in China between 2000 and 2005. In that period, in fact, the Asian giant grew by 55 percent per year in the number of patent applications. During the same period, Germany has benefited from significant growth as well (annual growth of 27% on the number of patent applications). Finally, the United States has benefited from a strong growth rate from 1990 to 1995 (up 43 percent per year).

In addition, the trends that have just been observed – of an increased participation of the developed countries – seem to match with the statements from Dechezlepretre et al and regarding Climate Change Mitigation Technologies, or:

"*Transfers mostly occur between developed countries (75% of exported inventions). North-South transfers are still limited (18%) but are growing rapidly. Flows between emerging economies are almost non-existent. In this regard it should be noted that innovators from emerging countries like China, Russia or South Korea export much less than do innovators located in developed countries*"(M Glachant, A Dechezlepretre, & I Hascic, 2008).

Finally, the observed results appear in contradiction with the claims of Datamonitor, or the observation of a leadership status in the innovative efforts from Japan, Germany and the US – unless the theory of delays in registrations obtains confirmation. Citing the previously mentioned report:

"*In order to sustain the rising competition from Asian solar PV producers, the developed countries producing solar cells such as Germany, the US, and Japan,* *will continue to drive the technological developments in solar PV*" (Datamonitor, 2010).

One reason that could drive this apparent discrepancy is that, in the considered dataset, only the patents referring to solar photovoltaic technologies, and not the materials that these solar cells are made of, have been subject of the study. The major reason for this choice was purely technical, as it was not possible to download all the required data from ESPACENET. This impossibility was solved by restricting the scope of the analysis. Therefore, if innovation has occurred specifically on materials, then it could be that the major innovations have occurred in Germany, US and Japan – and that this result was not captured in this analysis.

5.4 Main Areas of Innovation

In this subsection the aim is to discover the primary areas of innovation, and looking at patent applications as a proxy of technological improvement in solar photovoltaic technology.

5.4.1 Mapping Innovations: the Use Patent's Sub-Classification Codes

Following the analysis that has been carried out in the previous section, first a study covering the most innovative countries has been developed, and looking at the different areas of focus to see if it is possible to find any specialization of some country (back to the previous section, the most innovative countries in this field are the United States, China, Japan, Germany and South Korea). An extract for those countries, and listing the 10 most adopted sub-classification patent codes (that are used to describe the patentable technology), is provided in the following table. In order to provide a significant snapshot of the major areas of innovation, only the first 4-digits of the sub-classification codes have been taken into consideration. The primary reason for applying this method is to group innovations in areas of technological improvement rather than looking at each single classification code. The aim is to gain from the broader picture that the use of less-detailed classification codes is able to provide.

Main Areas of Innovation (Excerpt of the 10 main areas of Innovation as from the sub classification codes of patents)/by Nation	
By Application Sub classification Code and National Code	**Count**
C23C _(Coating Metallic Material)	**23**
JP	14
US	9
E04B_(General Building Constructions _ Roof))	**15**
CN	10
JP	2
US	3
E04D_(Roof Coverings; Sky-Lights; Gutters; Roof-Working Tools)	**123**
CN	19
DE	12
JP	65
US	27
F24J_(Producing or Use of Heat Not Otherwise Provided For)	**66**

CN	17
DE	14
JP	7
KR	20
US	8
H01L_(Semiconductor Devices; Electric Solid State Devices Not Otherwise Provided For)	**1009**
CN	118
DE	53
JP	500
KR	78
US	260
H02J_(Circuit Arrangements Or Systems For Supplying Or Distributing Electric Power; Systems For Storing Electric Energy)	**31**
CN	1
DE	3
JP	21
KR	1
US	5

H02N_(Electric Machines Not Otherwise Provided For)	**40**
CN	15
DE	10
JP	1
US	14
Total	**1307**

Table 3 The major (Top 10) fields of innovation for the top-5 most-cited countries by patent sub-classification code

From the table shown above it is possible to observe the following:

Looking at patents that belong to the H01L sub-classification code, Japan maintains its leadership position with 500 patents over a total of 1009, and followed by the United States and China. The description that is bound to this code is H01L, and refers to all semiconductors that are not devices for measuring; resistors in general; magnets, inductors, transformers; capacitors in general; electrolytic devices; batteries, accumulators; semi-infinite, resonators or lines of the waveguide type; line connectors, current collectors H01R; stimulated emission devices.

Another impression that you can get by looking at the previous table code H02J – Circuit Arrangements Or Systems For Supplying Or Distributing Electric Power – is that Japan holds the leadership position and outperforms all the other top cited countries in this area as well.

5.4.2 Mapping Innovations: the Use of Tag Clouds

To gain a better understanding of the topic of the different innovations, it is interesting to analyze the most used words in the description of the patents. To perform this task, a tool for the creation of Tag Clouds, Wordle, will be used. In fact, this instrument that is freely available on the internet - thanks to the Java code that composes it - will count the number of times a word is inserted in the text description of each patent for the whole dataset. The purpose of this exercise is to discover what are the most frequently used words in the descriptions of innovations. This information would, then, complement the knowledge gained from the analysis of the categories that has been carried out above.

The results of the script Wordle, then, were cleaned from those that are common words such as conjunctions, adverbs, common grammatical constructions, etc.

