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Ph. D. Dissertation in Engineering

Study on the nexus between production and innovation, and its effects on the firm's capabilities

생산활동, 혁신활동 간의 관계에 관한 연구

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Study on the nexus between production and innovation, and its effects on the firm's capabilities

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이 논문을 공학박사학위 논문으로 제출함

2017 년 2 월

서울대학교 대학원

협동과정 기술경영경제정책 전공

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Dedicated to my beloved parents and my lovely sister

Abstract

Study on the nexus between production and innovation, and its effects on the firm's capabilities

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In the 1990s, industrial restructuring from the manufacturing industry to the service industry began to spread, led by developed countries such as the United States. As a result, offshoring occurred, and more production facilities were moved to developing countries with the aim of improving industrial performance through higher productivity and efficiency. Efforts were made to move production facilities that were losing their competitive edge to countries that can secure price competitiveness, and to improve the quality of the economy by reorganizing as a research and development base. However, as production facilities moved into developing countries, the basis for stable employment creation was shaken and the economy lost its vitality. Recently, problems of rising wages, logistics costs, and technology outflows have been raised in developing countries. In

addition, the innovation of the industry, which is the basis for sustained economic growth, has begun to slow down. This is because the manufacturing base and the overseas transfer of production facilities have reduced the foundation for implementing new ideas.

Despite the importance of production in creating innovation for sustained growth, most existing empirical studies merely focus on emphasizing the role of production in terms of industrial restructuring or job creation. Therefore, examining the effect of production on innovation is very important at this point in setting future directions for our industrial economic system.

This study attempts to examine the role of production in innovation activity and the industrial structure that can continuously generate innovation. First, we emphasize the importance of technological learning that can strengthen the link between production and innovation, by reviewing existing research on the relationship between production and innovation. Next, we identify the correlation between production capacity and innovation performance by considering the case of the Korean manufacturing industry. Thereafter, we analyze the high-tech industry, the driving force of the future society. Finally, we offer suggestions for a desirable relationship between production and innovation for continuous innovation creation and growth.

The results of the study are summarized as follows. First, the decline in the production capacity of the domestic manufacturing industry leads to a decline in the quality of innovation. This tendency was particularly evident in the case of overseas transfer of production facilities for the purpose of cost reduction. In the high-tech industry, it is also

confirmed that the possession of production capacity is an important factor in the formation of innovation performance and knowledge network. However, possessing only the production capacity does not always lead to the improvement of innovation. Forming a cooperative relationship plays a key role, between the company with production and application capacity and universities and research institutes conducting basic knowledge research. Therefore, for a virtuous cycle between production and innovation, it is necessary to facilitate the smooth flow of knowledge accumulated through cooperation and network between the two.

Keywords: Production, Innovation, Manufacturing, Knowledge network, Network analysis, Patent citation analysis

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Chapter 1. Introduction

1.1 Research motivation

Korea has achieved significant economic growth for the past half century since the 1960s, described as the “miracle of the Han River.” From the labor-intensive light industry in the 1960s to the capital-intensive heavy industry and electronics industry in the 1970s and 1980s, and the knowledge-intensive IT (information technology) industry in the 1990s and 2000s, the industrial structure underwent a transformation in accordance with time. However, as the economic structure changed, the share of agriculture and manufacturing in GDP (gross domestic product) and total employment gradually decreased, whereas the proportion of services increased. In order to achieve sustainable growth, it has been suggested that the industry should advance by improving productivity and efficiency. As a result, in the process of reorganization as a technology-based industry, many production facilities have moved to developing countries that provide cheap labor, such as China, Vietnam, and Indonesia. Efforts were made to move manufacturing facilities that were losing their competitive edge to countries with price competitiveness and to improve the quality of the economy through the reorganization of domestic facilities into advanced research and development (hereafter, R&D) bases. This phenomenon has been regarded as natural and transitional due to changes in consumption patterns and productivity gaps between manufacturing and service industries (Baumol, Blackman, & Wolff, 1989; Ramaswamy & Rowthorn, 1997; Rowthorn & Wells, 1987). Lawrence Summers, former US Treasury Secretary, argued that “America’s role is to feed a global economy that’s increasingly based on knowledge and services rather than on making stuff” (Gertner, 2011), and encouraged to relocate manufacturing facilities in the US abroad and focus on R&D. Owing to this trend, the share of manufacturing to the total value added in G7[1] countries has gradually decreased, while that of the service industry has increased in the same period.

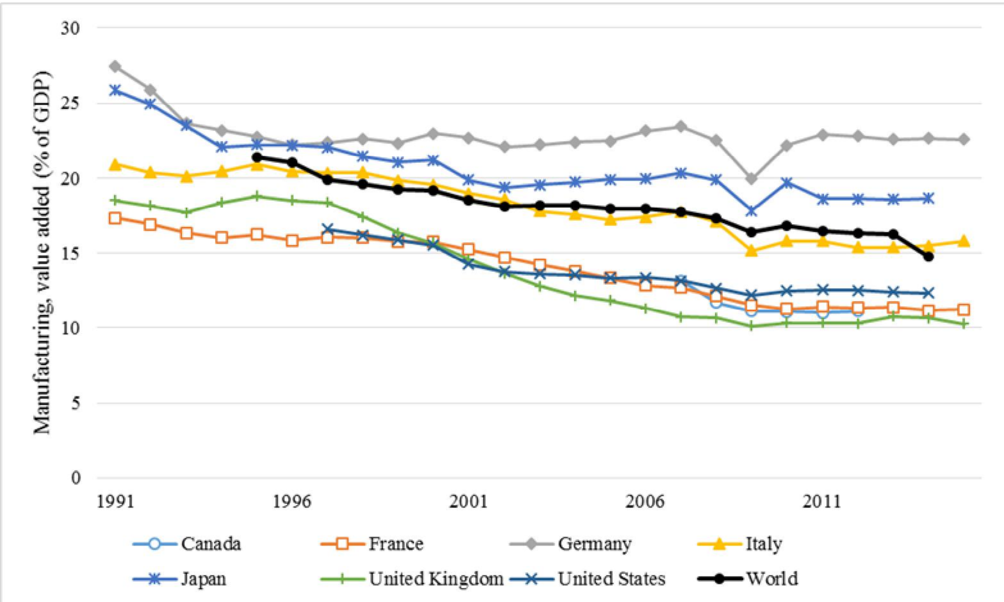


Figure 1. Ratio of manufacturing value-added to GDP of G7 countries

Source: The World Bank DataBank (http://databank.worldbank.org/)

[1] G7 (Group of Seven): Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States

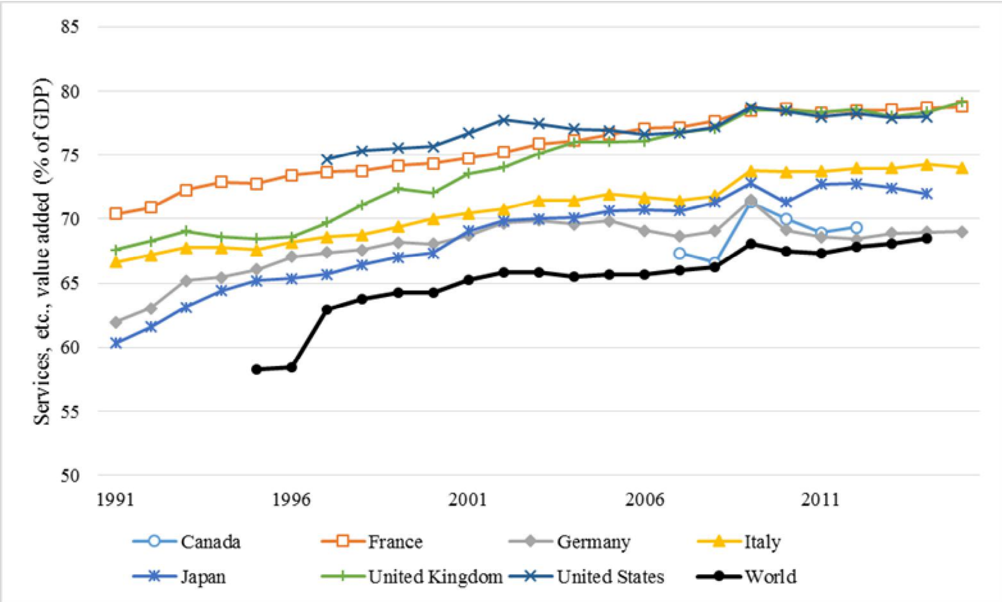


Figure 2. Ratio of service value-added to GDP of G7 countries

Source: The World Bank DataBank (http://databank.worldbank.org/)

However, the transfer of production facilities overseas for the past 20 years has caused a decrease in investment in the home country, and social phenomena such as high unemployment rate and lower productivity has emerged due to jobless growth. Hollowing out of manufacturing has intensified as the economy has shifted to service-oriented industries, and economic indicators such as corporate profitability and potential growth rate also had negative results. According to the Hyundai Research Institute (2016), Korea's dependence rate on overseas manufacturing production rose from 13.9% in 2009 to 18.5% in 2014, and thus, the production inducement coefficient dropped from 2.092 in 2005 to 2.036 in 2013 and the value-added inducement coefficient also dropped from 0.627 in 2000 to 0.534 in 2013. Furthermore, the employment inducement coefficient declined from 20.3 per billion won in 2000 to 8.6 in 2013. This is not the case in Korea alone. The US has also faced difficulties such as decreasing number of jobs and field-based innovations, as a consequence of moving manufacturing facilities to developing countries such as China.

The importance of manufacturing has begun to be emphasized in order to overcome the hollowing out phenomenon. Pisano & Shih (2009) argued that the industrial commons, including industrial ecosystems such as skilled workers and know-how, related parts suppliers, and industry-academia networks, would be eroded if the developed countries moved their manufacturing plants abroad. They point out that manufacturing is the source of innovation and productivity, and that the main reason for the weakening of US manufacturing is offshoring. The MIT published “Making in America,” which emphasized the necessity of manufacturing in the US, overturning claims made in “Made in America” in 1989. In this book, Suzanne Berger, professor in MIT’s Production in the Innovation Economy (PIE), argued that it is hard to state that the cheap labor of the emerging economies leads to US trade deficit even in the high-tech industry, and manufacturing or function of production are keys to solve social problems such as economic recession and unemployment (Berger, 2013).

Based on these arguments, the Obama administration announced the *AMP (Advanced Manufacturing Partnership) 2.0* Initiative, which combines US-dominated innovation capabilities and manufacturing based on advanced IT technologies, and attempts to narrow the gap between the innovation and the market. Recently, Germany has also begun to make efforts to improve its industrial competitiveness through the combination of manufacturing and ICT (information and communications technology), similar to the US, through *Industry 4.0*. In order to strengthen its weakened manufacturing capability, Japan has also been promoting *Monozukuri* (ものづくり) strategy. In addition, Korea has enacted the *Act on assistance to Korean off-shore enterprises in repatriation* in 2013, which is also called the "U-turn enterprise assistance act," and introduced various tax reductions, including those for corporate and income taxes. The Korean government is promoting policies to encourage companies to reshore production by providing various benefits such as subsidy support and preferential occupancy of industrial complexes.

The commonalities of these countries' policies are efforts to reinforce the weakened manufacturing base, revive manufacturing, create employment, and solve social problems. However, despite the growing importance of domestic production for innovation, most of the existing empirical studies focus on emphasizing the role of production in the country in terms of industrial restructuring or job creation, and lack research from the innovation perspective. Locke & Wellhausen (2014) argue that the ultimate significance of manufacturing is no longer the creation of large-scale jobs, and because manufacturing is the place where new ideas come into existence as new products, it has to serve as an incubator of innovation in order to contribute to the economy. In this light, a theoretical and empirical examination of the impact of production on innovation is very important at this point in setting future directions for our industrial economic system.

1.2 Research purpose and outline of study

In this study, we attempt to examine the role of production, which has not been discussed sufficiently in spite of its significant role in innovation policies, and the industrial structure that can continuously generate innovation. To this end, we begin by emphasizing the importance of technological learning that can reinforce the link between production and innovation through a review of previous research on the relationship between production and innovation. First, we identify the correlation between production capability and innovation performance through the case of Korea's manufacturing industry. Thereafter, we discuss the importance of production in innovation creation in the high-tech industry.

This paper is organized as follows. Chapter 2 presents the theoretical background of this study. We will summarize and emphasize the relationship between production and innovation as mentioned above based on previous research. Chapter 3 analyzes the effects of changes in domestic production capability due to internationalization of production in Korea since the 1990s on the change in innovation performance of the Korean manufacturing industry in the same period. Chapter 4 discusses the role of production in the technology-intensive emerging industry and the virtuous cycle between production and innovation, through an analysis of the solar industry as a high-tech manufacturing industry. Lastly, Chapter 5 summarizes the results of analysis and suggests policy implications.

Chapter 2. The relationship between production capability and innovation : A literature review and research framework

2.1 Introduction

Manufacturing has traditionally served as a driving force behind the growth of the global economy since the Industrial Revolution; however, its importance has been overlooked over the service industry, as the economic and consumption structures have changed with economic growth. However, the expansion of a service-oriented industrial structure has led to social problems such as jobless growth, higher unemployment rates, deteriorating profitability and lowered productivity, and particularly standstill innovation. As a result, recently, advanced economies such as the US, Germany, and Japan have begun to pay attention to manufacturing as a solution to solve social problems. Manufacturing can lead to innovation and productivity improvement for sustainable growth and solve employment problems. The core of the manufacturing industry is production, and production capability is the most distinctive feature between manufacturing and service industries. Therefore, in order to explain the role of manufacturing as a driving force for social problem-solving and continuous growth, the relationship between production and innovation should be preceded.

In this chapter, previous studies on production and innovation are summarized and explained. In the past, many researchers have described production capability as a component of innovation capability. Recently, however, there have been attempts to emphasize and interpret the interaction of production and innovation. After discussing these studies in Sections 2.2 and 2.3, Section 2.4 describes the factors that influence the interaction between production and innovation. In Section 2.5, we propose a future research topic that can extend the previous studies.

2.2 Linear model

Previous studies have emphasized the role of technological capability rather than that of production in creating innovation. The technological capability of a company means the ability to effectively use and apply technology knowledge to create new technologies (Kim, 1980; Westphal, Kim, & Dahlman, 1984). These technological capabilities are not only created and disseminated in the form of patents, papers, or manuals, but are also available in the form of tacit knowledge acquired through actual practice and application. In particular, tacit knowledge acquired and accumulated through experience cannot be acquired through formality or by imitation of routine. Thus, the accumulation of production experience in creating innovation is one of the important technological capabilities.

Bell & Pavitt (1993) argue that technological capability can be enhanced through technology accumulation such as R&D investment and new technology development, and accumulated knowledge, technology, and production experience can trigger technological change. This change in technology can lead to changes in production capability, which also affects industrial output. However, the authors asserted only a one-way process, whereby the production capability naturally increases with accumulated technological capability.

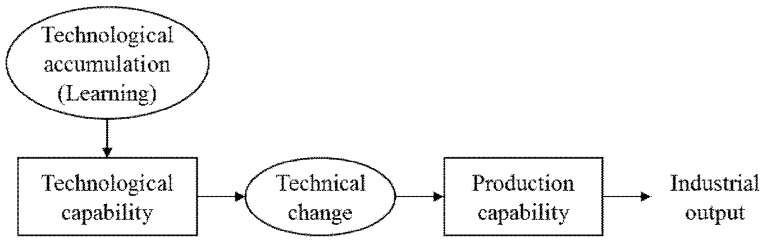


Figure 3. Accumulation of technological capability and industrial growth

Source: Bell & Pavitt (1993)

Pakes & Griliches (1984) present a theory that includes knowledge as an intermediary in a technology innovation model. They explain that the various inputs that contribute to technological innovation are linked through the intermediary of knowledge rather than being directly linked to the performance of the firm. In their knowledge production function, the input is viewed as investment in patents and R&D, and innovation creates new value-added by means of R&D investments and internal patents that represent existing knowledge. Crepon, Duguet, & Mairesse (1998) develop the knowledge production function from Pakes & Griliches (1984), and analyze how knowledge affected improvement in productivity and resulted in the economic ripple effect. In the CDM model named after the authors, R&D investment considered as inputs in many previous studies was considered as knowledge capital after accumulation. The accumulated knowledge assets act as an input factor in the process of creating innovation and the created innovation can be measured through the patent. In addition, the innovation created in this way leads to the improvement of productivity of the company, and therefore improves competitiveness. As a result of their empirical studies on companies in European countries, there is a positive correlation between R&D investment and the number of patents, and the higher the patent registration rate, the higher the productivity of companies.

However, there is a limitation that the linear model cannot explain if the application to the industrial field is smooth even when new innovation and knowledge are created through R&D investment. It also cannot explain whether new knowledge can be accumulated through production experience. In contrast to the role of technological capability in R&D and innovation creation, Bell & Pavitt (1997) describe the ability to continue production in a given production process as production capability, and many researches defined production capability as the ability to transform R&D results into competency as commercial products or services (Guan, Mok, Yam, Chin, & Pun, 2006; Kocoglu, Imamoglu, Ince, & Keskin, 2012; Yam, Guan, Pun, & Tang, 2004). More broadly, production capability has been defined as the ability of a company's production system to gain competitive advantage by improving cost efficiency, flexibility, circulation capability, and product quality in the market (Mukerji, Fantazy, Kumar, & Kumar, 2010).

Previous studies have described production capability as a component of technological capability or innovation. Westphal et al. (1984) classify technological capability into production capability, investment capability, and innovation capability, and define production capability as a capability to operate the production process and adapt to market conditions. Investment capability is defined as expanding the capabilities of a company, such as constructing additional production facilities, and innovation capability is defined as creating new technologies or implementing changes in operational processes. Rangone (1999) also distinguishes between innovation capability, production capability, and market management capability by analyzing small and medium enterprises' sustainable competitive advantage. This study explains production capability as the capability required during the process from production to delivery of the product to consumers, and includes not only tangible elements such as producing capacity but also quality, flexibility, and reliability. Guan & Ma (2003) suggest manufacturing capability as one of the seven elements of innovation capability of a company, and Andriamihavana (2016) also considered production capability as one of the internal capabilities of a company to influence its innovation along with absorption capability and R&D capability. Kocoglu et al. (2012) divide technological innovation capability as learning capability, R&D capability, and manufacturing capability, and argue that they lead to innovation and firm's performance after the technological learning process. They also argue that firms can improve their existing knowledge of technology, process, and resource inputs through production activities.

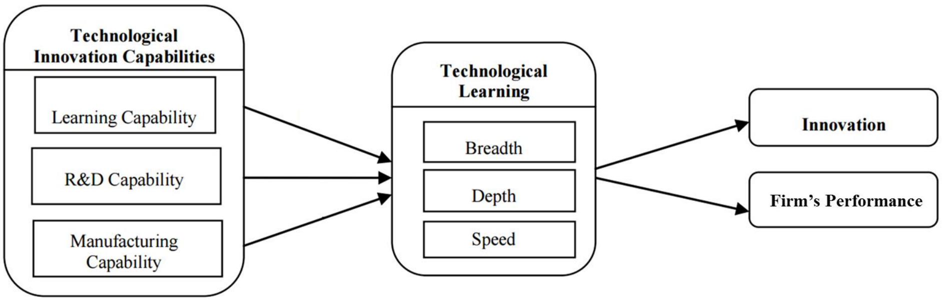


Figure 4. Technological capabilities and innovation through technological learning

Source: Kocoglu et al. (2012)

As the economies expanded in many developed countries, they perceived production activities as low value-added activities and pursued the transition to high value-added knowledge service activities such as R&D. After the Second World War, the US classified the role of innovation from the initial R&D stage to the early stage of marketization according to the strategy of "Innovate here and Produce here," and claimed that the driving force of economic development was in technological innovation activities (Bonvillian, 2012). Based on these arguments, for around past 20 years, many corporations, including multinational corporations, have outsourced the production facilities and offshored to labor-intensive countries such as China with the aim of improving productivity through cost reduction (Valle, García, & Avella, 2015). The main motivations for outsourcing and offshoring in the manufacturing sector were labor savings, movement near the product destination, and facility expansion (Dachs, Borowiecki, Kinkel, & Schmall, 2012). Regarding this phenomenon, Frobel et al. (1980) argue that a "new international division," in which low-wage developing countries are involved in the production part and developed countries are involved in the development and sales of products, emerged. They argue that the world economy was getting integrated, the production process was subdivided in accordance with the development of technology, and the subdivided process became geographically dispersed due to the development of transportation and communication. In addition, because of the increase in unskilled work processes in the production process, developed countries are exploring the need to move production bases to developing countries in order to improve cost efficiency. However, they also pointed out that the traditional industrial base of industrialized countries declined and the unemployment rate increased, but on the other hand, the corporate profits have increased (Frobel et al., 1980). They argue that developing countries have not been able to accumulate knowledge or develop technology because they can only attract some unskilled processes in the subdivided production process. They also explain that the factories that have moved to developing countries only work with companies in developed countries and cannot establish a cooperative network of knowledge and production with neighboring companies or universities. Therefore, the structure of international identity does not ultimately contribute to the accumulation of capacity of developing countries, but rather causes polarization.

Sturgeon (1997) argues that firms should operate R&D and production organizations separately, and that innovation capability to create new markets is unique to companies that perform R&D with a brand name. However, this is because the study misunderstands the role of production companies as being far from the innovation ecosystem, unlike the research institutes, venture capital, and universities (Pisano & Shih, 2012), and considers the jobs created by the production activities as low-skilled labor. It also overlooks the importance of tacit knowledge flow coming from the proximity between production and innovation. This is because the innovation created through production activities is limited to the role of reducing product prices by increasing production efficiency by saving labor or capital as a part of the process innovation (Edquist, Hommen, & McKelvey, 2001).

The perspective that production is passive in the process of creation of innovation is based on a wrong premise that production is a low value-added activity and R&D is a high value-added activity. Moreover, it is based on the interpretation that process innovation at the production site only affects profit maximization through process efficiency. However, since process innovation and product innovation have mutually changing attributes, the accumulated capability in the production process can lead to the enhancement of technical competence. Therefore, production is one of the most important factors in creating innovation and it is necessary to consider the interaction between production and innovation.

2.3 Interaction model

Utterback & Abernathy (1975) show how process innovation and product innovation change interactively and dynamically. They explain the phenomenon of innovation as a dynamic model of product innovation and process innovation. They argue that product innovation is high during the dynamic period of the industry or product, and process innovation begins to increase in the transition period when product innovation begins to decline. von Hippel & Tyre (1995) present a framework for a completely different process architecture through the accumulation of production capacity through learning during the production process, explaining that this can affect both process and product innovation. Thus, the two types of innovation are not separate, but interconnected and indivisible. von Hippel (1994) argues that manufacturing firms with internal production capacities have an advantage in creating innovation that meets the needs of users. He further explains that production capacity is essential in developing a prototype according to market demand, testing it, and verifying and stabilizing the performance. Therefore, companies with production capacity can rapidly carry out these processes to facilitate the information transfer necessary for the R&D stage, and experience more steps of trial and error, leading to advantage in creating innovation suitable for the user's needs.

Kline & Rosenberg (1986) and Rothwell (1992) argue that technological learning in production activities is an important asset in product and process innovation. Abbey & Dickson (1983) state that production capacity is essential for organizational innovation, and Kim, Lee, & Lee (1987) claim that firms with high levels of innovation have high production capacity. Griliches (1998) insists that a firm's technological capabilities and potentials emerge from the cumulative retention of its past knowledge. Therefore, the technological innovation that takes place in the course of the production activities of companies can be explained as the result of accumulation of knowledge and experience of technology through production activities. Innovation can be attributed to Schumpeterian recombination of existing knowledge (Weitzman, 1998), and knowledge and experience gained through production can be considered as one of the key factors in creating new innovation. For this reason, firms should recognize production capability as a strategic resource, and have a production capacity that is beyond their competitors' ability to create a competitive advantage (Hamel, 1991).

Many studies emphasize the importance of production capability as well as technical competence in creating innovation (Guan & Ma, 2003; Guan et al., 2006; Kocoglu et al., 2012; Saunila & Ukko, 2014). Bell & Pavitt (1993) explain that in the early stages of technological catching up, production capability is especially more important than innovation capability. This tendency was evident in the growth process of Asian countries such as Korea, Taiwan, and China. Hobday (1995) analyze the electronics industry in Korea, Taiwan, Hong Kong, and Singapore, and explain the production and technology learning in the process of industrial growth and success in these countries. He also argues that companies in these Asian countries initially entered the market as original equipment manufacturers (OEM) with those in the developed countries, such as the US and Japan. It was possible to accumulate production capability through OEM production, which simply assembled products by a standard procedure, and it was also possible to accumulate technical knowledge in this process to save production cost through "learning by doing" (Gray, Tomlin, & Roth, 2009). Based on their advanced technological capabilities, these countries could develop into ODM (own design manufacturers), who were responsible for the design of products, and further developed into OBM (original brand manufacturers). These examples illustrate that production was essential in the process of technological capacity building and innovation creation, and especially, technological learning in production played an important role.

Since factory facilities are the same as those of a laboratory (Leonard-Barton, 1992), there are arguments that increasing the distance between the R&D site and the production site will reduce technological learning from production activities (Ketokivi & Ali-Yrkkö, 2009; Pisano & Shih, 2012). In addition, the increase in geographical distance between production and innovation activities hinders the communication and coordination of knowledge, such as face-to-face communication and informal contact, which were taken for granted (Argote, McEvily, & Reagans, 2003; Stringfellow, Teagarden, & Nie, 2008). The external effects of knowledge are geographically limited (Jaffe, Trajtenberg, Henderson, Narin, & Development, 1993), and firms closer to knowledge show more innovative performance than those located far away (Audretsch & Feldman, 1996). Pisano & Shih (2012) find that the supply infrastructure of manufacturing plants and materials, skilled workers with knowledge of manufacturing process, R&D personnel, research institutes of neighboring universities and companies, and government policies supporting them form industrial commons, where innovation occurs. Therefore, production is an important element for constructing industrial commons, a source of new technological innovation. The authors also stress that it is difficult to recover once the industrial commons is weakened.

The importance of production is also being emphasized in high-tech industries. Fuchs & Kirchain (2010) conduct a process-based cost-modeling simulation of emerging and prevailing technologies in the US optoelectronics industry. They point out that manufacturing facilities in the optoelectronics field move from the US to developing East Asia (dEA). While overseas production may be more cost-effective in case of prevailing technologies, domestic production will be more cost-effective in case of emerging technologies. Therefore, they warn that transferring all of the production facilities overseas will lead to difficulty in taking the lead in emerging technology. Yang, Nugent, & Fuchs (2016) analyze the trends of R&D after offshoring of US optoelectronics companies at firm- and inventor-levels. They claim that offshoring both assembly (back-end) and fabrication (front-end) manufacturing would decrease the patent activity in emerging technology. However, in the case of non-emerging technology, such as intermediate or other optoelectronic technologies, this phenomenon can be explained by the fact that offshoring can be helpful in saving money and reallocating resources to more valuable activities (Baily & Farrell, 2004). Nahm & Steinfeld (2014) in the research emphasizing the role of production in advanced technology state that the fundamental competitiveness of China's growth in the solar industry is achieved by applying the technologies of the US and Germany, and through this process, China could acquire information about the latest technology.

Traditionally, innovation through production and R&D investments has been carried out within a system, making it difficult to distinguish between the two activities. However, with the development of transportation technology and information and communication technology, the phenomenon of "internationalization of production" has rapidly progressed, such as human resources and knowledge as well as direct inputs such as parts and materials crossing national borders (Ahn, 2006). This led to increasing attention to the relationship between production and innovation. However, it is difficult to distinguish the effects of production from those of innovation, because the effects of innovation are different for each scope of analysis, country, and industry.

