# A structured MPA approach to explore technological core competence, knowledge flow, and technology development through social network patentometrics

Kuei-Kuei Lai, Hsueh-Chen Chen, Yu-Hsin Chang, Vimal Kumar and Priyanka C. Bhatt

(Information about the authors can be found at the end of this article.)





**Abstract**

**Purpose** – *This study aims to propose a methodology by integrating three approaches, namely, internal core technology, external knowledge flow and industrial technology development to help companies improve their decision-making quality for technology planning and enhance their research and development (R&D) portfolio efficiency.*

**Design/methodology/approach** – *The primary focus of this study is thin-film solar technology and patent data is retrieved from the United States Patent and Trademark Office (USPTO) database. This study presents a methodology based on the proposed integrated analysis method, constructed with patent indicators, centrality analysis of social networks and main path analysis.*

**Findings** – *The results of this study can be itemized as – the core technological competency: companies involved in two specific technology fields have lower strength in R&D portfolio than leading companies with single-core technology. Knowledge flow: most companies in a network are knowledge producers/ absorbers and technological development: diverse source and sink nodes were identified in the global main path during 1997-2003, 2004-2010 and 2011-2017.*

**Research limitations/implications** – *Latecomer companies can emulate leaders' innovation and enhance their technological competence to seek niche technology. Using the global main path, companies monitor outdated technologies that can be replaced by new technologies and aid to plan R&D strategy and implement appropriate strategic decisions avoiding path dependency.*

**Originality/value** – *The knowledge accumulation process helps in identifying the change of position and the role of companies; understanding the trend of industrial technology knowledge helps companies to develop new technology and direct strategic decisions. The novelty of this research lies in the integrated approach of three methods aiding industries to find their internal core technical competencies and identify the external position in the competitive market.*

**Keywords** *Knowledge flow, Patentometrics, Core technological competency, Main path analysis, Patent citation network, Thin-film photovoltaic*

**Paper type** *Research paper*

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## 1. Introduction

The foundation of technology is knowledge. The economic landscape, at present, is driven by knowledge, where knowledge is an imperative enabler to enrich and nurture organizations' innovativeness and competitiveness (Dangelico *et al.*, 2010). Future economy derives from technological innovation and for nations to develop such capability depends solely upon firm's ability to accumulate and interpret knowledge fragments efficiently (Petruzzelli *et al.*, 2010).

Technology strategy enables a company to gain a sustainable industrial advantage, which stipulates a competitive control. For firms to attain a competitive edge, both business and technological strategies should be entwined together. Firms can attain knowledge both internally [within a firm's research and development (R&D) sectors] and externally (from different partners/competitors) (Jiao *et al.*, 2019). It acts as a strategic resource for firms to achieve competitive advantage using knowledge as a strategic resource (Hu *et al.*, 2015). Technological innovations are considered responsible for a rapidly changing economic environment and firms need to imbibe a process of learning and developing new knowledge to combat the instability in such conditions (Del Giudice and Maggioni, 2014). Realizing the huge importance of knowledge in a firm's success, firms have started to invest a substantial amount of their resources for their technical innovation aided with strategies for interpreting knowledge based on their goals (Li *et al.*, 2018).

An effective technology strategy enables a firm to gain technological superiority among competitors. Companies need to integrate the business and technological strategies together (Porter, 1985). Any product or technology introduced by a firm has a base from existing technologies connected to the competencies of the firm or sometimes borrowed from technologies from other firms. Importance of such technologies either core or borrowed needs to be identified by their importance within the firm. Three levels of technologies are defined by Ford (1988), namely, distinctive (which are unique to the company and provide distinct capability), basic (which are the basic technologies in operations for firm's survival) and external (borrowed from other companies and available widely in the marketplace).

Apart from technological capabilities, companies need to focus on core competencies, which provide a competitive edge. Core competencies are the capabilities unique to the company, helping the company amplify their scope of success for the long term. Core competencies can be comprehended to capture both business and technological strategies of the firm.

However, technological advancement has led to exponential changes in the technological landscape, compelling companies to keep up with breakthrough innovations and understand the current technological trends. A firm might have good core competence but if the focus is not put on industrial trends then knowledge investment of such a firm may not be efficient. Further, if competence does not fit the trend, then the survival of the firm becomes challenging. In such a case, a question arises for firms to identify the technology trends within the marketplace. Trends can be identified by using knowledge. Knowledge can be absorbed either from internal or external sources. Thus, the importance of competence, knowledge and trends plays a vital role in a firm's success.

Scientific and technological innovation is an element for the industry to enhance competitiveness and patents are an embodiment of scientific and technological innovation and the output of scientific and technological development. Patents are considered as the quantifiable components of the intellectual property of a firm, which aid in forming the business strategies as well. Patent development is the outcome of integration of research and development innovations and supportive management (Cantrell, 2009). The collection of patents in a certain field represents the accumulation of technology in that field indicating the position of the technology in the technology life cycle and highlighting the development status (Liu *et al.*, 2011; Madani *et al.*, 2018). Therefore, companies having more well-developed patents are viewed as market leaders, and therefore, branded as innovative. Patents can be applied to economic analysis and technology assessment and forecasting (Porter and Cunningham, 2004). There is a long tradition of using patent data as technical indicators, but they are not incontrovertible. Investigations using patent statistics have both benefits and drawbacks and patent analysis are considered as output markers of innovation, not input indicators such as R&D expenditure (Griliches, 1990). Citations are considered to be valuable in investigating technology knowledge flows (Choe *et al.*, 2013) and an indicator of significance for the firm's inventive capability (Cantrell, 2009).

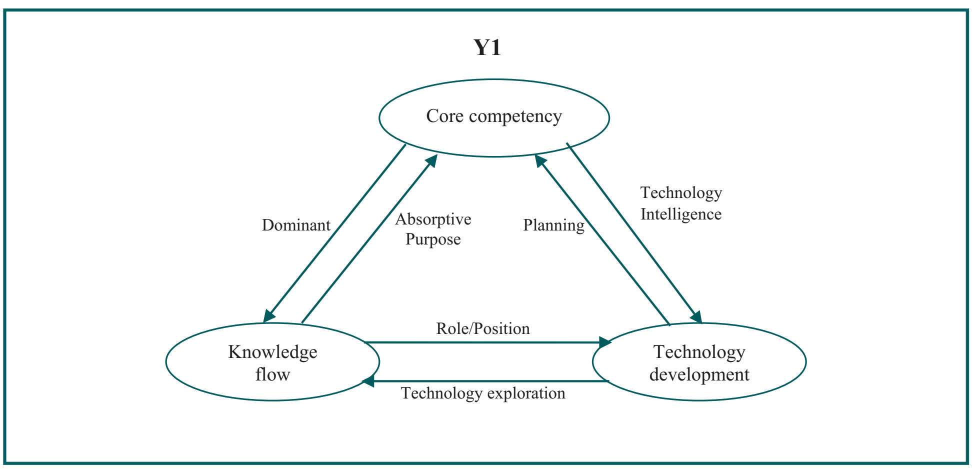
A business strategy will help a firm move from one competency to another, but it does not resolve uncertainties, which arise from the external sources or from within as well. Therefore, patent strategy plays a vital role to align the business strategy with the core competency of a firm (Cantrell, 2009). We might say, they are interconnected and the link is shown in Figure 1.

Therefore, in this study, we propose a hybrid model (Figure 1) interconnecting the core competencies, technology development and knowledge flow together for firms to attain a competitive edge based on the supplementary and complementary perspective to investment efficiency of the firm. Further, Badawy (1996) and Leonard-Barton (1995) focused on the external environment that helps to achieve competitive edge over its competitors and their innovative knowledge. Nerkar and Paruchuri (2005) have explored the intra-firm knowledge network of a company that predicts the possibility of involving new knowledge, more specifically created by the inventor, to be keyed into the R&D activities of the firm. Previous literature (Helfat, 1994) highlights that knowledge creation with respect to specific technological domains/fields is the more competent characteristics among firms. Mccluskey and Mccarthy (2012) examined the need of knowledge in the competence and vice versa cases depend on each other to make them robust.

Competency suggests firms to identify "where they are" (role/position), trends direct them "where to go" (planning) and finally knowledge puts the path for firms on "how to go" (capability).

The main difference between the success and failure of a firm's competition is the analysis of positive and negative technical competencies (Bettis and Hitt, 1995; Teece *et al.*, 1997). This specialization reflects the capability of a company to compete in different areas. Unlike large enterprises, small and medium-sized enterprises are unable to develop diversified technologies because of insufficient resources, so they tend to concentrate resources to develop a single technology, and thus, become the core technological competency of the enterprise (Lalitnorasate and Miyazaki, 2014). However, only identifying the internal technology competencies is not enough for a company. The firms need to learn from or

**Figure 1** The hybrid mode



follow the benchmark firms, reviewing the external view of their technological niche. Thus, this study purviews the following research questions:

*RQ1*. How does one company know its technology position and competitiveness?

*RQ2*. How to evaluate a company's position and capacity among all competitors?

*RQ3*. How to set up a technology strategy combining three methods into the hybrid model?

The purpose of this research is threefold, to increase the understanding of how the company's core technology competency portfolio and technology knowledge develop and apply it to specific business innovations. Firstly, on the niche of the technical route, the patent citation network is used to draw the technical trajectory, understand the changes in mainstream technologies and plan technology research and development and decision-making. Secondly, identifying the positions and roles of companies in the technology knowledge network and finally, understanding the leading or lagging situation of knowledge between the company and competitors, as a layout strategy for the company's technology research and development. Studying patents in the literature can be used as a substitute for technology and patent citations can be used to analyze the technical trajectory and technical knowledge flow. Previous studies have only discussed one part of the core competence, technical trajectory and knowledge flow, all these three facets have not been comprehensively explored. Therefore, this study constructs an integrated method based on patents and patent citations to simultaneously explore technological competencies, technological developments and knowledge flows. The methodology is validated with the use case of thin-film solar photovoltaic (PV) companies based on different time-periods, as an orientation for latecomers.