You may notice, finally, that since the patent publication code does not refer to cell construction materials specifically (other codes are more specific on that particular area of innovation for solar photovoltaic); the most-used words will refer to construction of cells, processes and other add-ons (like storage batteries). Now, before looking at the words coming up from this analysis, it is important to note that some other common words for this analysis, like *Solar*, *Power* and

Photovoltaic have been taken out from the results sheet. The outcomes, then, are the following:

Position	Count	Word	Position	Count	Word
1	403	DEVICE	22	40	LAYER
2	334	METHOD	23	39	GLASS
3	302	GENERATION	24	31	PLATE
4	257	CELL	25	31	FRAME
5	233	ENERGY	26	31	TUBE
6	222	MODULE	27	29	ARRAY
7	96	MANUFACTURE	28	29	MATERIAL
8	89	BATTERY	29	28	DEVICES
9	86	GENERATOR	30	28	CONTROL
10	86	ROOF	31	28	ORGANIC
11	73	HEAT	32	28	SUPPORT
12	69	STRUCTURE	33	27	ASSEMBLY
13	68	CELLS	34	27	RADIATION
14	61	FILM	35	27	HYBRID
15	58	BUILDING	36	27	EFFICIENCY
16	57	PANEL	37	26	STORAGE
17	56	ELECTRIC	38	25	INSTALLATION
18	55	COLLECTOR	39	25	TRACKING
19	46	CONVERSION	40	25	COLLECTION
20	45	SEMICONDUCTOR			
21	45	THIN			

Table 4 Extract of the Most-Frequently used words in Patent Applications, with the respective count

It is interesting to note that the majority of patents include, within their descriptions, words that point to the very structure of photovoltaic cells, as well as the invention of methods for the creation of new modules.

5.4.3 Innovation in solar PV technology: Battery and Storage

So, to narrow down the scope of the analysis, among the innovation fields that have been highlighted above, the one that is going to be taken care of in the next lines regards the topic of storage and batteries as a means of storing energy for later use.

Among the top-cited words in the patents' descriptions, it is interesting to note that the words *Battery* and Storage come up at the 8th and 37th place respectively. The reasons why battery and/or storage can be included in the patents' description are two. One is having innovative devices that have been thought of with a battery, so they are mobile. Another perspective of including the word battery and/or storage in the title is the thinking of systems that allow for the storage of energy for use when there is need.

In fact, a characteristic of solar PV is the variability in power production, so much influenced by weather conditions. These storage systems – like batteries - make it possible to mitigate this negative aspect from the use of solar photovoltaic as a power production technology, and in particular allow for the use of the charge accumulated during the day for night use. That represents, still, a small percentage over the total number of innovations.

The criteria that are going to be employed in the next sections to map the relevant patents in a static and dynamic way are the following:

- The patent’s title contains the word Battery
- The patent’s title contains the word Storage
- Within the patent’s title both the words Battery and Storage are contained

And then, after filtering for each of these instances, the aim is to see the development in each of these cases.

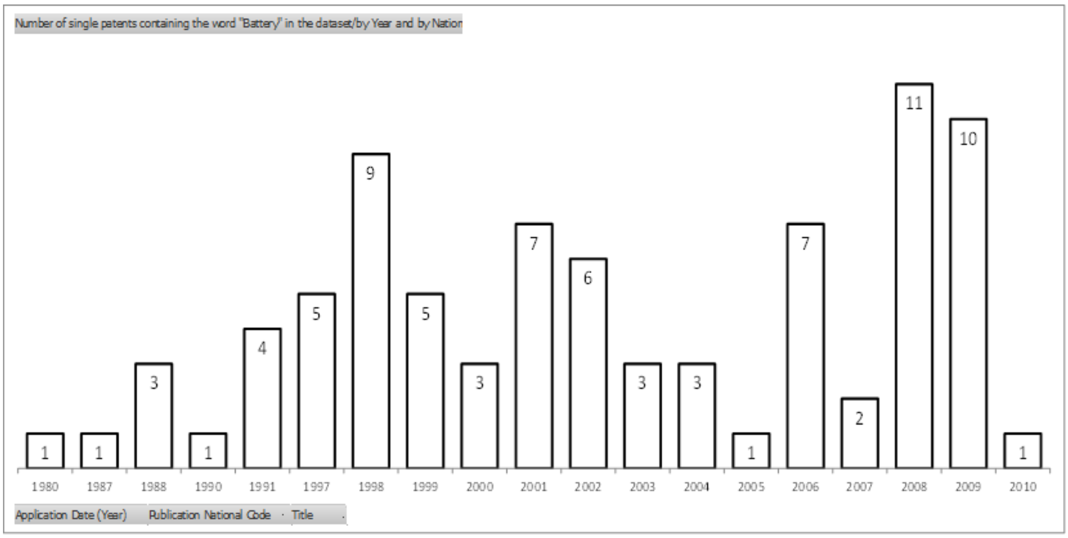
Patents containing the word Battery in their title

Let me start with the battery case first. The results described in the previous section are the following. Please note that the total number of patents in the last line differs from the one found before because of repetitions that are accounted for using Wordle, but not using Excel. The results are the following:

Year/Nation	Number of Single Patents containing the word "Battery" in the Dataset/by Year and by Nation
1980	**1**
JP	1
1987	**1**
JP	1
1988	**3**
JP	2
US	1
1990	**1**
DE	1
1991	**4**
AU	1
CA	1
IL	1
US	1
1997	**5**
JP	4
US	1
1998	**9**
JP	9
1999	**5**
JP	5
2000	**3**
JP	3
2001	**7**
FR	1
JP	5
US	1
2002	**6**
AU	1
CN	1
JP	3

Table 5 Table showing the number of single patents containing the word battery in the Dataset by Year and by Nation

The graph below is based on the previous table. It shows the distribution over time of patent applications that include the word Battery in their description. It is possible to see that a peak was reached both in 1998 and in the two-year period 2008-2009. In fact, over the considered 30-year period, it seems that innovation in this field – in terms of new patent applications – has been quite stationary, or not subject to a particular growth pattern.