Most empirical studies have indirectly analyzed the relationship between production and innovation through studying offshoring cases of transferring production facilities to countries with low labor costs. Based on past studies, we can categorize the effects of offshoring on innovation in the home country as follows: i) effects from accessibility to new resources; ii) effects of corporate culture and employment; and iii) effects on firm competence and resource allocation. In terms of access to new resources, a number of studies show that offshoring is beneficial in that it provides new opportunities to create innovation. Companies can acquire new or complementary skills, assets, and experiences through the globalization of production. (Dunning, 1995; Shan & Song, 1997). In particular, it is possible to acquire information that cannot be obtained in the home country, thereby securing diversity of knowledge and expanding the range of knowledge, thus positively affecting innovation performance (Castellani & Pieri, 2013; Chung & Alcácer, 2002; Ghoshal & Bartlett, 1990; Pennings & Harianto, 1992). In addition, offshoring facilitates access to high-skilled but relatively inexpensive human resources, one of the most important factors driving innovation (Jensen, 2009; Lewin, Massini, & Peeters, 2009; Manning, Massini, Lewin, Stephan, & Silvia, 2008; Martínez-Noya & García-Canal, 2011). Offshoring enables a new alliance network with companies and innovative entities in offshoring target countries (D'Agostino, Laursen, & Santangelo, 2013; Mihalache, Jansen, van den Bosch, & Volberda, 2012).

However, a number of studies show that the reduction of production capability due to the external transfer of production facilities negatively affects innovation, if we look only at the relationship between production and innovation rather than the acquisition of new resources. Argote et al. (2003), Stringfellow et al. (2008), and Valle et al. (2015) point out that offshoring increases the physical distance between activities on a company's value chain, leading to disruption of communication. This phenomenon leads to excessive dependence on external knowledge, which in turn suggests that innovation capacity will decrease in the home country (Cohen & Levinthal, 1990; Dachs et al., 2012; Kotabe & Murray, 2004). Berger (2013) explains that the industrial ecosystem in the US is threat because of the development and globalization of digital technology, in which many functions of the innovation creation process, from idea to commodification, are modularized and distributed all over the world.

Table 1. Literatures on the effect of offshoring on innovation

Aspect		Effect on innovation	Study
Accessibility to external resources	Acquire new or complementary resources	Positive	Dunning (1995), Shan & Song (1997)
	Expand new alliance networks	Positive	Castellani & Pieri (2013), D'Agostino et al. (2013), Mihalache et al. (2012)
	Expand the human resource base	Positive	Jensen (2009), Lewin et al. (2009), Manning et al. (2008), Martínez-Noya & García-Canal (2011)
	Expand the diversity of knowledge	Positive	Chung & Alcácer, (2002), Ghoshal & Bartlett (1990), Kotabe & Murray (2004)
Internal capability	Decrease in "learning effect" from production	Negative	Ketokivi & Ali-Yrkkö, (2009), Pisano & Shih (2012)
	High dependence on external knowledge	Negative	Cohen & Levinthal (1990), Kotabe & Murray (2004)
Organizational perspective	Enhance efficiency through reorganization	Positive	Grossman & Rossi-Hansberg (2006), Markusen & Maskus (2002)
	Difficulty in communication	Negative	Argote et al. (2003), Stringfellow et al. (2008)
	Enhance complexity	Negative	Ceci & Prencipe (2013), Stringfellow et al. (2008)

However, most of these studies have been approached from the organizational and management perspectives of companies; there have not been many empirical studies in terms of innovation. In addition, most of these empirical studies use subjective questionnaires; therefore, objectivity may be lacking in the results. Furthermore, not all production activities have a positive impact on innovation, and it is necessary to distinguish the effect of production activities on innovation depending on the maturity or modularity of production activities or technology.

Pisano & Shih (2012) state that the impact and type of innovation can be classified depending on the degree of modularity, whether production activities can be conducted independently of R&D and innovation, and maturity of production technology. If the production process and R&D activities are independent of each other, the basic attributes of the product are not affected by the production process. In other words, if the modularity of the two activities is high, they will not interfere with each other and geographical distance does not matter. On the other hand, if the degree of modularization is low, mutual exchange between the production process and the R&D activities will be continuously required, and it will be advantageous for the production site to be close. Regarding technology maturity, technologies that are not yet mature are likely to be continually improved in the future, which will result in frequent interactions between the two sectors.

Pisano & Shih (2012) propose a modularity-maturity matrix based on this concept, and described the relationship between production activity and innovation in the following four categories.

First, in the process-embedded innovation, production technology has reached the maturity stage, but there is still no distinction between production activities and R&D activities. Therefore, technology development in production activities can help product innovation, and it is necessary to maintain and integrate production sites and R&D sites geographically close.

Second, in the pure product innovation, the maturity of technology is high, so the linkage between production and innovation will be small, especially the modularization of production activities. Therefore, outsourcing production activities can be more beneficial to corporate performance.

Third, process-driven innovation is mainly represented in high-tech fields. Technology is developing at a rapid pace, and moderate development of these technologies has a great impact on product innovation. Therefore, production sites and R&D should stay close.

Lastly, in the pure process innovation, even though the production technology continues to evolve, vertical integration or proximity to the production facility may not be an important factor because the technologies are not closely related to product innovation.

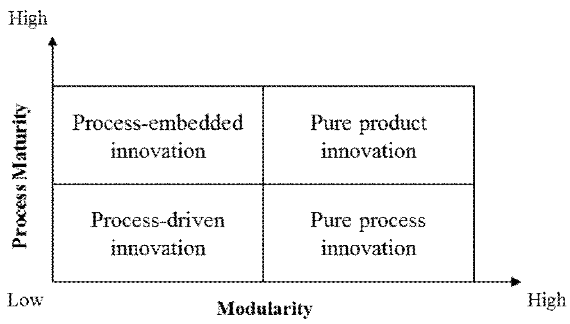


Figure 5. The modularity-maturity matrix

Source: Pisano & Shih (2012)

These studies point out that the relationship between production and innovation may be different depending on the types of production activities and technologies. However, there is a limitation in these studies that there is no description of the virtuous cycle or conditions that can contribute to the improvement of innovation performance.

2.4 Importance of knowledge flow in the relationship between production and innovation

As we have seen from the previous parts, there have been many studies on the relationship between production and innovation. In the past, production has been described as an element of innovation. However, in recent years, there have been attempts to emphasize and interpret the interaction between production and innovation. Nevertheless, discussions about the interaction and relationship between production and innovation were lacking. In this section, we attempt to explain previous empirical studies analyzing the relationship between production and innovation through the intermediary of knowledge. Archibugi & Coco (2005) describe embodied and disembodied, codified and tacit as characteristics of technical knowledge important to innovation. Technological knowledge can not only be embodied in the form of equipment or infrastructure, but also be accumulated in a discrete form, such as skilled personnel or knowledge. In this study, knowledge that affects the relationship between production and innovation is classified according to these types.

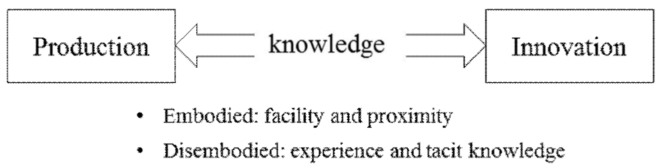


Figure 6. Knowledge flow between production and innovation

2.4.1 Importance of embodied knowledge in the relationship between production and innovation

First, there are studies showing that the exchange of embodied knowledge is important in the interaction between production and innovation. Knowledge can be embedded in tangible assets such as equipment and infrastructure, and thus, the proximity between the production site and innovation is important. In particular, as emphasized by von Hippel (1994), production capacity is essential in making and testing prototypes, and proximity between production and R&D sites facilitates the transfer of this information. Most of the empirical studies are based on cases of the location of production facilities such as industrial clusters and offshoring.

Delgado, Porter, & Stern (2014) analyze the clustering effects between production and R&D for the US industry. Their analysis shows that as production and R&D sites are close to each other or have strong clusters, it is confirmed that the tendency of patent activity is stronger. In addition, they argue that a new service industry or manufacturing industry could be created based on a strong local cluster. They state that strong clusters could facilitate the transfer of knowledge and information, resulting in greater and better innovation performance.

Dachs & Ebersberger (2015) study the offshoring effects of manufacturing in seven European countries of Germany, Austria, Switzerland, the Netherlands, Finland, Spain, and Slovenia through the European Manufacturing Survey. The authors analyze firms with offshoring experience between 1999 and 2006 and find that offshoring is not negative for each company's innovation performance. In particular, they examine innovation performance in terms of process innovation and product innovation. In the process innovation, the effect of offshoring was not confirmed, but firms with more offshoring had more active product innovation. However, these studies did not take into account the changes in competitiveness in the country or industry because they used company-specific questionnaires. Rather, they find that changes in competitiveness are the result of more reallocation of resources from an organizational point of view.

Slepniov, Wæhrens, & Johansen (2014) use the global operations networks (GONE), a survey of manufacturing companies in Denmark and Sweden, to explain the importance of manufacturing plants in the manufacturing process. Scandinavian manufacturing companies have shown a preference for offshoring production abroad. However, they have cautioned that companies which are offshoring in the form of establishing overseas subsidiaries are stalled in terms of innovation performance, even though the communication between the subsidiary and the home country is well established. They also point out that despite the relocation of production facilities overseas, there is not a high tendency to reorganize the organization of the home country to a R&D-friendly one.

Kinkel & Maloca (2009) analyze the determinants of corporate offshoring and reshoring using the German Manufacturing Survey data. They explain that the main reason for German companies to decide on reshoring is their flexibility in decision making and quality problems in overseas production. In particular, they point out that in the case of production using advanced technology and high-quality manpower, performance cannot be improved through offshoring.

Fuchs & Kirchain (2010) conducted interviews with 23 companies in the US optoelectronics field and performed process-based cost modeling based on the information in the interviews. As a result, they argue that it is not advantageous to produce goods based on emerging technologies outside the US in terms of cost effectiveness. Therefore, in order to lead the future technology in the high-technology field and gain market advantage, it is suggested that the production and innovation sites be situated in close proximity, and therefore, the authors warned the transfer of production base to East Asian countries.

Tecu (2013) identified production facilities and R&D facilities in 128 US chemical companies by the metropolitan statistical area (MSA). An analysis of these facilities scattered in 313 MSAs shows that the production facilities and R&D facilities in the same MSA had higher R&D productivity than those that are not. R&D productivity increased by about 1.8% and patent activity increased about 10%, as the number of production workers in the same MSA increased by 10%. This tendency suggests that knowledge from the production site can positively influence innovation activities of firms.

There are more researches showing that knowledge embodied in production facilities or infrastructure also has positive effects on innovation in other technologies or industries. Hidalgo, Klinger, Barabasi, & Hausmann (2007) argue that a country is likely to acquire advantage in a new product that is close to its existing production structure and export capabilities. They use the 2000 global export data to calculate the RCA (Revealed Comparative Advantage) and draw a product space for the distance between products. They analyze the cases of Chile and Korea, and explain the reason for the rapid growth of Korea as securing the production facilities of the steel industry and successfully converting them to manufacturing industries such as the heavy chemicals industry. They claim that Korea could develop other heavy chemicals industries such as automobiles and ships based on the production facilities of the steel industry. If we take a closer look at these claims from the perspectives of production and innovation, we can say that Korea could achieve innovation through infrastructure to produce similar products and industries as well as accumulation of production experience and capability. Felipe, Kumar, Abdon, & Bacate (2012) also argue that the development of a country depends on what products it produces, through an analysis using 5,107 product export data from 124 countries worldwide. They point out that the reason behind the slow growth of developing countries is that the production capacity they possess does not cause additional innovation such as the production of new products.

Based on the claim that innovation can be created more easily and more through sharing production facilities, innovative creation platforms have been spreading through sharing production facilities like Makerspace, Hackerspace, FabLab, and TechShop. This sharing of production equipment is attracting attention, as it can promote the era of prosumer, where individuals can make and spread prototypes of innovative ideas through direct production facilities. Mortara & Parisot (forthcoming) conducted interviews and case studies on 20 Fab-space managers in the US and Europe. The advantages of Fab-space include sharing and spreading knowledge, sharing resources, and offering learning opportunities. In particular, the quality and quantity of high-quality production facilities can be shared, which can lower the cost of access to production facilities and thus contribute to innovation. Capdevila (2015) analyzed 118 co-working spaces (CWS) in Barcelona, Spain, and explains that CWS is a link between creative individuals and innovative companies. Therefore, the author argues that these CWS should be recognized as an important part of innovation from outside the company, and policy support is needed. In other words, having a production facility in a country or a community serves not only as an input of innovation in various industries sharing the same production facilities, but also as a medium of convergence of technologies and knowledge in various fields.

Table 2. Literatures on the relationship between production and innovation: emphasis on embodied knowledge

Study	Period	Country	Methodology	Results/Findings
Delgado et al. (2014)	1990–2005	US	Econometric model (OLS)	· Patent applications tend to be higher when production and R&D sites are clustered in the emerging industry. · Manufacturing and service in the new regional cluster can be born with strong connection.
Dachs & Ebersberger (2015)	1999–2006	EU	Survey (European Manufacturing Survey 2009)	· Analysis through the cases of offshoring in Europe. · Distinguishes the offshoring effect on innovation into process innovation and product innovation. · The more the firms offshored, the more product innovation they achieved. · However, there is no significant relationship between offshoring and process innovation.
Slepniov et al. (2014)	2011–2012	Denmark, Sweden	Survey (Global operations networks survey)	· Although the firm separates the production facilities as a subsidiary and maintains sound communication, it cannot be proved that offshoring positively influences innovation performances of firms.

(continued)

Study	Period	Country	Methodology	Results/Findings
Kinkel & Maloca (2009)	2006	Germany	Survey (German Manufacturing Survey) and Econometric model (Probit)	· Analysis of the determinants of strategies between offshoring and reshoring decisions. · The determinants of reshoring were flexibility in decision making and quality problems in overseas production. · The larger the distance, the more negative the innovation, especially in the high-tech industry and among high-skilled labor.
Fuchs & Kirchain (2010)	-	US	Interviews and Cost simulation	· Analysis on project-based cost simulation in the US optoelectronic industry. · Simulation results show that prevailing technology is cost effective even if the distance between the production and innovation sites is large. · However, in the case of emerging technology, it is inefficient when the distances increase.
Tecu (2013)	1988–1992	US	Econometric model (Zero-Inflated Poisson Regression)	· R&D productivity is higher when the production facility and R&D institutions are located in the same MSA (metropolitan statistical area).

(continued)

Study	Period	Country	Methodology	Results/Findings
Hidalgo et al. (2007)	2000	World (Chile, Korea)	RCA, product space	· The reason behind the rapid growth of Korea is the securing of production facilities of the steel industry and reorganizing them to heavy industries. · Based on the production facilities of the steel industry, Korea was able to utilize the infrastructure for producing similar products and industries.
Felipe et al. (2012)	2001–2007	World	Product complexity	· The development of a country depends on what product it produces. · The reason for the stagnation of growth in developing countries is that their production activities did not lead the production of new products.

(continued)

Study	Period	Country	Methodology	Results/Findings
Mortara & Parisot (forthcoming)	2013	US, Europe	Interviews and Case studies	· Sharing of production facilities is beneficial in terms of i) sharing and diffusion of knowledge; ii) sharing of resources; iii) opportunity for learning; and iv) cultural environment. · Especially, reducing the cost of access to high-quality production facilities can help innovation.
Capdevila (2015)	2015	Spain	Interviews and Case studies	· The co-working space (CWS) can serve as a link between creative individuals and innovative companies.

2.4.2 Importance of disembodied knowledge in the relationship between production and innovation

Disembodied knowledge is also important in the interaction between production and innovation. Moreover, it is important that the tacit experience of production is accumulated through learning, and innovation can be created in accumulated knowledge.

Schroeder, Bates, Junttila, & Wiley (2012) highlight the importance of learning in production through an analysis of 164 manufacturing companies in Germany, Italy, Japan, the United Kingdom, and the US. They explain the effects of internal and external learning in the production process using the structural equation model. Internal learning refers to the efforts to strengthen competencies such as the training of employees in the operation of the production process and the know-how in the operation of the company. External learning refers to learning about relationships with other members of the supply chain, such as maintaining long-term relationships with suppliers, communicating with consumers, and reflecting feedback. They emphasize the importance of tacit knowledge that can be gained through the production process and argue that tacit knowledge can create better innovation through internal and external learning.

Macher & Mowery (2009) analyze 36 production facilities of 32 semiconductor companies from 1995 to 2001. The authors argue that not only knowledge from R&D, but experience and formal knowledge in production are also an important part of a firm’s problem-solving effort. Learning has a positive impact on the quality of production and the development of new production methods, and therefore, it is advantageous to co-locate production facilities and R&D facilities.

Examples of achieving technological growth based on production capacity can also be seen in the catch-up cases of Asian countries. Altenburg, Schmitz, & Stamm (2008) insist that production capacity was the cause of improved competitiveness in China’s electronics and automobile industries and India’s software and aerospace industries. They explain that technological learning in the industry was achieved through the expansion of production capacity with cost reduction, and technological catch-up was achieved through accumulated knowledge. Korea also showed similar success strategies in the automobile, electronics, and semiconductor industries through its production capacity (Kim, 1997). Kim (1997) emphasizes the role of production during economic growth and suggested a growth strategy for developing countries called “From imitation to innovation.”

There are also empirical studies showing that accumulated capability in production activities can affect not only the internal capabilities of a country, industry, or firm, but also human capital. Macduffie (1995) stresses the importance of human resources in production by investigating 62 automotive assembly plants worldwide. Particularly, the author argues that human resources and production systems affect the performance of companies as a bundle, and points out that high-commitment human resources and flexible production systems can outperform corporate performance in mass production.

Hansen, Winther, & Hansen (2014), through an analysis of 275 manufacturing companies in Denmark from 1993 to 2006, argue that human resources are important not only in low technology but also in high-tech manufacturing industries. In all types of manufacturing, the number of highly skilled workers was increasing, especially in high technology industries. In addition, the share of high-skilled manpower was higher in the high-technology industry than in the medium- and low-technology industry. These results show that the human resources possessing accumulated capability in the production field are also important in the high-tech industry.

Table 3. Literatures on the relationship between production and innovation: emphasis on disembodied knowledge

Study	Period	Country	Methodology	Results/Findings
Schroeder et al. (2012)	-	Germany, Italy, Japan, UK, US	Survey and structural equation model	· Emphasis on internal learning[2] and external learning[3] in the production process. · Accumulation of tacit knowledge through learning can enhance production and innovation performances.
Macher & Mowery (2009)	1995–2001	US, EU, Japan, Korea, Taiwan	Econometric	· Analysis of semiconductor facilities around the world. · Knowledge from production experiences and tacit knowledge as well as that from R&D are important in “problem-solving effort.”

[2] Internal learning: Enhancement of employees’ capability and acquisition of know-how in business administration

[3] External learning: Acquisition of capability on maintaining relationships with suppliers and consumers in the supply chain

(continued)

Study	Period	Country	Methodology	Results/Findings
Altenburg et al. (2008)	-	China, India	Case studies	· Point out the role of production capability for competitive enhancement in the cases of China's electronics and automotive industries, and India's software and aerospace industries. · The main factor for technological catch-up is based on cost minimization through expanding production capabilities.
Kim (1997)	-	Korea	Case studies	· Explains Korea's growth strategies based on production capacity in automotive, electronics, and semiconductor industries. · Emphasize the role of production capacity in growth. · Suggest growth strategies for developing countries, "From imitation to innovation."

(continued)

Study	Period	Country	Methodology	Results/Findings
Macduffie (1995)	1989–1990	World	Survey and Econometric model (OLS)	· Human resources and production systems are considered as a bundle, and not separate elements. · High-commitment personnel and flexible production systems can have outstanding corporate performance in a mass production system.
Hansen et al. (2014)	1993–2006	Denmark	T-test	· The number of highly skilled labor in all of the manufacturing industry has been increasing, especially in the high-tech industry. · Human capital with accumulated capability in the production process is also important for the high-tech industry.

2.5 Conclusion and future research agenda

As we have seen so far, many studies have dealt with the relationship between production and innovation. However, most of the existing studies have approached the role and importance of production from the organizational and managerial perspectives of the company, and there have been few cases of quantitative empirical studies in terms of innovation. Although most of these studies describe production capability as one of the components of innovation, there are not many studies focusing on the relationship between the two factors. There is also lack of research on the conditions or industrial structure that can lead to innovation in production. Many studies have overlooked the structure in which technological learning can actively take place, despite its importance in reinforcing the link between production and innovation. Therefore, future research should focus on theoretical and empirical studies on the following research questions.

2.5.1 Future research agenda 1: Confirming the effect of production capability on innovation

As we have seen, many previous studies on the relationship between production and innovation have been conducted in the form of surveys or case studies. Therefore, there is a limit in the dynamic analysis of the relationship between production and innovation. In addition, most of them have used surveys at the firm level, and there is a need for additional empirical studies to generalize the findings.

- Does the relocation of production facilities affect the innovation performance and global standing of the industry or company
- Does the firm that owns the production facility create innovative performance that is more valuable than the company that does not
- Whether an industry or a firm improves its overall innovation performance as a production capability is gained
- What kind of changes in innovation performance occurs due to changes in production capacity, by type of industry or technology

2.5.2 Future research agenda 2: Studying the preconditions to enable the virtuous cycle between production and innovation

There are many studies on the importance of production. Recently, policies on manufacturing-oriented countries have been initiated, but research on what kinds of production can positively influence innovation still needs to advance. In addition, there are cases in which even if industries have production capacity, they cannot further develop into high value-added ones and remain in the simple manufacturing stage. Therefore, the following questions arise.

- What kind of characteristics, and where in the value chain does a production activity take place, if the activity can positively influence innovation creation

- What are the social structures and industrial conditions in which production can lead to innovation
- How can production, innovation, and industrial performance form virtuous cycles
- What are the desirable government policies that can motivate individual companies to possess production capacity

The answers to these questions can provide new implications, especially to policymakers involved in innovation. The impact of production on innovation depends on the capacity and industrial structure of each country. Therefore, in order to examine the effect of production capacity on innovation performance in the Korean manufacturing industry, analyzing Korean data is necessary. Furthermore, examining the role of production in emerging industries based on cutting-edge technologies and the conditions and structures that can lead to innovation performance for sustainable growth will provide a sound framework for future economic growth and industrial economic system.

In the following chapter, we will empirically and quantitatively analyze the effect of production capacity on innovation performance through the relationship between changes in domestic production capability and innovation performance in Korea after the 1990s. Chapter 4 analyzes the solar industry, which is attracting attention as a high-tech manufacturing industry, and discusses the role of production in the emerging industry.

Chapter 3. Empirical analysis on the effect of production capability on innovation competence: The case of Korean manufacturing industries[4]

3.1 Background and purpose of study

In the 1990s, industrial restructuring from the manufacturing industry to the service industry began to spread, led by developed countries such as the US. Offshoring to developing countries occurred with the aim of improving the industry through productivity and efficiency improvements. Efforts were made to move the production facilities that are losing their competitive advantage to countries that can secure price competitiveness, and to improve the quality of the economy by reorganizing the home country as a high-level R&D base. Korea has also relocated many production facilities to countries with low-cost labor power to overcome the phenomenon of industrial downturn caused by the global economic slowdown and weakening of price competitiveness caused by the entry of emerging countries such as China and India. During this period, the amount of foreign direct investment (FDI) by Korean manufacturers grew rapidly. According to the Foreign Investment Statistics of Korea Export-Import Bank, the total

[4] A draft version of this chapter was presented in the 2016 Spring Conference of the Korea Productivity Association in Seoul, Korea, May 21st, 2016.

FDI of Korean manufacturing companies has grown rapidly from 32.32 million USD (US dollars) in 1980 to 4.8 billion USD in 1990 and to 1.63 billion USD in 2000. As of 2015, the total amount of FDI has grown to 7.33 billion USD. The number of FDI occurrences was only 58 in 1980, but expanded to 3,819 in 2015. In particular, the amount and proportion of FDI in China are increasing rapidly. FDI outflows by Korean manufacturing companies to China began in 1988, and the total amount at that time was only 9,935 USD, which was 0.01% of the total FDI. However, the amount and proportion of FDI in China have increased steadily, reaching 20.42 million USD (4.26% of total) in 1990, 5.9 billion USD (35.95%) in 2000, 2.75 billion USD (36.95%) in 2010, and 4.46 billion USD (47.99%) in 2013. In particular, the increase in FDI outflows to China was due to the transfer of production facilities to reduce production costs. Therefore, it is important to consider the relationship with China in examining the changes in domestic production capacity of Korean manufacturing enterprises.

As production facilities have moved into developing countries including China, the economy began to lose its vitality and stable employment structure. Recently, some problems such as rising wages, technology outflows, and logistics costs have been raised in developing countries. In addition, the innovation capability of the industry, the foundation for sustainable growth, has reduced. This is because the manufacturing industry and the overseas transfer of production facilities have reduced the foundation for implementing new ideas. As a result, the embedded knowledge in the field does not lead to R&D, and it is not leading the new technology of the industry anymore. Therefore, examining the relationship between production capacity and innovation performance is very important at this point.

Previous studies on the production capacity of Korean manufacturing companies mainly focused on the structure of industry or changes in job creation due to offshoring. Kim (2006) analyzes the effects of raw material offshoring and service offshoring on manufacturing employment. The analysis of the Korean manufacturing industry during 1990–2000 shows that both raw material offshoring and service offshoring have a negative effect on manufacturing employment. Suh, Lee, Park, & Kim (2008) analyze the effects of market opening and offshoring on employment in the Korean manufacturing sector. The analysis based on the Mining Statistics Survey and the industry association table shows that the impact of offshoring on the total employment in Korea is not significant. However, before and after the financial crisis in 1997, unskilled employment increased when offshoring increased, while employment of skilled labor increased after the financial crisis. Thus, offshoring led to situations where low-skill production activities moved overseas, and domestic activities shifted to activities that require skilled workers. Park (2009) also analyzes the impact of offshoring on employment in 18 manufacturing industries in Korea, and explains that the analysis did not show any significance. Ahn (2006) analyzes the firm-level data of Korean manufacturing companies from the statistics survey. The author finds that the proportion of low-tech manufacturing industries in Korea declined as the amount of FDI to and imports from China increased, and changes in trade structure due to the rise of China led to changes in Korea's industrial structure. In addition, the internationalization of production positively affects the employment and productivity growth of Korea, but the FDI outflow to China has a negative effect on employment and productivity. A subsequent study by Ahn (2013) shows a similar result. According to the analysis of Ahn (2013), although the growth rate of FDI itself did not have a significant effect on the employment growth rate of each company, the employment growth rate of firms with higher FDI in China was lower. He explains this as “the Chinese effect” and argues that the effects of trade and FDI are similar. In particular, he points out that this problem is not solely a matter of low-tech manufacturing. Through the analysis using OECD-TiVA (Trade in Value Added), he cautions that the decline in employment growth rate due to offshoring will also appear in high-tech and second-hand manufacturing industries.

Lee, Park, & Kim (2010) analyze the determinants of offshoring in the Korean manufacturing industry. The main factors that determine whether Korean companies will offshore were the number of employees, R&D investment per employee, and export share. They also analyze the impact of offshoring on productivity and employment in Korean industries. The effect of offshoring on the productivity of the manufacturing industry was largely insignificant and was rather negative for the service industry. Furthermore, across industries in general, the effect of offshoring on employment was negative.