The further structure of the paper is categorized into seven sections as follows. Section 2 discusses the literature review followed by explaining the theoretical background and highlighting the research gaps, thus, formed in this section. Section 3 outlines the research methodology adopted by combining the aforementioned three approaches followed by results and analysis in Section 4. Section 5 describes the discussion including theoretical and managerial implications. Finally, Sections 6 and 7 discuss the conclusions and limitations and future research directions, respectively.

## 2. Literature review

This study builds upon the gap in the existing literature and further provides a social network analysis for the validation of the gaps identified. An in-depth study of previous literature is carried out, more specifically in the context of technical competencies, patent citations and main path analysis (MPA), technology trajectory and knowledge flow. Research gaps are identified after the thorough review of literature further in this section.

### *2.1 Technical competencies*

To consider a company's future technological advantages, it is imperative to continuously invest in R&D to continue to build strong technical competencies and form a unique patent portfolio. A proprietary combination is a company that uses core technology expertise to compare it with previous technologies and competitors' patents to build a combination of specific core technologies or strengths. To solve the problem of how enterprises, evaluate whether to invest in a certain technology, patent information is used as a benchmark for adjudicating technology combinations. Patent information is emphasized as a significant pillar of technical planning to engage in the R&D portfolio development to build superior competencies (Ernst, 1998). Tseng *et al.* (2011) used patents to examine developments and technical approaches of the amorphous silicon thin-film solar cell industry to understand the patent performance, technical competencies and R&D background of a-Si.

Sutopo *et al.* (2014) explored the technology research and development portfolio of solar PV companies based on technological attractiveness, relative patent status and relative patent advantages and analyzes the company's R&D advantages and technological competitiveness. Lai *et al.* (2017) used patent indicators to explore the solar technology company's technological competencies and R&D portfolio advantages in four major areas of silicon crystal, thin-film, emerging and interface from 2009 to 2014. Knowledge of the link between core competence and the selection of technology or products facilitates firms to reach a competitive edge (Torkkeli and Tuominen, 2002). The purpose of technical core competencies is "to distinguish competitors, create value for customers and become a platform for growth and strategic focus" (Goddard, 1997). R&D generates core technologies and helps firms to ascertain a competitive position as the strategic goal (Lavoie and Daim, 2019). This research believes that identifying the company's core technology and benefits of R&D combination are important research approaches to explore the technology combination in the market.

### *2.2 Patent citations and main path analysis*

Patents are considered as indicators of the intellectual output of an organization in terms of R&D, technological innovation and technology management. Many patents do not lead to innovation and the tendency of patent innovation may vary by industry and company (Daim *et al.*, 2006). Through published patent performance indicators, potential disruptive innovations can be identified (Kassicieh and Rahal, 2007). Before the formation of the patent, many previous patents were cited and after the formation of the patent, it would be cited by subsequent patents (Madani *et al.*, 2018). From the perspective of technical knowledge flow, the patent includes the existing technology and a medium for technology disclosure, which describes the technological development trajectory (Fallatah, 2018). Analysts use patent citations to measure these outputs (Harhoff *et al.*, 1999) using the patent count index. When a target patent as the analysis object refers to other patents, it is known as a backward citation while it is cited by other patents, it is termed forward citation (Nicotra *et al.*, 2013). The number of forward citations can be used as an indicator of the impact of successive technologies (Benson and Magee, 2015; Czarnitzki *et al.*, 2011); and the number of backward citations is an indicator of the degree of dependence on the previous technology (Liu *et al.*, 2011), so patent citations are used to characterize the status of technology flows (Wagner *et al.*, 2014).

MPA is a method of analyzing citation networks, which identifies the information flow to highlight the prominent development path of technology. From the context of technological evolution, the main path identified in a citation network is the primary technology trajectory (Dosi, 1982). Hummon and Dereian (1989) first proposed the MPA and started the follow-up theory and application-based research. Batagelj and Mrvar (2004) integrated MPA algorithms into large-scale social network analysis program Pajek, thus becoming an important method for identifying the core components of a technology network. Liu and Lu (2012) proposed an integrated MPA method, which advocates observing the main path from different perspectives. The main path discussed includes local main path, global main path, multiple main paths, key-route main path, etc.

### *2.3 Technical trajectory*

The process of gradual innovation and diffusion in technical innovation involves both technological paradigms and technological trajectories (Dosi, 1982). Scientific progress and the interaction between institutional variables and economic factors aid in establishing the knowledge of the progression of technological trajectories (Hu and Jaffe, 2003). The technical trajectory in a citation network is created by the path followed by the citations in that network (Bottazzi *et al.*, 2001). Patent connectivity analysis in the patent citation network may form a continuous patent development path, thereby catching up with previous technologies (Mina *et al.*, 2007). Verspagen (2007) used fuel cell data to describe the main paths of knowledge flow. The concept of technological trajectories shows that there are several main knowledge flows (or pathways) and developments in the network. Liu *et al.* (2011) explored the development of solar materials and battery technology from the perspective of patent growth analysis. The concept of technology trajectory points out that technological innovation is a sequential and interrelated event. Therefore, a gap in the technology field can be found in such trajectory. It is worthwhile for companies to explore technology development and patent layout.

### *2.4 Knowledge flow*

Technological development is cumulative, where the invention and development of new technologies are mostly based on previously developed technologies. Therefore, a technology citation relationship will form a technology network where inventions represent nodes (Nodes) and links (Ties) represent technology associations (Lai *et al.*, 2009). The network, formed by mutual citation and similarity of technology, seeks the position of technology in the network by the relationship of technology network. It further reflects the development of technology by the structural change of network with the consideration of time.

The technology network formed by citations is rich in information based on the development of technical knowledge (Huang *et al.*, 2003; Kajikawa and Takeda, 2009). Examining the company from an evolutionary perspective, the changes in the flow of technical knowledge can directly affect the accumulation of a company's core technology competencies. Wu and Mathews (2012) investigated patent citations to identify the knowledge diffusion path of solar PV related technologies and pointed out that the less developed countries have gradually used their knowledge to generate and flow, from imitation to innovation. Choe *et al.* (2013) used the patent citation network to explore the flow and characteristics of knowledge among countries, institutions and technical fields of organic solar cells. Chang *et al.* (2017a) used the patent citation index to explore the patent portfolio of solar PV companies and the knowledge flow between the fields of silicon, thin-film, emerging and interface technologies. Larruscain *et al.* (2017) used social network analysis to explore the efficiency of knowledge transfer between organizations in the renewable energy sector in Europe from 2000 to 2013. Johnstone *et al.* (2010) discussed patents related to renewable energy technologies, confirming that public policies have patented renewable energy technologies. In the process of technology development, the externality of technology will affect the spillover effects of competing manufacturers in the industry and promote technological progress in the industry (Bernstein, 1988), which will additionally be subject to the protection system for knowledge and innovation among industries (Cohen *et al.*, 2002). Therefore, identifying the source and destination of technical knowledge can help firms to understand the technology framework concerning the exchange of knowledge between organizations through patent backward citation analysis of the activities of leaders and followers in technological development (Yu and Daim, 2017).

### *2.5 Research gaps*

Technical planning is considered an important aspect for firms to establish R&D portfolios for building superior capabilities (Ernst, 2003). The primary goal of R&D is to construct and accrue core technologies to ascertain a competitive edge. This research, therefore, constructs upon the fact that identifying core technologies and examining the benefits of R&D combination are significant research approaches to explore the technology combination focusing specifically on the market.

The concept of technology trajectory points out that technological innovation is a sequential and interrelated event (Verspagen, 2007). Therefore, a niche or gap in the technology field can be found in this trajectory (Lai *et al.*, 2017). It is worthwhile for companies to explore technology development and patent layout (Lai *et al.*, 2017).

The spillover effect comprehends the protection system for innovation knowledge among industries (Cohen *et al.*, 2002). Therefore, examining the source and destination of technical knowledge assists firms to comprehend the core technology framework. In industrial development, Wu and Mathews (2012) used patent backward citation analysis to propose relative citation inclinations, investigating the knowledge flow among participant countries and understand the correlation among knowledge-exporting (leading) and knowledge-importing countries. Therefore, researching and observing the information about enterprise technology knowledge flow and the source of technical knowledge is an efficient process. Patent backward citation analysis is also effective in measuring the exchange of knowledge between organizations. Activities of leaders and followers in technological development.

Existing literature lacks in filling the gap between the core competencies, business strategies and technology development trends for firms to attain competitive advantage. This research, therefore, identifies a hybrid approach based on patent data to explore technological competencies, technological developments and knowledge flows confirmed with the case of thin-film solar technology.