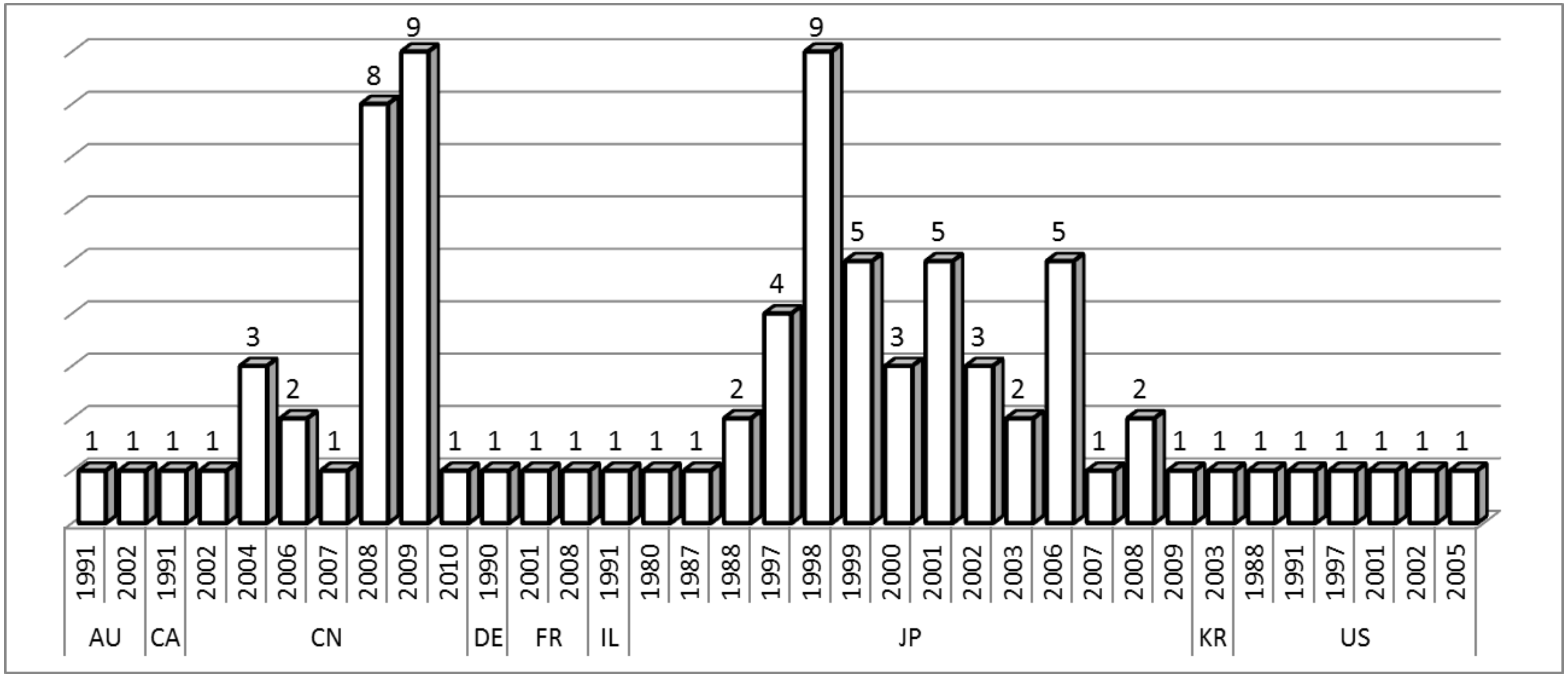


Graph 4 Graph showing the distribution of the number of single patents containing the word battery in the Dataset by Year

In the next page, then, an extract of patent applications with the same search criteria has been produced, but with the aim of highlighting the contribution of the different countries to the total number of applications per year. The results show that, in this field, Japan and China play a major role when it comes to patent applications on solar photovoltaic and with the word battery included in the title or description. In addition, it is impressive to see the stunning development of China that has occurred in the years 2008 and 2009, and basically leading the country at the world's first place in this particular type of innovations, taking the position from Japan. To complete this section, the aim is to provide the full title description of the innovations that led China to the first place in the latest part of the time period of reference. These are provided in the next table, and then the graph covering patent developments (that was mentioned before) in this field is shown.

CN
(1980-2007)
2008
Aluminium alloy backboard solar battery component
Automatic set level device for full-automatic solar photovoltaic battery plate
Double side photovoltaic battery wall component and manufacturing process thereof
Soft coiled film type copper indium gallium selenide (CIGS) solar battery
Solar photovoltaic heat energy battery
Solar photovoltaic integrated battery plate
Solar photovoltaic thermal energy battery
Two-sided photovoltaic battery curtain wall component
2009
Amorphous silicon solar energy battery assembly
Composite power source device based on solar battery and thermobattery
High-efficiency solar photovoltaic battery pack
Mechanism for improving power generation efficiency of solar energy photovoltaic battery components
Novel battery board for photovoltaic solar tracking power station
Organic photovoltaic battery with Cr2O3 as HTL (hole transport layer) and preparation method thereof
Photovoltaic power-generating roof battery panel sealing device
Profile frame of photovoltaic power-generating solar battery assembly
Solar photovoltaic battery for daylighting with parallel cylindrical wide-angle lenses
2010

