Mapping Technological Trajectories of Crystalline Silicon (c-Si) PV Using Patent Analysis

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Abstract- This paper is the first to identify the technological development of crystalline silicon (c-Si) PV technology by analyzing network patent and main trajectory. The data used is the US granted patent from 1976 until 2010, thus resulted of 1,100 patents data. The network of patent citation data is analysed based on the key network measure (i.e., number of nodes, density, in-degree centrality, and out-degree centrality) and followed by developing the network trajectory. The main path analysis is obtained by using both SPLC method (Search Path Link Count) and the SPNP method (Search Path Nodes Pair). The main path further is analyzed along with its sub-path to understand the evolution of c-Si PV technology. The results indicate that: 1) the c-Si Solar cells technology has very low network density which means the patents are sparsely connected with each other, 2) The connected patents are the representative of the 'new' thin-film solar technology, 3) The most cited patent is not a part the main trajectory, meaning that there is a low correlation between patent and technology development, 4) The US, Japan, and Germany are the main actors in c-Si solar cells technology. US and Germany are identified as key pioneers during the early stage of this technology, while Japan appears at later stages, 5) Siemens is the main actor in the initial c-Si PV technology.

Keywords Crystalline silicon (c-Si) PV technology, Network patent analysis, Technology development, Technology trajectory

1. Introduction

With the growing concerns of energy security and climate change, research and development efforts for reducing the world's dependence on fossil fuel are intensified. As a result, various sustainable energy technologies from renewable energy sources has been flourished in the past decade; its average growth is 5.4% in the last ten years [1]. Moreover, the share of renewable energy in the energy mix is expected to rise from 15% by 2017 to reach 60% by 2050 in order to meet the Paris agreement [2]. The power sector is expected to contribute to a higher share of renewables in the energy mix as electricity is becoming more and more favourable as the form of end-use energy by the world’s population. Power generation from renewables is experiencing a remarkable growth [3] with one technology stand out among others: Solar Photovoltaic (PV) technology, 55% of newly installed renewables power plants in 2017 is from PV [1].

Many factors are attributed to the exceptional growth of solar PV technology apart from the decreasing cost of PV module [4], one of which is R&D of the PV technology. R&D is influential in technology development as it is a proxy for companies to create product development for the future. Moreover, the R&D of PV technology has been started as early as the 1850s, and it has yet shown any sign to stop in R&D with companies from various countries that are still developing PV technology. The state of the art of PV technology is a part of prior R&D that results in more than thousands of knowledge in PV technology. Both knowledge creation/development and knowledge diffusion are two of the essential seven functions in technological innovation system [5]. The knowledge development, as knowledge in other innovation, is fundamental in technological innovation as knowledge represents the function of learning by doing and learning by using [6]. Meanwhile, knowledge diffusion represents the exchange of information between actors in the field [5]. We argue that the exceptional growth of solar PV can be associated with a strong network of linking knowledge within PV technology, thus enabling a positive environmental condition for R&D to develop appropriate technology.

Investigating the process of knowledge development and knowledge diffusion would provide insight with regards to technological evolution during the development of PV technology. The aim of investigating such evolution is to find the pattern of the trajectories to the current stage of PV technology and to unravel the future of PV technology. This study will focus on PV technology development, particularly the crystalline silicon (c-Si) PV technology, by using patent citations as this method can measure the interrelatedness of innovation [7]. This method is argued as being one of the quantitative ways to find the trajectory of a specific innovation [8]. Moreover, the formal mechanism of mobilizing knowledge that links R&D and the industry is well documented in the patents [9]. Patents are also commonly used as sources of information to analyze the trends and trajectory of particular technology over time and explain the relationship between technological innovation and R&D [10].

This study will focus solely on the development of c-Si technology as c-Si shows an increasing trend in terms of research, development and installation of solar grids worldwide [11]. This study aims to examine the pattern of c-Si technological development and how these trajectories have contributed to the current status of c-Si technology. Our analysis is based on the study of patent citation data in solar cells technology granted by the US patent office. The technology trajectories are evaluated based on quantitative tests in which patent citations are being "weighted" to find the main trajectory within the network. By doing so, this study contributes to the evaluation of the evolution process of c-Si PV technology in a quantitative approach (i.e., network analysis).