## 3. Research framework

This section discusses the model construction, network analysis, MPA and centrality analysis:

### *3.1 Model construction*

The concept and model construction of this research is to first collect data about the selected technology from the patent database and then organize the patent data set, $\Omega$. Rate [patent shares (PS)] and revealed technology advantage (RTA) indicators are used to analyze the company's technical competencies and measure the company's core technologies. We find the citation relationship from $\Omega$ to form the patent citation data set $(\Omega)_{mpa}$, build the adjacent matrix $(\omega_{\mathrm{ij}})_{m\times m}$to make a network relationship, analyze the main path, analyze the information flow to categorize the group, the distinctive features in each group and the influence among select technologies, to understand the trajectory of the select technology. Finally, the patents that belong to the same company are merged. The network centrality statistics are calculated by the adjacent matrix $(\alpha_{ij})_{k\times k}$ of the citation relationship between the companies. The indicator construction patent owns the position of the knowledge role among the companies and analyzes the knowledge flow. The patent data set is defined as follows:

$$\Omega = \left\{ D_{ijt} \left| \begin{array}{c} D_{ijt}\, \textit{Represent patents obtained by the j company in the i technical field during the t period} \\ j = 1, 2, \ldots, n_i;\ i = 1, 2, \ldots, k;\ t = 1, 2, \ldots, T \end{array} \right. \right\} \tag{1}$$

Considering only the technical field and period in $\Omega$ (1), the number of all patents $G_{it}$ can indicate that the number of patents in the *i-th* technical field during the *t* period is:

$$G_{it} \sum_{j=1}^{n_i} D_{ijt} \quad i = 1, 2 \ldots, k;\ t = 1, 2, \ldots, T \ldots, T \tag{2}$$

The organized data set discusses the technological development trends of the technical fields of technology in sequence, which can be expressed as follows:

$$I_{it} = \sum_{t=1}^{T} D_{ijt} \quad \cdot j = 1, 2, \ldots, n_i;\ i = 1, 2, \ldots, k \tag{3}$$

Where $I_{ij}$ represents the number of patents of the $j$-th company in the $i$-th technical field.

### 3.2 Network analysis

The analysis method of this study is explained in terms of the company's core technology competencies, thin-film solar technology trajectory and the positions and role of knowledge networks.

*3.2.1 The company's core technical competencies.* Two indicators PS and RTA (Patel and Pavitt, 1997) were used in this study, where, PS is "the ratio of a number of patents of a company in a specific technology field to the total number of patents in a specific technology field that indicates the degree of investment of the company in a single technology relative to other companies.*"* The combined observation of the two indicators is to identify the development across a firm's internal technical competencies, which means that the internal technical competencies of a firm in a particular technology area are self-positioning, which is a tendency of the company's internal core technical competencies. It can be shown in the form of the equation as the ratio of the number of patents in $i$-th technology of the $j$-th company and the total number of patents in $i$-th technology field, as given in equation (4):

$$PS_{ij} = \frac{I_{ij}}{\sum_{j=1}^{n_i} I_{ij}} \qquad j = 1, 2, \ldots, n_i;\ \mathrm{i} = 1, 2, \ldots, k \tag{4}$$

Where, $\sum_{j=1}^{n_i} I_{ij}$: Sum of the number of patents of all companies in the *i-th* technology.

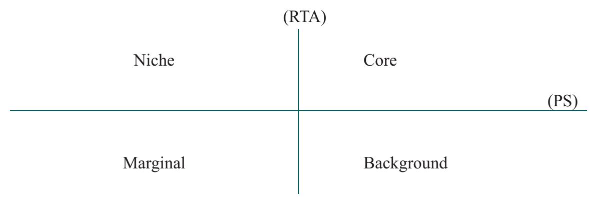
*3.2.2 Revealed technical advantages.* RTA can be represented as 'the index of a specific company's technology in a specific technical field*"* (Patel and Pavitt, 1997). A larger value of RTA signifies a relatively high advantage in a particular technical field. A lower value indicates lower or null competitive advantage in a particular technical field. The calculation method of RTA is given in equation (5) below:

$$RTA_{ij} = \frac{PS_{ij}}{\dfrac{\sum_{i=1}^{k} I_{ij}}{\sum_{i=1}^{k} \sum_{j=1}^{n_i} I_{ij}}} \quad j = 1, 2, \ldots, n_i;\ i = 1, 2, \ldots, k \tag{5}$$

where, $\sum_{i=1}^{k} I_{ij}$: Sum of the number of technology patents in all fields of company $j$;$\sum_{i=1}^{k} \sum_{j=1}^{n_i} I_{ij}$: Sum of the patents in all technical fields of all companies;$\frac{\sum_{i=1}^{k} I_{ij}}{\sum_{i=1}^{k} \sum_{j=1}^{n_i} I_{ij}}$: All technical fields of $j$-th company the ratio of the sum of patents of $j$-th company to the sum of patents in all technical fields of all companies.$_{RTAij}$: Represents the RTA index of the $j$-th company in the $i$-th technology area.

*3.2.3 Analysis of combined technical competencies.* We integrate the two indicators, PS and RTA to analyze the technical competencies and divide the firms to be analyzed into four categories, namely, Core, Marginal, Background and Niche (Lalitnorasate and Miyazaki, 2014; Patel and Pavitt, 1997), given in Figure 2 below. The Core has a tendency of high PS and high RTA values, which is the company's main input project and has been important valued with high RTA tendency. The Marginal has low PS and RTA, which indicates the technology project has low investment, low importance in the company. The Background has high PS value but low RTA tendency. The technology project is valued and

**Figure 2** Analysis of the company's technical competencies




**Source:** Patel and Pavitt (1997)

it has the company's investment in R&D resources. Niche has a low PS value with a high RTA and this technology project has a low investment in the company.

The source of the specialized resources of this research object is mainly taken from the patent resources database of the USPTO. From this database, the title and abstract are selected in the column of bibliometrics, as shown in Table 2. As, title indicates the patent right, which is the primary term anyone will see in a patent, it is included in the search strategy. The abstract content mainly mentions the content and significance of this patent. The important items are also included in the search strategy.

### 3.3 Main path analysis

*3.3.1 Construct the patent citation data set* $\Omega_{mpa}$. We sort out equation (1) $\Omega$ and find out the citation relationship between patents $P_i$, ($i$= 1, 2, ..., n) to form the patent citation set $\Omega_{mpa}$ in the form of a matrix:

$$\Omega_{mpa} = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2n} \\ . & . & \dots & . \\ . & . & \dots & . \\ . & . & \dots & . \\ C_{n1} & C_{n2} & \dots & C_{nn} \end{bmatrix} \tag{6}$$

where:

$$C_{ij} = \begin{cases} 1 & \text{Patent } P_i \text{ citing Patent } P_j \\ 0 & \text{No citation relationship between patents} \end{cases} \quad i \neq j$$

$C_{ij} = 0$ $i = 1,2, \dots,n$; $j = 1,2, \dots n$If $S_i = 0$ and $S_i' = 0$ at the same time, then $P_i$ is deleted.

Among them, $S_i = 0$ and $S_i' = 0$, all $C_{ij}$ values in the $i$-th column of the table are 0, the patent $P_i$ does not have any backward references. $S_j' = \sum_{i=1}^{n} C_{ij} = 0$, all $C_{ij}$ values in row $j$-th of the table are 0 and patent $P_j$ does not have any forward citations.

*3.3.2 Constructing patent adjacency matrix.* To discuss the analysis of the main path, we construct a citation network-adjacency matrix between patents. From the previous section, we delete all patents without backward citations and no forward citations at the same time and keep the remaining number as $m$. These $m$ patents $P_1$, $P_2$, ..., $P_m$ are sorted into an adjacency matrix with a relationship of $m$ patents is as follows:

$$[\omega_{ij}]_{m\times m} = \begin{bmatrix} \omega_{11} & \omega_{12} & \cdots & \omega_{1m} \\ \omega_{21} & \omega_{22} & \cdots & \omega_{2m} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ \omega_{m1} & \omega_{m2} & \cdots & \omega_{mm} \end{bmatrix} \tag{7}$$

where:

$$\omega_{ij} = \begin{cases} 1 & \text{Patent} \quad P_i \quad \text{citing} \quad \text{Patent} \quad P_j \\ 0 & \text{No} \quad \text{citation} \quad \text{relationship} \quad \text{between} \quad \text{patents} \end{cases} \cdot i \neq j$$

$\omega_{ii} = 0$ $i = 1,2,\ldots,m$; $j = 1,2,\ldots m$.

*3.3.3 Create network.* In the MPA, we calculate the traversal weight, calculated using search path link count (SPLC), of each edge from the source point to the sink point and then find out the patent main path at the stage of technological development to analyze the dynamic evolution process of the industry-leading technology. The adjacent matrix equation (7) is used to measure the information flow between companies (Batagelj and Mrvar, 2004). The set of patent and citation relationships in the patent citation network is N (U, R), where U and R represent the set of all patents (nodes) and the set of all citation relationships (edges), respectively. The knowledge transfer is sent to all sinks by the preceding files (Ancestor) of *u*, so the information flow of the link (u, v) is the sum of all u pioneering documents and all possible combinations of meeting points (Batagelj and Mrvar, 2004; Liu and Lu, 2012):

$$w_{SPLC}(u,v) = \; n^{-}(u)\cdot n^{+}(v) \tag{8}$$

where $n^{-}(u)$ is the number of all possible paths from the pioneer file to node u$n^{+}(v)$ is the number of all possible paths from node v to the sink; $(u,v) \in R$.

Once all nodes are connected and their network is established, we begin to find the primary path. We used the established patent to cite the adjacency matrix equation (7), SPLC equation (8) for information flow and Pajek to conduct the search path network statistics. Finally, we observe the mainstream development of technology through the overall main path and understand the evolution and trajectory of the technology according to the key extension paths.

The knowledge network discussed in this section also uses the patent citation adjacency matrix equation (7) to merge patents belonging to the same company, constructs the adjacency matrix of company citation network relationships and uses network statistics to comprehend the citation network structure of a firm. Centrality has been used to compute the outward-inward (O-I) index and betweenness to understand the position and influence of knowledge between patent firms and analyze the company's knowledge role.