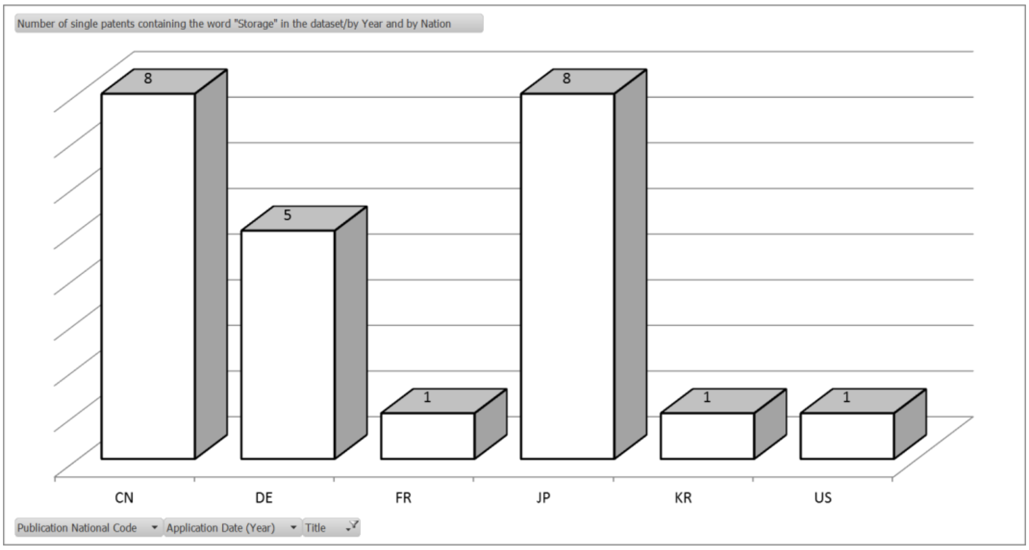
Table 6 shows the patents with the word battery contained in the title for China



Graph 5 Graph showing the distribution by Country and by Year of Patent applications containing the word Battery in the Title

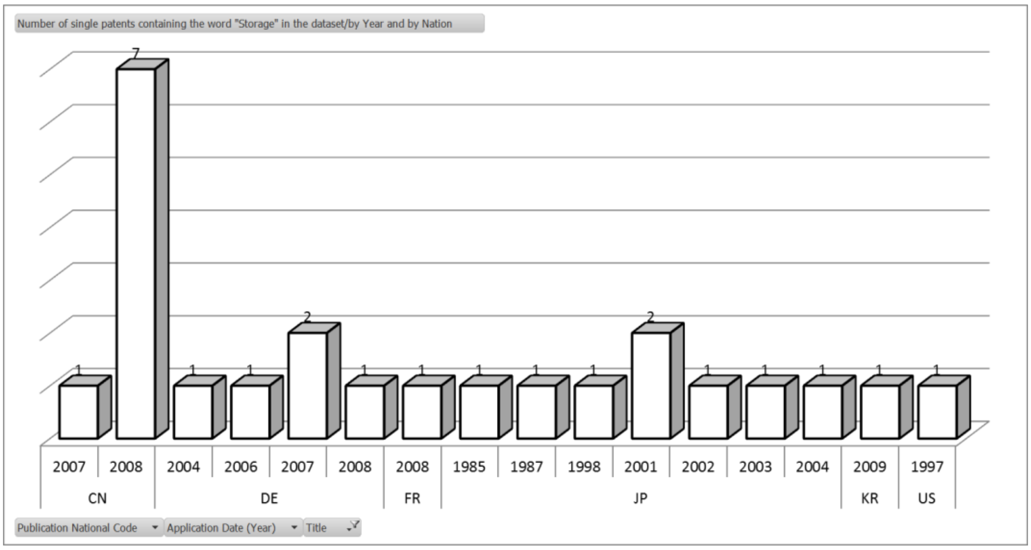
Patents containing the word Storage in their title

In this section, the same type of analysis that has been performed in the previous lines will be replicated for those patents in the dataset whose title includes the word storage. To recall the grounds of this distinction, already expressed above, the patents that include the word *storage* refer to innovations that - as their purpose – are aimed at developing mechanisms or systems for the storage of energy during the day, when power is produced– to use this power when in need at a later time, for example in the evening. These tools can be batteries or other storage systems. On the contrary, patents that contain the word battery may refer both to the case of batteries as a tool for storage of energy from solar PV only, but also it may refer to mobile instruments that come with battery powered – among others – via photovoltaic solar cells. In this part of the document a study on the innovations in the dataset, and referring specifically to those patents that include the word storage within the title, and with the ability to store electric power is provided. The results are shown in the graph below.



Graph 6 Graph showing the distribution of the number of single patents containing the word storage in the Dataset by National Code

Also in this case you can still see the primacy of China and Japan (each with 8 patents over a total of 24); although – unlike the previously stated case– Germany is an important player (5 patents) in this aspect of innovation on solar PV. In fact, the European country is not far from the two Asian giants. Let's now see what has been the development of innovation from a temporal point of view (chart below).



Graph 7 Graph showing the distribution by Country and by Year of Patent applications containing the word Storage in the Title

From the chart above it is possible to see that China has had a considerable growth in the biennium 2007-2008 when it passed from just a patent registered in 2007 to seven during 2008. On the contrary, the release of patent on the studied subject was much more constant in Japan with the release of a patent for six years between those considered (in 2001 there was the release of two patents). The latter consideration made for Japan applies to Germany also. A difference from the latter, however, is that the years of development are much closer to today than for the Asian country of reference. As done previously, in the table below there is a list of patents that have been the subject of study in this part of the document and, in particular, those that refer to China. This is one of the two countries with the largest number of patents in this branch of innovation on solar PV.

CN
2007
Multiple dot circulation water-cooling and heat storage device
2008
Cold-storage cool-down type solar cell component
Compound heat collection and storage tube of all-glass evacuated photovoltaic collector tube
Compound heat collection and storage tube of flat tube heat collection all-glass evacuated photovoltaic collector tube
Flat tube heat collection all-glass evacuated photovoltaic heat collection and storage tube
Necking reducer all-glass evacuated photovoltaic heat collection and storage tube
Necking reducer flat tube heat collection all-glass evacuated photovoltaic heat collection and storage tube
Semiconductor storage device and storage system

Table 7 shows the patents with the word storage contained in the title for China

Patents containing the word Battery and Storage in their description

When, finally, among the patents in our dataset those that are considered include the ones that contain both the words battery and storage, the results are shown in the table below. In practice, the resulting patents are those that refer to products that are equipped with a battery that allows for the energy storage.