Table 4. Literatures on the effect of offshoring in Korea

Study	Focus	Results/Findings
Kim (2006)	· Employment	· Raw material offshoring and service offshoring both negatively impact employment in the manufacturing sector.
Suh et al. (2008)	· Employment	· The impact of offshoring on total domestic employment is not significant. · Prior to the IMF crisis in 1998, when offshoring increased, unskilled employment increased. · After the IMF crisis, employment of skilled workers rather increased.
Park (2009)	· Employment structure	· The effect of offshoring on employment is not significant.
Ahn (2006)	· Industrial structure · Productivity · Employment	· FDI into China and imports from China increased, while the share of low-tech manufacturing in Korea declined. · Internationalization of production positively affects Korea’s employment and productivity. · However, FDI outflow to China has a negative impact on employment and productivity growth.
Ahn (2013)	· Employment	· The growth rate of FDI itself does not have a significant effect on the employment growth rate of each company. · The rate of employment growth is lower for firms with higher FDI in China.

(continued)

Study	Focus	Results/Findings
Lee et al. (2010)	· Determinant factor analysis · Productivity · Employment	· Key factors to decide whether to offshore are number of employees, R&D expenditures per employee, and export share. · Productivity effect of offshoring is either not significant (manufacturing) or negative (service industry). · Effect of offshoring on employment is negative.

There are a number of previous studies analyzing the effect of offshoring in Korean manufacturing. However, most empirical studies focus on the role of production to solve employment or productivity problems, and lack the perspective of innovation. Production is important in creating innovation for sustainable growth; thus, we should look at the impact of production on innovation, especially when setting the future direction of our industrial system. Therefore, this chapter empirically examines the relationship between changes in domestic production capacity and changes in innovation performance in the Korean manufacturing industry since the 1990s.

3.2 Analytical framework

This study uses patent data as innovation performance to analyze how internationalization of production in Korea since 1990 has affected the innovation performance of the Korean manufacturing industry in the same period. In addition, the study utilizes the concept of internationalization of production as a proxy variable for domestic production capacity. Through this, we examine the changes in innovation performance in industries where FDI has surged.

3.2.1 Data and variables

The subjects of analysis were manufacturing enterprises classified under the Korean Standard Statistical Classification (KSIC). During the research period, the Korean standard industry classification was revised from sixth edition in 1991, seventh revision in 1998, eighth revision in 2000, and ninth revision in 2007. The Korean Standard Industrial Classification is based on the third revision of the International Standard Industrial Classification (ISIC), while the ninth classification is based on the fourth revision of the ISIC. In this study, 20 manufacturing industries were selected based on the industrial classification at the two-digit level in the third revision of the ISIC for uniformity of classification during the entire research period. The industry and international standard industry classification codes used in the analysis are presented in the Appendix.

We use the growth rate of patents as the dependent variable and as a measure of industry-specific innovation performance. In analyzing innovation activities in the industrial innovation system and the national innovation system, Godoe & Nygaard

(2006) argue that we can use patent as an indicator of technology creativity and innovation activities, especially as a quantitative indicator of the sector. Furthermore, many other researches have used patents as an index of technological innovation performance (Acs, Anselin, & Varga, 2002; Archibugi & Pianta, 1992; Brouwer & Kleinknecht, 1999; Deyle & Grupp, 2005). In this study, the number of patents was also used as an index of innovation performance in the Korean manufacturing industry. For calculating the number of patents, this study used PATSTAT, a patent database of the European Patent Office (EPO). The PATSTAT used in this study is 2013 April version, and the study period is set taking into consideration that it takes 18 months from patent application to publication. First, we extracted patents related to the manufacturing industry from 1991 to 2010 in Korea using the PATSTAT database. In extracting manufacturing-related patents, we used the International Patent Classification (IPC) provided by the Korean Intellectual Property Office (KIPO) and the link table of the Korean standard industry classification, and extracted only those patents that include the IPC corresponding to the manufacturing industry of the Korean standard industry category. Thereafter, we used the IPC-KSIC linkage table to sum up the two-digit classification of the Korean standard industry classification, and derived the growth rate of patents for each industry as the innovation performance index.

However, it should be noted that patents do not measure the economic value of innovation (Hall, Jaffe, & Trajtenberg, 2001). Furthermore, Pakes & Griliches (1980) point out that not all innovations are patentable, and that the value of each patent also differs. In this study, patent citation network analysis was employed to reflect the relative qualitative value of patents. Patent citation information is useful because it not only reveals the relationship between patents, but also provides information on the quality level of the technology, such as the relative importance, through the degree of patent citation (Hirschey & Richardson, 2001). Wang, Chiang, & Lin (2010) apply the network analysis methodology to the analysis of patent quality. They describe a citation network between patents and then explain that patents that brokerage each other according to their status in the network are more valuable.

In order to calculate the innovation performance that reflects the qualitative value, the first stage of patent citation network analysis was performed using the backward citation information of the extracted patents, and the centrality of each IPC was calculated. Centrality is one of the most commonly used quantitative indicators in network analysis (Lee, Kim, Cho, & Park, 2009). In particular, the degree centrality, closeness centrality, and betweenness centrality proposed by Freeman (1979) are the main concepts often used. Degree centrality means the number of edges connected to a certain node, and in directed network where connected edges have directions, there exist in-degree centrality and out-degree centrality depending on the direction of connection. In-degree centrality refers to the number of connected edges from other nodes to the corresponding node, and out-degree centrality refers to the number of connected edges from the corresponding node to other nodes. Thus, convergence of information can be measured in the case of in-degree connection centrality and divergence of information can be measured in out-degree centrality. However, the effect of each node on neighboring nodes is not the same, and nodes with higher centrality and neighbors will have a greater impact on the network than those with lower ones. Bonacich (1972) proposes eigenvector centrality to compensate for this. As the centrality of other nodes connected to one node is higher, the eigenvector centrality considers the centrality of that node as higher in the entire network. In this study, we used the eigenvector centrality in analyzing the qualitative performance of patents. Nodes with high eigenvector centrality are considered more important IPC in patent citation networks and can be interpreted as more valuable innovation achievements. The calculated centrality of each IPC is again calculated by adding the IPC-KSIC linkage table for each subdivision (two-digit) of the Korean standard industry classification. Finally, we derived the innovation performance index reflecting the qualitative value of each industry.

For the explanatory variables, data on FDI by industry was used to reflect changes in domestic production capacity. Offshoring, which relocates manufacturing bases overseas, is the internationalization of production in a narrow sense, and it can be seen that a parent company in the home country establishes subsidiaries overseas and performs some of the production process overseas (Ahn, 2013). FDI is a good example of internationalization investment in a narrow sense of production. FDI involves vertical FDI to reduce the overall production cost by moving and carrying out part of the production stage overseas, and horizontal FDI to focus on meeting foreign demand rather than reducing the cost in the form of establishing subsidiaries abroad. (Ahn, 2006). In this study, we tried to distinguish the effects of vertical and horizontal FDI on innovation performance. The amount of FDI by industry was calculated by using the data of Korea Export-Import Bank. FDI data are obtained from the Korea Export-Import Bank, which uses its own industry classification (Ahn, 2013), which is linked to the two-digit level of Korean standard industry classification. In order to distinguish the characteristics of FDI, we calculated the proportion of FDI to China and the US, respectively.

For the control variables, R&D intensity by industry, export intensity by industry, value-added ratio by industry, and shipment growth by industry were included. R&D intensity by industry is the ratio of total R&D expenditure to industry total shipment value. R&D cost data is the sum of ordinary development cost and research cost on the income statement and ordinary development cost on the manufacturing cost statement, according to the definition from the Bank of Korea. The export intensity by industry is the ratio of total export value to total industry shipment value. The export value data is based on the UN Commodity Trade Statistics (UN ComTrade) and the shipment data is obtained from the mining industry survey data of the National Statistical Office. For the UN ComTrade data, the Standard International Trade Classification (SITC) is used. Under the years of this study's time frame, SITC classification was revised twice, in 1988 and in 2007. In this study, SITC Revision 3 data were used and matched with the Korean standard industry classification in order to reflect the past data as much as possible. The value-added ratio of industry to shipment value is the ratio of total value added from the mining industry survey data to shipment value of the industry as a whole. The value added in the mining industry survey is calculated by deducting raw material costs, consigned production costs, and fuel costs directly related to intermediate consumption from production costs of the industry. The value-added ratio to industry shipment represents how much value-added products the industry produces. In order to control the growth effect and industry effect by year, the growth rate of shipments by industry was also added to the analysis.

The balanced panel data were collected for 20 years from 20 industries in the manufacturing industry from 1991 to 2010, giving a total of 400 observations. Table 5 shows the definitions and sources of variables considered in the regression analysis process.

Table 5. Definition of variables for the relationship between offshoring and innovation

Variable	Definition	Source
IP_growth	Growth ratio of innovation performance (Model I-IV: Growth ratio of number of patents, Model V-VIII: Growth ratio of patent quality)	Source of patent data: EPO PATSTAT (2013 April version) Calculated through patent citation network
FDI_inten	FDI intensity (Ratio of FDI to value of shipment)	Foreign Investment Statistics (The Export-Import Bank of Korea) Monthly Survey of Mining and Manufacturing (Statistics Korea)
FDI_Chinashare	Ratio of FDI to China to total FDI	Foreign Investment Statistics (The Export-Import Bank of Korea)
FDI_USshare	Ratio of FDI to US to total FDI	Foreign Investment Statistics (The Export-Import Bank of Korea)
RDinten	R&D intensity (Ratio of R&D expenditure[5] to value of shipment)	Foreign Investment Statistics (The Export-Import Bank of Korea)
EXPinten	Export intensity (Ratio of export to value of shipment)	UN Commodity Trade Statistics

[5] R&D expenditure = (current R&D expense in income statement) + (current development expense in manufacturing statement)

(continued)

Variable	Definition	Source
VAratio	Ratio of value-added to value of shipment	Monthly Survey of Mining and Manufacturing (Statistics Korea)
VA_growth	Growth ratio of value of shipment by industry	Monthly Survey of Mining and Manufacturing (Statistics Korea)

3.2.2 Analysis model

The basic form of the regression analysis model used in this study is as follows:

$$\begin{aligned} IP\_growth_{i,t} &= \beta_0 + \beta_1 IP\_growth_{i,t-1} + \beta_2 FDI\_inten_{i,t-1} \\ &+ \beta_3 FDI\_Chinashare_{i,t-1} + \beta_4 FDI\_USshare_{i,t-1} \\ &+ \beta_5 RDinten_{i,t-1} + \beta_6 EXPinten_{i,t-1} \\ &+ \beta_7 VAratio_{i,t} + \beta_8 VA\_growth_{i,t} + \varepsilon_{i,t} \end{aligned} \qquad \text{(Eq. 1)}$$

Here, the explanatory variable $IP\_growth_{i,t}$ is the rate of increase in the innovation performance in period t of industry i, obtained by the following equation.

$$IP\_growth_{i,t} = \frac{IP_{i,t} - IP_{i,t-1}}{IP_{i,t-1}} \qquad \text{(Eq. 2)}$$

For the explanatory variables describing the growth rate of innovation performance in the corresponding year, we include the growth of innovation performance of the previous period $t-1$ ($IP\_growth_{i,t-1}$), and FDI relative to shipment value as the proxy of the change in the domestic production capacity ($FDI\_inten_{i,t-1}$). In addition, in order to distinguish the nature of FDI, we included share of FDI in China ($FDI\_Chinashare_{i,t-1}$), and that of FDI in the US ($FDI\_USshare_{i,t-1}$). For the control variables, $RDinten_{i,t-1}$ and $EXPinten_{i,t-1}$ were included in order to control R&D tendency by industry and export-oriented industrial tendency. For variables of time t, value-added ratio of shipment value of each industry ($VAratio_{i,t}$) and growth rate of shipments by industry to take into account the growth effects over time by industry ($VA\_growth_{i,t}$) were also included in the analysis.

This study used panel data during the analysis. Since panel data have both time-series and cross-sectional data for individual industries, heteroscedasticity and autocorrelation are likely to be present in error terms. Moreover, among the characteristics of unobserved variables, there may be characteristics that do not change with time, or external factors that affect the same object at the same time point, which may cause bias in the estimation process. Therefore, the data constructed for the analysis using panel data should satisfy the following assumptions. First, for all panel entities, the expected value of the error term should be zero at all points. Second, for all panel entities, the variance of the error term should be the same at every point in time (homoscedasticity). Third, there should be no correlation between the error terms at different points in the same panel entity. Finally, there should be no correlation between the error term and the explanatory variable. However, since the model in this study is a dynamic panel model and the lagged variables of other variables explaining innovation performance are used in the model, endogeneity between these lagged variables and error terms should be considered. There is also a limitation that there can be a two-way causality between production and innovation, and thus, endogeneity problem may occur. Therefore in order to control this expected endogeneity problem, this study adopts System GMM (generalized method of moments) suggested by Blundell & Bond (1998). System GMM considers level equation and first-differenced equation of dynamic panel model as a single system during estimation. In this case, the lagged difference variable of the explanatory variable is used as the instrument variable in the level expression, and the lagged level variable is used as the instrument variable in the difference form. Therefore, in this study, the endogeneity during analysis was controlled by using GMM.

3.3 Empirical analysis

First, we examined whether the tendency of FDI in the domestic industry is correlated with changes in domestic production capacity. For this purpose, we analyze the correlation between the total FDI ratio and the capital equipment ratio against the shipment value. The capital equipment ratio to the shipment value by industry is the value of the tangible assets (capital equipment amount) in the mining manufacturing survey divided by the shipment amount, and the result represents the size of domestic capital equipment of the company. Therefore, if domestic capital equipment is transferred overseas due to the increase of FDI, the capital equipment ratio will decrease. As a result, the ratio of total FDI by industry to the shipment amount and the capital equipment ratio compared to shipment by industry showed a negative correlation (-0.2448). This indicates that FDI data used as proxy variables to measure changes in domestic production capacity are appropriate in this study.

Next, we examined the trends of FDI in 1991–2010 and the share of FDI in China and the US.

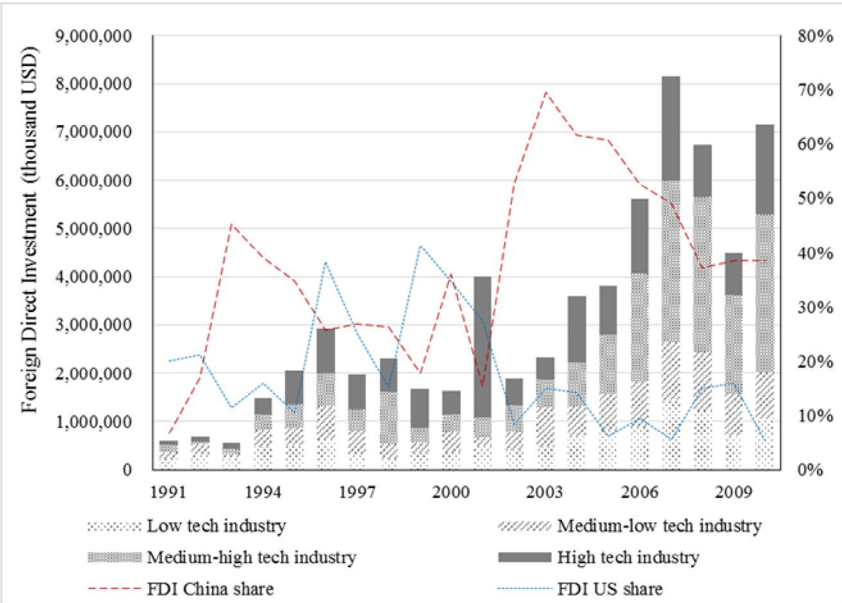


Figure 7. Trends of FDI in the Korean manufacturing industry

Source: Calculated from Foreign Investment Statistics, The Export-Import Bank of Korea

Korea's FDI has been steadily rising from 1991 to 2010. In particular, FDI of manufacturing companies in Korea was mostly focused on medium-high technology. In 2001, the share of FDI in high-tech technology was higher than that in other technology sectors. In this period, the share of FDI in the US was higher than that in China. This can be seen as explaining the situation just before the 2001 IT bubble. This is because many overseas direct investments have been made to cooperate with US IT companies and venture companies and to enter the US market. Looking at the year 2002 again, the total amount of FDI declined to the same level as the previous year, and the share of FDI in the US also plummeted. It was the result of a downturn in investment activity, especially for entrance and collaboration with overseas markets, in the US due to the collapse of IT bubble. The decrease in the total amount of FDI due to the economic crisis can be confirmed in the period around 1997 and 2008, which was the period of Korea's economic crisis. In particular, the proportion of FDI to China in 1997 was higher than that to the US. This is because FDI into China is mainly active in low- and medium-technology fields for FDI aimed at reducing production costs.

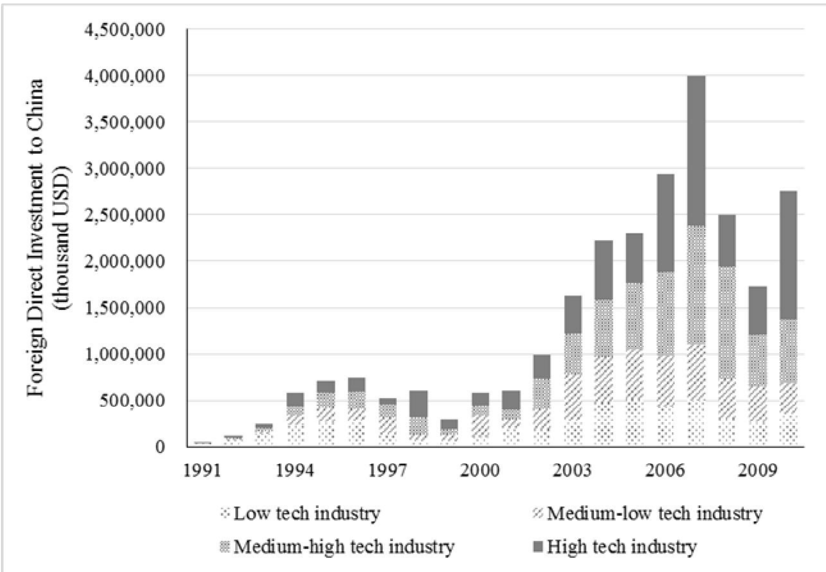


Figure 8. Trends of FDI to China

Source: Calculated from Foreign Investment Statistics, The Export-Import Bank of Korea

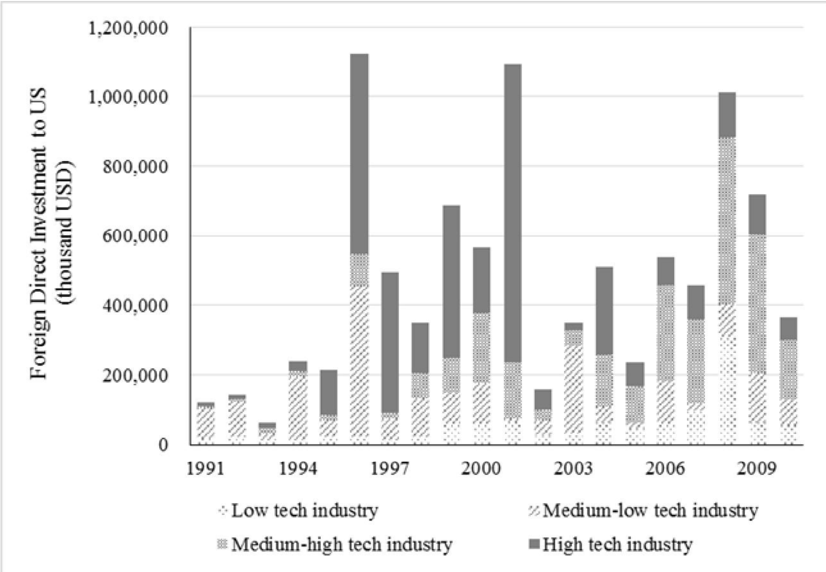


Figure 9. Trends of FDI to the US

Source: Calculated from Foreign Investment Statistics, The Export-Import Bank of Korea

Most of the FDI made in the early China is focused on low and low-medium technology, whereas that made in the US is focused on high technology. While the amount of FDI to China has continued to increase, that to the US has changed due to economic fluctuations such as the economic crisis. This is because, as mentioned above, FDI to the US aims to cooperate with foreign companies and entrance into the US market. If we look at Korea’s share of FDI into China and the US by each technology, it is clear that FDI to China at all skill levels exceeds that to the US. In particular, since the early 2000s, the share of FDI in high and medium-high technology has increased sharply (Figure 10). Therefore, it is essential to consider the impact of China, which has the greatest impact on Korea’s FDI. In addition, it is important to confirm that FDI in China is actively engaged not only in low-skilled labor but also in high-tech sectors, and how it is related to the performance of the industry.

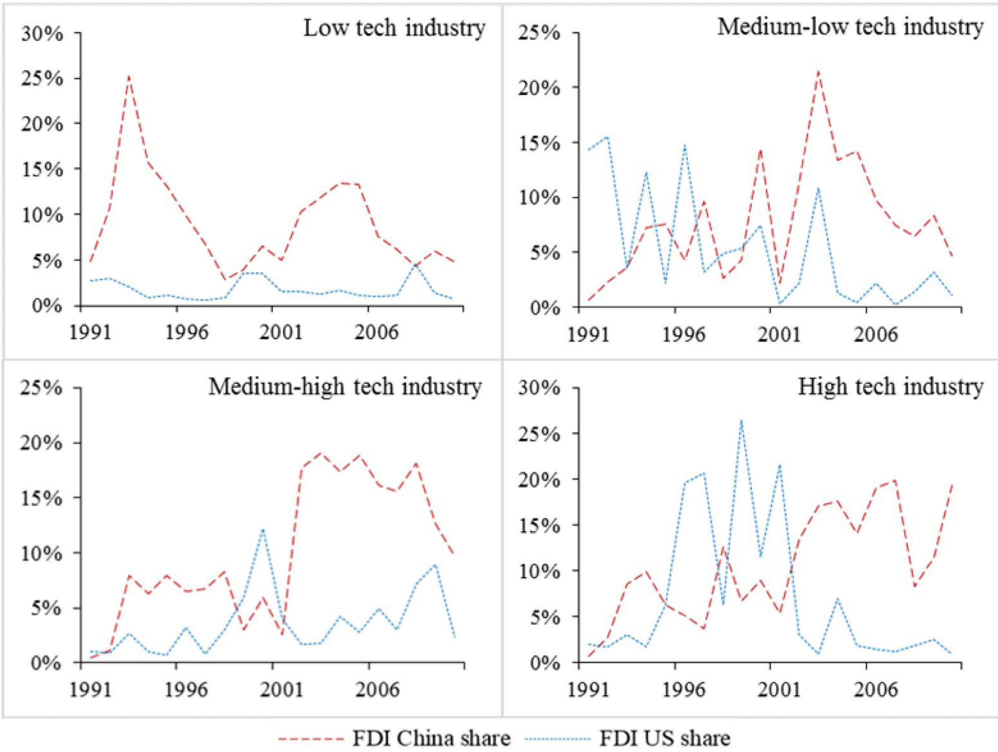


Figure 10. FDI shares of China and the US by technology level

Source: Calculated from Foreign Investment Statistics, The Export-Import Bank of Korea

We conducted a basic analysis prior to the regression analysis of how innovation result represented by number of patents changed as a result of changing FDI. The analysis on the relationship between growth rates of innovation and FDI focuses on three years: 1992, when Korea initiated FDI; 2001, when the share of FDI in China began to reverse the proportion of FDI in the US; 2007, when Korea's FDI was the highest.

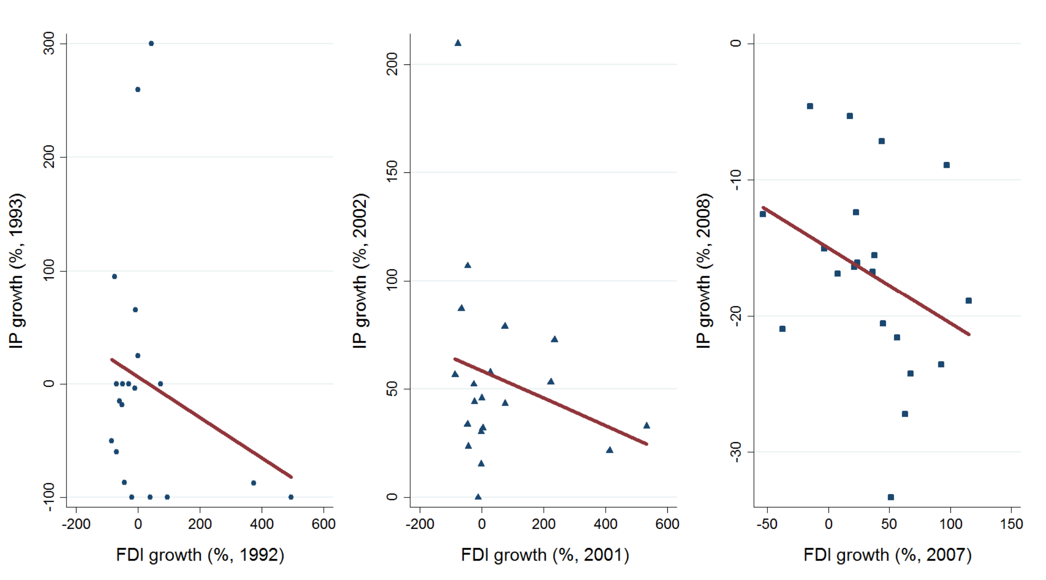


Figure 11. Relationship between innovation performance and FDI
(Left) 1992, (Middle) 2001, (Right) 2007

As a result, the growth rate of FDI in Korea was found to be generally negative for the growth rate of innovation performance. Since the beginning of Korea's FDI in 1992, the increase in FDI has been negative for the growth rate of innovation performance. However, in this period, Korea's innovation performance did not grow much and the growth rate of innovation performance was negative; therefore, it was difficult to interpret the direct correlation. However, in 2001, when the share of FDI in China surpassed that in the US, Korea's innovation performance increased, but the growth rate decreased with the increase of FDI. Therefore, FDI could be negative for innovation performance. However, because of the difficulty in explaining the direct correlation based on the trend alone, regression analysis was performed and the results are presented in detail in the latter part.

Table 6 shows the correlation between the main variables used in the empirical analysis of this study. The correlation between FDI variables (FDI_inten_{t-1}, $FDI\_Chinashare_{t-1}$, $FDI\_USshare_{t-1}$) used as the main explanatory variables in this study was not high, and therefore, the model considering all of these variables was also included in the regression analysis. In order to distinguish the characteristic of FDI, FDI into China and that into the US were included in the explanatory variables, and it was confirmed that they had a negative correlation (-0.277). Therefore, it seems appropriate to use as a variable to distinguish the direction and nature of FDI.

Table 6. Correlation among the variables for the relationship between offshoring and innovation

Variable	1	2	3	4	5	6	7	8
1. IP_growth_{t-1}	1.000							
2. FDI_inten_{t-1}	-0.023	1.000						
3. $FDI\_Chinashare_{t-1}$	-0.081	-0.057	1.000					
4. $FDI\_USshare_{t-1}$	0.028	0.102**	-0.277***	1.000				
5. $RDinten_{t-1}$	-0.079	0.191***	0.099*	0.097*	1.000			
6. $EXPinten_{t-1}$	0.002	0.286***	0.099**	0.111**	0.402***	1.000		
7. $VAratio_{t}$	0.013	0.010	-0.162***	-0.034	0.055	-0.123**	1.000	
8. VA_growth_{t}	0.078	0.023	0.010	0.024	0.089*	0.009*	-0.142***	1.000

Note: * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

There is a certain degree of correlation between the selected explanatory variables, but if this correlation is too high, multi-collinearity may occur. In the presence of multi-collinearity, the accuracy of the regression model may be lowered due to the mutual influence between independent variables. As a result of verifying the variance inflation factor (VIF), VIF was smaller than 10 in all explanatory variables. Therefore, it can be said that this study does not show problems arising from multi-collinearity.