*Constructing citation network relationships between companies: Adjacency Matrix*

The patents belonging to the same company among *m* patents in equation (7) are merged, cited companies, *k* and the adjacency matrix is constructed as follows:

$$[\alpha_{ab}]_{k\times k} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1k} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2k} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ \alpha_{k1} & \alpha_{k2} & \cdots & \alpha_{kk} \end{bmatrix} \quad (9)$$

where:

$$\alpha_{ab} = \left\{ \begin{matrix} 1, & \textit{Company a has a patent citing any patent of company b} \\ 0 & \textit{No patents cited between companies} \end{matrix} \right\}$$
$$a = 1, 2, \ldots, k;\ b = 1, 2, \ldots, k$$

### *3.4 Centrality analysis*

We calculate In-degree Centrality, Out-degree Centrality and betweenness, and further devise a network of centrality relationship to analyze the degree of knowledge flow in a company. In-degree centrality is calculated as the number of backward citations received by a company's patents, which is used to identify the capability of the actor's knowledge to flow in. Out-degree centrality is calculated as the number of patent citations of a firm by other firms, which is calculated to identify the knowledge outflow of a company. Betweenness centrality is considered as the ability of a firm to act as an intermediary in a citation network and it represents the degree of control of the actor's transfer of knowledge flow.

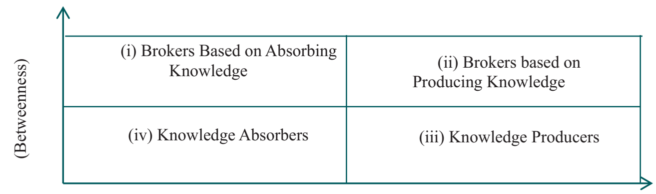
*3.4.1 Calculating the outward-inward index.* The O-I index is theoretically related to the E-I (external-internal) index (Krackhardt and Stern, 1988). The E-I is mainly used to analyze the degree of aggregation of subgroups in the overall network or the degree of distribution in an overall network. However, the O-I index associates with the degree to which one set of nodes refers to other nodes. It is measured by the "difference between out-degree centrality and in-degree centrality divided by their sum" (Chang *et al.*, 2017b). The value of the O-I index lies within the range of $-1$ and 1. The value closer to 1 indicates the higher invention quality, whereas the value closer to $-1$ indicates more accumulation of technical knowledge toward the node. The knowledge producers or absorbers in a network can be identified with the help of O-I index (Chang *et al.*, 2017b; Choe *et al.*, 2013). Degree centrality and betweenness are considered as substantial actors for important nodes in a network (Marzi *et al.*, 2017):

$$\mathrm{O} - \mathrm{I} \cdot \mathrm{Index} = \frac{(Outward\ \ centrality - inward\ \ centrality)}{(outward\ \ centrality\ + \ inward\ \ centrality)} \quad (10)$$

*3.4.2 Performing outward-inward index and mediation centrality analysis.* The citation relationship of firms is categorized into four clusters (Choe *et al.*, 2013):

- intermediate centrality, relatively large and with an O-I index greater than 0, labeled as "brokers based on producing knowledge";
- intermediary with relatively large centrality and O-I index less than 0, labeled with "brokers based on intermediary absorbing knowledge";
- the intermediary centrality is relatively small and the O-I index is greater than 0 and is labeled as "knowledge producers"; and
- the intermediary centrality with O-I index less than 0 is labeled as the "knowledge absorber;" as shown in Figure 3.

**Figure 3** Position and role of intercompany knowledge




**Source:** Choe *et al.* (2016)

We calculate degree centrality and then we combine the O-I index and intermediary centrality to establish a knowledge flow.

In the next section, we discuss the results based on the analysis of data for solar energy industry from our proposed methodology.

## 4. Case study: analysis of the thin-film solar technology track

To confirm the integration of three approaches proposed in this research, we analyze firms in the field of thin-film solar technology as experiential objects and use patent information and patent citations to construct an integrated analysis method to explore the company's technological competencies, knowledge flow and industrial technology development. In terms of the research process, we first, select the research target as the solar energy industry. We devise keywords based on relevant literature, theoretical discussions and interviews with experts. The patent data is retrieved from USPTO. We further analyze whether the company's technological competence is the company's core technology, followed by MPA. Finally, a knowledge flow analysis is performed to understand the position of the company's technological knowledge among the citation network. The proposed research process is given in Figure 4.

### *4.1 Solar photovoltaic technology*

Existing energy resources will soon be exhausted and now the focus and support have shifted to renewable sources of energy. A report (Reuters, 2014) based on global patent data and scientific literature, "The World in 2025: 10 Predictions of Innovation," predicts that solar energy will become the main energy source on the planet. The solar PV technology has grappled to reach the status of reliable renewable energy and gradually expanded to form an emerging cost-efficient and compliant industry to promote the economic development (Cho *et al.*, 2019; Zervos, 2019). The development of solar cells can be divided into four generations based on distinctive features (Sutopo *et al.*, 2014): First-generation includes 'the Crystalline Si field, constituting single-crystal silicon wafers, polycrystalline silicon wafers, thick film silicon and silicon heterojunctions," etc. The second generation introduced the use of "thin-film, including copper indium gallium selenide, cadmium telluride, microcrystalline silicon and amorphous silicon," etc. Third-generation solar cells can be considered as the beginning of PV technology called the emerging PV field, which includes dye-sensitized batteries, organic batteries and organic strings batteries, inorganic batteries, quantum dot batteries, etc. Finally, the fourth generation of solar cells focuses upon concentrating battery junction field, including "a three-junction transistor, double-junction transistor, junction transistor, single crystal." The emerging path of solar PV technology is shown in Figure 5 (NREL, 2019). The distinction between silicon wafers and thin-film solar technology is necessary because the latter has significant

**Figure 4** Research process and structure

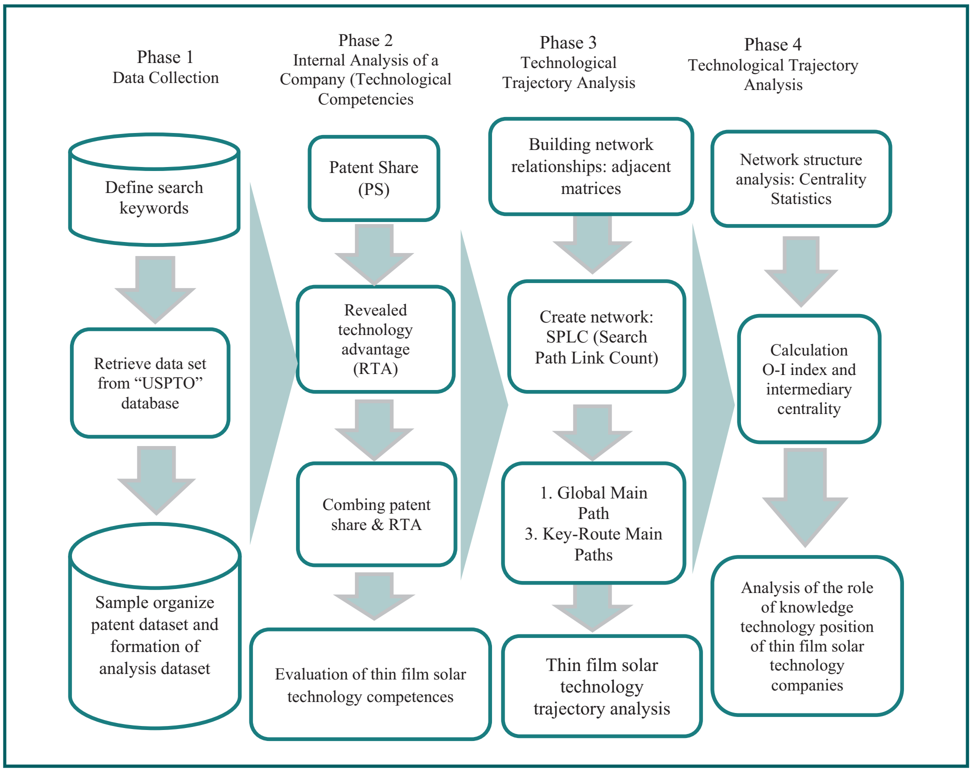
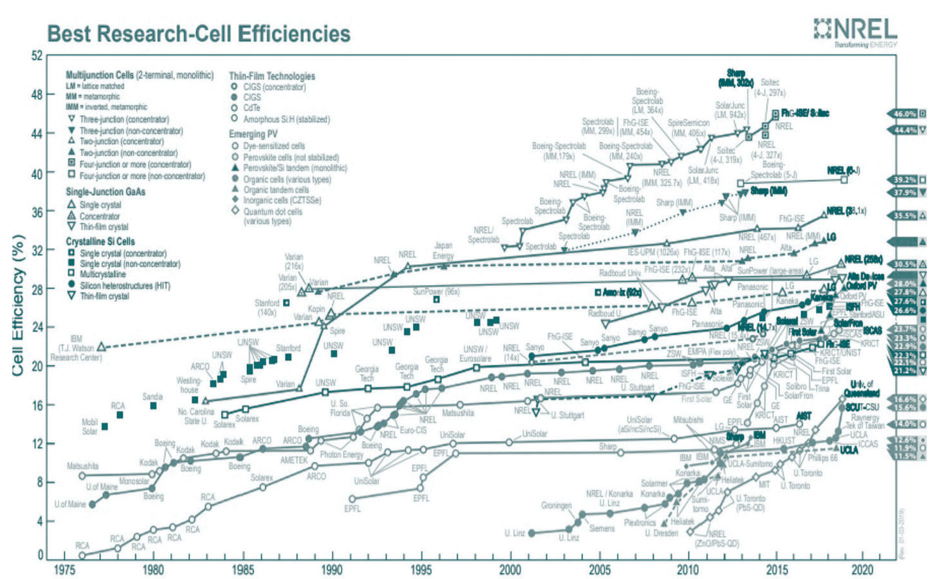



**Figure 5** Solar PV technology path




**Source:** National Renewable Energy Laboratory (NREL) advantages over the former in building-integrated PV applications such as lighter weight and lower installation costs and improved flexibility and optical translucency (Han *et al.*, 2017; Jean *et al.*, 2015; Kylili and Fokaides, 2014).