By Nation and By Year	Number
FR	1
2008	1
Construction for capturing and transforming solar energy into electrical energy, has photovoltaic kit with storage battery, transformer and lighting system that are housed in garden shed, and panel support fixed at wall of shed	1
JP	2
1998	1
STORAGE BATTERY PROTECTIVE SYSTEM IN PHOTOVOLTAIC GENERATION SYSTEM	1
2002	1
METHOD AND SYSTEM FOR PROVIDING INFORMATION OF HYBRID SYSTEM USING SECONDARY BATTERY FOR POWER STORAGE	1
Total	3

Table 8 shows the patents with the word battery and storage contained in the title

It is possible to see that the total number of patents that belong to this category is considerably less than in the cases studied before. In particular, in this circumstance, Japan has primacy, and followed by France with a single patent less in comparison with Japan. In addition, from a temporal perspective, patents are spread over a long period of time, ranging from 1998 to 2008. This means that there is not such a great attention over this specific type of innovation.

5.5 Mapping Inventors and Applicants

The purpose of this section is to observe who are the inventors based on patent information for solar photovoltaic technologies - if individuals, organizations or academic institutions. In addition, it will be interesting to see whether Inventors and Applicants are the same individuals - or organizations - or different entities, such as individuals who sell their inventions to companies that would bear the costs of carrying out the application. Finally, once these data have been collected and presented here, the aim is to better understand who the most-cited companies - cited as Inventor or as Applicant - are. The methodology used in this section was to add an additional column in the dataset that indicates if the Inventor(s) and the Applicant(s) is/are the same, and then filter the data for one or the other case. It was found that for 156 of them – out of a total of 1666 - the Applicant and Inventor are the same person / company / academic institution. For the remaining 1510 patents, however, patent's Applicants differ from Inventors.

5.5.1 Inventors and Applicants are the same

For completeness, it is fair to point out that, for five of the resulting records, the patent's fields named *Applicants* and *Inventors* were left empty. As a result, these patents are mistakenly treated as if their Applicants/Inventors are the same person without – actually - knowing if they are the same person or not. This, however, is not considered a problem for the purposes of this study due to the marginal impact over the total number of patents (5 patents over a subtotal of 156).

The next step was to see who the applicants/inventors are when they are the same. In the table below shows the first 5 inventor/applicants by the number of patents that belong to them.

Inventor/Applicant are the same person/individual/organization	**Count of Patents**
PAN GE [CN]	3
SUN YUEJING [CN]	3
IGA ATSUSHI	3
UMETSU KENJI	3
IGUCHI SADAO	2

Table 9 Table showing the top-5 most-represented inventors/applicants when inventors and applicants are the same

In addition, it is possible to see that - in this case – applicants and inventors are individuals, and not corporations or universities.

Another consideration is that the number of individuals that make up this population is 134. It is interesting to note that most of them hold only one patent, as it is reported in the table below.

Count of Patents that belong to one Individual Inventor/Applicant	Count of the number Inventors / Applicants with the given Number of Patent References when the Inventor and Applicant are the same	%
1	119	88.81%
2	10	7.46%
3	4	2.99%
4	0	0.00%
5	1	0.75%
Total	134	100.00%

Table 10 Table showing the distribution in the counting of patents that belong to the same inventor / Applicant

The table shows that approximately 89 per cent out of a total of 134 single patent holders is attributed with one patent only, 10 are attributed with two, etc.

The aim now is to observe whether this situation occurs in the condition where Applicants and Inventors are not the same as well.

5.5.2 Inventors and Applicants are not the same

In this part of the document the aim is to study innovation in solar photovoltaic technology and, in particular, looking at patents' applicants, the objective is to understand who they are (whether individuals, corporations or academic institutions) when Applicants and Inventors are not the same for a given patent.

In detail, as it can be seen in the table below, the Applicants are mainly large corporations. One reason behind this finding is that corporations are better able to bear the financial costs for the application to get a patent after filling an innovation to the respective patent offices.

Given the prohibitive costs, therefore, inventors - when not already belonging to the workforce of a given corporations operating in the solar photovoltaic industry – need to sell their inventions to the large corporations. The latter would, then, take care of the filling of the Application to get the patent approved.

The top-15 list of corporations by the number of citations in patent applications is, therefore, shown in the next page.

Applicant	Count of Patents
SANYO ELECTRIC CO	**152**
CANON KK	**141**
KYOCERA CORP	**37**
MITSUBISHI ELECTRIC CORP	**35**
SHARP KK	**28**
MATSUSHITA ELECTRIC IND CO LTD	**16**
MITSUBISHI HEAVY IND LTD	**12**
TOYOTA MOTOR CORP	**10**
MATSUSHITA ELECTRIC WORKS LTD	**10**
SONY CORP	**9**
KANEGAFUCHI CHEMICAL IND	**9**
ENERGY CONVERSION DEVICES INC	**8**
HITACHI LTD	**8**
TOSHIBA CORP	**7**

Table 11 Top-15 list of companies being cited in a patent “applicants” field

The primacy of Sanyo and Canon KK over all other companies is made clear after having looked at the number of citations. Finally, it was decided not to report the results for inventors in the case where Applicants and Inventors are not the same person. The logic is that the results would be dominated by individual inventors who sell their inventions to the above mentioned corporations. Only two names will be mentioned - Baoan Zu - which has sold more than 13 inventions to Beijing Hikeen Tech Co. Ltd (placing himself at the first place for the number of citations as an inventor); and Masami Kurosawa, who sold 9 inventions to Kyocera Corp. before selling one invention to Sharp – at the 3rd and 1st place respectively of the previously shown table (and placing himself at the second place in the inventors’ ranking).