Table 7. Multicollinearity test result among the variables

Variable	VIF
IP_growth_{t-1}	1.03
FDI_inten_{t-1}	1.12
$FDI\_Chinashare_{t-1}$	1.19
$FDI\_USshare_{t-1}$	1.17
$RDinten_{t-1}$	1.25
$EXPinten_{t-1}$	1.27
$VAratio_{t}$	1.05
VA_growth_{t}	1.03
Mean VIF	1.14

Regression analysis was conducted to examine the effect of changes in domestic production capacity on innovation performance in the Korean manufacturing industry. Considering that the period of the significant increase in FDI by Korean companies in the manufacturing industry was in the 1990s (Ahn, 2013), the analysis period was set from 1991 to 2010, and the analysis results are summarized in Table 8. Model I considers only the proportion of FDI relative to shipment value, and analyzes the effect of changes in domestic production capacity represented by FDI on innovation performance. Model II considers the proportion of FDI into China, and Model III considers the proportion of FDI into the US. Model IV shows a model considering all these variables.

Table 8. Analysis results (System GMM model)

Dependent variable: IP_growth_t	**Model (I)** Coeff. (std. err)	**Model (II)** Coeff. (std. err)	**Model (III)** Coeff. (std. err)	**Model (IV)** Coeff. (std. err)
IP_growth_{t-1}	-0.211***	-0.245***	-0.211***	-0.247***
	(0.042)	(0.038)	(0.041)	(0.394)
FDI_inten_{t-1}	-0.570***	-0.693***	-0.567***	-0.674***
	(0.131)	(0.134)	(0.134)	(0.123)
$FDI\_Chinashare_{t-1}$		-1.232***		-1.378***
		(0.366)		(0.457)
$FDI\_USshare_{t-1}$			-0.038	-0.804
			(0.443)	(0.648)
$RDinten_{t-1}$	-0.698***	-0.654***	-0.699***	-0.661***
	(0.202)	(0.214)	(0.205)	(0.210)
$EXPinten_{t-1}$	0.440	0.447	0.440	0.459
	(0.492)	(0.462)	(0.491)	(0.479)
$VAratio_t$	7.592***	6.404***	7.574***	6.280***
	(2.079)	(1.867)	(2.071)	(1.889)
VA_growth_t	-0.228	-0.126	-0.227	-0.108
	(0.381)	(0.383)	(0.383)	(0.395)
Constant	-1.723*	-0.651	-1.712**	-0.449
	(0.852)	(0.753)	(0.862)	(0.806)
Wald Chi^2	145.72	219.36	168.63	212.80
Number of industries	20	20	20	20
Observations	380	380	380	380

Note: Numbers in parentheses represent standard errors; * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

As a result of the analysis, the innovation performance of the previous period showed a negative effect on all models. This suggests that the persistence of innovation creation tendency in the Korean manufacturing industry is not confirmed. Malerba & Orsenigo (1999) and Cefis & Orsenigo (2001) use EPO patents as innovation results and they explain that each firm's innovation persistence is not confirmed. Also, this result was re-confirmed in the study of Geroski, Van Reenen, & Walters (1997) using patents from USPTO (The United States Patent and Trademark Office). In the case of Korean manufacturing, persistence is not confirmed in the creation of innovation performance, and we can consider it as a case with high volatility.

We can confirm that the proportion of FDI has a negative effect on innovation performance in all models. In other words, the higher the tendency of FDI, the lower the innovation performance. Previous analysis of the correlation between the ratio of total FDI to shipment and the ratio of capital equipment to industry shipment shows that the capital equipment ratio decreases as the FDI ratio increases. Therefore, the transfer of domestic production facilities abroad through FDI in the previous year leads to a decline in innovation performance in the following year.

Models II and III show the analysis results that distinguish FDI as i) transfer of production facilities to reduce costs; and ii) creation of new local demand and market, and R&D cooperation. According to Ha & Sagong (2007), the motivation for overseas investment in general by Korean manufacturing companies was found as 46.1% of local market entrance, 20.7% of overseas transfer of partner companies, and 9.8% of strategic alliances with local companies. On the other hand, in the case of investment incentives to China, 70.8% was to reduce costs such as labor costs. Therefore, in this study, FDI tendency related to production facility transfer is explained by the ratio of FDI to China, and that related to market creation and R&D cooperation is explained by the proportion of FDI to the US.

In all models, the proportion of FDI in China had a negative impact on innovation performance. On the contrary, the share of FDI in the US did not have a significant correlation with innovation performance. Dachs & Ebersberger (2015) and Yang et al. (2016) study firm- and inventor-level data and argue that offshoring saves money and positively impacts innovation because it can reallocate resources to more valuable activities. However, in the Korean case of manufacturing, it was rather negative. This means that the innovation capacity of the industry as a whole is weakened by the transfer of the production base, unlike the case of the enterprise or the inventor. This result is due to the fact that offshoring does not efficiently relocate resources and activities as predicted in previous studies. The negative correlation between R&D intensity and innovation performance indicates that R&D is not efficiently performed.

Unlike FDI in China, that in the US had the purpose of market creation and R&D cooperation; however, it is difficult to say that the latter led to innovation. The results of this study are limited to the patents filed in Korea from the Korean Intellectual Property Office when measuring the innovation performance in this study. Therefore, the innovation performance through R&D cooperation may not reflect a different tendency in other countries' patent offices. Nevertheless, it can be seen that the transfer of production facilities and FDI for cost reduction have a negative effect on the innovation performance of the industry. This can be attributed to the weakening of the feedback reinforcement between production and innovation as production facilities in the Korean manufacturing industry moved overseas.

The value-added ratio to the shipment value was positively related to the innovation performance, which means that the more value-added industry led to more innovation outcome. Other control variables such as export concentration and industry shipment growth rate were not significant.

In order to take into account the qualitative performance of innovation, additional analyses were conducted using the growth rate of the centrality of patent in the patent citation network as the dependent variable (Table 9). The results are not significantly different from those of Table 8, where the growth rate of patents is the dependent variable for all models. In particular, when we look at the variables related to FDI, which was included as a proxy for domestic production capacity, the sign of the regression coefficient remained unchanged. Moreover, the share of FDI in China also maintained a negative relationship with innovation performance. Therefore, it can be seen that the high tendency of FDI in industry has a negative effect on not only quantitative growth of innovation performance but also qualitative growth. In particular, it has been confirmed that FDI in China has a negative effect on innovation performance compared to that in the US.

However, the eigenvector centrality used in this study as the quality achievement of innovation performance needs to be carefully interpreted. In the case of Korean patents, a provision has been made in 2011 to provide obligatory description of prior art information when a patent application is filed. Accordingly, there is a limitation that the citation information of the Korean patents of 1991–2010, which is the scope of this study, may not be perfect. Therefore, the results of Models V–VIII may involve some limitations. In addition, we should keep in mind that explanatory variables in this study—industrial FDI, FDI in China, and FDI in the US—are proxy variables that interpret the changes in domestic production capacity through the internationalization effect of production. Nevertheless, this study used long-term statistical data instead of a case study or survey to examine the correlation between the change of domestic production capacity and innovation performance. In addition, this study contributes to the previous discussions, since through classifying the nature of FDI, it confirmed that the transfer of production facilities abroad for cost reduction had a particularly negative effect on the innovation performance of the domestic manufacturing industry.

Table 9. Analysis results (considering quality of patents)

Dependent variable: IP_growth_t	**Model (V)** Coeff. (std. err)	**Model (VI)** Coeff. (std. err)	**Model (VII)** Coeff. (std. err)	**Model (VIII)** Coeff. (std. err)
IP_growth_{t-1}	-0.198***	-0.204***	-0.198***	-0.204***
	(0.032)	(0.031)	(0.032)	(0.313)
FDI_inten_{t-1}	-0.827***	-0.922***	-0.823***	-0.908***
	(0.276)	(0.280)	(0.282)	(0.279)
$FDI\_Chinashare_{t-1}$		-1.180**		-1.332**
		(0.558)		(0.632)
$FDI\_USshare_{t-1}$			-0.083	-0.815
			(0.564)	(0.765)
$RDinten_{t-1}$	-0.606	-0.525	-0.610	-0.547
	(0.425)	(0.419)	(0.426)	(0.415)
$EXPinten_{t-1}$	-1.270	-1.197	-1.274	-1.234
	(1.123)	(1.092)	(1.131)	(1.113)
$VAratio_t$	14.762***	14.459***	14.737***	14.339***
	(4.468)	(4.486)	(4.498)	(4.493)
VA_growth_t	-0.981	-0.974	-0.977	-0.944
	(1.077)	(1.080)	(1.090)	(1.098)
Constant	-3.773**	-3.150*	-3.751**	-2.916
	(1.774)	(1.727)	(1.834)	(1.792)
Wald Chi^2	50.00	76.08	50.07	86.05
Number of industries	20	20	20	20
Observations	380	380	380	380

Note: Numbers in parentheses represent standard errors; * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

3.4 Conclusion

This chapter analyzed how internationalization of production in Korea since the 1990s affected the innovation performance of Korean manufacturing industry in the same period. We used patent data as a measure of innovation performance and FDI data as proxy variables for changes in domestic production capacity. This study examined the changes in innovation performance in Korean industries where FDI took place and production capacity decreased.

The results suggest that high FDI in the industry has a negative effect on innovation performance, and that there is a difference in the effect on the innovation performance of the industry depending on the direction of FDI flows. More innovation is reduced in the industry with a high proportion of FDI to China. On the other hand, the share of FDI in the US did not show any significant relationship with innovation performance. This is because Korea's manufacturing companies that have relatively large FDI in China aim to pursue cost efficiency, while those that have conducted FDI in the US are aiming to enter overseas markets or to cooperate with local companies and universities.

However, the limitation of this study is that the analysis is based on the manufacturing industry-level data rather than firm-level data, due to the limitation of data accessibility. As pointed out in Helpman (2006) and Ahn (2013), this is because there is no data that can directly reflect changes in production capacity at the firm level. Ahn (2013) analyzes the firm-level effect of internationalization of production on employment, but uses industry-level data as a proxy of firm-level data due to the limited data accessibility. There are also limitations in analyzing the difference in innovation performance by technology. In addition, the data in this study targeted industries classified at the two-digit level in the Korean standard industry category. This is based on the IPC-KSIC linkage classification provided by the Korean Intellectual Property Office (KIPO), and there is a limitation to the number of data when the industries to be analyzed are classified by the technology level. Therefore, in future research, it will be necessary to carry out an analysis at the firm-level, using a broader range of data and technology classifications. Nonetheless, this study is meaningful in that it analyzes the effects of domestic production capacity on innovation performance empirically and quantitatively, without using survey or interview data.

In this chapter, we analyzed the changes of innovation performance and the degradation of domestic production capacity from the progress of internationalization of production, focusing on the relationship between production and innovation. As the role of production is being emphasized worldwide, interest in high-tech manufacturing sector is increasing, especially in recent years. Because this study analyzes the entire manufacturing industry, there is a limitation in explaining the role of production in the high-tech industry. In the next chapter, we will analyze the impact of production on innovation in high-tech industries and the structure of knowledge networks that can lead to a virtuous cycle between production and innovation.

Chapter 4. Empirical analysis on the linkage between production and innovation : The case of photovoltaic industry

4.1 Background and purpose of study

Recently, major countries around the world are making efforts to attract high-tech manufacturing industries to overcome the stagnation of national and industrial growth and solve social problems. As mentioned in the previous chapter, Pisano & Shih (2012) explain that innovation takes place in the industry commons, which includes the supply chain such as producing factories and material companies, skilled labor, R&D personnel, research institutes, universities, and supporting government policies. They argue that not only production and innovation are closely related, but production is also an important factor in forming the industrial commons, which is a source of new technological innovation. In particular, in the high-tech industry, production capability is important in that it enables the realization and verification of new knowledge.

Fuchs & Kirchain (2010) point out that it is more cost-effective to produce in the US in the case of advanced technology, using the example of the photovoltaic materials industry, and state that it might be difficult to take the initiative in advanced technology when all production facilities are moved abroad. In the study by Nahm & Steinfeld (2014), it was mentioned that the recent growth in China's photovoltaic industry has arisen from the learning of state-of-the-art technology through contracting manufacturing from the US and German companies.

However, there are cases where production capacity does not lead to innovation in the industry. Thailand designated the automobile industry as a strategic upbringing industry and has provided various tax benefits and administrative support to the industry since 1960, and it is the largest automobile producer in the ASEAN (Association of Southeast Asian Nations). Despite these facts, Thailand possesses neither a representative brand of automobiles nor the core knowledge and capabilities of the automobile industry. Ghazali, Lafortune, Latiff, Limjaroenrat, & Whitesides (2011) point out that lack of knowledgeable and well-trained personnel was the reason for the failure to have innovative growth in the Thailand's automobile industry. In other words, it can be said that the knowledge was not accumulated, and thus, innovation in Thailand's automobile industry has not advanced enough as much as production.

We can see a similar case in the Indian pharmaceutical industry. India is the fourth largest producer of pharmaceuticals in the world, producing 8% of the global production and 1.5% of value-added (Shukla & Sangal, 2009). However, there is a limitation to improving the innovation capability of India as compared to the growth of the pharmaceutical market in India. Nevertheless, generics constitute a significant portion in production and new drug development capability is still insufficient (Chataway, Tait, & Wield, 2007). Chataway et al. (2007) explain that the lack of public investment in the health sector and the weak R&D cooperation between the enterprise and the public sector are the reasons for the stagnated growth of the innovation capability of the Indian pharmaceutical industry. They point out that Indian universities particularly lack research capacity, and that the economic and social structure of India also encourage the activation of the generic production rather than the development of new drugs.

There is also an opinion that the role of R&D is more important than that of production in creating innovation in high-tech industries. Hagedoorn, Roijakkers, & Kranenburg (2006) find that R&D collaboration in the high-tech industry has a significant impact on innovation through the analysis in the biopharmaceutical industry. They also argue that in order to create better innovation performance, it is important to consider R&D capability and influence of R&D network in the decision of R&D partnership. Furthermore, there are several studies stating that R&D cooperation may enable economies of scale in R&D activities and therefore promote innovation (Das & Teng, 2000; Narula & Duysters, 2004; Nieto & Santamaría, 2007).

There is a lot of interest in the impact of production on innovation, as there are cases of conflicting roles of production on innovation in the high-tech industry. However, it is difficult to find any conditions or examples of a virtuous cycle structure in which production can contribute to the improvement of innovation. As mentioned earlier, majority of studies still focus on the effects of maintaining production capacities inside the firms on their performance (Dachs & Ebersberger, 2015; Delgado et al., 2014; Kinkel & Maloca, 2009). The results of these analyses were also focused on productivity rather than innovation. In addition, there is insufficient explanation as to how production activities affect innovation. Pisano & Shih (2012) suggest that the degree of modularity of production and the maturity of technology should be considered in explaining the relationship between production and innovation, and that the effects of production on innovation need to be distinguished. However, this study describes the role of only production in the comparison of industries, and there is a limitation in that all production activities in a particular industry are regarded as the same. The production activities in the industry consist of various activities according to the value chain of the industry, and the kinds of firms participating in the production activities are also diverse. Moreover, innovation performance of research institutes such as universities and public research institutes can affect production activities, even though they do not have production capacity. Therefore, analyzing only the relationship between corporate production strategies and innovation performance, such as outsourcing and offshoring, has a limitation in understanding the relationship between production and innovation across the entire industrial sector.

In the light of the above, it is necessary to analyze the role and impact of all participants in the industrial production system and knowledge network for looking more closely at the relationship between production and innovation. Production activities also need to be distinguished because their characteristics vary depending on their location in the value chain. However, previous studies have limitations in considering these points and fail to suggest any conditions that could lead to a virtuous cycle between production and innovation. In Section 2.4, we mentioned that it is important to understand the flow of knowledge in understanding the interaction between production and innovation, and knowledge network intuitively describing this interaction would be a useful methodology.

Therefore, in this study, the effect of production on innovation in high-tech industry and the suggestion of a desirable virtuous cycle structure between the two are explained by using the concept of knowledge network. For this purpose, patent citation network analysis was carried out using patent data of the photovoltaic industry from China, Germany, Korea, and Taiwan. Hirschey & Richardson (2001) address that patent citation information can provide the relative importance of patents and their relationship. In addition, the network analysis methodology can explain the interactions among agents in the system that have not been analyzed in traditional social science methodologies (Choi, Park, & Lee, 2011), and are widely used in recent studies related to innovation. This study categorized the agents of the technology and knowledge network of the photovoltaic industry by the value chain of the industry. Then, the study examined the citation network and analyzed the relative status of the production firms in the knowledge network in each period. The study also investigated the characteristics of the knowledge network that can continuously generate innovation performance and sought to derive a virtuous cycle condition between production and innovation.

The contents in this chapter are as follows. Section 4.2 presents an introduction of the photovoltaic industry and explores the need for research on the relationship between production and innovation in the photovoltaic industry. Section 4.3 explains the data and network analysis methodology used in this study. Section 4.4 describes the network analysis results. Finally, Section 4.5 summarizes the analysis results and offers policy implications.

4.2 Background of the photovoltaic industry

Renewable energy technology is one of the emerging technologies that not only plays an important role in the mitigation of greenhouse gas emission but also attracts attention for being the driving force of sustainable growth of the nation and is expected to create new economic ripple effects. Many researchers stated that various social problems can be solved through renewable energy (Ackermann & Soder, 2000; Amer & Daim, 2010; Chen, Yu, Hsu, Hsu, & Sung, 2009; Dincer, 2000; Lee & Lee, 2013; Park & Ohm, 2014; Wong, Keng, Mohamad, & Azizan, 2016). Several countries around the world have increased the investment in R&D in this field over the past two decades. In particular, photovoltaic power generation is the most focused energy source due to its abundance, efficient space utilization, and ease of access by ordinary consumers compared with wind power and other renewable energy sources. In recent years, it has achieved economies of scale and continues to outperform other renewable energy generation through sustained drop in generation costs (Bazilian et al., 2013). Photovoltaic power generation is expected to be close to the economic efficiency of existing fossil fuels such as coal and oil soon, and it has been regarded as the most important energy source in the future energy industry. In addition, the importance of solar power is anticipated to grow further in the future, as the paradigm of power generation is expected to change from large-scale development to distributed generation. Not only photovoltaic power generation is growing in importance as an alternative energy source, but also the photovoltaic industry promotes production in related industries, thereby enabling a stronger industrial base (Jang, Chen, Chen, & Chiu, 2013).

The value chain of photovoltaic industry is generally divided into four parts, as shown in Figure 12: i) materials; ii) manufacturing and assembly; iii) balance-of-system components; and iv) system integration. The materials part refers to the stage from the production of polysilicon, which is raw material, to ingot and wafer processing, and the manufacturing and assembly part involves manufacturing the solar cell and assembling the module. The balance-of-system components part involves an inverter converting DC (direct current) to AC (alternating current) and a battery capable of storing electric power. Finally, system integration involves the parts that build, maintain, and repair the photovoltaic system.

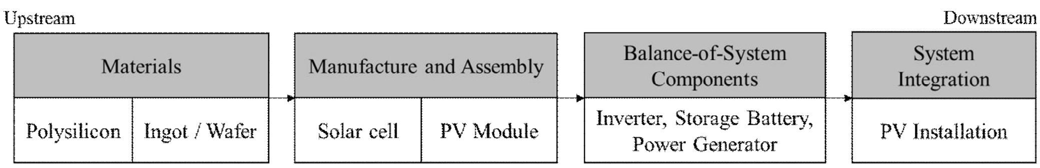


Figure 12. Value chain of the photovoltaic industry

Source: Reprinted from Jia, Sun, & Koh (2016)

The most important sectors of the photovoltaic industry are the polysilicon and inverter sectors, in which the top 10 companies have an oligopolistic structure with a market share of over 70%, while the top 10 companies in the solar cell and module sector have a market share of 40% (New Growth Inititative Industry Information Technology Research Group, 2013). The part in the upstream of value chain is a high value-added industry with high barriers to technology entry. In the photovoltaic industry, it is difficult to develop high-quality technology for polysilicon in the materials part, and large companies are mainly entering the market. On the other hand, the parts of assembly, manufacturing, and services have labor-intensive characteristics with comparatively lower added value in the photovoltaic industry. They have lower barriers to entry into the market and require economies of scale. Especially, in the process after the module assembly, the profitability is weak, since many companies participate in the market due to the large procurement costs for parts such as inverters and labor costs. In this way, the industry structure of the photovoltaic industry is similar to that of the semiconductor industry, as there are a number of large enterprises in the upstream value chain and SMEs (small and medium-sized enterprises) are mainly participating in the downstream one.

Figure 13 shows the changes in solar photovoltaics production by country. Photovoltaic power generation, which began in the early 2000s in the US, Germany, and Japan, is increasing rapidly in Asia, including China, and six of the top 10 companies based on module output in 2013 have their headquarters in China (Platzer, 2015). Recently, the photovoltaic industry has been suffering from oversupply with the emergence and development of Chinese firms in the industry. As a result, some US and European companies have withdrawn production and shut down operations in recent years due to the restructuring effect, and the center of the photovoltaic industry also tends to move to Asian countries such as China, Taiwan, and Korea.

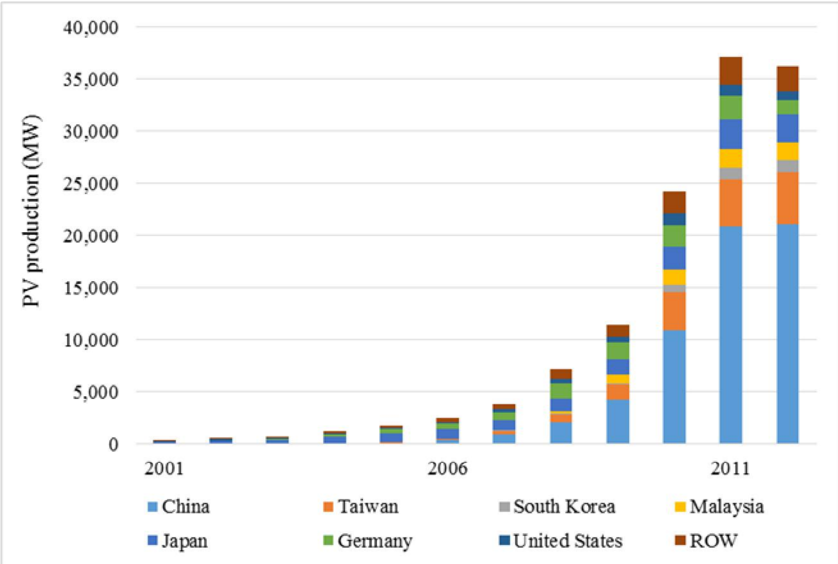


Figure 13. Annual solar photovoltaics production by country

Source: Reprinted from Earth Policy Institute (2013)

Note: ROW indicates rest of the world.

Therefore, a question that arises is whether Asian countries, such as China, which maintains a high level of production volume, are able to create innovation in the future photovoltaic industry and to lead the future technology based on the expansion of production capacity. Jang et al. (2013) analyze the relationship between the number of patents in the photovoltaic industry and solar photovoltaics production from 1996 to 2006.

They point out that the US, Japan, and Germany have an “inefficient” structure with higher number of patents but lower production volume, whereas Taiwan and China have the opposite structure with few patents but high production volume. They conclude that forerunner countries have a comparative advantage in technology, and latecomer countries have one in power generation, and that the advantage in power generation production is not a prerequisite for creating innovation performance. On the other hand, Wu (2014) distinguishes Taiwanese, Chinese, and Korean photovoltaic patents by technology platform with technological generation, and suggests that Korea focused on new technology such as thin-film and organic compound, but Taiwan and China concentrated on the dominant technology of the time, such as c-Si and epitaxy. He argues that these contrasting results do not stem from the differences of production base. Rather, Korea and Taiwan have strong advantages in c-Si and thin-film based on their technological advantage in semiconductors, but China has entered into a chemical-based epitaxy because chemical technology was located in the core of its innovation system. However, this study has a limitation in that it could not distinguish innovation at the production site because it analyzed innovation performance with the technological generation division. In addition, since the division by technological generation is more influenced by R&D investment than production, this study did not clearly confirm the effects of production on innovation. Jia et al. (2016) examine the effects of each country’s photovoltaic support policy by the supply chain, and state that not only increasing the government support in the consumption sector but also strengthening production capability through the entire supply chain made China's growth possible in the photovoltaic sector. They also argue that, in solar power generation, Taiwan has promoted the competitiveness of the entire industry through selective support for the stage in which it has already secured production competitiveness. Their study points the need for policy support to strengthen the production capacity of companies, which leads to the overall competitiveness of the industry. Quitzow (2015) also suggests that Chinese manufacturers played a key role in China's technological innovation system (TIS) formation.

4.3 Analytical framework

4.3.1 Data

The purpose of this study is to examine the effect of production capacity on innovation through changes in the knowledge network in the photovoltaic industry in China, Germany, Korea, and Taiwan. First, IPC, an international patent classification, was used to select technologies related to the photovoltaic industry. Based on the classification of the patent related to renewable energy in World Intellectual Property Organization (2010), we reclassified into three categories according to the value chain of the photovoltaic industry. Since the installation and service parts are not part of the actual production of the product, they are excluded from this study, which focuses on the relationship between production and innovation. In total, data on 26,649 patents from 1981 to 2015 registered with the USPTO were extracted using IPC codes. In this study, the information up to first step backward citation was collected in order to construct a patent citation network. The information on 77,474 patents (26,649 patents with IPC codes for photovoltaic industry, and 50,825 patents with backward citations to these photovoltaic patents) and 140,164 citation links among the patents was extracted. Next, innovation performance of each country was analyzed based on the assignee's nationality of these patents. Since this study focuses on the firm as the analytical unit, the analysis only considered patents in which the applicant was not an individual but an institution. To organize the names of applicants, this study used OpenRefine, a data cleaning tool, and finally, the researcher of this study confirmed the cleaning results. Which part of the value chain of the photovoltaic industry these applicants belong to was determined through their existence in the corporate directory of ENF Solar, the solar market research firm. Companies that are not included in the ENF Solar data were categorized according to the sector they are applying for the patents. Similarly, since this study is conducted at the firm level, it was analyzed except for the cases in which the assignee was not an institution but an individual.

Table 10. IPC codes for photovoltaic technology

Description	IPC Code
Silicon, Ingot and Wafer (20,592 patents, 100,847 citation links)	
· Silicon; single-crystal growth	C01B 33/02, C23C 14/14, C23C 16/24, C30B 29/06
· Devices adapted for the conversion of radiation energy into electrical energy	H01L 27/142, H01L 31/00-31/078, H02N 6/00
· Dye-sensitised solar cells (DSSC)	H01G 9/20, H01M 14/00
Solar Cell or Module Manufacture and Assembly (4,854 patents, 34,283 citation links)	
· Assemblies of a plurality of solar cells	H01L 25/00, H01L 25/03, H01L 25/16, H01L 25/18, H01L 31/042
Inverter, Storage Battery and Generator (1,203 patents, 5,034 citation links)	
· Charging batteries with light sensitive cells	H02J 7/35
· Generators in which light radiation is directly converted into electrical energy	H02N 6/00
· Regulating the maximum power available from solar cells	G05F 1/67
· Producing mechanical power from solar energy	F03G 6/00

Source: Adapted from World Intellectual Property Organization (2010).