### *4.2 Data collection and constructing a patent data set (Ω)*

Before data collection, the search keywords are determined after the aggregation of expert interviews and relevant literature on thin-film solar energy (Li *et al.*, 2007; Yang *et al.*, 1997). The important technical names of thin-film solar energy for patent search are obtained to develop the keywords such as "a-Si, mc-Si, copper indium gallium selenium (CIGS), thin film and solar cell." Four major thin-film solar technologies are considered as described in the previous section are summarized in Table 1. The international patent classification (IPC) Code was identified based on these major technologies and the broad classification was H01L (*"*semiconductor devices, electric solid-state devices*"*) and B05D *("*processes for applying liquids or other fluent materials to surfaces"*)*, further subclasses are provided in Appendix 1, 2 and 3 based on the time-period of the key source patents identified on the main path. The search keywords and patents, thus, identified are given in Table 2.

**Table 1** Limited search syntax and number of patents from 1977 to 2017

| *Name* | *Category 1* | *Category 2* | *Syntax search in the first stage* | *Sum of first-order patents* | *Syntax search in the second stage* | *The sum of second-order patent* |
|---|---|---|---|---|---|---|
| Thin-film solar cell | Amorphous Silicon | a-Si | TAC:("thin film") and TAC:("a-Si" or "amorphous silicon") (A) | 6,327 | A+B+C | *946* |
| | | Multi-junction | TAC:("thin-film") and TAC:("multi-junction") and TAC:("a-Si" or "amorphous silicon") (B) | | | |
| | | Tandem | TAC:("thin-film") and TAC:("tandem" or "hybrid" or "micromorphous") and TAC:("a-Si" or "amorphous silicon") (C) | | | |
| | Nanocrystalline Silicon | nc-Si/ mc-Si | TAC:("thin-film") and TAC:("nc-Si" or "nanocrystalline silicon" or "mc-Si" or "microcrystalline silicon") | 508 | TAC:("thin-film") and TAC:("nc-Si" or "nanocrystalline silicon" or "mc-Si" or "microcrystalline silicon") TAC:("solar cell" or "PV") | *245* |
| | Thin-film compound semiconductor | CdTe | TAC:("thin-film") and TAC:("CdTe" or "cadmium telluride") (D) | 2,490 | D+E+F+G+H | *1,269* |
| | | CIGS | TAC:("thin-film") and TAC:("CIGS" or "copper-indium-gallium-diselenide" or "copper indium gallium diselenide") (E) | | | |
| | | CIS | TAC:("thin-film") and TAC:("CIS" or "copper indium disenillide" or "CuInSe2") (F) | | | |
| | | GaAs | TAC:("thin-film") and TAC:("GaAs" or "gallium arsenide") (G) | | | |
| | | GaAs Multi-junction | TAC:("thin-film") and TAC:("multi-junction" or "multi-junction") and TAC:("GaAs" or "gallium arsenide") (H) | | | |
| | Total | | | 9,325 | | *2,460* |

**Note:** TAC means searching merely on TTL, ABST and CLMS projects

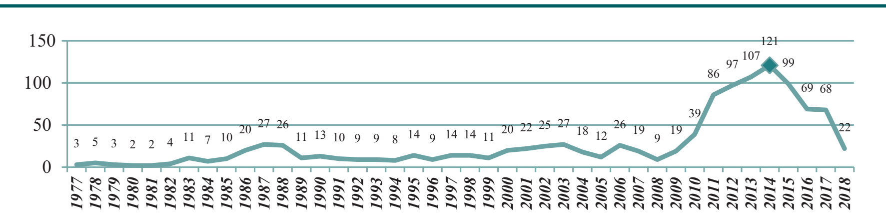
| Table 2 Search keywords and patents | | | | |
|---|---|---|---|---|
| *And* *Keywords* | *Solar* | *GaAs* | *Silicon* | *No. of patents* |
| Three-junction | ○ | | | 57 |
| Two-junction | ○ | | | 50 |
| Four-junction | ○ | | | 55 |
| Single crystal | ○ | ○ | | 80 |
| Concentrator | ○ | ○ | | 14 |
| Thin-film crystal | ○ | | | 35 |
| Single crystal | ○ | | ○ | 1,311 |
| Multicrystalline | ○ | | | 226 |
| Thick silicon film | ○ | | | 2 |
| Silicon heterostructure | ○ | | | 0 |
| Dye-sensitized cell | ○ | | | 19 |
| Organic cell | ○ | | | 0 |
| Organic tandem | ○ | | | 18 |
| Inorganic cell | ○ | | | 4 |
| Quantum dot cell | ○ | | | 0 |
| CIGS | ○ | | | 1,215 |
| Cdte | ○ | | | 579 |
| Polycrystalline Silicon | ○ | | | 1,562 |
| Nanocrystalline Silicon | ○ | | | 36 |
| Microcrystalline | ○ | | | 197 |
| Amorphous Silicon | ○ | | | 3,933 |

The data is retrieved from USPTO database from 1997 to 2017 in terms of patent portfolios and the patents and affiliated companies that have a citation relationship in this period are analyzed. A total of 2,460 patents from different companies were obtained, of which 1,125 were citation patents.

To study the transformations in a firm's core technology competencies, this study is divided into three periods for analysis. The number of patents changed from the highest to the lowest in 2014 as given in Figure 6. The three-time periods categorized are: 1997-2003, 1997-2010 and 1997-2017. The total number of 922 patents for analyzes are collected in the three-time. The patent count between 1977 and 1996 was only 203, which is a significantly small change, therefore, not considered for this study. We also realized that no patents were spanning microcrystalline silicon and compounds in these periods, so the initial seven lists of technical fields were finalized to six. The final data is divided into *T* periods and belongs to *k* technical fields. Each technical field contains different companies, the *i-th* technical field contains $n_i$ companies.

The organized data set $\Omega$ is defined according to equation (1) and it discusses the technological development trends of the six technical fields equation (2) of thin-film solar technology in sequence, which can be expressed in terms of equation (3).

**Figure 6** Changes in the number of patents approved by the solar industry from 1977 to 2017



To explore the trajectory of thin-film solar technology, a matrix with backward and forward citation relationships was constructed and combined to form an adjacent matrix. We first retrieved each patent data $P_i$, $i$ = 1,2, . . ., $n$, where $n$ is the number of patents retrieved.

### 4.3 Identification and analysis of the firm's internal core technology

To achieve the purpose of identifying the transformation in the core competencies (technological) of solar thin-film companies, this study combined two indicators PS and RTA to divide the companies into four groups, each named core, marginal, base and niche. The core position of the company's technical competencies is shown in Table 3.

Analyzing the results from Table 3, we identify that Kaneka Corporation, Samsung and Semiconductor Energy Laboratory, have core technologies in the domain of "amorphous silicon." Kaneka Corporation had core technological competencies for "amorphous silicon + microcrystalline silicon" during the first and third period (1997-2003 and 1997-2017), whereas for Semiconductor Energy Laboratory it was during the second and third period (1997-2010 and 1997-2017). These 3 firms locked their resources in the development of "amorphous silicon." Unique resources and competencies are the sources of the company's sustainable competitive advantage. Similarly, we see that Miasole is the only company having core technology competency in the domain of "compounds" during its second and third period of classification. We also notice that Applied Materials Inc. has core competencies in both "amorphous silicon + compounds" and "amorphous silicon + microcrystalline silicon" during the second and third period and for "compound" domain it has marginal technological competency for the second and third period. It is the only company that has strong R&D competencies in four major areas. British petroleum (BP) has been involved in the solar industry since the 1980s, it has acquired marginal technology competency for "amorphous silicon" in the first period, however, "microcrystalline silicon" and "amorphous silicon + compound + microcrystalline silicon" are both considered core technology for BP. Sanyo Electric Co., Ltd had the core technology competency in the first two periods of the "amorphous silicon" field but it is identified as a niche in the third period. We observe the changing competencies for companies in different periods of time.

### 4.4 Thin-film solar company: technology trajectory

The overall main path primarily observes the core path of the overall technology, identifies the main trajectory of technological development and comprehends the technological development changes with time. The main path of technology includes nine key patents, as shown in Figure 7. The technology trajectory of thin-film solar energy is analyzed in three periods, 1997-2003 (initial technology development path), 1997-2010 (main development path) and 1997-2017 (overall development path) described further.

*4.4.1 The overall main path from 1997 to 2003.* During the period 1997-2003, the principal technical development of the main path focused on the development of thin-film solar cells and the technical field was more focused on the "amorphous silicon".