Finally, it is interesting to note that Suntech Power, the global major manufacturer of crystalline PV in 2010 (back to the technological description, crystalline PV is the technology accounting for about 90 per cent of the total production of solar PV modules on a global scale) and with a total production volume of 1,585MW (1.6GW), accounting for 6.7% of global production (Datamonitor, 2010) – is not mentioned in the previous table listing the major innovators.

5.6 Technological Transfers in Solar Photovoltaic Technology

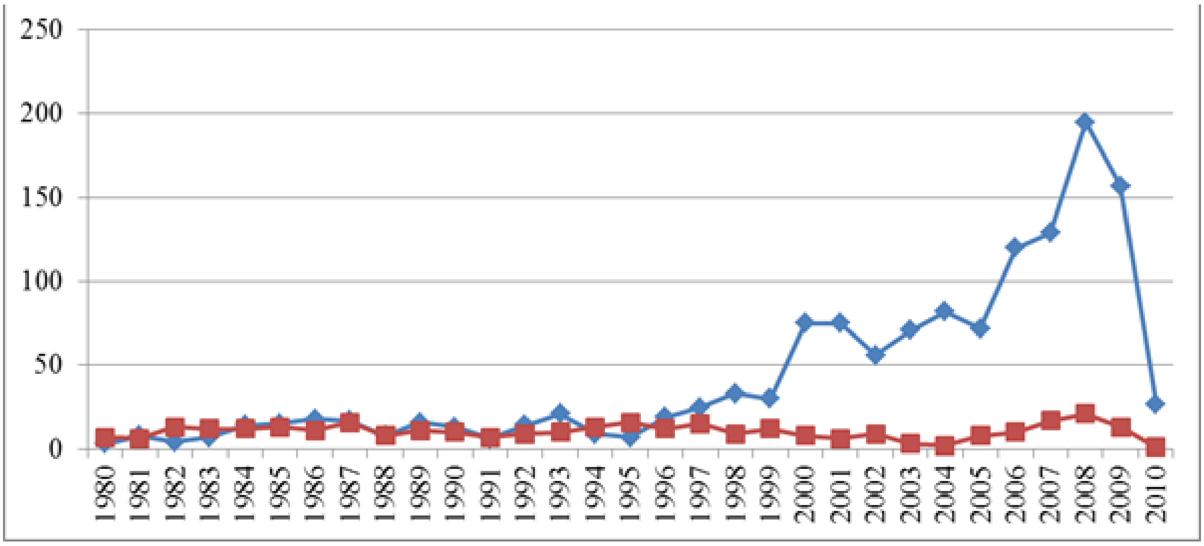
In this section of the document, the aim is to investigate whether technological advances have occurred in the considered time period more in an incremental or in a discontinuous way.

Sustaining innovations – as Called by Christensen – occur when "*new technologies foster improved product performance*" (Christensen, 1997). In particular, the previously mentioned scholar claims that "*some sustaining technologies can be discontinuous in character, while others are of an incremental nature*" (Christensen, 1997).

On the other hand, disruptive technologies "*bring to a market a very different value proposition than had been available previously. Generally, disruptive technologies underperform established products in mainstream markets*" (Christensen, 1997).

Patents are imperfect indicators of technology transfers. In fact, it is not possible to establish a clear cut between sustaining discontinuous technologies from disruptive technologies. In both these cases it is possible to imagine that there could be no record under the *patent citations* field. One possible factor that could help in this distinction could be the number of innovators. In fact, it is possible to imagine that disruptive innovations would require the help of more individuals for their development. Unfortunately, no study has been found that establishes such a causal relationship. Therefore, this section will look only at technological transfers that have occurred as reported in the patents included in the dataset.

For this purpose, the citations as suggested in the *Patents Cited in the Search Report* field are considered.



Graph 8 The graph shows the Distribution of Patents without Citations in the search report (Blue Line) and Patents with Citations (Red Line)[2]

The chart above shows the picture for all these patents in the dataset (1,666 in total) and distinguishing between those patents with citations to other patents and those that do not cite other patents. From the graph, then it is possible to see that - in contrast to the patents that do refer to other patents, which have remained stable over the time period - the number of innovations that do not cite other innovations have increased considerably between 1997 and 2008 (after which a fall in the numbers has been registered in the next two years 2009-2010).

This result suggests a potential growth for technology based on solar PV. This conclusion is based on the results of patent citations, and in particular the observation of a decreasing proportion of patents that present other patents in the citations field. The result is that it is possible to forecast an increase in potential for solar photovoltaic technologies and based on the discussion at the beginning of this chapter. In fact, innovation appears to be either sustaining discontinuous, or disruptive.

[2] For a full reference, please see the Appendix number 6

6. Conclusions

In the final chapter of this document, the aim is to summarize the findings of this study on innovation in solar photovoltaic technology. As mentioned many times in this document, the primary purpose of this document – or the research question – is:

To look at the inventions and innovations occurred in solar photovoltaic technology in the past thirty years, and observe whether the innovation process has intensified or declined in the relevant time period.

From the analysis that has been carried out in Chapter 5_Section 1, it has been observed that – looking at the trend in the number of inventions and innovations that have occurred in the solar PV technology in the last 30 years - the tendency is of a strong increase (except made for the last two years, 2009-2010, in which the number of patent applications has fallen; and maybe due to delays in patent registrations).