Following the contribution of Verspagen (2007) [7] and Fontana, Nuyolari, and Verspagenl (2009) [8] in the evolutionary perspective of innovation, in recent years, many empirical studies have utilized patent network to identify the technological trajectories in specific sector. Among them are trajectories of telecommunication switching industry [12], semiconductor miniaturization [13], and energy storage device [14]. Although, several studies also focus on photovoltaic industry in general [15, 16], this study is the first to emphasize the role of crystalline silicon (c-Si) trajectories as the most dominant technology in PV market.

The paper will be structured as follows. Section 2 briefly introduces c-Si PV technology development, especially the most critical milestones in the history of c-Si development. Section 3 contains the used methodology in the creation of a patent citation network; this includes collecting patent information, creating a network of patents, and analyzing the network. Section 4 presents the analysis and discussion, while section 5 comprises of conclusion.

2. History/ Development of c-SI

Commercial PV technology can generally be divided into two categories based on the production method: crystalline-silicon (c-Si) and thin-film, which can also distinguish as first (c-Si) and second (thin-film) generation of PV technology respectively [17]. The former accounts for 95% of the market share, while the latter accounts for 5% of the market share by 2017 [18]. Silicon is favourable as the material for solar cells because of its earth-abundance, suitable band-gap of 1.12 eV, and non-toxic material [19]. Higher efficiency in terms of yielded energy and cost per module has made c-Si PV superior among other types of solar PV technology. Moreover, it is predicted that in the next decade, the quality of c-Si PV technology will increase and the cost will reduce [20]. Hence, making c-Si PV technology evolution likely to take another leap from state of the art.

C-Si PV technology could trace back as early as 1941 when Ohl discovered p-n junction diode in impure silicon while measuring its electrical characteristics. Indeed, the first silicon-based solar cells are inefficient – only 1% of efficiency – but it was of great importance as this discovery led to several further technology developments. One of the most historical developments in c-Si PV technology occurred in 1954 when Daryl Chapin, Calvin Fuller and Gerald Pearson invented the first practical solar cells with 6% efficiency at Bell Laboratories. They received US patent US2780765 "Solar Energy Converting Apparatus" by 1957 [13]. Elsewhere in Japan, Sharp opened its first research and development of PV technology by 1959. Sharp installed the first largest PV technology array in Ogami island at that time by 1963.

During the 1960s-1970s, the most notable c-Si technology development was the improved efficiency that reached 14% (laboratory efficiency), while the commercial application is still limited) by 1960 in which invented by Hoffmann electronics. However, during this period, the application of PV was limited mostly to space application. For example, by 1962 Telstar installed a solar-powered communication satellite and by 1964 NASA launched the first solar-powered spacecraft that was solar-powered. It was during the 1970s onward the application of c-Si PV technology commercialised for terrestrial application. Elliot Berman, under Exxon funding, was perhaps one of the most influential scientists that were responsible for reducing solar cells price from US $ 100 to $ 20 per watt. He introduced the used of multi-crystalline silicon instead of mono-crystalline silicon to produce PV that trade the less reduced efficiency with high reduced in price. Coupled with oil crisis in the early 1970s, this period was the turning point of c-Si PV research and development before its massive commercialisation in the next period.

1980-2000 period has been marked by several milestones in c-Si PV technology development. The utility-scale solar PV power plant started to be built as early as 1982 when ARCO solar build 1 Megawatt-peak in Hisperia, California. Moreover, the modern technology of passivating silicon wafer was also first introduced by Kyocera in the mid-1980s and still become the mainstream technology in recent days for commercial PV technology [21]. Kyocera afterwards provides a 10-year guarantee to its module, knowing the performance was more robust. Laboratory efficiency of the module reached 20% during the 1980s, while the commercial efficiency still stuck at 10% [21]. The milestone of commercial PV efficiency occurred by 1992 when BP Solar announced its 14.3% efficiency module superior compared to others in 10% efficiency. In addition, BP offered 20 years warranty during which ten years was a standard; the warranty period broke by Siemens by 1997, which provided 25 years of warranty. This period also marked with PV installation that reaches 1000 Megawatt with c-Si as the dominant PV module technology.