4.3.2 Network analysis

Network analysis is a useful method for analyzing and interpreting social structures composed of actors (nodes in network theory) and their interactions (edge of network theory) based on network and graph theory, Informatics), and it is widely utilized in various fields such as geography, economics, and informatics (Otte & Rousseau, 2002).

Social network analysis can intuitively show an evolutionary pattern of interaction between actors that traditional social science methodologies have not identified (Choi et al., 2011). Therefore, network analysis is attracting attention as a methodology for analyzing interdisciplinary fields and has been widely used recently. This study analyzed the development patterns of knowledge networks in each country using network analysis. In the analysis, each node represents the applicant, and edge refers to the interaction between two applicants. This method describes the connection between the applicants and the flow of knowledge, which can identify the patterns of change in the knowledge network at the country level. First, this study depicted the network structure of each country between 1981 and 2015 and described the structure and properties of the network by analyzing the network topology of each network. Thereafter, centrality analysis was performed to analyze the relative importance of each individual node.

Network visualization is a method of describing the general structure of a network, and it enables easier understanding about the spreading and changing aspects of the network structure. Network visualization is based on graph theory, and there are several visualization programs such as NetMiner, UCINet, NodeXL, Pajek, and Gephi. This study used Gephi for network visualization. Network visualization can be a useful tool for intuitive understanding of structures, such as dynamic changes in network complexity. However, there is a limitation in understanding the characteristics of network, node, and edge only through network visualization. To conduct a clear analysis, this study used various statistical indicators such as the number of nodes and edges, which Albert &

Barabási (2002) proposed, network density, average degree, path length, clustering coefficient, and centralization index. These indicators are widely used to identify the structure of the network (Okamura & Vonortas, 2006).

The number of nodes and connection edges represents the size of the network. An increase in the number of nodes in the patent citation network means that there are more applicants and the diversity of the network has increased. On the other hand, an increase in the number of edges indicates that the interaction between two applicants is active. The density of the graph is an index of the efficiency of the network, and the density of the network refers to the ratio of the actually connected edges among the possible number of edges of the entire network (Coleman & Moré, 1983). The higher the density, the more efficient and stronger the network. The network density can be expressed as follows.

$$density = \frac{2 \times (number\ of\ edges)}{(number\ of\ nodes) \times \{(number\ of\ nodes) - 1\}} \qquad \text{(Eq. 3)}$$

The average degree refers to the average of degrees for all nodes, and the average path length means the shortest path among all the combinations of the nodes in the network. The average path length can be expressed as follows (Watts & Strogatz, 1998).

$$average\ path\ length = \frac{\sum_{i \neq j} d(n_i, n_j)}{(number\ of\ nodes) \times \{(number\ of\ nodes) - 1\}} \qquad \text{(Eq. 4)}$$

In Eq. 4, $d(n_i, n_j)$ indicates the distance between node n_i and n_j. The average path length can be used as an index to estimate the diffusion rate of information in the network. Technology or knowledge can be easily spread in networks with short average path lengths. The diameter of the network indicates the longest geodesic distance on the network.

The clustering coefficient is the number of edges that are actually connected to the maximum number of edges between adjacent nodes, and can be expressed as follows.

$$clustering\ coefficient = \frac{3 \times (number\ of\ triangles)}{number\ of\ connected\ triplets\ of\ nodes} \qquad \text{(Eq. 5)}$$

4.4 Empirical analysis

4.4.1 Descriptive statistics of knowledge network

To compare national knowledge networks, this study first looked at the descriptive statistics of physical characteristics. Table 11 shows the descriptive statistics of each country's knowledge network in 2015. The total statistics for each country are presented in the Appendix. The knowledge networks of Germany and Taiwan are the most active knowledge networks among the four countries. Germany has the largest number of participating institutions in the knowledge network. On the other hand, in Taiwan, the number of participating institutions was smaller than in Germany; however, the connections between the participating institutions in Taiwan were more active than those in Germany. Also, as more connections existed, Taiwan's average degree was higher than other countries. China has a relatively immature knowledge network and is shown to have smaller networks than other countries.

Table 11. Major characteristics of photovoltaic knowledge networks in 2015

	China	Germany	Korea	Taiwan
Number of nodes	361	884	741	773
Number of links	1,390	5,471	7,132	7,944
Network density	0.011	0.007	0.013	0.013
Average degree	7.701	12.378	19.250	20.554
Average path length	1.130	3.736	2.562	2.984
Clustering coefficient	0.007	0.036	0.043	0.041
Centralization	0.984	0.990	0.994	0.994

4.4.2 China

First, we looked at China's photovoltaic knowledge network. 2010 was a year of major transformation in the global solar industry. The European fiscal crisis has worsened the profitability of European photovoltaic companies. Moreover, the significant increase in production of Chinese companies led to an overall oversupply, and the US Department of Commerce imposed anti-dumping duties. These profitability deterioration problems have led to a restructuring in which many companies shut down operations. In 2010–2011, the number of mergers and acquisitions in the solar industry was 44, of which the total transaction volume of 22 opened mergers and acquisitions was approximately USD 2 billion (New Growth Inititative Industry Information Technology Research Group, 2013). In 2011, Evergreen Solar and Solyndra of the US and Solon of Germany went bankrupt, and Sunway, a German solar cell manufacturer, was acquired by the Chinese company LDK Solar. Moreover, the Chinese companies TFG Radiant and Aiko Solar acquired the US company Ascent Solar and the German company Scheuten Solar, respectively. As such, China has been expanding its production capacity by restructuring the global photovoltaic industry based on price competitiveness. In this study, we attempt to explore how the expansion of production capacity among Chinese photovoltaic companies influenced China's photovoltaic knowledge network from 2010, using network analysis. First, we schematized the network from 2002, when the Chinese applicant filed the patent for the first time in the US Patent Office, to 2010, and the network from 2011 to 2015. The knowledge network is expressed on the basis of both out-degree centrality and in-degree centrality. Through the out-degree centrality network, we can identify the applicants who have an influence on China's photovoltaic knowledge network. Through the in-degree centrality network, we can observe the patent activities of Chinese applicants and how these patents are utilized.

The network for the entire period from 2002 to 2015 is shown in Figure 14. Figures 15 and 16 show the Chinese photovoltaic knowledge network from 2002 to 2010 and 2011 to 2015, respectively. Depending on the colors, each node indicates a different institute. White indicates a university and a research institute that does not have production capacity (University and public institute); blue indicates a company that manufactures materials (Material (silicon, ingot, and wafer) manufacturer); red represents a manufacturer with the production capacity of cell and module parts (solar cell and module manufacturer); and yellow represents the companies that have not only the production capacity of cells and modules but also the production capacity of system peripherals such as inverters (solar inverters and storage battery manufacturers).

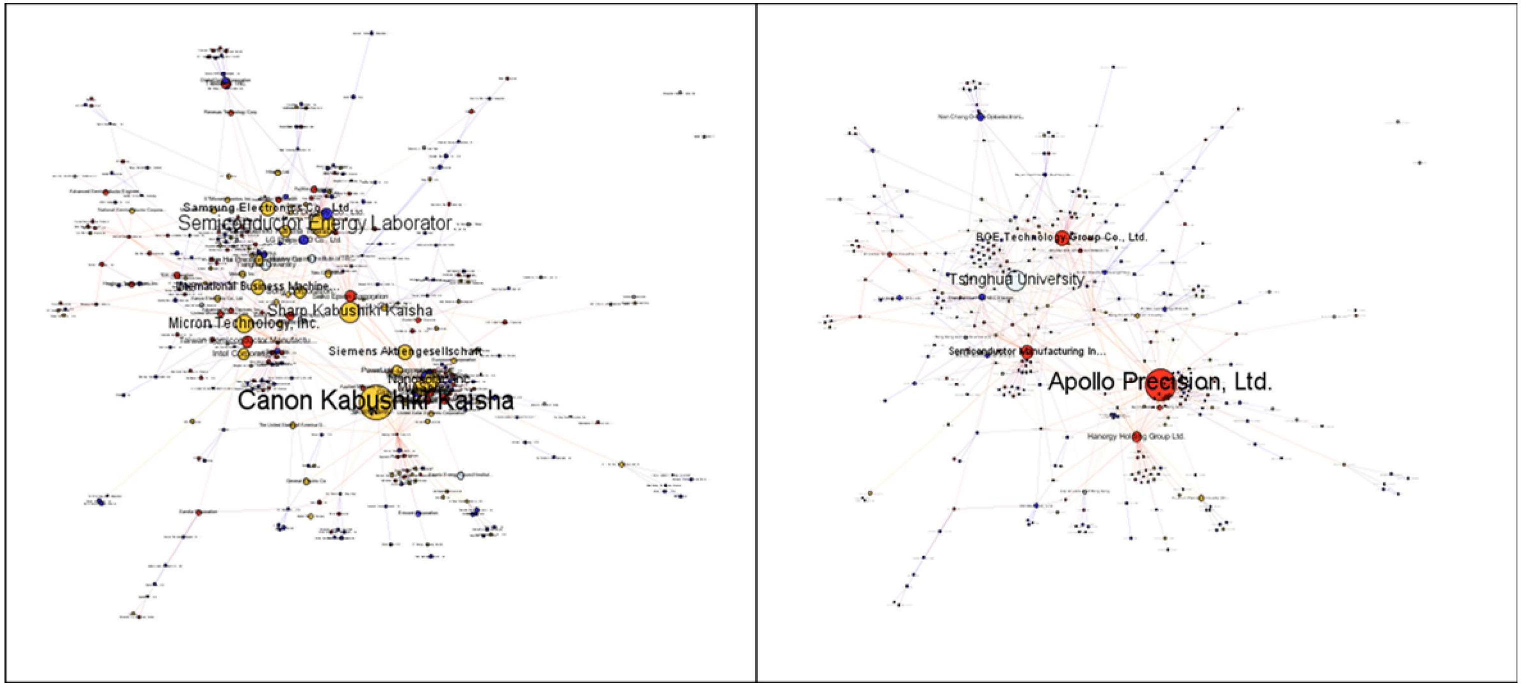


Figure 14. Photovoltaic knowledge network in China (Overall, 2002–2015)
(left) out-degree centrality, (right) in-degree centrality

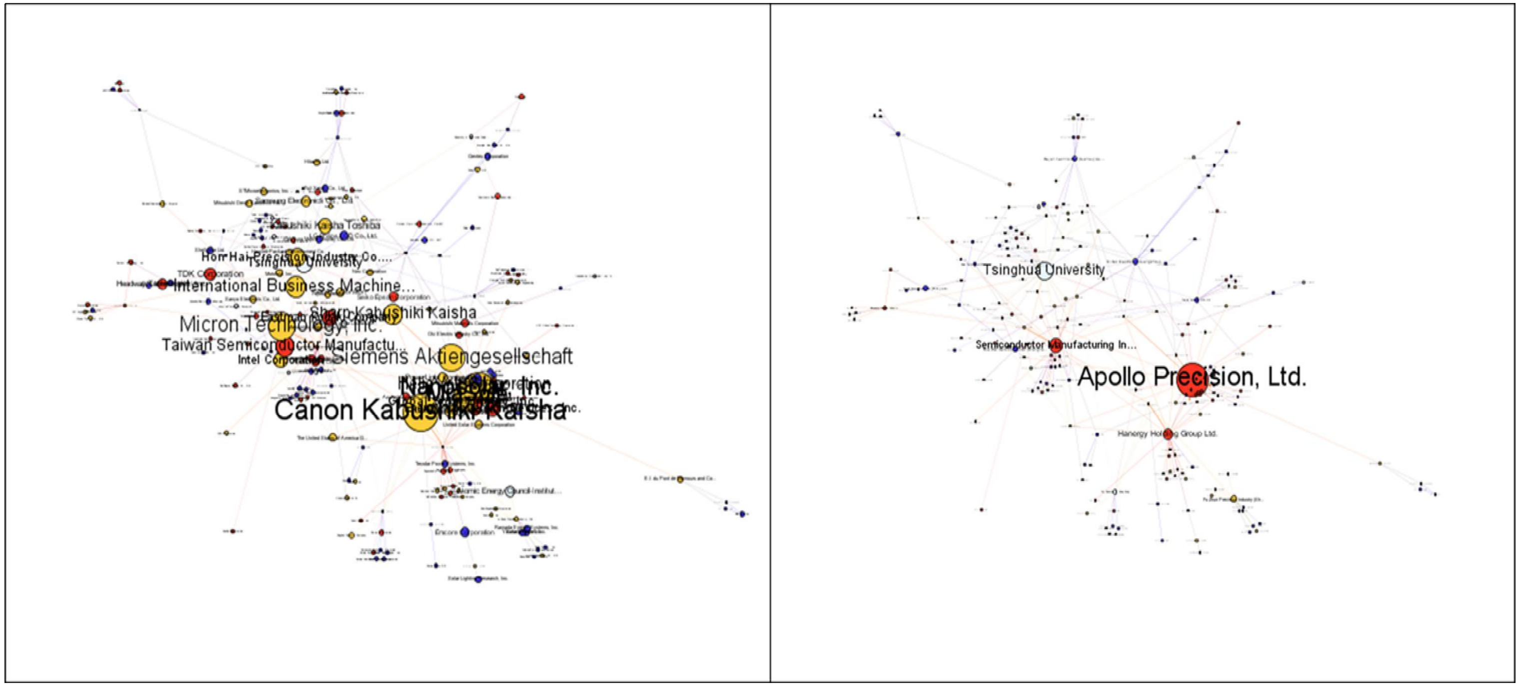


Figure 15. Photovoltaic knowledge network in China (2002–2010)

(left) out-degree centrality, (right) in-degree centrality

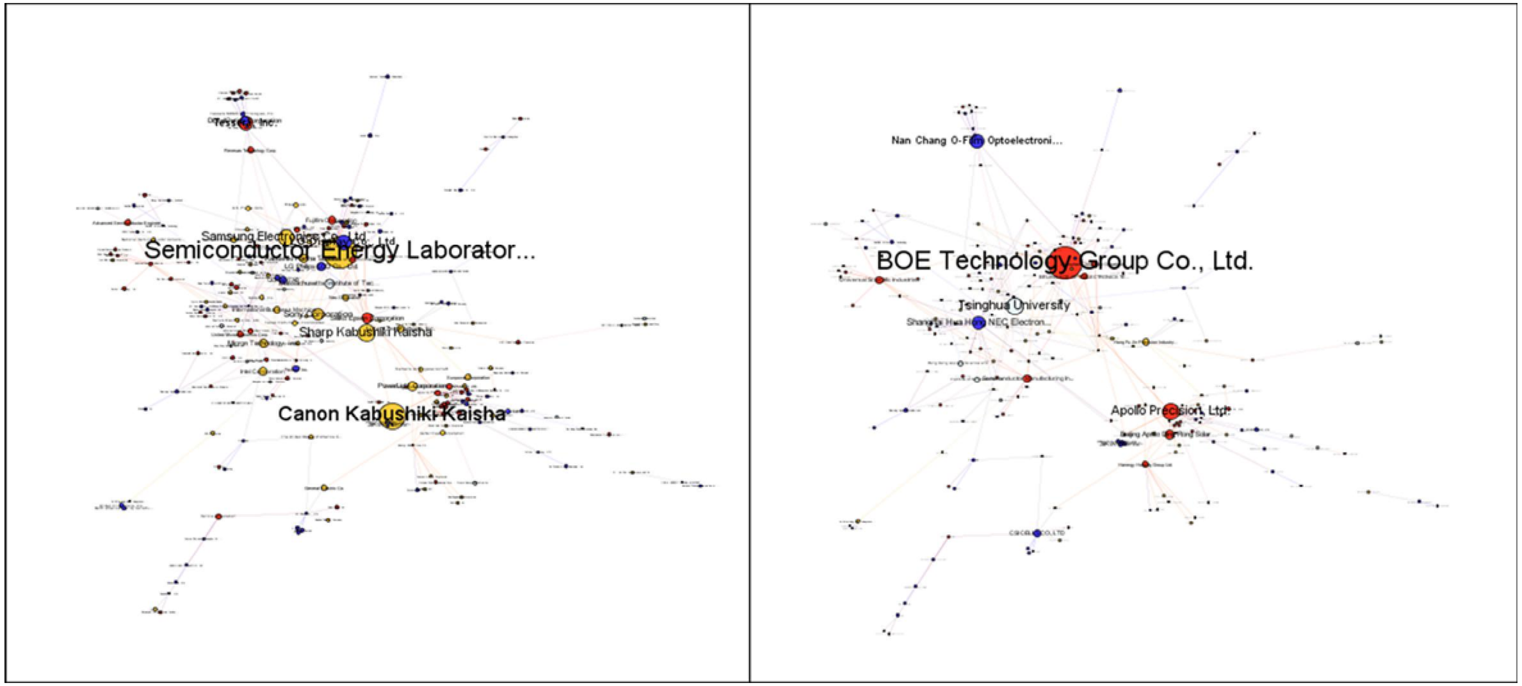


Figure 16. Photovoltaic knowledge network in China (2011–2015)
(left) out-degree centrality, (right) in-degree centrality

The result of the network analysis suggests that Canon and Semiconductor Energy Laboratory Co., Ltd. were the largest nodes. Both companies are Japanese companies, which have the capacity to produce solar cells and modules as well as the capacity to manufacture system peripherals such as inverters. Therefore, it can be said that most part of China's solar photovoltaic knowledge is constructed by utilizing the knowledge of Japanese companies. The largest nodes in the in-degree centrality network were Apollo Precision, Tsinghua University, and BOE Technology Group. Particularly noteworthy was that Tsinghua University, which along with Apollo Precision, was the largest node in the knowledge network in 2002–2010, before China was able to secure its production capacity earnestly. In other words, the patents filed by Apollo Precision and Tsinghua University were those that had the greatest impact on Chinese applicants. However, after 2011, the influence of Tsinghua University has decreased, while that of BOE Technology Group has grown significantly. Companies such as Nanchang O-Film Optoelectronics Technology and Shanghai Hua Hong Electronics have also emerged as major actors in the knowledge network.

We conducted centrality and physical characteristic analyses of the network to explore the network in detail. Companies with the top five centrality scores for 2002–2010 and 2011–2015 are listed in Tables 12 and 13. The average out-degree centrality and average in-degree centrality for each assignee are shown in Figure 17.

Table 12. Top five influential assignees in the Chinese photovoltaic knowledge network

Rank	2002–2010		2011–2015	
	Assignee	**Out-degree centrality**	**Assignee**	**Out-degree centrality**
1	Canon (JP)	28	Semiconductor Energy Laboratory Co., Ltd.(JP)	38
2	Nanosolar (TW)	24	Canon (JP)	30
3	MiaSole (TW)	22	Sharp (JP)	18
4	Siemens (DE)	20	Samsung Electronics (KR)	17
5	Micron Technology (US)	20	LG Display (KR)	16

Note: Information in parentheses represents the company's country of headquarters.
Abbreviation of the country name: CN (China); DE (Germany); JP (Japan); KR (Korea); SG (Singapore); TW (Taiwan); US (the United States).
The shaded column indicates foreign assignee.

Table 13. Top five innovating assignees in the Chinese photovoltaic knowledge network

Rank	2002–2010		2011–2015	
	Assignee	**In-degree centrality**	**Assignee**	**In-degree centrality**
1	Apollo Precision	192	BOE Technology Group	102
2	Tsinghua University	97	Tsinghua University	51
3	Semiconductor Manufacturing International Corporation	71	Apollo Precision	48
4	Hanergy	47	Nan Chang O-Film Optoelectronics Technology	39
5	Fu Zhun Precision	25	Shanghai Hua Hong NEC Electronics	34

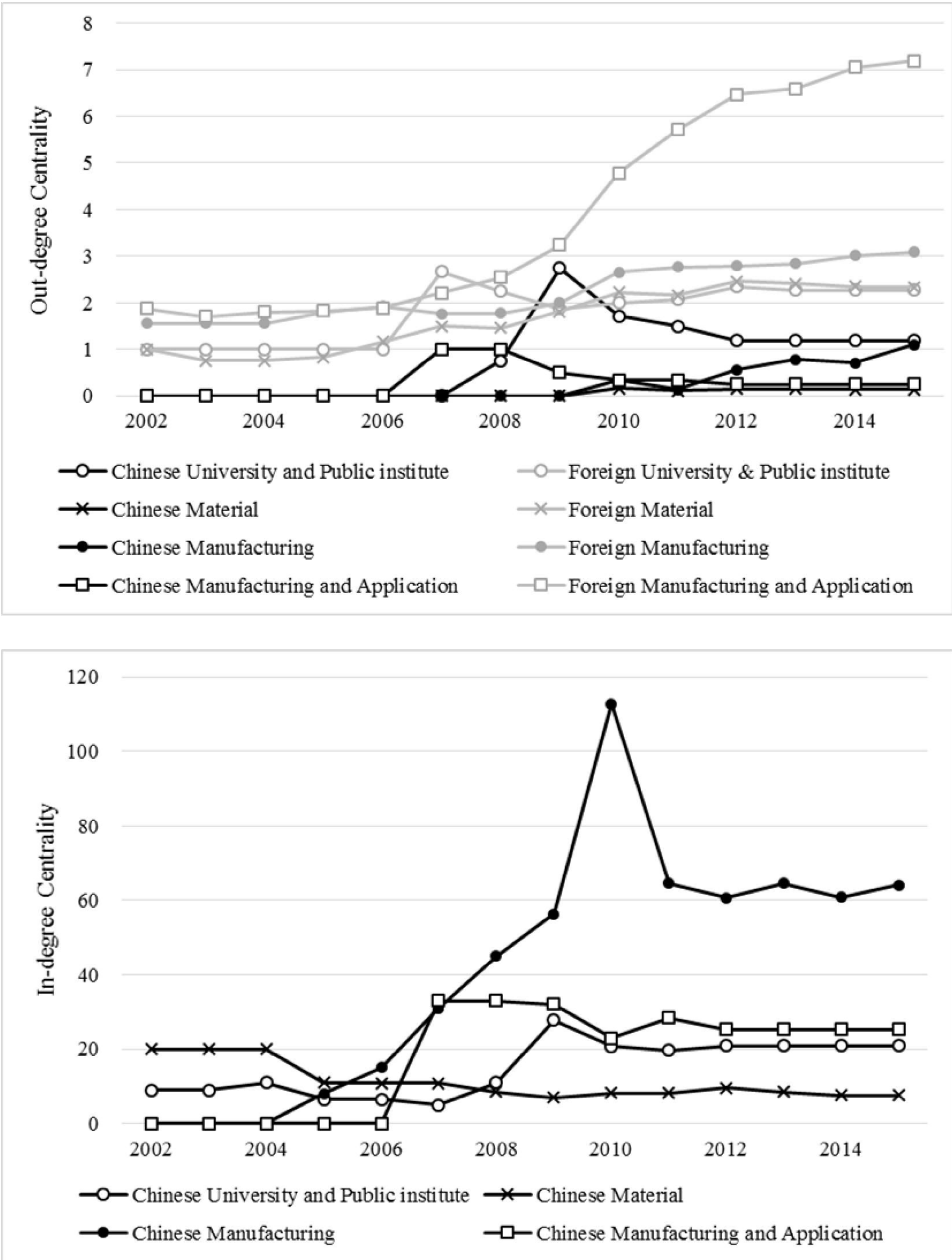


Figure 17. Trends of assignee's influence on innovation (up) and innovating activity (down) in the Chinese photovoltaic knowledge network

In the early days of China’s photovoltaic knowledge network, universities and public research institutes and materials producers have mainly created innovation. However, the patents they created did not have a major impact on China’s knowledge network, and they were still dependent on foreign knowledge. Therefore, in the early days, China’s knowledge network was not developing significantly. Beginning from 2006, the innovation performance of Chinese photovoltaic cell and module producers has started to advance, and in 2010, the industry achieved rapid advancement. However, the growth has not sustained, and therefore, it can be said that this was a temporary effect through the acquisition of foreign companies. Rather, the largest influence on China’s knowledge network since 2010 came from overseas photovoltaic companies. Although China is dominating the production capacity and restructuring the global photovoltaic industry, its core competence comes from overseas knowledge.

In the Chinese knowledge network, it can be seen that there is a clear difference between innovation in the industrial field and that in public research institutes and materials. Although they are generating innovation performance based on their production capacity in solar cells and modules, their knowledge and capabilities are limited and not leading to material and system peripherals, which are at upstream and downstream of the industrial value chain. This is a different result from that of Pisano & Shih (2012), which states that companies with production capacities can form industrial commons with nearby universities and research institutes, and that they can continue to create better innovation outcomes. Therefore, it is not possible to achieve innovation performance by holding only the production capacity, and it is necessary to provide policy support to encourage the flow of knowledge to other sectors of the industry.

4.4.3 Germany

As we have seen earlier, unlike the explosive growth of Chinese photovoltaic companies after 2010, German photovoltaic companies have suffered from bankruptcy or acquisitions by foreign companies during the global restructuring process. In this study, we examine how the German photovoltaic knowledge network has changed and the innovation performance of German companies has declined in the same period, through network analysis. In Germany, technical innovation in photovoltaic technology has occurred since 1981, the beginning of the research period.