Next, in the period between 1979 and 2009, the compound annual growth rate index has been calculated for the total of patent applications in the dataset. It has been possible to note that the overall growth for the thirty-year period is around 10.5 percent. This percentage number means that the number of patent applications has grown by a yearly average of 10.5 percent, compared to the previous year, from 1979 to 2009. Unfortunately, though, it is not possible to state whether this is a high (or low) number in relative terms, and with respect to other power production technologies – because it would be necessary to perform the same analysis on solar photovoltaic's substitutes. But an overall CAGR of this dimension is still a piece of information that indicates an increasing interest, on the side of both individual innovators and companies, in power generation based on solar photovoltaic technologies.

As for the national codes, cited in the patents' application codes, it is possible to see that the main players during the period were Japan, the United States, China, Germany and South Korea. It is also interesting to note that these five countries have attracted 92.62% of the total number of patents in the dataset, thus suggesting a strong geographical concentration in innovation.

In addition, looking at the innovator's countries from a dynamic point of view, – among the previous top-five – China has acquired a leading position in the last five years, while Japan (a country that dominated the technological sphere surrounding solar photovoltaic innovations until 1998-1999) seems to have suffered from a downturn in the last 10 years. United States and Germany, as well, have observed an upward trend since 2000 (although CAGR for Japan and Germany in the last five years of -100 percent is seen as a problem derived from missing data).

Then, when looking at the major areas that attract the innovative efforts, given the great importance of the batteries and storage issue, a separate study was conducted on this topic – as it has been already widely discussed in the introduction and in the relevant section of this document. This analysis showed that the countries that are leading in this area of solar PV-applied technological innovations are essentially the same that were observed earlier when dealing with the general trend in innovations, namely the United States, Japan and China.

Furthermore, it was noted that when applicants are the same person that applies for patents, 88% of the inventors' names - or names referring to groups of innovators - appear only once in the list - as only one patent belongs to them. This means that the innovation process is widespread and attended by a large number of inventors, therefore, increasing the growth potential of solar photovoltaic technology.

When observing, however, the data about innovators - when inventors and applicants are not the same - it was possible to see which companies were leading the field of technological innovation in solar photovoltaic. In particular, Sanyo, Canon and Kyocera occupy - indeed - the first three places in the ranking of most-cited applicants.

Finally, innovations whose patents do not cite other innovations in their *patents citation field* have increased considerably between the years 1997 and 2008 (after which a fall in the numbers has been registered in the next two years 2009-2010). This result suggests a high growth potential for power production technologies based on solar photovoltaic. This conclusion is based on the results of patent citations, and in particular the observation of a decreasing proportion of patents that present other patents in the citations field to the total. In fact, innovation appears to be characterized by either sustaining discontinuous or disruptive type of improvements.

All in all, it seems – then – that there is an all-time high attention covering solar photovoltaic technologies. If, on the one side, the interest is proven to have increased in the past thirty years, on the other, there is uncertainty in whether the pace of innovation is strong enough to guarantee solar photovoltaic a strong position in the future mix of power production technologies to solve the climate problem.

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8. Appendix

8.1 Full List of Espacenet Classification and Sub-Classification Codes

Y02E			
	CLASSIFICATION CODE	***Description***	***Comment***
	10/00	*Energy generation through renewable energy sources*	*Geothermal, hydro, oceanic, solar (PV and thermal), wind*
		SUBCLASSIFICATION	
		10/40	*Solar thermal energy*
		10/41	*Tower concentrators*
		10/42	*Dish collectors*
		10/43	*Fresnel lenses*
		10/44	*Heat exchange systems*
		10/45	*Trough concentrators*
		10/46	*Solar-thermal plants for electricity generation, e.g. Rankine, Stirling solar-thermal generators*

	10/47	*Mountings or tracking*
	10/48	*Mechanical power, e.g. thermal updraft*
	10/50	*Photovoltaic (PV) energy*
	10/52	*PV systems with concentrators*
	10/54	*Material technologies*
	10/54B	*CuInSe2 material PV cells*
	10/54D	*Dye sensitized solar cells*
	10/54F	*Solar cells from Group II-VI materials*
	10/54H	*Solar cells from Group III-V materials*
	10/54J	*Microcrystalline silicon PV cells*
	10/54L	*Polycrystalline silicon PV cells*
	10/54N	*Amorphous silicon PV cells*
	10/56	*Power conversion electrical/electronic aspects*
	10/56B	*for grid-connected applications*

		10/56D	*concerning power management inside the plant, e.g. battery charging/discharging, economical operation, hybridization with other*
		10/58	*M.P.P.T. systems (maximum power point tracking)*
		10/60	*TPV hybrids*
	20/00	*Combustion technologies with mitigation potential*	*CHP, CCPP, IGCC, synair, cold flame, etc.*
	30/00	*Energy generation of nuclear origin*	*Fusion and fission*
	40/00	*Technologies for efficient electrical power generation,*	*Reactive power compensation, efficient operation of power networks, etc.*
	50/00	*Technologies for the production of fuel of non-fossil origin*	*Biofuels, from waste*
	60/00	*Technologies with potential or indirect contribution to GHG*	*Energy storage (batteries, ultracapacitors, flywheels...), hydrogen technology, fuel cells, etc.*
	70/00	*Other energy conversion or management systems reducing*	*Synergies among renewable energies, fuel cells and energy storage*

8.2 Patent Applications per Year (Full Reference)

Total Number of Patents Applications/Year (Publication Number Period: 1980 - 2010)

Application Date (Year)	**Count of Application number**
1980	10
1981	14
1982	17
1983	19
1984	26
1985	28
1986	29
1987	33
1988	16
1989	27
1990	23
1991	13
1992	23
1993	31
1994	22