The period of 2000-present shows an even more significant improvement in c-Si PV technology. Most of the commercial c-Si PV module has 12% efficiency with the highest at 16% and laboratory efficiency reach 25%. With growing demands, advanced technology, and advanced manufacturing process, the price per watt of c-Si module drops significantly during this period. In the early 2000s the price was US$ 2 per watt while by 2018 the price is now US$ 0.25 per watt. PV installation then growth spectacularly where it was reported that 402 Gigawatt had been installed by 2017, where it was only 1 Gigawatt at the early 2000s [22]. Moreover, research and development to improve module efficiency, to find the new technique in c-Si passivation, to increase silicon band-gap, to use heterojunction cell [23] and to ease PV panel mounting [24] are currently undergoing, thus indicating that c-Si PV technology is still evolving even further.

3. Methodology

This study focuses on investigating the evolution of c-Si PV technology by using patent citations. This study is a descriptive study with the quantitative approach that is resulting in the description of the technology evolution of c-Si PV technology. The principal methods used are social network analysis and main path analysis.

For data collection processes, we focus mainly on those granted by the US patent office, as indicated in chapter 2 that US is started early and extensively in c-Si PV technology research and development. We use a specific set of US patent data from 1976 until 2010 as c-Si PV technology began to grow in faster pace during this period. We examined the extent to which each patent is cited with the argument that if the patent is frequently cited, then those specific patents are considered important in the patent network.

Our study consists of three main steps, i.e. data collection, network creation, and main trajectory analysis within the resulting network. The first step is data collection by using several keywords in Derwent DII Patent database to ensure the correct and right amount of data. This study focuses on finding the patents of c-Si and Solar PV by using the keywords of 'Crystalline Silicon Solar cells', 'Wafer based', 'Mono-Csi', and 'Poly-Csi'. As a result, 1,302 patents data from DII are found with several patents have more than one US Patent number. The cleansing data, thus, is conducted by using only the oldest patent number among the redundant. Finally, only 1,100 patents are used as these represent a match with the patent dataset developed by the National Bureau of Economic Research (NBER). Most of the patents that are included in our results correspond to the International Patent Classification (IPC) subclass H01L (60.9%), which stands for semiconductor devices and solid-state electric devices specifically subclass H01L 031 (317 patents) and H01L 021 (260 patents).

The second step is building a network of patents with nodes from the patents and the arcs from citation connection among patent data. Next, the network of patent citation data is analysed based on the key network measure, such as number of nodes, number of arcs, density, in-degree centrality and out-degree centrality. Density describes the general level of linkage among the points in the network and analyses the level of inclusiveness of the network [25]. The more inclusive the network, the denser will it be. Meanwhile, centrality relates to the analysis of the "importance" or "influence" of a particular node within a network [26]. The more connected a node to others in the network, the greater their centrality in the network. While in-degree centrality represents the in-coming relations in specific nodes, out-degree centrality shows the out-going relations from a specific node to others [21]. Based on the network patent developed other descriptive information also produced, such as countries and companies with the most contribution to the development of c-Si technology.

The third step is to determine the network trajectory by performing the main path analysis as proposed by Hummon and Doreian (1990). The main path analysis focuses on measuring the significance of all links in a citation network through the concept of traversal counts and then identifying the most significant link as a main path. Several methods for measuring the significance of a link, known as traversal counts, have been proposed. One of the most commons are the SPLC (Search Path Link Count) and the SPNP (Search Path Nodes Pair) as introduced by Hummon and Doreian (1989) [27], and the SPC (Search Path Count) suggested by Batagelj and Mrvar (1998) [28]. In this study, the SPLC and the SPNP are both used to develop the main path as both methods produced almost the same result of main path [29]. The used of both methods are also used as a confirmation for the main path creation. SPLC method is performed by counting the frequency of edges existent in a specific network, while SPNP method is conducted by measuring the "weight" in the middle of the path [8] [30]. The main path further is analysed along with its sub-path to understand the evolution of c-Si PV technology.

4. Results and Discussions

4.1. Network Patent Analysis

Table 1 summarizes the critical network measure of the patent network. Number of nodes represents the total entity of the network, which explains further the size of the network. Density indicates the ratio of actual and possible ties; it provides insight on the rate at which information can be spread among the nodes. Meanwhile, the degree centrality represents the number of ties a node has to other nodes; more connection leads to more paths to achieve a goal. In-degree centrality is used to measure inbound links, while out-degree centrality is used to measure outbound links.