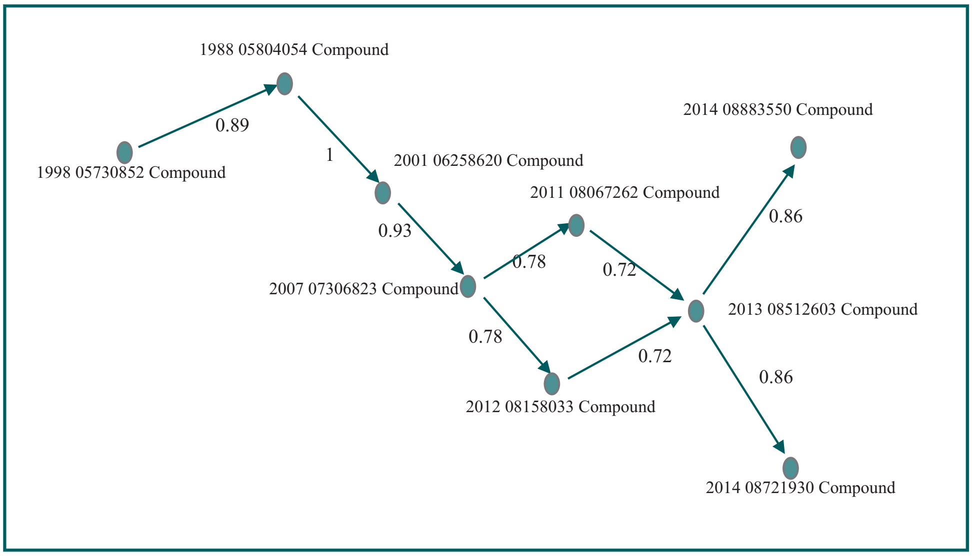
The overall main path during this period includes four key patents. The technical development trajectory during this period started in 2000. Patent 06040521-N-type window layer of thin-film solar cells and its manufacturing method (IPC: H01L31/0749), developed to 2001 patent 06187150, a device for manufacturing thin-film PVs, a technical method for manufacturing thin-film solar cells (IPC: H01L31/1884). There are two patents, one of which is Patent No. 06500690 in 2002, a method for producing a thin-film PV device (IPC: H01L31/052) and the second is 2003 patent 06670542, a semiconductor device and its manufacturing method (IPC: H01L31/0745). The description of each patent is given in Appendix 1. The entire main path expresses the key patents, directions and technical trajectories of thin-film solar technology during this period.

**Table 3** Thin-film solar technology capabilities, (I) is 1997-2003; (II) is 2004-2010; (III) is 2011-2017

| *Company technology* | *Microcrystalline silicon* | | | *Amorphous silicon* | | | *Compound* | | | *Amorphous silicon + compound* | | | *Amorphous silicon + microcrystalline silicon* | | | *Amorphous silicon + compound + microcrystalline silicon* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *I* | *II* | *III* | *I* | *II* | *III* | *I* | *II* | *III* | *I* | *II* | *III* | *I* | *II* | *III* | *I* | *II* | *III* |
| Alliance for Sustainable Energy, Llc | | | | M | M | | C | M | N | | C | | | | | | | |
| Antec Solar Gmbh | | | | | | | C | | | | | | | | | | | |
| Applied Materials, Inc. | | | | | B | C | | M | M | | C | C | | C | C | | | C |
| BP | | | | M | | | | C | | C | C | | C | | | C | | |
| Cannon | C | | | C | C | | | | | | | | B | C | | | | |
| Csg Solar Ag | | | | B | | | B | | | C | | | | | | | | |
| Department of Energy | | | | | | M | C | M | N | | C | C | | C | | | | |
| E. I. Du Pont De Nemours and Company | | | | | N | C | | N | M | | | | | | | | | C |
| First Solar, Inc. | | | | | | M | | | C | | | B | | | | | | |
| Global Solar Energy, Inc. | | | | | | | C | | N | | | | | | | | | |
| Globalfoundries Inc. | | | | | | | | C | N | | | C | | | | | | |
| HP | | | | | | | | C | | | | | | | | | | |
| IBM | | | | | | M | | | C | | | C | | | | | | |
| Industrial Technology Research Institute (tw) | | | C | N | C | M | | M | M | | | C | | | | | | C |
| Jpmorgan Chase Bank, As Collateral Agent | | | | | | | | | C | | | B | | | | | | |
| Kaneka Corporation | | | | C | C | C | | | | | | | C | | C | | | |
| Merck Patent Gmbh | | | | | | | | | C | | | | | | | | | |
| Miasole | | | | | | | | C | C | | | | | | | | | |
| Nanosys, Inc. | | | | | C | | | C | | | | | | | | | | |
| Nippon Sheet Glass Co., Ltd. | | | | C | | | | | | | | | | | | | | |
| Panasonic | | | | B | N | | | | | | | | C | | | | | |
| Precursor Energetics, Inc. | | | | | | | | | C | | | | | | | | | |
| Samsung | | | | C | C | C | | | M | | | | | | | | | |
| Sanyo Electric Co. Ltd | | | | C | C | N | | | | | | | | | | | | |
| Semiconductor Energy Laboratory | | | C | C | C | C | B | | M | | | C | | C | C | | | |
| Sharp Kabushiki Kaisha | | | C | C | C | N | B | | | | | | | | | | | C |
| Snaptrack, Inc. | | | | | C | N | | C | | | | C | | | | | | |
| Solar Frontier K. K. | | | | | | | C | | C | | | | | | | | | |
| Sony Corporation | | | | C | M | N | | | M | | | | C | | | | C | |
| Stion Corporation | | | | | | | | | C | | C | B | | | | | | |
| Thin Film Electronics Asa | | | | | C | N | | M | | | | | | | | | | |

**Notes:** *N* is the “niche,” B is the “base,” M is the “marginal” and C is the “core”

**Figure 7** The main path of patents from 1997 to 2017




*4.4.2 The overall main path from 1997 to 2010.* In the main path from 1997 to 2010, the main development during early stages was dominated by patents in the field of "amorphous silicon + microcrystalline silicon," but later there were two patents in the compound field in all four branches, indicating "compound" technology field steadily attaining importance. The overall main path during this period includes seven key patents. The source point of the main path is changed when the solar thin-film battery is developed from 1997 to 2010. The source patent from the previous period, 06040521 changed to 1997 patent 05593901, a monolithic series and parallel photoelectric modules (IPC: H01L31/046).

Furthermore, in 1997, the patent 05593901; in 2000 the patent 06007722; and in 2001 the patent 06288325, their main classification could be identified as to deposit "a PV module composed of multiple thin-film solar cells on the same substrate,*"* which is confirmed by their IPC codes H01L31/046. The 2008 patent 07319190 and the 2009 patent 07576017 are used for specific processes or equipment of batch processing devices. The 2009 patent 07582515 is for *'*the technological development of multi-junction or tandem solar cells.*"* The 2010 patent 07741144 is for the reduction of gaseous compounds or Decomposition processing. The description of each patent is given in Appendix 2.

*4.4.3 The overall main path from 1997 to 2017.* In the period from 1997 to 2017, it is seen that "amorphous silicon" and "microcrystalline silicon" have disappeared from the mainstream technology field, indicating that the entire industrial technology's main axis is finally dominated by the compound technology domain.

During this period, the overall main path includes nine key patents. The source changed to patent 05730852 in 1998, preparation of precursor films by electrodeposition to manufacture high-efficiency solar cells. This period highlights the patents 05804054 in 1998, 06258620 in 2001 and 07306823 in 2007.

The 1998 patents 05730852 and 05804054 are mainly used for "the electrodeposition of copper indium gallium selenide thin films for solar cells" (IPC: H01L31/0749), while the 2001 patent 06258620 relates more specifically to the manufacture of copper indium gallium diselenide using elemental selenium.

The 2007 patent 07306823 is used for the manufacture of battery "IB-IIIA-VIA active layer," the patents from 2011 to 2014, 08067262, 08158033, 08512603 and 08721930, all belong to the preparation of the photoelectric layer before polymerization, respectively. The description of each patent during this period is provided in Appendix 3.

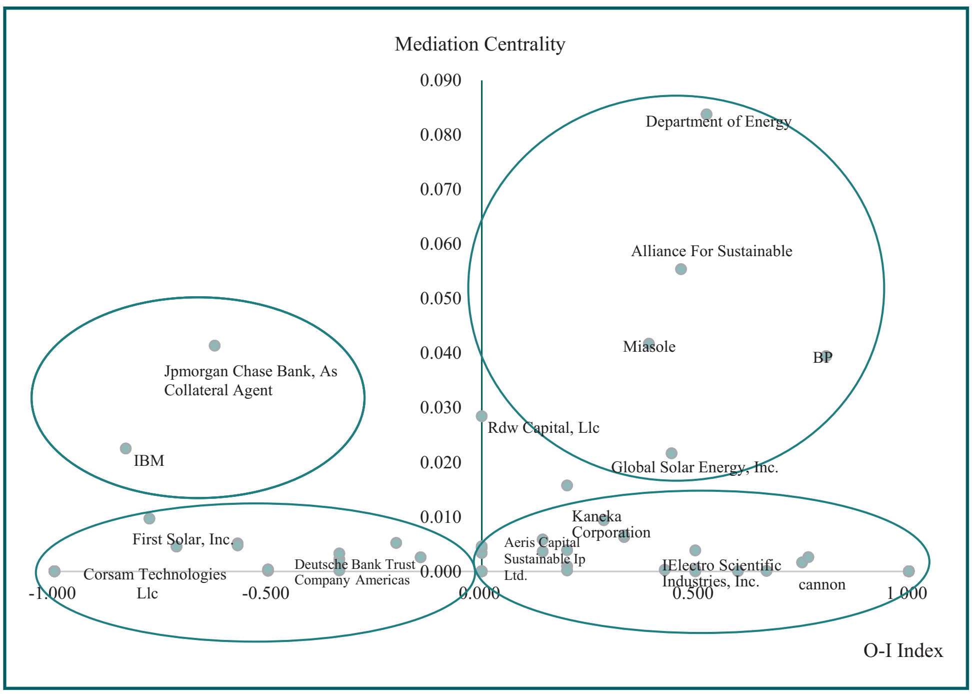
The source of the main path is seen changed from 1997 to 2017 period of development of solar thin-film cells, at a different time horizon. Patent US5539901 in 1997 changed into the patent US5730852 in 1998 that represent the preparation of precursor film to produce high-efficiency solar cells through electrodeposition. During the period of technological development, the main path passes through the 1998 patent US5804054, 2001 patent US6258620 and development to patent US7306823 in 2007 and 2011 patent US8067262. The patent US8158033 in 2012 and the patent US8512603 in 2013 are combined into one, while the patent US8792930 in 2014 and the patent US8835550 in 2014 are divided. Patents US8067262 (2011), US8158033 (2012), US8512603 (2013) and US8721930 (2014), all signify *"*preparing polymeric precursor compounds and materials.*"* Patent no. US8885550 (2014) is the innovation related to deposit a material called *"*CIGS on the substrate, a thin light-absorbing solid layer.*"* The primary difference between the two patents can be considered in the itemization of compound materials. The entire main path expresses the key patents, directions and technological trajectories of thin-film solar technology during this period.