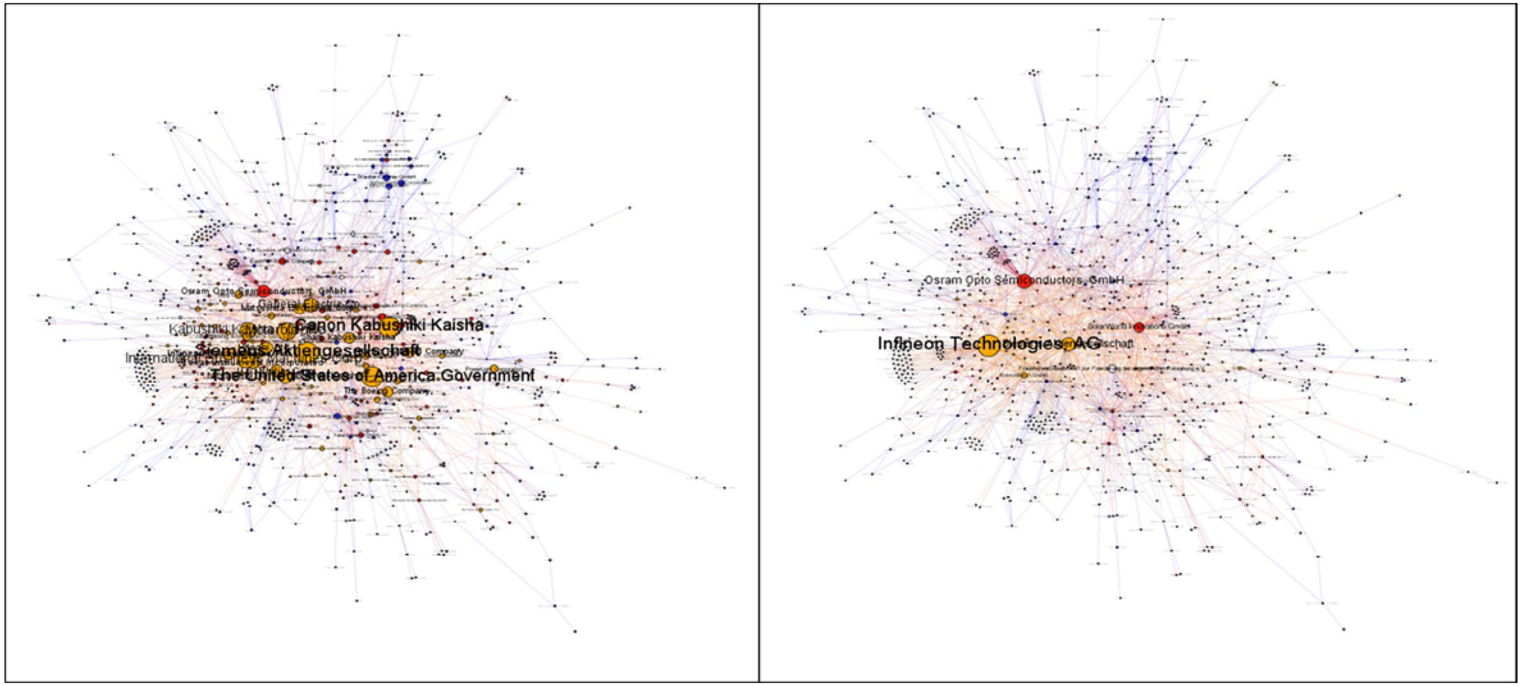


Figure 18. Photovoltaic knowledge network in Germany (Overall, 1981–2015)
(left) out-degree centrality, (right) in-degree centrality

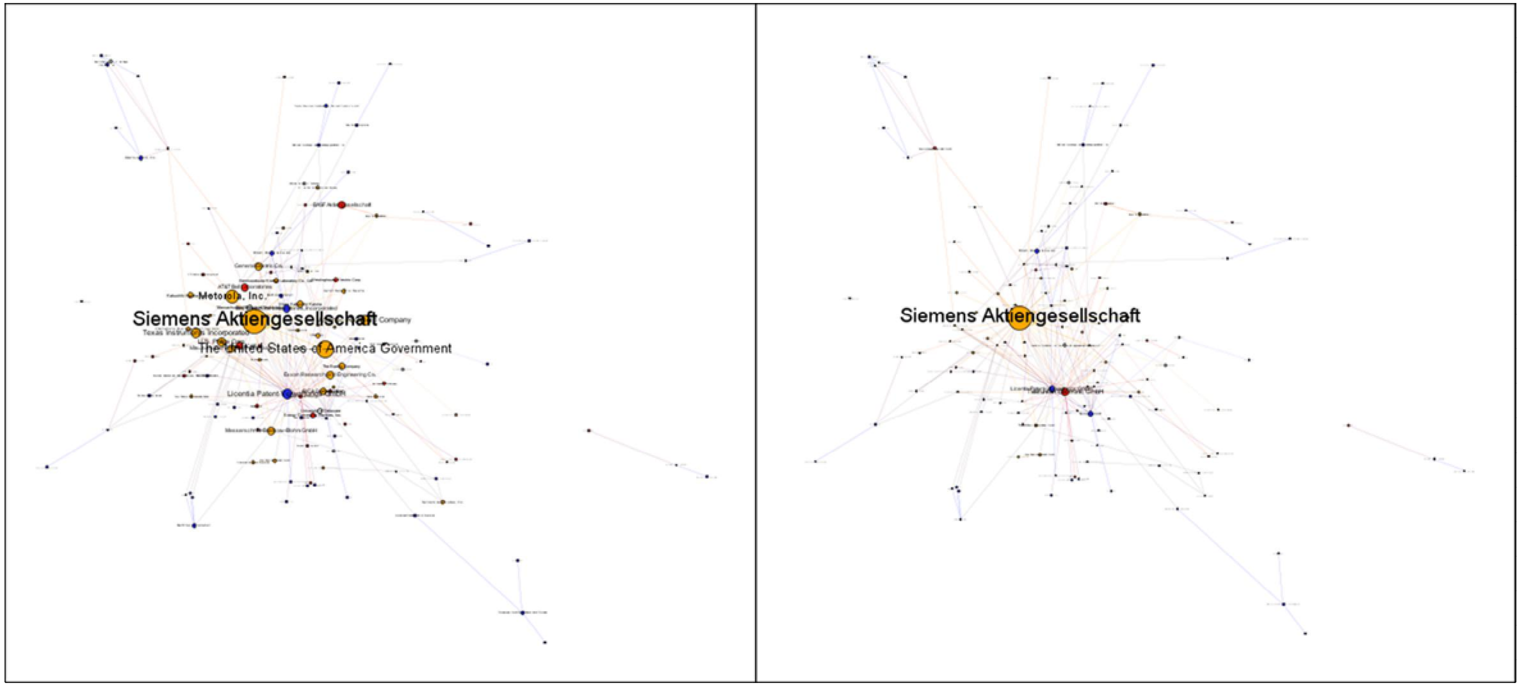


Figure 19. Photovoltaic knowledge network in Germany (1981–1990)
(left) out-degree centrality, (right) in-degree centrality

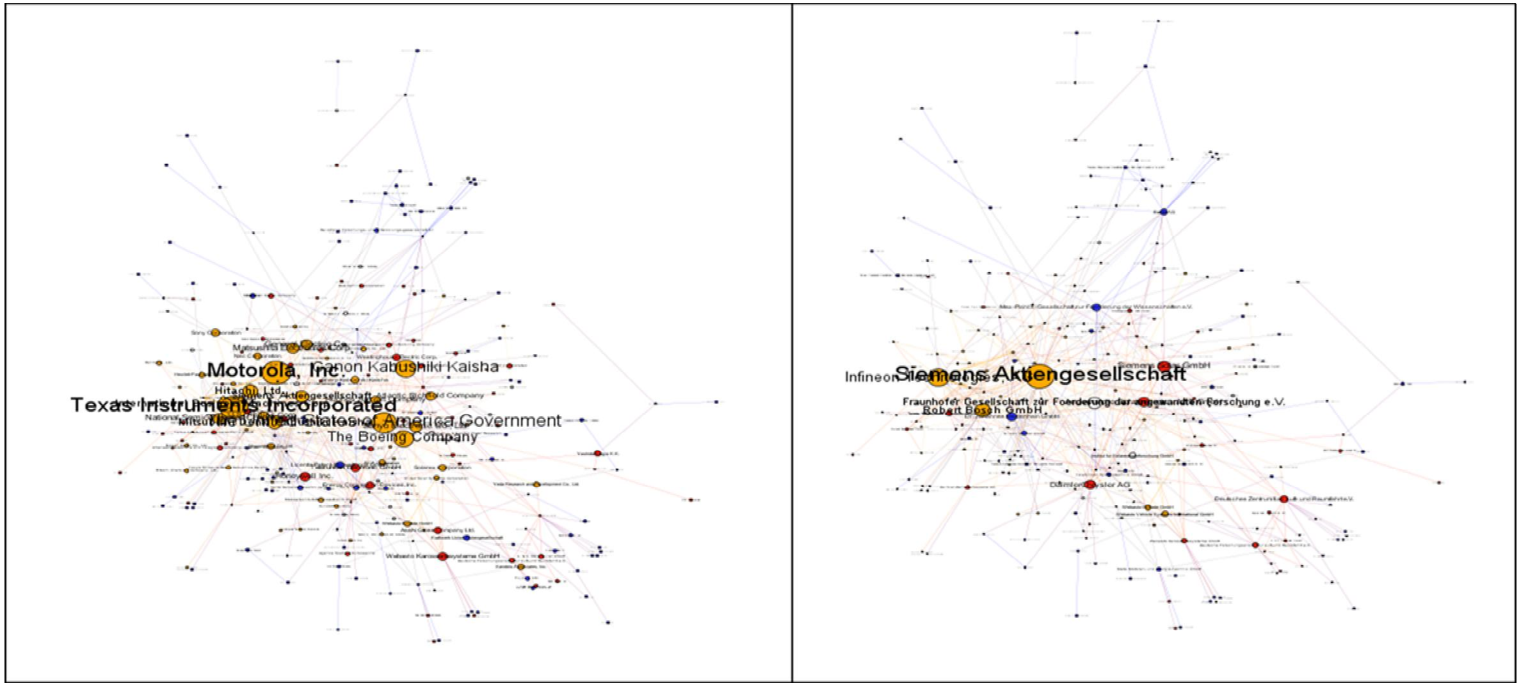


Figure 20. Photovoltaic knowledge network in Germany (1991–2000)

(left) out-degree centrality, (right) in-degree centrality

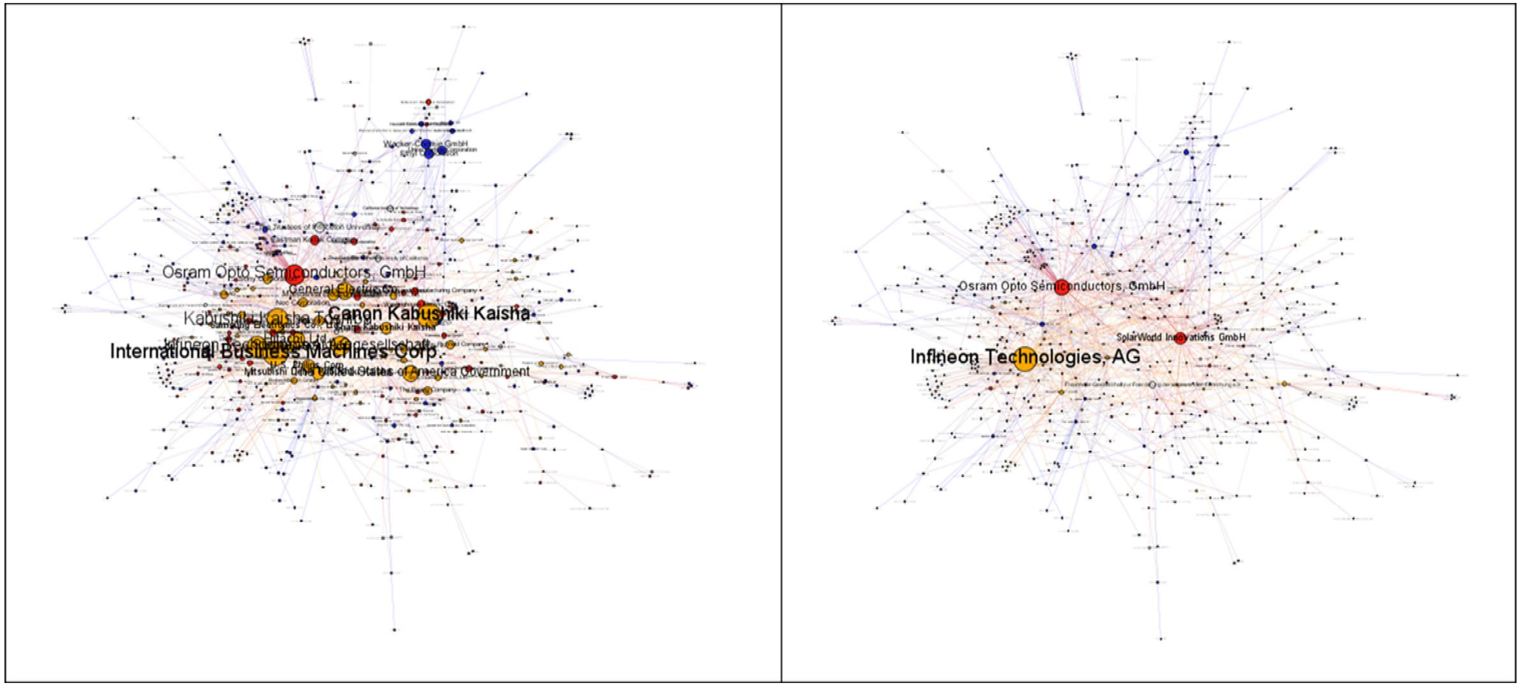


Figure 21. Photovoltaic knowledge network in Germany (2001–2010)
(left) out-degree centrality, (right) in-degree centrality

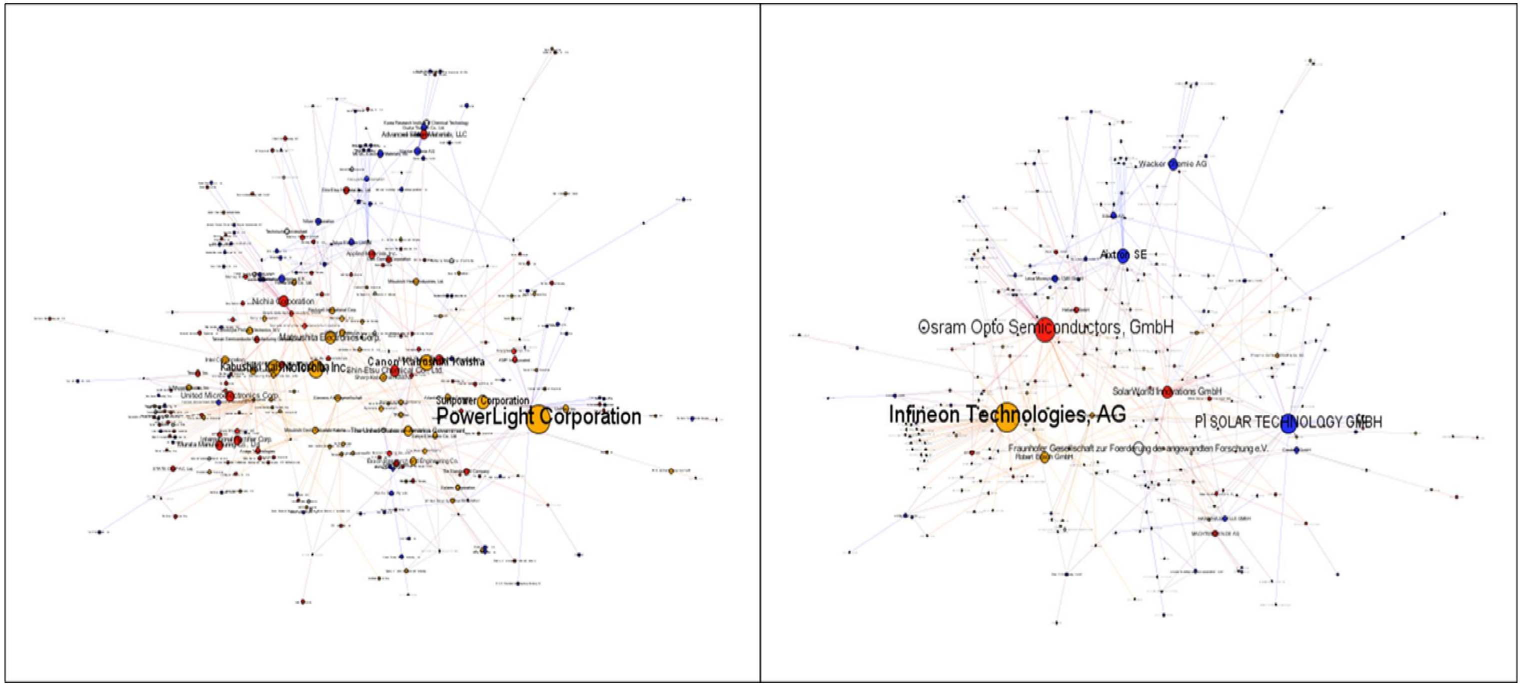


Figure 22. Photovoltaic knowledge network in Germany (2011–2015)

(left) out-degree centrality, (right) in-degree centrality

The result of the network analysis suggests that Siemens was the dominant enterprise in the initial network from 1981 to 1990. However, since 1991, US companies such as Motorola and Texas Instrument have been major nodes, and since 2001, Japanese companies such as Canon and Toshiba also showed high out-degree centrality. However, the influence of German companies, such as Osram Opto Semiconductor and Infineon Technologies, has declined. This can be seen in Table 14, which lists the top five companies with the highest out-degree centrality. Recently, between 2011 and 2015, all top five companies with the highest out-degree centrality were non-German companies.

Looking at the German knowledge network through in-degree centrality, it can be seen that Infineon Technologies and Siemens have made a great contribution in the early years and since 2001, respectively. From 1981 to 2000, before the solar industry was actually established, most of the top five companies were electronics companies. Since the 2000s, photovoltaic companies such as Angewandte Solarenergie, SolarWorld Innovations, and Pi Solar Technology have emerged as major nodes. As a university and public research institute, the Fraunhofer Institute has been consistently located in the top five from 1991 to the present.

Trends in average degree centrality for each sector are shown in Figure 23.

Table 14. Top five influential assignees in the German photovoltaic knowledge network

Rank	1981–1990		1991–2000	
	Assignee	**Out-degree centrality**	**Assignee**	**Out-degree centrality**
1	Siemens (DE)	43	Motorola (US)	32
2	US Government (US)	29	Texas Instruments (US)	32
3	Motorola (US)	21	US Government (US)	27
4	Licentia Patent-Verwaltungs (DE)	15	Canon (JP)	23
5	Atlantic Richfield (US)	15	Boeing (US)	21

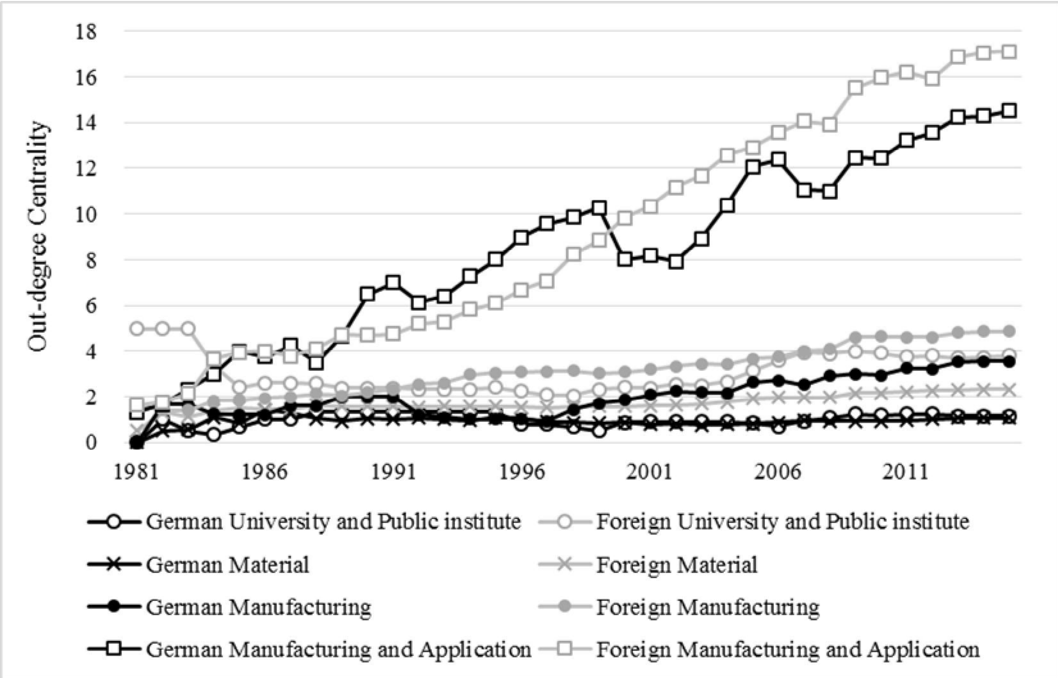
Rank	2001–2010		2011–2015	
	Assignee	**Out-degree centrality**	**Assignee**	**Out-degree centrality**
1	IBM (US)	70	PowerLight (US)	27
2	Canon (JP)	68	Motorola (US)	16
3	Toshiba (JP)	61	Canon (JP)	14
4	Osram Opto Semiconductors (DE)	58	Toshiba (JP)	13
5	Infineon Technologies (DE)	58	Sunpower (US)	12

Note: Information in parentheses represents the company's country of headquarters.
Abbreviation of the country name: CN (China); DE (Germany); JP (Japan); KR (Korea); SG (Singapore); TW (Taiwan); US (the United States).
The shaded column indicates foreign assignee.

Table 15. Top five innovating assignees in the German photovoltaic knowledge network

Rank	1981–1990		1991–2000	
	Assignee	In-degree centrality	Assignee	In-degree centrality
1	Siemens	196	Siemens	134
2	Telefunken Electronic	50	Infineon Technologies	67
3	Licentia Patent-Verwaltungs	39	Robert Bosch	50
4	Nukem	27	Fraunhofer-Gesellschaft	42
5	Brown, Boveri & Cie	19	Angewandte Solarenergie	32

Rank	2001–2010		2011–2015	
	Assignee	In-degree centrality	Assignee	In-degree centrality
1	Infineon Technologies	436	Infineon Technologies	93
2	Osram Opto Semiconductors	282	Osram Opto Semiconductors	72
3	SolarWorld Innovations	200	Pi Solar Technology	60
4	Fraunhofer-Gesellschaft	92	Aixtron SE	42
5	Wacker Chemie	63	Fraunhofer-Gesellschaft	36



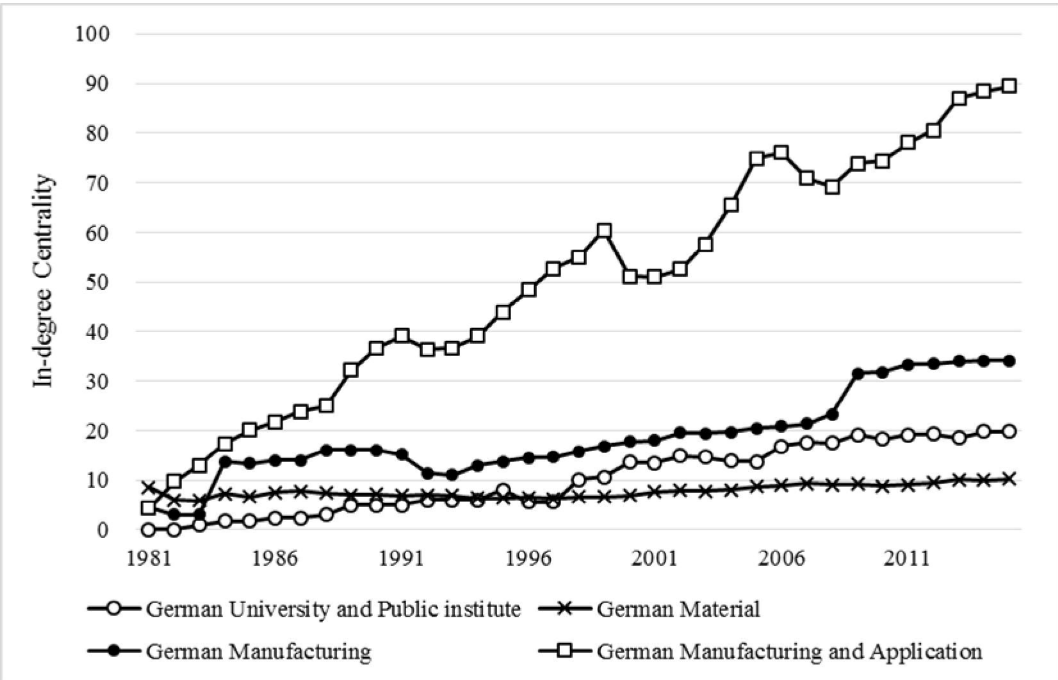


Figure 23. Trends of assignee's influence on innovation (up) and innovating activity (down) in the German photovoltaic knowledge network

In Germany, universities and public research institutes were major applicants in the early 1980s—the early days of knowledge network formation. Most of them have been innovating mainly by using the knowledge of overseas universities and public research institutes, and they have played a role in conveying advanced technology and knowledge from overseas to the German knowledge network. Based on the brokerage efforts in the public sector, German manufacturing companies were able to accumulate relevant knowledge and acquire technical advantages. From 1990 to 1999, German companies utilized the knowledge and patents of domestic companies.

However, from 2000, the innovation of foreign companies was more utilized than that of German domestic production companies. Between 2006 and 2010, when the price competition of the photovoltaic industry became fierce and the industry was reorganized, reliance on foreign companies' innovation increased, while that on domestic companies' innovation decreased. If we look at the innovation performance of the public sector between 1990 and 1999, when the innovation performance of German manufacturers dominated, we can find the reason behind. This is because the reliance on innovation of domestic universities and public research institutes has decreased, while that on innovation of overseas universities and public research institutes has increased. In other words, it can be said that the virtuous cycle of knowledge has not been achieved smoothly in the growth period of the knowledge network of the photovoltaic industry. This tendency is similar to the previously mentioned Chinese case, and this was the result from the weak linkage of the knowledge embodied in the production site to the entire industry.

Since the virtuous cycle of knowledge has not been achieved, the influence of foreign firms with production capacity has been increasing since 2000. As reliance on external knowledge increases, internal innovation capacity decreases. In addition, there is a concern that companies that collaborate with public research institutes or companies in Germany turn out to be mostly foreign companies. This trend may result in increasing dependence on external knowledge and also leakage of German knowledge to foreign countries.

4.4.4 Korea

Korea has successfully developed on the basis of production capability in the semiconductor industry. In Korea, the Korea Institute of Electronics Technology, the forerunner of the Electronics and Telecommunications Research Institute (ETRI) played a leading role in the early stages of semiconductor technology. However, they not only contributed to technology development but also educated the R&D personnel. The excellent human resources in the R&D field moved to other semiconductor companies such as Samsung, LG, and Hyundai, and the accumulated knowledge could be transferred to actual production stage (Kim, 1997). Therefore, by looking at the examples of solar power generation in Korea that share solar power technologies and knowledge, we can re-visit the past lesson of Korea that production is important in the process of innovation creation, and check whether the lesson is still applicable today.