Based on the network data, the patent network has very low density, low in-degree centrality, and low-out degree centrality. Another result found is that among 1100 patents, only 661 patents that develop relationship with other patents within the network. This result suggests the other 439 patents may be related to the solar cells topics but not associated with the specific keyword used.

The network of the patent also provides information of both countries and companies that contribute most to the development of technology of c-Si PV technology. As shown in the following Table 2, the US is considered as the most active countries with 461 granted patents, followed by Japan with 324 patents, and Germany with 129 patents. Those countries also contribute most of the patent in the main trajectories. Table 3 also presents the top contributors of c-Si PV technology in terms of companies. It is found that the company with the most patent relates to c-Si solar cells is Canon with 95 patents granted. The second is Siemens with 36 patents, while the third is US Government Representation with 32 patents.

Another interesting finding from the network patent is that the most cited patents in the complete network are not part of the main trajectory, both for SPLC and SPNP method. The first most cited patent is patent number 5374564 that stands for the process to produce thin semiconductor material films from the early 1990s, with the number of citations 22. Then it is followed by patent number 3969747 that stands for a semiconductor device suitable for use in a semiconductor integrated circuit from the 1970s with 13 citations. This indicates that the most cited patents in the network are not always part of the main trajectory but still provide a significant impact to the technology development.

4.2. Main Trajectory Analysis

SPLC and SPNP calculation methods resulted in two different main trajectories. The main trajectory that is obtained by the SPNP method includes 16 patents, while the other main trajectory obtained while SPLC consists of 11 patents. Figure 1 presents the visualisation of the main trajectory both by using SPLC method and SPNP method.

To verify our findings, further investigation is performed by using a truncated trajectory analysis based on a group of years. This process produced three new data sets divided on lapses of years of technology development. As a result, the finding in the first part of the truncated network patents within 1976 to 1990 period) and the second part (patents within 1991 to 2000 period) confirms the similar main trajectories with the main path that is calculated before. However, in the third part of a truncated network (patents within 2001 to 2010 period), we found a new main trajectory that is different from the previous trajectory. The following Figure 1 presents the main path and sub-trajectory that are acquired from the truncated networks while Table 4, Table 5, and Table 6 capture the detail of each network, respectively.

Despite the difference of the main trajectories resulted from SPLC and SPNP, some similarities can be seen in which reflected on same matches of the same patents and on the organisation that issued the patents.

Table 1. Key Network Measure Summary

Key network measures	Patent Data Network
Patents obtained from DII database	1,302
Patents match with NBER dataset after merge the duplicate (Number of Nodes)	1,100
Number of Arcs	1,030
Density	0.029
Out degree Centrality	1.31
In degree Centrality	1.31

Table 2. The main countries of the complete network patents

Country	Number of patents
United States of America	461
Japan	324
Germany	129
South Korea	22
France	21
Taiwan	17
Australia	9

Table 3. The main companies of the complete network patent

Company Name	Country	Number of patents
Canon Kabushiki Kaish	Japan	95
Siemens Aktiengesellschaft	Germany	36
The United States Of America Representation	US	32
Sharp Kabushiki Kaisha	Japan	23
Sanyo Electric Co Ltd	Japan	18
Solarex Corporation	US	17

Fig 1. Visualization of Main-Trajectories and Sub-Trajectories based on Patent's Networks