### *4.5 Position and role of companies: knowledge flow*

O-I index with relation to intermediary centrality enables us to identify the role of companies with respect to their position in the network. It helps to identify the positions and roles of the company's knowledge flow, as shown in Figure 8 for different time horizons from 1997 to 2017.

Six companies including Alliance for Sustainable Energy, Llc., BP, Department of Energy, Global Solar Energy, Inc., Miasole and Rdw Capital, Llc. are classified as "Brokers based on producing knowledge'. The Department of Energy has the highest intermediary centrality

**Figure 8** Position and role of knowledge flow companies from 1997 to 2017



during this period, i.e. the company plays a significant association role in transmitting knowledge, and hence, acts as a leader. IBM and JPMorgan Chase Bank fall under "brokers based on absorbing knowledge" classification. IBM's I-O index value is close to $-1$, i.e. the company has been cited less in comparison to other companies. An odd 73 companies including Aeris Capital Sustainable Ip Ltd., Beijing Apollo Ding Rong Solar Technology Co., Ltd, CA Institute of Technology, Cannon, CO State University Research Foundation, Electro Scientific Industries, Inc., and Solar Frontier KK, etc. are classified as "knowledge producer." The O-I index is greater than 0, that is, the company is cited more times than other companies are cited. Because of the relatively small centrality of the brokers, i.e. the company's associating role in transmitting knowledge is of slight importance. The O-I indexes of Cannon and Solar Frontier KK is close to 1, but the intermediary centrality is very small, which indicates that these two companies have the competency to produce knowledge but not to transfer knowledge. Finally, companies such as Applied Materials, Inc., Corsam Technologies Llc, Deutsche Bank Trust Company Americas, EI Du Pont De Nemours and Company, First Solar, Inc. Industrial Technology Research Institute (tw), LG and Taiwan Semiconductor Manufacturing Co. Ltd. fell under the category of "knowledge absorbers" with an O-I index less than 0. Additionally, for First Solar, Inc.'s, O-I index is close to $-1$ and the intermediary centrality is also very small signifying that the two companies only absorb knowledge and do not have the ability to transfer knowledge.

## 5. Discussion

This section substantiates our research framework. This research is embedded around knowledge flow and MPA to obtain the core of technical competencies in an organization that validates our research framework with the analysis of thin-film solar cell technology. Previous researchers (Bhupatiraju *et al.*, 2012; Chang *et al.*, 2017c; Kumar *et al.*, 2018; Lee and Kim, 2017; Su *et al.*, 2017; Subtil Lacerda, 2019) have discussed the importance of identifying the role and positions of companies using knowledge flow. MPA (Ho *et al.*, 2014; Hung *et al.*, 2014; Wang *et al.*, 2016; Gwak and Sohn, 2018; Kumar *et al.*, 2018; Liu *et al.*, 2019) highlights the important players in the technology. After identifying the literature gap, we introduce a novel concept of identifying core technical competencies for companies based on the case of thin-film solar cell manufacturers. We identify that company, Miasole company only focused on the "compounds" field, which indicates the highest efficiency proven in commercial-scale and can efficiently connect the gap with polysilicon device efficiency. Based on analyzing the core technology of thin-film solar cell companies, it might be of indication that BP and other petroleum industry giants have a higher tendency to invest in the renewable energy industry. This research also identifies nine significant patents along the main path, along with the roles of companies based on the O-I centrality index.

This research first explored the core competencies of solar thin-film companies with patent data sets, then uses patent citations and MPA to understand the trajectory of technological evolution, then we calculate network centrality statistics, combine the O-I index and betweenness and understand the knowledge flow between companies. Above mentioned analysis also answers our postulated research questions and approve of our proposed methodology. Further in this section, we discuss theoretical implications, contributing to the academic landscape and adding to the gap in the existing literature. We further discuss the managerial implications of this research in the second part. This section contributes a substantial and perceptible managerial implication, which aids companies to comprehend their resource position with the technologies' performance.

### *5.1 Theoretical implications*

Continual development of a company's core technical competency and standards for improving R&D portfolios requires analysis and monitoring from both internal and external factors. Researchers usually use indicators (such as a number of patents in a specific period) based on classifications, keywords or index terminologies to identify technical components to explore emerging technologies and their prospective marketplaces (Cozzens *et al.*, 2010; Guo *et al.*, 2011; Seymour, 2008; Tseng *et al.*, 2011; Yoon and Park, 2005) for identifying core technologies. Previous research on patent indicators has mostly explored technology development trends and lacked a method to identify the company's core technology in different time periods. Therefore, this study constructs an integrated method based on patents and patent citations to simultaneously explore firms and their technical core competencies in different periods. PS enables us to measure R&D investment of a firm with respect to other companies. The self-positioning of internal technical competencies in a specific technological field signifies the core technological competency of a company. The primary purpose of the main path is to find a critical mainstream development path in the process of technological development. An organization can create an enhanced blueprint for its R&D strategy and technology forecasting by investigating their presence or absence in terms of key patents on the main path. This also helps organizations to apprehend the technological development and innovation, thus adding the value to main path research. O-I index calculated using centrality measures of social network analysis aids organizations to identify knowledge producers or knowledge absorbers in the citation network. The index also formulates the roles and positions of companies in their competitive market. It is difficult to identify the process that includes innovation and patents are proven as instruments to study and analyze technological innovations (Coluccia *et al.*, 2019). Existing literature lacks in finding a connection between the core competencies, technology development trends and the knowledge flow. This study, therefore, linked these three strands in the context of technological intelligence, exploration and knowledge absorption. The roles and positions of companies prove to be a vital instrument between knowledge flow and technology development. Therefore, adding to the literature, this study proposed an integrated method focusing on the core technical competencies of a company and facilitating them to reevaluate their R&D innovative strategies based on their position in the market.

### *5.2 Managerial implications*

Every industrial evolution has path-dependent characteristics, i.e. once a certain path is entered, entities may become dependent on this path (North, 1990). Therefore, it is essential for companies to gain a competitive advantage by investigating the future technological development path and perform technical monitoring to understand the latest industrial progress. This research identified that the overall main path for thin-film solar cell technology developed through different sources and sinks during the three periods of 1997-2003, 1997-2010 and 1997-2017, forming different technological evolution trajectories. The results will help organizations to monitor whether a new technological innovation entered the path substituting the preceding ones, and therefore, abetting in formulating the R&D strategies to circumvent path dependence. As solar PV technology has become more mature, competition among enterprises has become increasingly fierce. Organizations try to understand the layout of patents, their roles, the advantages and disadvantages of technology development, to enhance corporate value. Follower companies often play the role of knowledge absorber.

Disruptive technologies often create a major threat mostly ignored by incumbents (Garces and Daim, 2012). New knowledge is an attribute of R&D, and thus, it is important for managers to continuously improve strategies based on prior knowledge and new challenges (De Massis *et al.*, 2016; Petruzzelli, 2011). The major concern for any organization is to identify and surmount the innovation pattern of its core technology domain, find its role and position in the competitive market and develop a sustainable competitive advantage for superior operational performance. Core technical competencies are the foundation of a company's competitiveness. Enterprises must interminably perform technological innovation, consciously cultivate their core technical competencies combined with values and strategic goals to establish and maintain a competitive advantage. In general, companies engaged in two or more specific technology domains have lower R&D portfolio advantages than leading companies with single-core technology. Therefore, it is important for a company to research and develop a single patent applied to its technology fields, enabling the decision-makers to seek technological niche points. Knowledge flow helps companies to understand, which company owns, which technology (or knowledge *per se*). Decision-makers must identify the firm's core competency and the competitors. This research provides a layout for managers whether they should continue with their niche or focus on competitive strategies. Also, sometimes, it is better to cooperate than to compete, specifically with the benchmarkers, which will depend upon the company's position in the external environment.

## 6. Conclusion

In a nutshell, technical competencies are the internal competencies, whereas roles and positions in the competitive market showcase the external competencies of an organization. The main path validates the position of the company, enabling it to determine its innovation output using patent data. Therefore, companies pursue their best business performance by maintaining a constant competitive advantage through understanding the trend of technology development along with the evolution of technology in industries, developing the core technological competencies of companies and identifying the position of companies in technology knowledge flow. The advantage of the proposed method in this research is that the leader company can identify new innovating firms based on patent data and decide upon enhancing its technical strength, whereas new entrants can learn from the main path and identify their competitive edge in the market, whether it decides to become a follower or articulates a competitive strategy to become a leader in the market. This research not only enables managers to decide the R&D innovation strategies but also helps academicians and researchers to contemplate the significance of patent analysis in decision-making and initiate the research toward blending the patent statistics techniques with organizational theories.