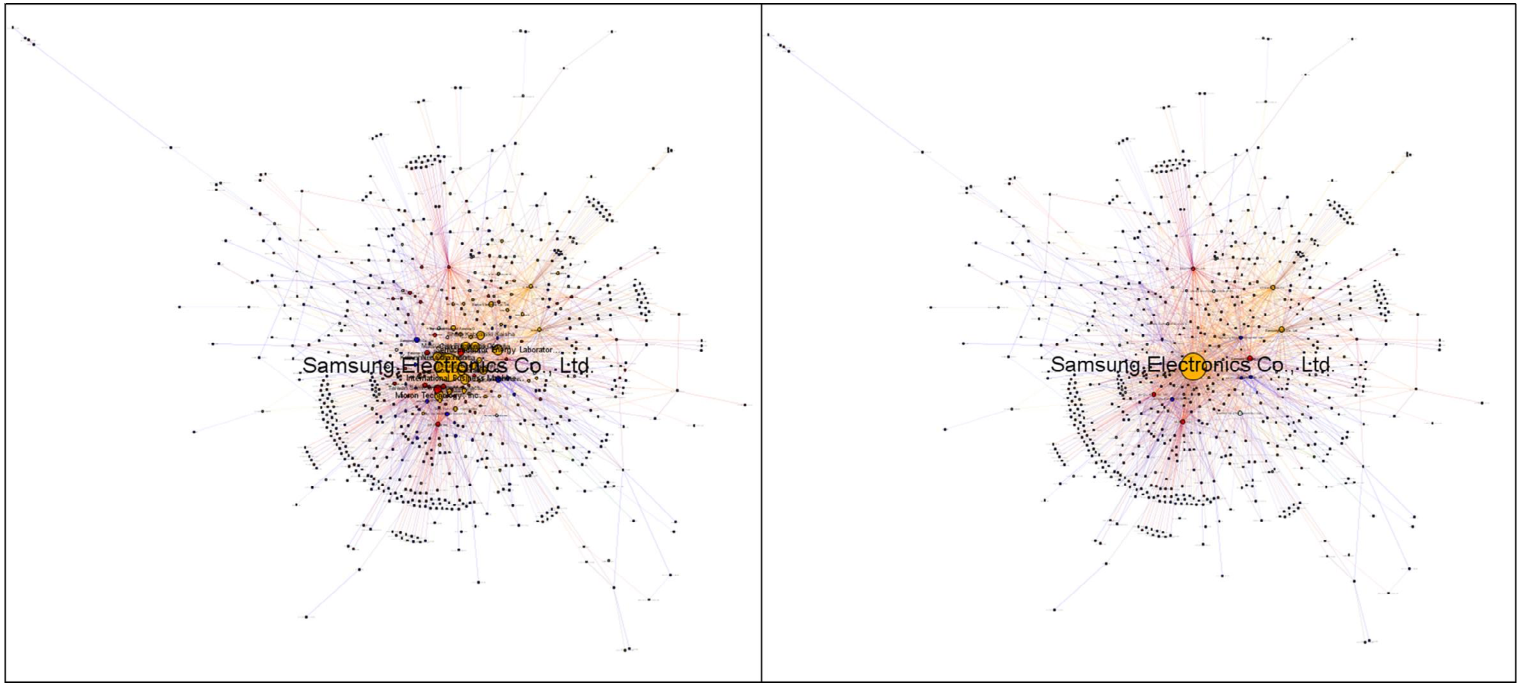


Figure 24. Photovoltaic knowledge network in Korea (Overall, 1990–2015)

(left) out-degree centrality, (right) in-degree centrality

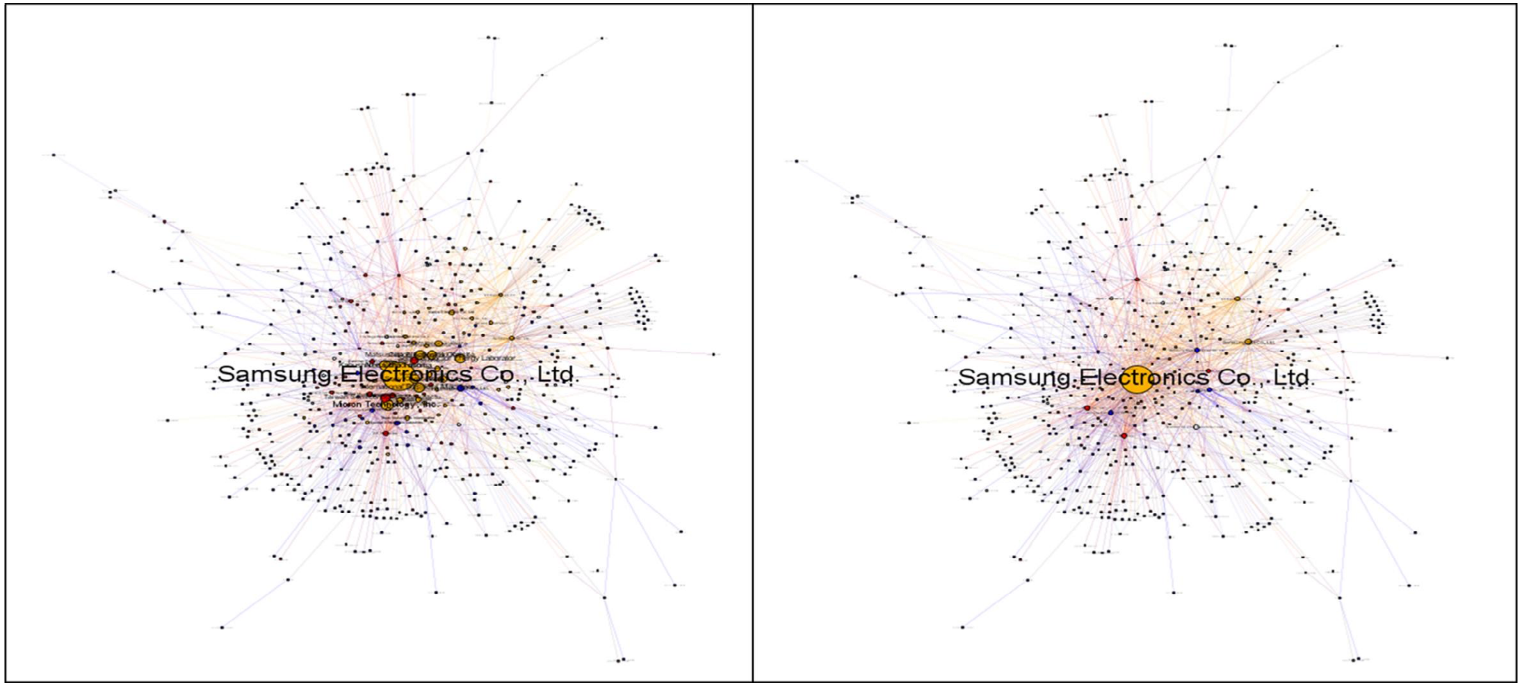


Figure 25. Photovoltaic knowledge network in Korea (1990–2010)
(left) out-degree centrality, (right) in-degree centrality

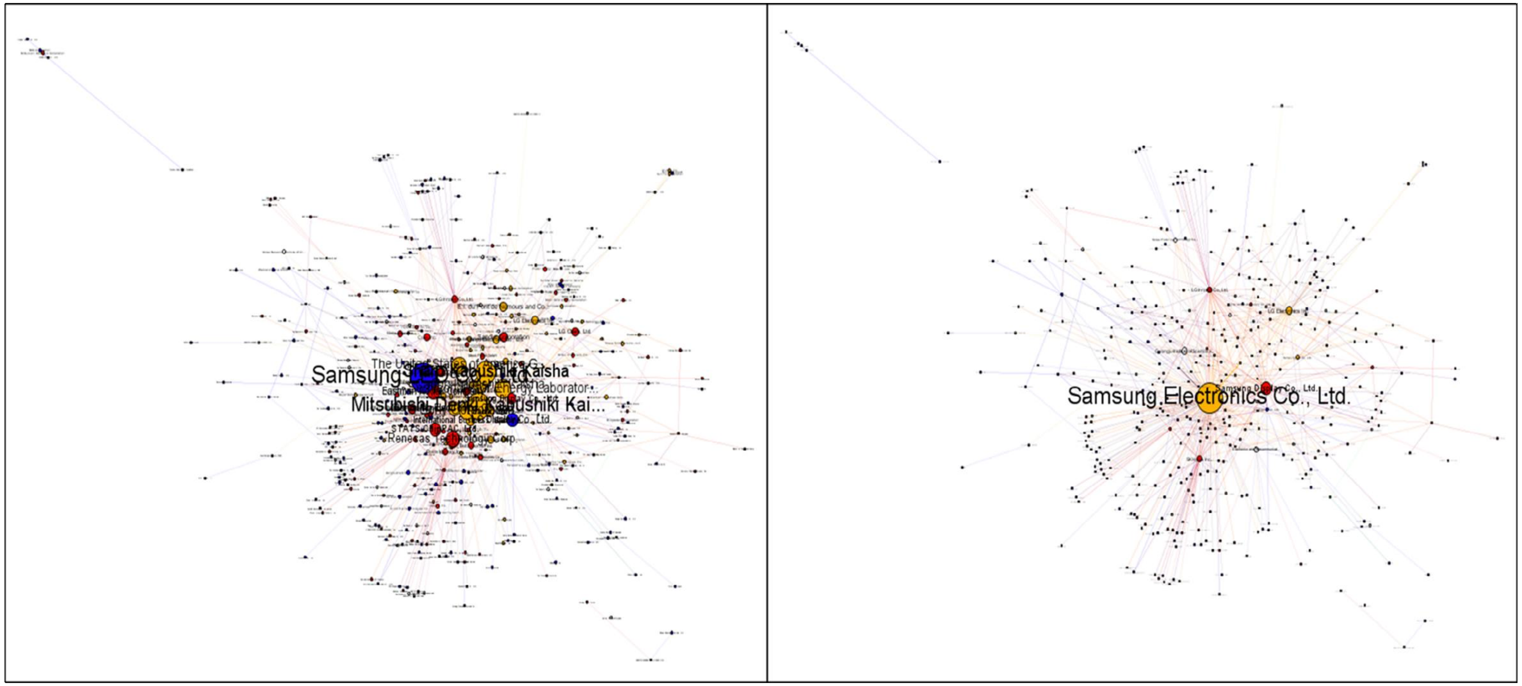


Figure 26. Photovoltaic knowledge network in Korea (2011–2015)
(left) out-degree centrality, (right) in-degree centrality

Samsung Electronics possessed the largest share of the knowledge network in Korea. Samsung Electronics turned out to be the largest node in both out-degree and in-degree centrality. Wu (2014) points out the excessive influence of *chaebol* such as Samsung in Korea's R&D and investment. Wu (2014) argues that Korea's aggressive investment in the photovoltaic industry since the 2000s has been led by *chaebol*, and that it tends to form a vertical integration for the entire value chain during investment.

With the exception of Samsung Electronics, most Korean companies have been generating innovation results by utilizing the knowledge from Japanese companies, and most of them came from electronics and semiconductor companies. Regarding universities and public research institutes, the Korea Electronics and Telecommunications Research Institute and the Gwangju Institute of Science and Technology were among the top five applicants.

Table 16. Top five influential assignees in the Korean photovoltaic knowledge network

Rank	1990–2010		2011–2015	
	Assignee	Out-degree centrality	Assignee	Out-degree centrality
1	Samsung Electronics (KR)	427	Samsung LED (KR)	65
2	Semiconductor Energy Laboratory Co., Ltd.(JP)	133	Mitsubishi (JP)	53
3	Micron Technology (US)	130	Sharp (JP)	42
4	Toshiba (JP)	129	Semiconductor Energy Laboratory Co., Ltd. (JP)	38
5	Matsushita Electronics (Panasonic) (JP)	127	Sony (JP)	33

Note: Information in parentheses represents the company's country of headquarters.
Abbreviation of the country name: CN (China); DE (Germany); JP (Japan); KR (Korea); SG (Singapore); TW (Taiwan); US (the United States).
The shaded column indicates foreign assignee.

Table 17. Top five innovating assignees in the Korean photovoltaic knowledge network

Rank	1990–2010		2011–2015	
	Assignee	In-degree centrality	Assignee	In-degree centrality
1	Samsung Electronics	1,805	Samsung Electronics	394
2	Samsung SDI	288	Samsung Display	196
3	Dongbu HiTek	227	Gwangju Institute of Science and Technology	77
4	Dongbu Electronics	196	LG Electronics	72
5	Electronics and Telecommunications Research Institute	176	LG Innotek	59

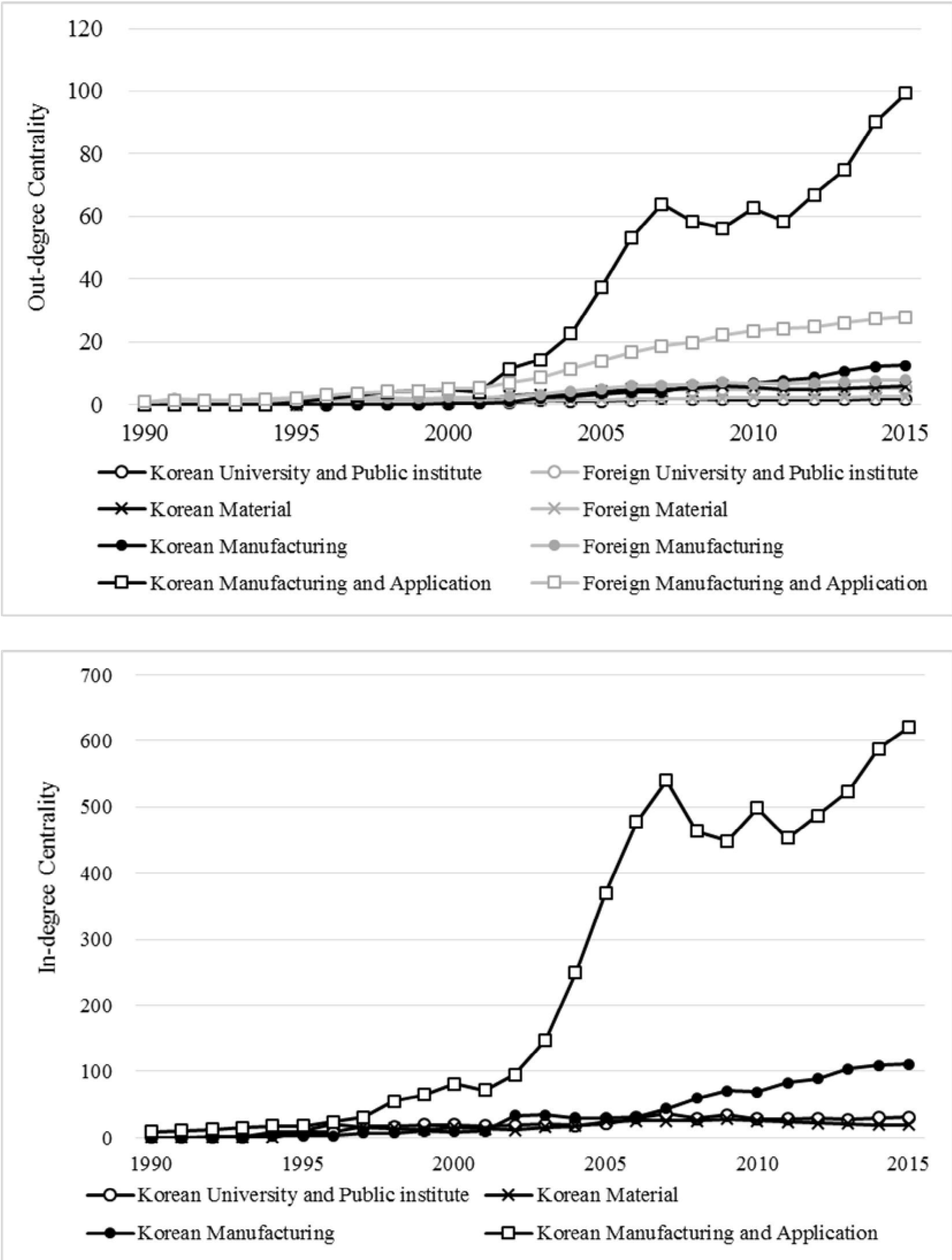


Figure 27. Trends of assignee's influence on innovation (up) and innovating activity (down) in the Korean photovoltaic knowledge network

The trend of average degree centrality also shows that the most influential part in Korea's knowledge network was domestic manufacturing and application companies, including Samsung Electronics. Since the mid-1990s, Korean manufacturing and application companies began to generate more active innovation performance than other sectors, especially in the early 2000s. Since the mid-2000s, these companies began to bring more influences to knowledge networks than foreign manufacturing and application companies. In the early days of forming a knowledge network, Korean domestic companies created only results that were mainly implemented and improved based on foreign knowledge. However, after Korean semiconductor companies developed as global companies, they created new innovations based on active domestic innovation activities. Nevertheless, during the same period, the innovation activities of universities and public research institutes and materials sectors have not improved significantly, because of the excessive influence of *chaebol* firms in Korean innovation activities since 2000.

In order to examine Korea's knowledge network except for this excessive influence from *chaebol*, the influence of affiliates of Samsung Electronics and Samsung Group, which have the largest influence, have been excluded. Table 18 and Figures 19 and 28 show the average centrality trends among the top five companies in the knowledge network of the Korean solar industry, excluding the influence of affiliates of Samsung Electronics and Samsung Group.

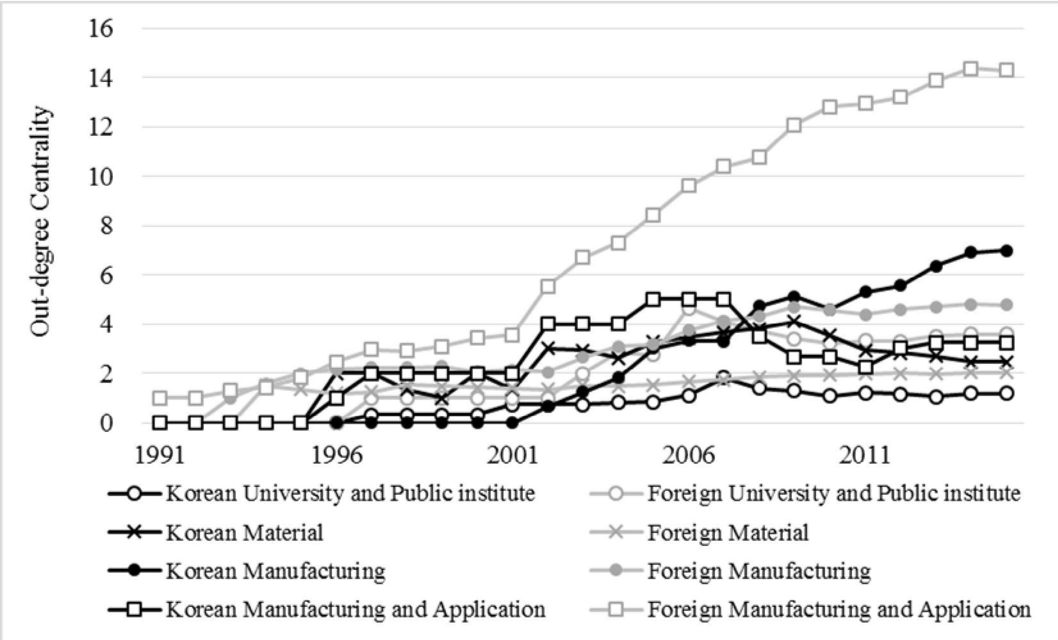
Table 18. Top five influential assignees in the Korean photovoltaic knowledge network without Samsung Group

Rank	1990–2010		2011–2015	
	Assignee	**Out-degree centrality**	**Assignee**	**Out-degree centrality**
1	Micron Technology (US)	71	Canon (JP)	33
2	Toshiba (JP)	64	Sony (JP)	20
3	NEC Corporation (JP)	53	IBM (US)	17
4	Sharp (JP)	52	US Government (US)	12
5	Matsushita Electronics (Panasonic) (JP)	48	Sandia Corporation (US)	12

Note: Information in parentheses represents the company's country of headquarters.
Abbreviation of the country name: CN (China); DE (Germany); JP (Japan); KR (Korea); SG (Singapore); TW (Taiwan); US (the United States).
The shaded column indicates foreign assignee.

Table 19. Top five innovating assignees in the Korean photovoltaic knowledge network without Samsung Group

Rank	1990–2010		2011–2015	
	Assignee	**In-degree centrality**	**Assignee**	**In-degree centrality**
1	Dongbu HiTek	220	LG Electronics	101
2	Dongbu Electronics	193	SK Hynix	72
3	LG Electronics	190	LG Innotek	68
4	Electronics and Telecommunications Research Institute	186	Electronics and Telecommunications Research Institute	55
5	Hynix	174	Gwangju Institute of Science and Technology	48



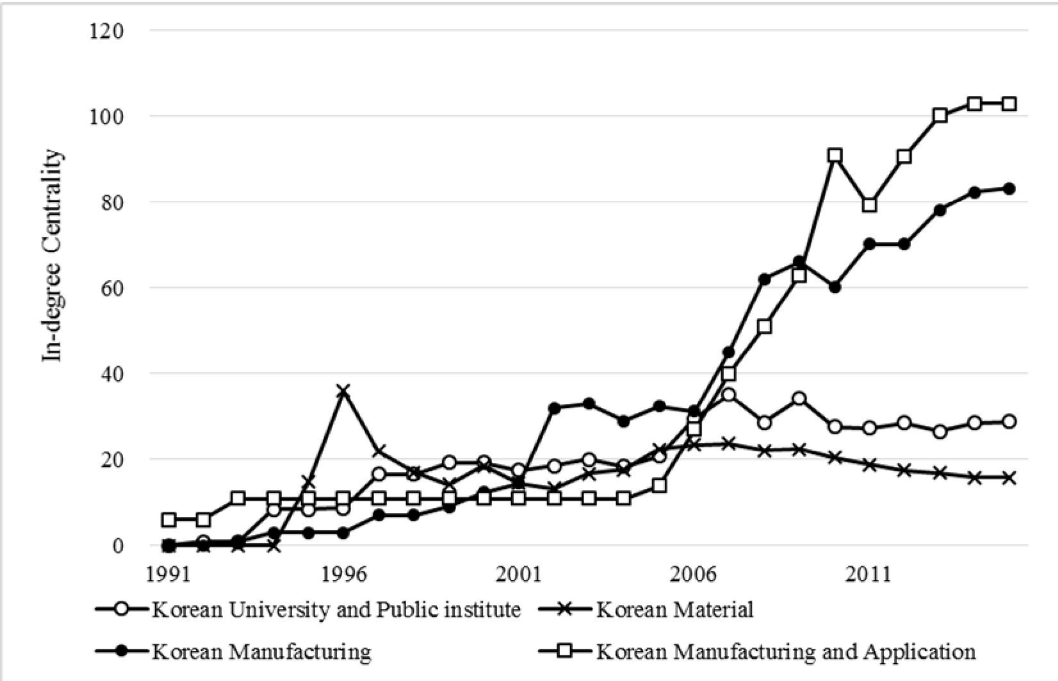


Figure 28. Trends of assignee's influence on innovation (up) and innovating activity (down) in the Korean photovoltaic knowledge network without Samsung Group

Except for the influence of the Samsung Group, unlike Figure 27, the most influential firms in the Korean knowledge network are foreign companies. In the knowledge network excluding the Samsung Group, the top five applicants with high outward orientation were all foreign companies. Therefore, the Korean knowledge network is highly dependent on the knowledge of the Samsung Group, and it is still highly dependent on foreign knowledge, except for the Samsung Group. In the early stages of the knowledge network (1991–2001), innovation activities in universities and public research institutes have been more active and widely used than those from manufacturing companies. However, in the growth period of the knowledge network (2002–2010), the innovation activity of public research institutes in Korea has not achieved significant growth, and it has been stagnant since 2006. On the other hand, the innovation activities of Korean manufacturing companies have increased dramatically, widening the gap with the public sector.

The case of Korean manufacturing companies can be seen as a case in which Samsung Group continues to promote innovation based on its huge production capacity. On the other hand, however, the influence of the Samsung Group on the Korean knowledge network is too strong and the interactions between public institutions and production companies are negligible. There is a concern that production may be confined to the role of facilitating innovation just for implementation. There is also a concern that public research institutes will not be able to create a new cycle of transferring new innovations based on new knowledge embodied in production sites, and transfer them back to companies.

4.4.5 Taiwan

Taiwan’s development pattern seems similar to that of Korea in the field of semiconductors. However, unlike Korea, Taiwan is not dominated by large corporations, but small and medium enterprises. Taiwanese companies have acquired the patents from the Industrial Technology Research Institute of Taiwan, which filed patents in the early stages of the semiconductor industry. However, regarding the vertical integration system, Taiwan is different from Korea in that it develops specialized firms for each process (Wong, 1999). Therefore, we examined how this difference between Korea and Taiwan led to difference in the status of the knowledge network and that of the company with the production capacity in the knowledge network.

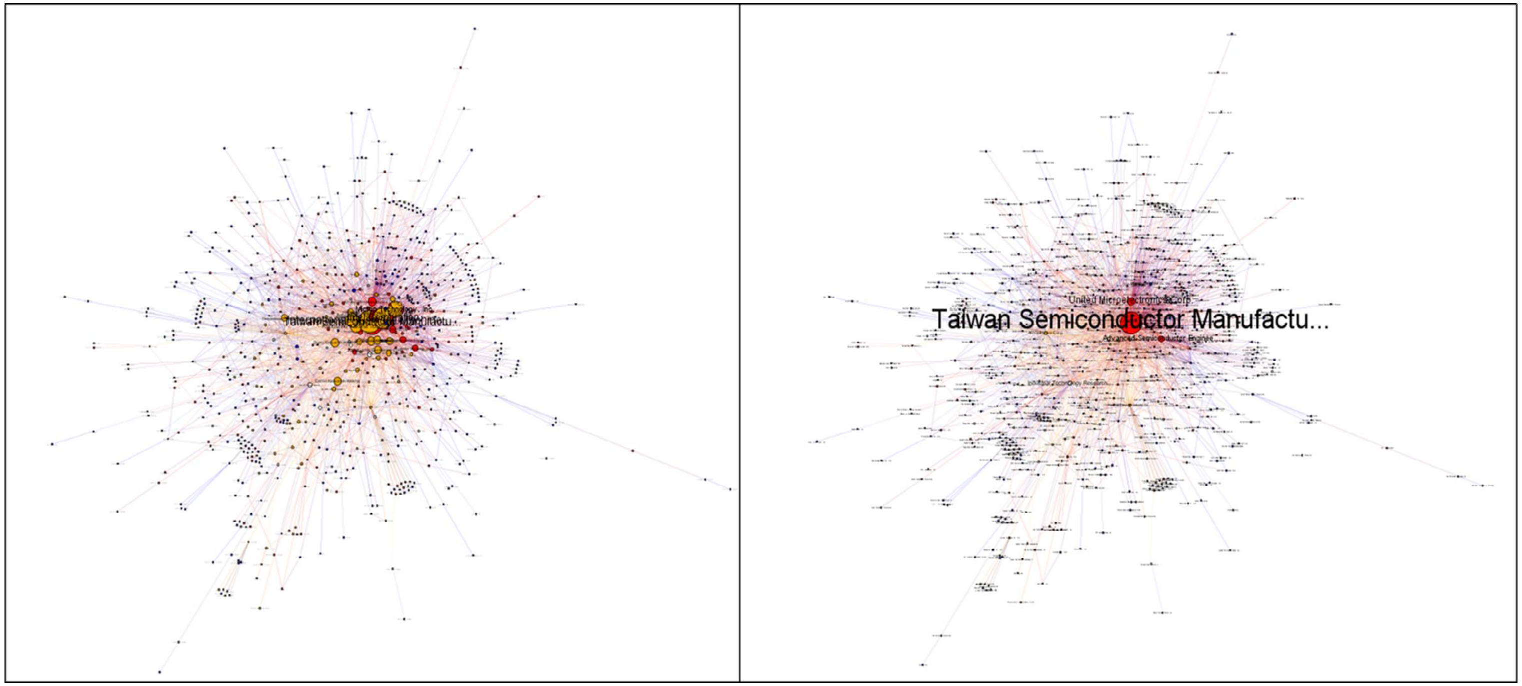


Figure 29. Photovoltaic knowledge network in Taiwan (Overall, 1992–2015)
(left) out-degree centrality, (right) in-degree centrality

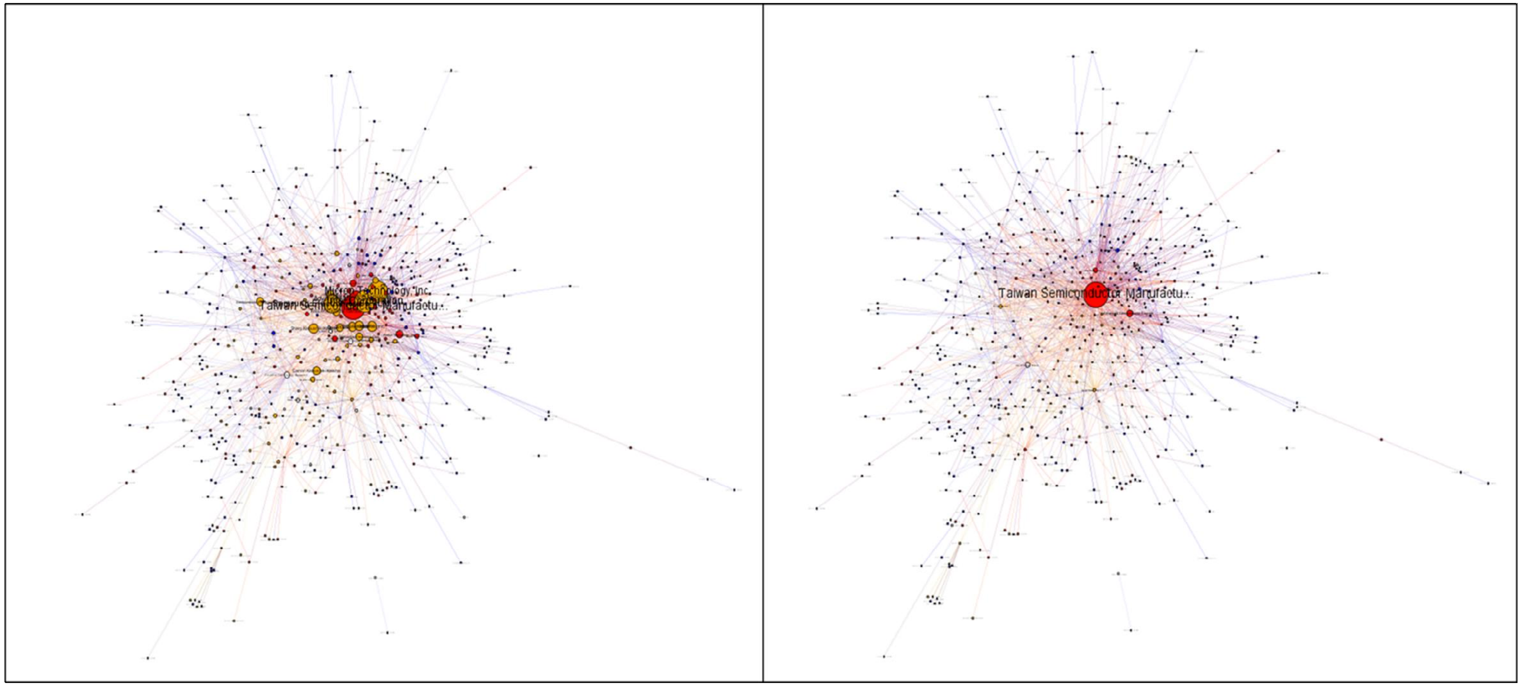


Figure 30. Photovoltaic knowledge network in Taiwan (1992–2010)
(left) out-degree centrality, (right) in-degree centrality