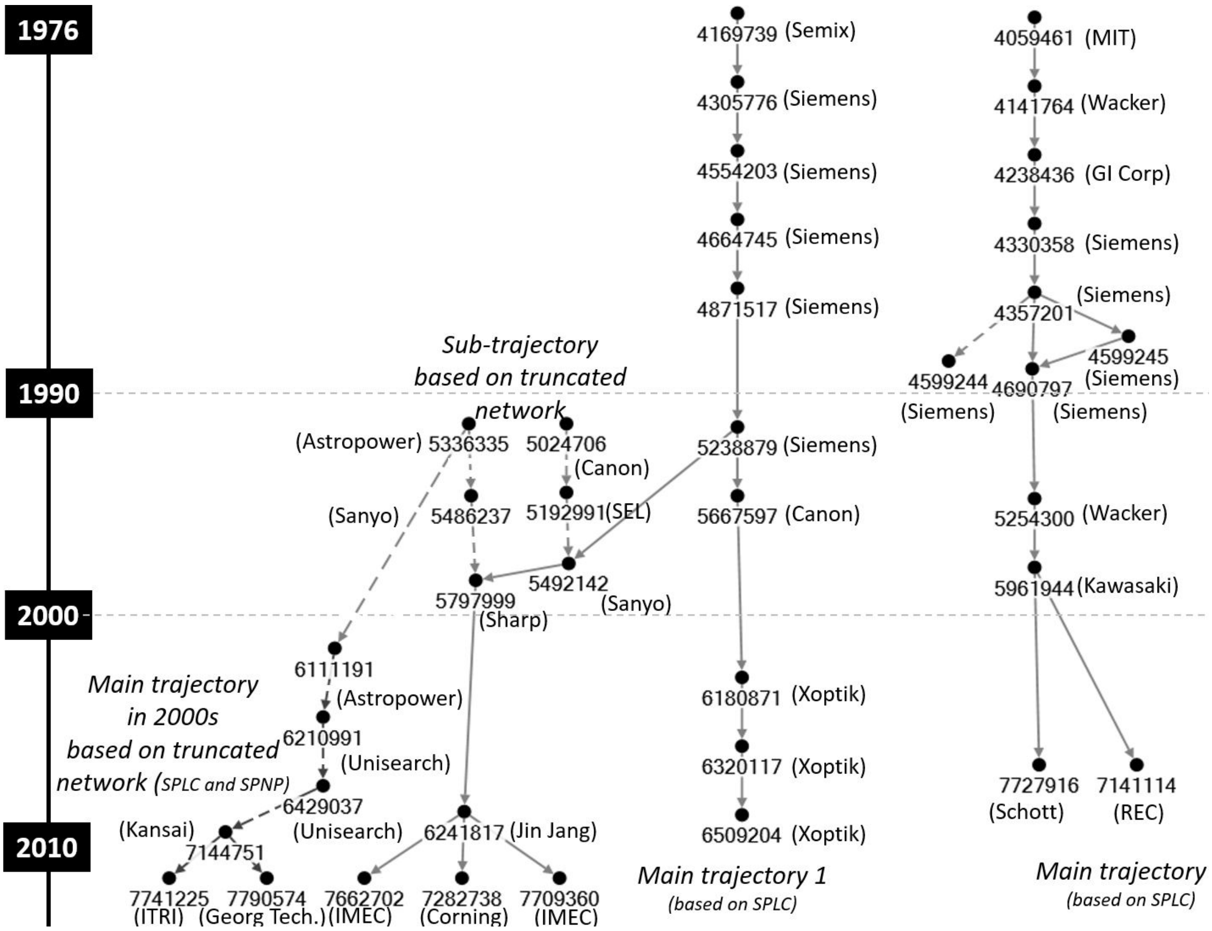

Table 4. Main Trajectory using SPLC

Patent Number	Title	Issuing Year	Assignee Name	Country	IPC Code
4059461	Method For Improving The Crystallinity Of Semiconductor Films By Laser Beam Scanning And The Products Thereof	1977	Massachusetts Institute Of Technology	US	H01L 021/26
4141764	Process For The Manufacture Of Silicon Of Large Surface Area Bonded To A Substrate And Silicon-Bonded Substrates So Made	1979	Wacker Chemitronic Gesellschaft Fur Elektronik Grundstroffe Mbh	DE	H01L 021/223; H01L 021/383
4238436	Method Of Obtaining Polycrystalline Silicon	1980	General Instrument Corporation	US	H01L 021/205
4330358	Method Of Producing Plate- Or Tape-Shaped Silicon Crystal Bodies Having Crystalline Pillar-Like Structures Therein, Equivalent To _Crystalline Columnar Structures, For Large Surface Solar cells	1982	Siemens Aktiengesellschaft	DE	H01L 031/18; C03B 001/02
4357201	Method For Producing Plate-, Tape- Or Film-Shaped Si Crystal Bodies For Solar cells	1982	Siemens Aktiengesellschaft	DE	C30B 029/06
4599245	Method For Making Large-Surface Silicon Crystal Bodies	1986	Siemens Aktiengesellschaft	DE	B05D003/02;B05D 005/12;H01L031/00
4059461	Method For Improving The Crystallinity Of Semiconductor Films By Laser Beam Scanning And The Products Thereof	1977	Massachusetts Institute Of Technology	US	H01L 021/26
4141764	Process For The Manufacture Of Silicon Of Large Surface Area Bonded To A Substrate And Silicon-Bonded Substrates So Made	1979	Wacker Chemitronic Gesellschaft Fur Elektronik Grundstroffe Mbh	DE	H01L 021/223; H01L 021/383
4238436	Method Of Obtaining Polycrystalline Silicon	1980	General Instrument Corporation	US	H01L 021/205
4330358	Method Of Producing Plate- Or Tape-Shaped Silicon Crystal Bodies Having Crystalline Pillar-Like Structures Therein, Equivalent To _Crystalline Columnar Structures, For Large Surface Solar cells	1982	Siemens Aktiengesellschaft	DE	H01L 031/18; C03B 001/02
4357201	Method For Producing Plate-, Tape- Or Film-Shaped Si Crystal Bodies For Solar cells	1982	Siemens Aktiengesellschaft	DE	C30B 029/06