## 7. Limitations and future research directions

Though this study proposed a new framework for analyzing patent data for identifying core technical competencies, the data source of this study was limited to thin-film solar patents using the USPTO database and analysis results were obtained using back citations. Secondly, the study is effective for organizations with superior technological operations. It would be interesting to extend the concept to competencies apart from technology. The research could be extended to establish the innovation path of technology areas other than thin-film solar cells. In addition, patent indicators can also be used to identify the technology life cycle and analyze and explore already studied aspects such as core technology competencies, main paths and knowledge flow phenomena alongside the technology life cycle curve with respect to different time periods of technology growth. The future research directions can include the conjunction of USPTO and other patent databases. Further integrating SNA central indicators, the number of patent approvals and patent citations to accurately identify company position in the technology development network. Finally, the study could be extended to include patent weights to obtain more accurate technical competencies, technology trajectories and knowledge flows.

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### Author affiliations

Kuei-Kuei Lai is based at the Department of Business Administration, Chaoyang University of Technology, Taichung, Taiwan.

Hsueh-Chen Chen is based at the Department of Management Sciences, Tamkang University, New Taipei City, Taiwan.

Yu-Hsin Chang is based at the Department of Marketing and Logistics Management, Chaoyang University of Technology, Taichung, Taiwan.

Vimal Kumar is based at the Department of Information Management, Chaoyang University of Technology, Taichung, Taiwan.

Priyanka C. Bhatt is based at the Department of Information Management, College of Informatics, Chaoyang University of Technology, Taichung, Taiwan.

## Appendix 1

**Table A1** Overall main path patent description for years between 1997-2003

| *Patent no* | *Year* | *IPC* | *The company* | *Patent name* | *Patent description* | *Classification category* |
|---|---|---|---|---|---|---|
| 06040521 | 2000 | H01L (H01L31 /0749) | Solar frontier KK | N-type window layer for a thin-film solar cell and method of making | Transparent conductive film used as window layer of CIGS thin-film solar cell and manufacturing method thereof | Compound |
| 06187150 | 2001 | H01L (H01L31 /1884) | Kaneka corporation | Method for manufacturing thin-film PV device | The present invention relates to a method for manufacturing a thin-film solar cell and the present invention relates to a method for manufacturing a thin-film solar cell, a PV cell containing an Amorphous silicon-based PV layer | Amorphous silicon |
| 06500690 | 2002 | H01L (H01L31 /052) | Kaneka corporation | Method of producing a thin-film PV device | An object of the present invention is to provide a method for manufacturing a thin-film solar cell having a silver-based back electrode having excellent bonding strength with a transparent conductive back layer | Amorphous silicon + |
| | | microcrystalline silicon | | | | |
| 06670542 | 2003 | H01L (H01L31 /0745) | Sanyo | Device and semiconductor manufacturing method thereof | Provided is a highly efficient semiconductor device that eliminates damage caused by plasma and maintains interface characteristics between an amorphous silicon semiconductor layer and an electrode | Amorphous silicon |

## Appendix 2

**Table A2** Overall main path patent description for years between 1997-2010

| *Patent no* | *Year* | *IPC* | *The company* | *Patent name* | *Patent description* | *classification category* |
|---|---|---|---|---|---|---|
| 05593901 | 1997 | H01L (H01L31 /046) | BP | Monolithic series and parallel connected PV module | PV module consisting of multiple thin-film solar cells deposited on the same substrate | Amorphous silicon + compound |
| 06077722 | 2000 | H01L (H01L31 /046 ) | BP | Producing thin film PV modules with high integrity interconnects and dual | PV module consisting of multiple thin-film solar cells deposited on the same substrate | Amorphous silicon |
| 06288325 | 2001 | H01L (H01L31 /046 ) | BP | Producing thin film PV modules with high integrity interconnects and dual layer contacts | PV module composed of multiple thin-film solar cells deposited on the same substrate | Amorphous silicon + microcrystalline silicon |
| 07319190 | 2008 | H01L ( H01L31 / 1876 ) | Td Waterhiuse Rrsp in trust for peter Alan lacey, as beneficiary | Thermal process for creation of an in-situ junction layer in CIGS | Specific process or equipment for batch processing plant | Compound |
| 07576017 | 2009 | H01L (H01L31 /1876 ) | Td waterhiuse Rrsp in trust for peter Alan lacey, as beneficiary | Method and apparatus for forming a thin-film solar cell using a continuous process | Specific process or equipment for batch processing plant | Compound |
| 07582515 | 2009 | H01L (H01L31 /076 ) | Applied Materials, Inc. | Multi-junction solar cells and methods and apparatuses for forming the same | Multi-junction or tandem solar cells | Amorphous silicon + microcrystalline silicon |
| 07741144 | 2010 | H01 L (H01L21 /0262 ) | Applied Materials, Inc. | Plasma treatment between deposition processes | Reduction or decomposition of gaseous compounds such as CVD | Amorphous silicon + microcrystalline silicon |

## Appendix 3

**Table A3** Overall main path patent description for years between 1997-2017

| *Patent no* | *Year* | *IPC* | *The company* | *Patent name* | *Patent description* | *classification category* |
|---|---|---|---|---|---|---|
| 05730852 | 1998 | H01L (H01L31 / 0749 ) | US Department of Energy | Preparation of cuxinygazsen (X = 0-2, Y = 0-2, Z = 0-2, N = 0-3) precursor films by electrodeposition for fabricating high efficiency solar cells | The invention relates to electrodeposition of a CIGS film for a solar cell | Compound |
| 05804054 | 1998 | H01L (H01L31 / 0749) | US Department of Energy | Preparation of copper indium gallium diselenide films for solar cells | The invention relates to electrodeposition of a CIGS film for a solar cell | Compound |
| 06258620 | 2001 | H01L (H01L31 / 0749) | US Department of Energy | Method of manufacturing CIGS PV devices | It involves the use of elemental selenium producing a copper indium gallium diselenide (a CuIn X Ga. 1-X Se 2 or only the CIGS ) optical electric device and requires no complex codeposition or the use of toxic H of two selenium gas | Compound |
| 07306823 | 2007 | B05D ( B05D 5/12 ) | Aeris Captial Sustainable Ip Ltd | Coated nanoparticles and quantum dots for solution-based fabrication of PV cells | Manufacturing of IB-IIIA-VIA active layer for battery | Compound |
| 08067262 | 2011 | H01L (H01L 21/00) | Precursor Energetics, Inc. | Polymeric precursors for CAIGAS Aluminum containing PVs | Molecular precursor compounds and precursor materials for preparing PV layers including CAIGAS | Compound |
| 08512603 | 2013 | H01B (H01B 1/12) | Precursor Energetics, Inc | Polymeric precursors for CIS and CIGS PVs | It relates to polymeric precursor compounds and precursor materials used to prepare PV layers | Compound |
| 08721930 | 2014 | H01B (H01B 1/14) | Precursor Energetics, Inc | Polymeric precursors for AIGS silver containing PVs | It relates to polymeric precursor compounds and precursor materials used to prepare PV layers | Compound |
| 08883550 | 2014 | H01L (H01L 21/00) | Precursor Energetics, Inc | Deposition processes for PV devices | Used to deposit a material calle CIGS, a thin light-absorbing solid layer of copper indium gallium diselenide on a substrate. Solar cell with thin film CIGS layer provides low to medium efficiency for converting sunlight to electricity | Compound |

## About the authors

Kuei-Kuei Lai is the Vice President and a professor of Department of Business Administration, Chaoyang University of Technology Taichung, Taiwan. He has served as a professor and the chairman in the Department of Business Administration, National Yunlin University of Science and Technology, Taiwan. He received his PhD degree in Graduate Institute of Management Sciences from Tamkang University in Taiwan. His research interest focuses on management of technology in patent citation analysis, patent portfolio and patent family and technological forecasting.

Hsueh-Chen Chen is a PhD scholar in the Department of Management Sciences, Tamkang University, New Taipei City, Taiwan. Her major research areas are financial, statistical analysis, patent analysis etc.

Yu-Hsin Chang is an Assistant Professor of Department of Marketing and Logistics Management, Chaoyang University of Technology. He completed his PhD degree at Graduate Institute of Business Administration, National Yunlin of University Science and

Technology. His major research area focuses on technology management, patent analysis and patent network analysis. His research papers have been published in Storage Management Solutions, Technology Analysis and Strategic Management, Scientometrics, Technological Forecasting and Social Change etc. He is interested in combining patent protection and marketing competition for further research.

Vimal Kumar is an Assistant Professor at Chaoyang University of Technology, Taichung, Taiwan (ROC) in the Department of Information Management. His research interests in the area of Technological Innovation and Patent Analysis, Total Quality Management, Manufacturing Strategy, Supply Chain Management. Vimal Kumar is the corresponding author and can be contacted at: vimaljss91@gmail.com

Priyanka C. Bhatt is PhD Research Scholar at Dept. of Information Management, College of Informatics, Chaoyang University of Technology, Taiwan. She has an extensive experience of more than five years in area of computer engineering and information science. She has been a lead developer of "research support services" in Bennett University, Bennett Coleman, Co. Ltd. from 2018-19. She has worked with institutes of national importance such as SIDBI, IIT Kanpur; HBCSE – Tata Institute of Fundamental Research, Mumbai; and National Medical Library, New Delhi. 'e-services' developed by her at National Medical Library, New Delhi received appreciation from the Ministry of Health and Family Welfare, Govt. of India, in 2016. Research areas of her publications include, scientometrics, patent statistics, social network analysis, data mining, cloud computing, ICT applications, etc.