1995	23
1996	31
1997	40
1998	42
1999	42
2000	83
2001	81
2002	65
2003	74
2004	84
2005	80
2006	130
2007	146
2008	216
2009	170
2010	28
Total (1980-2010)	**1666**

8.3 Most Cited Countries in the Patent's Publication Codes

National Code	*Count of Application number with National Code as the Patent's National Code*
JP	726
US	372
CN	222
DE	115
KR	108
FR	26
GB	25
CA	20
ES	9
AU	8
MX	7
GR	6
SG	3
BG	3
TW	2
CH	2
CZ	2
RU	2
NL	2
BE	1
ZA	1
AT	1
IL	1
NZ	1
MD	1
Total	**1666**

8.4 List of Country Codes and the Nations That They Refer To (Source: Espacenet)

CC	***Name***	***CC***	***Name***
AP	African Regional Industrial Property Organization	LU	Luxembourg
AR	Argentina	LV	Latvia
AT	Austria	MC	Monaco
AU	Australia	MD	Republic of Moldova
BA	Bosnia and Herzegovina	MN	Mongolia
BE	Belgium	MT	Malta
BG	Bulgaria	MW	Malawi
BR	Brazil	MX	Mexico
CA	Canada	MY	Malaysia
CH	Switzerland	NC	New Caledonia
CN	China	NL	Netherlands
CS	Czechoslovakia (up to 1993)	NO	Norway
CU	Cuba	NZ	New Zealand
CY	Cyprus	OA	African Intellectual Property Organization
CZ	Czech Republic	PH	Philippines
DD	Germany, excluding the territory that, prior to 3	PL	Poland
DE	Germany	PT	Portugal
DK	Denmark	RO	Romania
EA	Eurasian Patent Organization	RU	Russian Federation

EE	Estonia	SE	Sweden
EG	Egypt	SG	Singapore
EP	European Patent Office	SI	Slovenia
ES	Spain	SK	Slovakia
FI	Finland	SU	Union of Soviet Socialist Republics (USSR)
FR	France	TJ	Tajikistan
GB	United Kingdom	TR	Turkey
GR	Greece	TT	Trinidad and Tobago
HK	Hong Kong	TW	Taiwan
HR	Croatia	US	United States of America
HU	Hungary	VN	Vietnam
IE	Ireland	WO	World Intellectual Property Organization (WIPO)
IL	Israel	YU	Yugoslavia
IN	India	ZA	South Africa
IT	Italy	ZM	Zambia
JP	Japan	ZW	Zimbabwe
KE	Kenya		
KR	Republic of Korea		
LT	Lithuania		

8.5 Number of Patents Registered for each National Code and Year (Solar PV technology)

Count of Patents by National Code per Year

	JP	US	CN	DE	KR	FR	GB	CA	ES	AU	MX	GR	SG	BG	TW	CH	CZ	RU	NL	BE	ZA	AT	IL	NZ	MD	Tot
1980	2	6						1								1										10
1981	9	4						1																		14
1982	12	3					1	1																		17
1983	11	5						2												1						19
1984	17	8				1																				26
1985	14	8	1			1	1	3																		28
1986	22	4		1				2																		29
1987	26	5		1				1																		33
1988	8	4	1	2		1																				16
1989	20	4		1		1	1																			27

1990	16	2		2			1	1								1										23
1991	6	4						1		1													1			13
1992	13	6	1	3																						23
1993	17	5	1	5			2			1																31
1994	14	5	1	2																						22
1995	7	12		3			1																			23
1996	17	6		3					3			1						1								31
1997	24	12		1					2			1														40
1998	26	4	1	3		2	2		1	1			1						1							42
1999	25	9	3	3						2																42
2000	68	7	1	3			1		1					1	1											83
2001	57	16		5	1	1																1				81
2002	38	12	2	6			4	1		2																65
2003	47	18	2	4	1									1	1											74
2004	38	20	16	6		1		1				1	1													84

2005	32	21	9	10	2	2	2	1	1																	80
2006	38	32	28	15	9	3	1	1			1		1											1		130
2007	25	40	38	10	20	1	6	2	1			2		1												146
2008	37	41	65	20	39	8	1				1	1					1	1			1					216
2009	40	38	45	6	27	4	1	1		1	4						1		1						1	170
2010		11	7		9						1															28
Total	**726**	**372**	**222**	**115**	**108**	**26**	**25**	**20**	**9**	**8**	**7**	**6**	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1666**

8.6 Technology Transfer Based on Patent Citations

Count of Application number	*Patents that cite/or do not cite other patents' citation code*		
Year	*No citations*	*With citations*	**Total**
1980	*3*	*7*	**10**
1981	*8*	*6*	**14**
1982	*4*	*13*	**17**
1983	*7*	*12*	**19**
1984	*14*	*12*	**26**
1985	*15*	*13*	**28**
1986	*18*	*11*	**29**
1987	*17*	*16*	**33**
1988	*8*	*8*	**16**
1989	*16*	*11*	**27**

1990	*13*	*10*	**23**
1991	*6*	*7*	**13**
1992	*14*	*9*	**23**
1993	*21*	*10*	**31**
1994	*9*	*13*	**22**
1995	*7*	*16*	**23**
1996	*19*	*12*	**31**
1997	*25*	*15*	**40**
1998	*33*	*9*	**42**
1999	*30*	*12*	**42**
2000	*75*	*8*	**83**
2001	*75*	*6*	**81**
2002	*56*	*9*	**65**
2003	*71*	*3*	**74**

2004	*82*	*2*	**84**
2005	*72*	*8*	**80**
2006	*120*	*10*	**130**
2007	*129*	*17*	**146**
2008	*195*	*21*	**216**
2009	*157*	*13*	**170**
2010	*27*	*1*	**28**
Total	*1346*	*320*	**1666**