Patent Number	Title	Issuing Year	Assignee Name	Country	IPC Code
4599245	Method For Making Large-Surface Silicon Crystal Bodies	1986	Siemens Aktiengesellschaft	DE	B05D 003/02; B05D 005/12; H01L 031/00
4690797	Method For The Manufacture Of Large Area Silicon Crystal Bodies For Solar cells	1987	Siemens Aktiengesellschaft	DE	B22F 001/00
5254300	Process For Casting Silicon Blocks Of Columnar Structure	1993	Wacker Chemitronic Gesellschaft Fur Elektronik Grundstoffe Mbh	DE	C04B 035/60
5961944	Process And Apparatus For Manufacturing Polycrystalline Silicon, And Process For Manufacturing Silicon Wafer For Solar cells	1999	Kawasaki Steel Corporation	JP	C01B 033/02
7141114	Process For Producing A Crystalline Silicon Ingot	2006	Rec Silicon Inc	US	C30B 1520
7727916	Alkali-Free Aluminoborosilicate Glass, And Uses Thereof	2010	Schott Ag	DE	C03C 3091; C03C 3093

Table 5. Main Trajectory using SPNP

Patent Number	Title	Issuing Year	Assignee Name	Country	IPC Code
4169739	Method Of Making Silicon-Impregnated Foraminous Sheet By Partial Immersion And Capillary Action	1979	Semix Incorporated	US	H01L 021/208; H01L 021/84; H01L 027/14
4305776	Method For Producing Disc Or Band-Shaped Si Crystals With Columnar Structure For Solar cells	1981	Siemens Aktiengesellschaft	DE	C30B 029/00; C30B 019/12
4554203	Method For Manufacturing Large Surface Silicon Crystal Bodies For Solar cells, And Bodies So Produced	1985	Siemens Aktiengesellschaft	DE	H01L 021/84; H01L 027/14
4664745	Method And Apparatus For Manufacturing Tape-Shaped Silicon Crystals With A Threaded Carrier	1987	Siemens Aktiengesellschaft	DE	C30B 015/06
4871517	Apparatus For Parting Wafer-Shaped Silicon Bodies, Useful For Solar cells, From A Silicon Tape Manufactured In A Horizontal Tape-Drawing Method	1989	Siemens Aktiengesellschaft	DE	B01D 009/00
5238879	Method For The Production Of Polycrystalline Layers Having Granular Crystalline Structure For Thin-Film Semiconductor Components Such As Solar cells	1993	Siemens Aktiengesellschaft	DE	H01L 031/02; H01L 021/321; H01L 021/322; H01L 021/324

Patent Number	Title	Issuing Year	Assignee Name	Country	IPC Code
5492142	Polycrystalline Silicon Photovoltaic Device	1996	Sanyo Electric Co Ltd	JP	H01L 031/04; H01L 031/0392; H01L 031/0368
5667597	Polycrystalline Silicon Semiconductor Having An Amorphous Silicon Buffer Layer	1997	Canon Kabushiki Kaisha	JP	H01L 031/06; H01L 031/0368; H01L 031/0392
5797999	Solar cells And Method For Fabricating The Same	1998	Sharp Kabushiki Kaisha	JP	H01L 031/0368
6180871	Transparent Solar cells And Method Of Fabrication	2001	Xoptix Inc	US	H01L 031/109; H01L 031/045
6320117	Transparent Solar cells And Method Of Fabrication	2001	Xoptix Inc	US	C30B 001/06
6241817	Method For Crystallizing Amorphous Layer	2001	Jang; Jin	KR	H01L 031/109; H01L 031/045
6509204	Transparent Solar cells And Method Of Fabrication	2003	Xoptix Inc	US	H01L 021/00; H01L 021/20
7282738	Fabrication Of Crystalline Materials Over Substrates	2007	Corning Incorporated	US	H01L 2904; H01L 2701; B05D 302; C01B 3304
7709360	Method For Manufacturing A Crystalline Silicon Layer	2010	Imec	BE	H01L 2120; H01L 2136
7662702	Method For Manufacturing A Crystalline Silicon Layer	2010	Imec	BE	H01L 2120; H01L 2136

Table 6. Sub-Trajectories Based on Truncated Networks

Patent Number	Title	Issuing Year	Assignee Name	Country
5336335	Columnar-Grained Polycrystalline Solar cells And Process Of Manufacture	1994	Astropower Inc	US
5486237	Polysilicon Thin Film And Method Of Preparing Polysilicon Thin Film And Photovoltaic Element Containing Same	1996	Sanyo Electric Co Ltd	JP
5024706	Pin Heterojunction Photovoltaic Elements With Polycrystal Alp(H,F) Semiconductor Film	1991	Canon Kabushiki Kaisha	JP
5192991	Crystallized Polycrystalline Semiconductor Device	1993	Semiconductor Energy Laboratory Co Ltd	JP
6111191	Columnar-Grained Polycrystalline Solar cells Substrate And Improved Method Of Manufacture	2000	Astropower Inc	US

Patent Number	Title	Issuing Year	Assignee Name	Country
6210991	Metal Contact Scheme Using Selective Silicon Growth	2001	Unisearch Limited	AU
6429037	Self Aligning Method For Forming A Selective Emitter And Metallization In A Solar cells	2002	Unisearch Limited	AU
7144751	Method For Producing Multicrystalline Silicon Substrate For Solar cells	2006	Kansai Technology Licensing Organization Co., Ltd.	JP
7741225	Method Of Forming Pattern By Utilizing Coatable Inorganic Material	2010	Industrial Technology Research Institute	CH
7790574	Plasma Generator, Plasma Control Method, And Method Of Producing Substrate	2010	Georgia Tech. Univ	US

Table 7. Main Trajectory Using SPNP and SPLC

Descriptive subject	Main trajectory SPNP	Main trajectory SPLC
Most Pantents' Companies	• Siemens Aktiengesellschaft (5) • Xoptix Inc (3 • Imec (2)	• Siemens Aktiengesellschaft (4)
Pantents'Countries	United States of America (5) Germany (5) Japan (3)	Germany (7) United States of America (3) Japan (1)
Pantents' Truncated Time Lapse	1976-1989 (5) 1990-1999 (4) 2000-2010 (7)	1976-1989 (7) 1990-1999 (2) 2000-2010 (2)

As shown in Figure 1, Siemens Aktiengesellschaft, a German firm, own patents that cited the most, especially in the early stages of the trajectory (the 1980s). According to Razykov, Ferekides, and Stefanakos (2011) [31], the manufacturing processes of c-Si Solar cells developed by Siemens had an essential role in the initial development of this technology. Subsequent incremental improvements in the manufacturing process have been developed thanks to an increase in knowledge sharing and lower manufacturing costs [31] [32]. The Germans have the characteristic to be one of the first promoters of policies oriented to promote R&D and manufacturing activities by providing different sets of subsidies [33]. What it is a fact, is that Siemens is considered as one of the leading pioneers on c-Si Solar cells due to its research and manufacturing activities at the early stages of the Solar PV industry [34]. Acts as a filter: Ensures research is properly verified before being published stages of the Solar PV industry [34].

To overcome the issue of no visible sub-trajectories, then truncated timelines were created by using both SPLC and SPNP calculations. As noted in Figure 1, it is in the late 1990s and 2000s, where more companies are involved within the truncated sub-trajectories. Most of them are Japanese firms (e.g. Canon, Xoptik, Sharp and Sanyo) and firms from Australia, Taiwan and the USA are also within the technology trajectory. This situation roughly matches in terms of the timeline when the Kyoto protocol (1997) was adopted to promote policies that will facilitate research and manufacturing of sustainable technologies [35]. As a result, manufacturing cost reductions of c-Si Solar cells technologies were achieved, mainly, because of several policy structures implemented at different countries as discussed by Razykov, Ferekides, and Stefanakos (2011) [31] and also by Dunford, Lee, Liu and Yeung (2012) [32].

Moreover, by looking specifically at the technology, patents US5238879 A and US5797999 A correspond to two different breaking points of new sub-trajectories of the c-Si Solar cells. Both are awarded to Siemens and Sharp respectively. Both are related to the fabrication of improved and more efficient solar cells. This technology is recognized for its lightweight, materials flexibility, more possible applications (e.g. embeddedness in buildings), cheaper manufacturing process, and increased efficiency [35]. As noted, it can be argued that the importance of this particular patent relies on knowledge sharing since it provides a series of steps on how to manufacture Thin-Film Solar cells. Furthermore, it is also significant evidence of the pioneering role of Siemens in the development of solar cells technologies until the mid-1990s [34].

Following the above discussion, patent US5797999 A was granted in 1996, issued by Sharp. This particular patent provides information related to the design characteristics of Solar cells and their respective manufacturing processes. According to the patent information sheet, this specific invention offers the advantage to have an enhanced photoelectric conversion efficiency which is manufactured with inexpensive substrates (e.g. metal substrate or a glass substrate), and it also provides the respective fabrication methods. As seen, this particular patent represents another important incremental innovation on the c-Si Solar cells technology, which makes it another breakpoint for a new sub-trajectory mostly based on heat treatment methods as noted in the subsequent patents. Even though another research by Di Francia (2015) [36] argued that the R&D in increasing the efficiency of c-Si will only lead to a moderate decrease in the cost of electricity when PV is installed in a power plant but our findings show that R&D in this sector are still considered important by the PV module technology providers.

5. Conclusion

By analyzing the c-Si solar cells patent technology network as a whole, and also by using two different approaches to visualize the main trajectory of its development, we revealed some fascinating insights. First, we found that the c-Si Solar cells' technology has minimal network density, in which nearly half of the patents are not related to each other. One of the main findings was that the most cited patents are not part of the main trajectory; this was very interesting to analyze and at the end, it was found these patents are the representative of the 'new' thin-film solar technology, which matches our finding of a shift in the solar cells technology by using truncated network analysis. In practice however, the market share and type of application of c-Si is still more superior compared to thin-film technology.

When examining the main trajectories produced by SPLC and SPNP methods, some similarities, as well as structural differences, were found. Both networks depicted almost the same key players when talking about countries and companies. Nevertheless, the SPNP main trajectory seems to offer a broader and distributed picture of the evolution of this technology.

We noticed that the US, Japan, and Germany are the main actors in c-Si solar cells technology. We noticed that the US, Japan, and Germany are the main actors in c-Si solar cells technology. US and Germany are identified as key pioneers during the development of this technology, while Japan appears at later stages. We also find the countries which invested more in the early stages of technology, coincide with the countries with more patents in the network. When talking about companies, Siemens is the main actor in the initial c-Si solar technology; its contributions are key in at early development stages, and especially with the invention of thin-film cells as a new technology which defined a new development trajectory. This fact is realized after performing the truncated network analysis, which can capture sub-trajectories and significant technology shifts.

This network analysis could provide some insight into the future development of c-Si solar's technology. The sparsely connected network indicates that the future development will involve a more considerable number of patents from the outside patent domain. We could also expect the further contribution of the current dominant actors and nation for the development of c-Si solar cells technology. For further research, we consider it is better to analyze a broader picture, instead of relying only upon the general main trajectory, to understand the technology evolution. This analysis may be done in future research by adding keywords and by reading the summary of the patents to verify the suitability of the selected patents to the topic of the research.

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