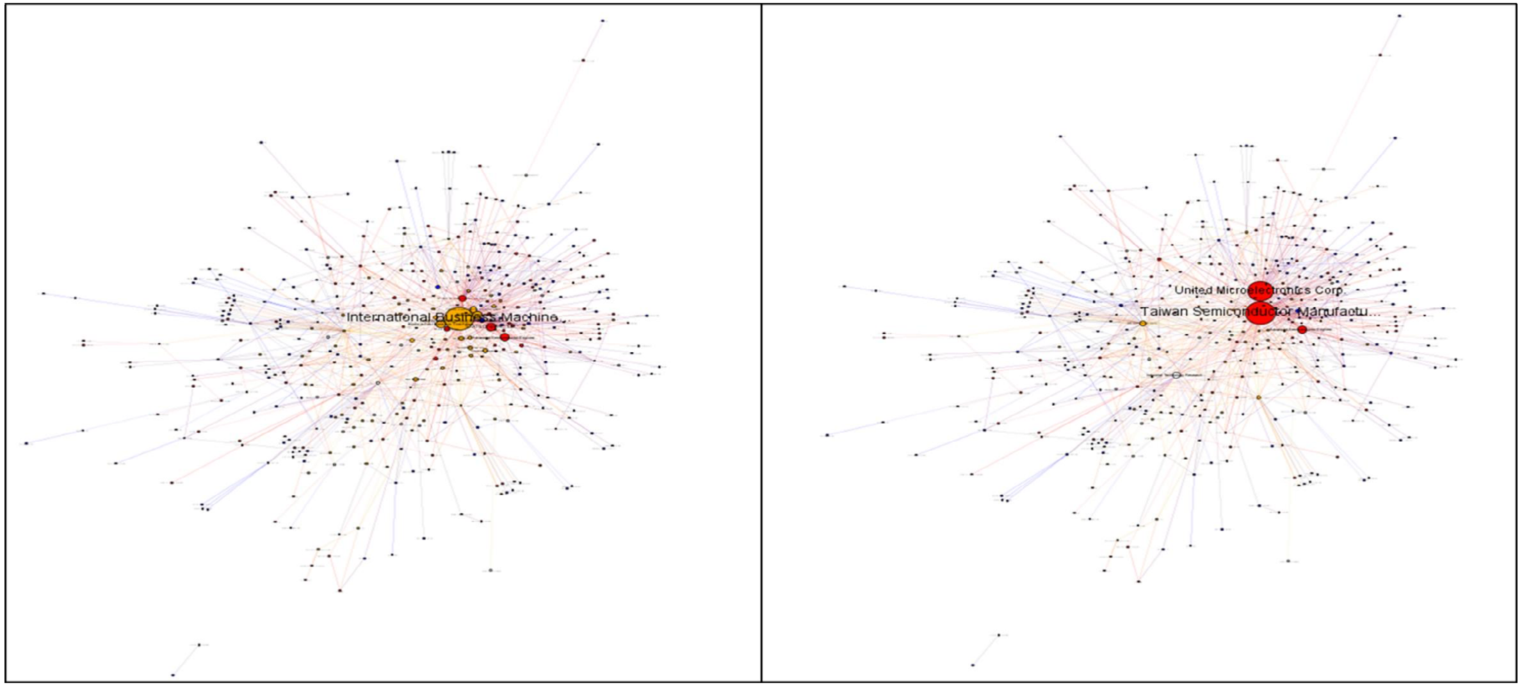


Figure 31. Photovoltaic knowledge network in Taiwan (2011–2015)
(left) out-degree centrality, (right) in-degree centrality

The result of the network analysis shows that Taiwan Semiconductor Manufacturing Company was the first to have the largest influence in the out-degree centrality network. Taiwan Semiconductor Manufacturing Company, which grew up based on semiconductor technology, was larger than other companies and created an overwhelmingly high level of innovation. However, the impact of the Taiwan Semiconductor Manufacturing Company has reduced sharply in recent years compared to 1990–2010, and its reliance on foreign knowledge has increased. This is because Taiwan’s solar industry has not been able to improve its innovation capacity other than Taiwan Semiconductor Manufacturing Company. As mentioned earlier, Taiwan’s industrial structure is a SME-oriented industry; therefore, large-scale R&D investments have not been made across the value chain. In addition, the knowledge of Taiwan Semiconductor Manufacturing Company has not been transmitted throughout the industry, which has led to the recent decline in the creation of innovation of Taiwan Semiconductor Manufacturing Company.

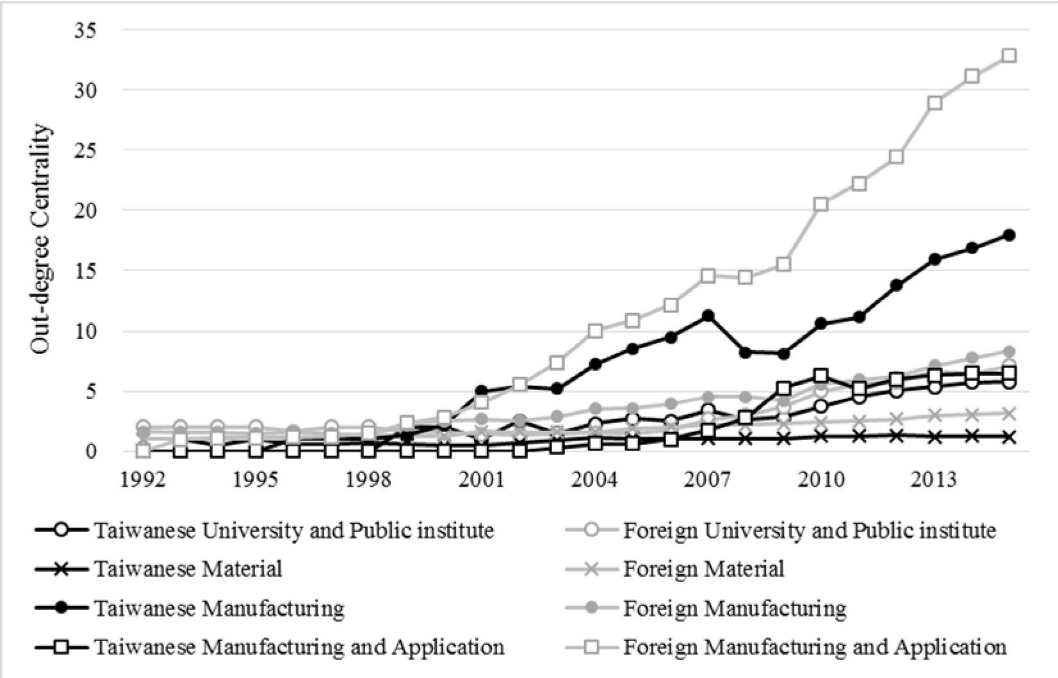
Table 20. Top five influential assignees in the Taiwanese photovoltaic knowledge network

Rank	1992–2010		2011–2015	
	Assignee	**Out-degree centrality**	**Assignee**	**Out-degree centrality**
1	Taiwan Semiconductor Manufacturing Company (TW)	277	IBM (US)	328
2	Intel (US)	243	STATS ChipPAC (SG)	97
3	Micron Technology (US)	234	Taiwan Semiconductor Manufacturing Company (TW)	95
4	Samsung Electronics (KR)	197	Intel (US)	95
5	Advanced Micro Devices (US)	165	Toshiba (JP)	93

Note: Information in parentheses represents the company's country of headquarters.
Abbreviation of the country name: CN (China); DE (Germany); JP (Japan); KR (Korea); SG (Singapore); TW (Taiwan); US (the United States).
The shaded column indicates foreign assignee.

Table 21. Top five innovating assignees in the Taiwanese photovoltaic knowledge network

Rank	1992–2010		2011–2015	
	Assignee	**In-degree centrality**	**Assignee**	**In-degree centrality**
1	Taiwan Semiconductor Manufacturing Company	2,026	Taiwan Semiconductor Manufacturing Company	708
2	Advanced Semiconductor Engineering	427	United Microelectronics	603
3	Industrial Technology Research Institute	261	Advanced Semiconductor Engineering	193
4	United Microelectronic	254	Industrial Technology Research Institute	155
5	Macronix International Co., Ltd.	149	AU Optronics	119



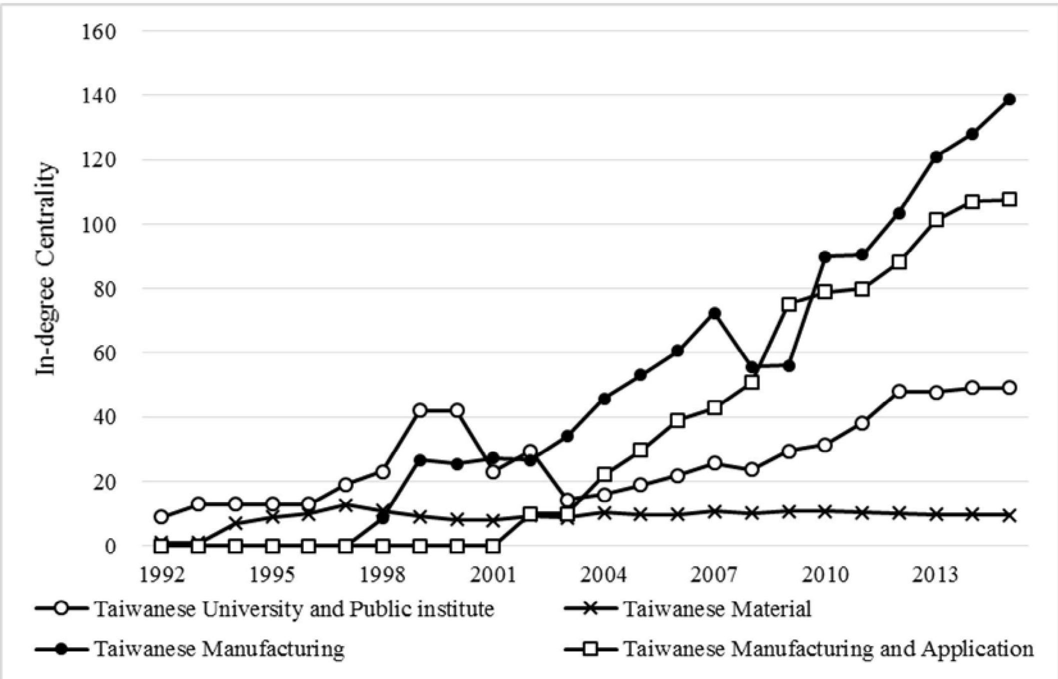


Figure 32. Trends of assignee's influence on innovation (up) and innovating activity (down) in the Taiwanese photovoltaic knowledge network

In the formation of knowledge network in the field of photovoltaics in Taiwan, innovation activities were mainly carried out by public research institutes and materials companies, and they often utilized the knowledge of overseas research institutes. Taiwan's manufacturing companies' innovation capacity has gradually improved, leading to a competitive advantage in 2001 compared to other organizations. However, this dominance did not continue, and the influence of foreign companies began to increase from 2003, and recently, the gap widened. The reason for this can be seen through the trends of innovation activities of Taiwanese companies in in-degree centrality networks. Taiwanese firms' innovation activities stagnated or declined between 2007 and 2009. This is because innovation activities were not active due to the global economic crisis in 2008. In particular, Taiwanese companies are mostly SMEs, unlike German or Korean companies; thus, their ability to overcome the economic crisis is relatively weak. Therefore, it was difficult to carry out additional R&D, resulting in a gap in innovation capacity with foreign companies.

In Taiwan's case, it is noteworthy that the gap between manufacturing companies and public research institutes is relatively small compared to other countries. It is difficult to say that there is a dominant domestic applicant in the Taiwanese knowledge network that dominates growth, but the innovation capacity of the entire value chain of the industry is rather even. The development of Taiwan's knowledge network in the early 1990s was led by universities and public research institutes, and by manufacturing companies until 2007. Companies and laboratories of the Taiwanese knowledge network from 1992 to 2007 can be considered as a well-cooperated case.

4.4.6 Relating production characteristics and innovation

In order to divide the types of applicants who have influenced the development process of each country's knowledge network, we defined the influence power index of the applicant. The relative influence power $P_{p-q}^{i,t}$ that applicant p has toward applicant q in the knowledge network of country i at time period t is the number of links at the corresponding country and time from applicant p to applicant q divided by the total number of links.

$$P_{p-q}^{i,t} = \frac{E_{p-q}^{i,t}}{E_{total}^{i,t}} \qquad \text{(Eq. 6)}$$

On the other hand, in the knowledge network of country i at time period t, innovation performance $I^{i,t}$ can be expressed as the number of US granted patents of the applicants of the corresponding country and time period. This study attempted to analyze the relationship between the applicant's influence and the national innovation performance during the development process of knowledge network in each country. Based on the year when the US patent application was first filed in each country, the first five years were regarded as the formation period of the knowledge network, and the subsequent period was considered as the growth period. We analyzed the correlation between applicants' influence power and innovation performance on each period's knowledge network. Here, considering the time-lag effect of influence power on the number of patents, we reflected a one-year time lag and studied the correlation between the influence power at time period $t-1$ and innovation performance at time period t. A positive correlation implies that innovation performance is also high when the applicant's power is relatively higher than other sectors. On the other hand, a negative correlation implies that the applicant's impact on the overall innovation of the country in question during that period has decreased.

In the case of China, patent applications of Chinese applicants between 2002 and 2005 were scarce, and the period from 2006, when Chinese applicants started noteworthy innovation, to 2010 was set as formation period. In China's knowledge network formation, the influence power of universities and public institutes had a positive correlation with innovation performance. Particularly, the correlation between innovation performance and knowledge utilization within universities and public research institutes was high (0.840), and correlation between innovation performance and influence power of universities and public research institutes to material manufacturers was also high (0.887). In addition, the influence power of public research institutes on cell and module production had a positive correlation (0.581). In other words, the knowledge of public research institutes had a significant impact on other production sectors of the industry. During this period, universities such as Tsinghua University, Nankai University and City University of Hong Kong led China's solar innovation. Particularly, Tsinghua University cited the patents of universities and companies in the

US and Japan to create innovative achievements and linked them back to Chinese companies.

Between 2011 and 2015, the impact of knowledge utilization in public research institutes declined, while the influence power of public research institutes on module producers increased (0.714). In addition, solar inverter and storage battery manufacturers' influence power on module manufacturers had a significant positive correlation with innovation performance (0.718). This implies that China's innovation activities are actively focused on cell and module production companies. However, despite the active innovation activities and production capacity of module manufacturing companies, their influence on other sectors of the industry has decreased. The influence power of public research institutes was positive, but the influence decreased compared to the previous period.

Although China is creating innovation in the solar cell field by increasing its production capacity in the cell and module sectors, it is limited to cell and module related parts, and innovation in the materials sector is still stagnant. This is because China has sought to secure production capacity in the absence of a policy to foster innovation infrastructures such as public research institutes in the initial growth of the Chinese solar industry. In reality, in 2006, China's photovoltaic module production was still small with a production volume of about 400 MW (Zhi, Sun, Li, Xu, & Su, 2014), and number of applications to US patents was also small. At that time, the Chinese policy to nurture the solar industry focused on the promotion of the manufacturing sector, especially the cell and module related industries. In particular, through tax concessions, China promoted FDI in the manufacturing sector and led the industry's growth, and recorded the production volume of module of around 21,000 MW (Zhi et al., 2014). However, China has only achieved growth in its volume in the module sector through securing production capacity in the absence of sufficient innovation base. Therefore, it is believed that the innovation capacity of materials such as silicon and ingot, which is another part of the industry, has not yet been secured sufficiently.

Table 22. The influence on innovation performance among Chinese assignees

	Correlation to innovation performance	
	2006–2010	**2011–2015**
University and public institute		
to University and public institute	0.840	-0.081
to Material (silicon, ingot, and wafer) manufacturer	0.887	0.605
to Solar cell and module manufacturer	0.581	0.714
to Solar inverter and storage battery manufacturer	-0.092	
Material (silicon, ingot, and wafer) manufacturer		
to University and public institute	0.359	-0.053
to Material (silicon, ingot, and wafer) manufacturer	-0.421	-0.033
to Solar cell and module manufacturer	0.688	-0.342
to Solar inverter and storage battery manufacturer	0.243	0.201
Solar cell and module manufacturer		
to University and public institute	0.520	0.367
to Material (silicon, ingot, and wafer) manufacturer	-0.473	-0.803
to Solar cell and module manufacturer	-0.542	-0.229
to Solar inverter and storage battery manufacturer		-0.123
Solar battery and generator manufacturer		
to University and public institute	0.556	0.380
to Material (silicon, ingot, and wafer) manufacturer	-0.338	-0.529
to Solar cell and module manufacturer	0.034	0.718
to Solar inverter and storage battery manufacturer	-0.092	0.674

In the first five years (1982–1986) of the German photovoltaic industry, the higher the influence power of material production companies on other sectors, the higher was the innovation performance. German material producers have been competitive in the existing chemical materials sector from the outset, and they have entered the solar photovoltaic industry based on this competitiveness. Wacker, a German chemical company, is a representative example of the company entering the solar industry by accumulating related technologies and knowledge, coming from Burghausen's polysilicon and polymer-related production facilities. In the same period, the influence power of German universities and public research institutes on the module production sector also positively correlated with innovation performance (0.639).

From 1987 to 2010, there is still a strong correlation between innovation and influence power of public sector on module manufacturing companies (0.555), and solar inverter and storage battery manufacturers had the largest influence power in creating innovation. Founded in 1981, SMA Solar Technology AG, a German company, was the world leader in solar inverter production in 2013 and grew based on its production capacity by operating a factory in Niestetal, Germany. In addition to inverters, SMA is also leading innovation in related technologies such as secondary batteries and energy storage systems (ESS). Furthermore, about 20 solar-related companies, mainly the solar cell module company Q-Cell, formed Solarvalley Mitteldeutschland in Thüringen, Sachsen, Sachsen-Anhalt and led Germany's photovoltaic innovation. Therefore, we can say this was an example of feedback reinforcement that the knowledge of companies with production capacity was transferred to other sectors of the industry in the period of growth of the German knowledge network in 1987–2010.

Solon, a manufacturer of solar modules in Germany, went bankrupt in 2011, and Q-Cell shut down operations in 2012 and was acquired by Hanwha Korea. Moreover, Q-Cell's production plant in Germany was closed in 2015. However, despite the declining production capacity of the cell and module segments in Germany, the influence power of the module sector on other sectors of the industry has not declined. This can be attributed to the fact that the innovation performance of the module companies of the solarvalley described above is sustained. In addition, material producers such as Wacker and companies in the solar inverter and storage battery production sectors, such as SMA, led innovation in module production. The influence power of material production on module production has been highly correlated with innovation performance (0.964). The influence power of solar inverter and storage battery production on module production was 0.644, also showing a high correlation with innovation performance.

However, since 2011, the impact of public research institutes on cell and module production has declined compared to the previous period (0.369). In addition, the impact of other sectors on public research institutes has decreased. This can be regarded as a breakdown of the virtuous cycle structure of the knowledge flow between domestic universities and public research institutes and production sites in Germany since 2011, when Germany began to depend on overseas companies for the production of solar cells and modules.

Table 23. The influence on innovation performance among German assignees

	Correlation to innovation performance		
	1982–1986	**1987–2010**	**2011–2015**
University and public institute			
to University and public institute		0.304	
to Material (silicon, ingot, and wafer) manufacturer	-0.200	0.175	-0.160
to Solar cell and module manufacturer	0.639	0.555	0.369
to Solar inverter and storage battery manufacturer	-0.355	-0.122	-0.641
Material (silicon, ingot, and wafer) manufacturer			
to University and public institute	0.366	0.145	-0.672
to Material (silicon, ingot, and wafer) manufacturer	0.741	-0.351	0.111
to Solar cell and module manufacturer	0.297	0.273	0.964
to Solar inverter and storage battery manufacturer	-0.038	-0.356	0.136
Solar cell and module manufacturer			
to University and public institute		0.446	-0.215
to Material (silicon, ingot, and wafer) manufacturer	-0.580	0.152	0.459
to Solar cell and module manufacturer	-0.097	0.375	0.611
to Solar inverter and storage battery manufacturer	-0.430	-0.213	-0.823
Solar battery and generator manufacturer			
to University and public institute	0.463	0.360	-0.704
to Material (silicon, ingot, and wafer) manufacturer	-0.256	0.180	0.081
to Solar cell and module manufacturer	-0.007	0.385	0.644
to Solar inverter and storage battery manufacturer	0.574	-0.470	-0.445

In Korea’s early knowledge network (1996–2000), the influence power of universities and public research institutes on the companies producing solar inverter and storage battery and those producing materials showed a strong positive correlation with innovation performance of 0.547 and 0.622. On the other hand, there was not a large correlation between the influence power of other sectors and innovation performance. Innovation activities in public enterprises and related materials companies are active only for securing solar inverter and storage battery technologies, but those in the early Korean knowledge network were generally not active.

During 2001–2010, Korea’s cell and module production companies’ influence power in other sectors grew significantly compared to the previous period. In addition, the influence power of universities and public research institutes on other sectors showed a positive correlation with innovation performance. In particular, the influence power of public research institutes on the solar inverter and storage battery sector was the highest at 0.727, and public research organizations in Korea at that time can be said to be more interested in field applications than basic research. The influence of the knowledge of applied companies on the public sector was not relatively high, and it can be said that the public research institute had a relatively positive influence on the innovation capacity of the industry.

From 2011 to 2015, the influence power of university and public research institutes on other sectors was also positively correlated with innovation performance. Also, the influence power of solar cell and module manufacturers and the solar inverter and storage battery manufacturers on materials manufacturers showed a strong relationship with the innovation performance (0.847, 0.839). The influence power of solar inverter and storage battery production on cell and module production also showed a strong positive correlation with innovation at 0.734. This shows that the innovation activity of Korea is still made for the purpose of utilization at the production site.

For example, LG Electronics began researching solar photovoltaics in 1995, and began producing its own solar modules in 2010 with a production capacity of 240 MW. They continued to invest in capacity expansion, and became able to produce around 1 GW of power per year by 2016. In particular, LG Electronics established an energy business center in 2014 to build a vertical supply structure among affiliates such as LG Electronics and LG Chem. Led by LG Chem, starting from materials such as polysilicon, LG aimed to achieve synergy among LG Electronics' solar cell and module production and LG Chem's battery business. Hanwha is also pursuing vertical integration to create synergies with existing Hanwha Chemical materials, such as acquiring Q-Cell, a German solar module maker, and merging with Hanwha SolarOne. In addition, Hanwha is trying to secure production capacity by establishing a solar cell factory and a module factory in Korea.

As such, the innovation activities of the Korean solar industry are aimed at practical use in the production field. In particular, *chaebol* companies are pursuing vertical integration through affiliates. This vertical integration enhances innovation capabilities by facilitating the transfer of knowledge embedded in the field to other sectors. Therefore, Korea's case emphasizes the role of companies with production capacity and the smooth flow of knowledge among industries in order to continuously reinforce innovation.

Table 24. The influence on innovation performance among Korean assignees

	Correlation to innovation performance		
	1996–2000	**2001–2010**	**2011–2015**
University and public institute			
to University and public institute	-0.467	-0.019	-0.454
to Material (silicon, ingot, and wafer) manufacturer		0.440	0.547
to Solar cell and module manufacturer		0.416	0.543
to Solar inverter and storage battery manufacturer	0.547	0.727	0.712
Material (silicon, ingot, and wafer) manufacturer			
to University and public institute	-0.467	0.641	-0.545
to Material (silicon, ingot, and wafer) manufacturer	0.622	-0.341	0.779
to Solar cell and module manufacturer	-0.467	0.105	0.330
to Solar inverter and storage battery manufacturer	-0.328	0.192	-0.880
Solar cell and module manufacturer			
to University and public institute	-0.034	0.572	-0.095
to Material (silicon, ingot, and wafer) manufacturer	-0.023	0.347	0.847
to Solar cell and module manufacturer	-0.034	0.646	0.195
to Solar inverter and storage battery manufacturer	0.096	-0.782	-0.887
Solar battery and generator manufacturer			
to University and public institute	-0.375	0.237	-0.863
to Material (silicon, ingot, and wafer) manufacturer	0.213	-0.367	0.839
to Solar cell and module manufacturer	-0.118	-0.173	0.734
to Solar inverter and storage battery manufacturer	-0.079	0.121	-0.256

In Taiwan, public innovation was transferred to the cell and module production sector for the first five years (1996–2000), and had a close correlation with the innovation performance of the industry (0.663). In addition, the correlation between the influence power of material manufacturers on the module production sector and innovation performance was also high at 0.829. Therefore, in the early stage of knowledge network in Taiwan, it seems that knowledge absorption and innovation activities were active to create technologies related to cell or module production.

Between 2001 and 2010, knowledge influence power to solar inverters and storage batteries manufacturing was high. Universities and public research institutes were also innovating by utilizing the knowledge of other sectors. In this period, the knowledge network of Taiwan was focused on technology in the actual production site, and the exchange of knowledge between the industrial site and the public sector was active. Motech Solar and Gintech Energy Corporation in solar cell and module production were included in the top 10 companies in the 2007 production volume. Taiwanese companies continued to expand their production facilities, and in 2007, they possessed the world's fourth largest solar cell production scale (New Growth Inititative Industry Information Technology Research Group, 2013).

In 2011–2015, Taiwan's material production sector, unlike the module production sector, continued to invest in R&D, resulting in a relatively higher impact on other sectors than in the previous period. In 2011, polysilicon producer Taiwan Polysilicon and wafer manufacturer Green Energy Technology established a joint venture with Motech Solar and invested in R&D of monocrystalline wafers. In particular, companies in each sector of the industry gathered to establish a joint venture, thereby promoting innovation capacity through vertical integration.

On the other hand, the influence power of public research institutes and solar inverter and storage battery production sectors on the module production sector showed a decrease in correlation with innovation performance. This can be attributed to the fact that after the 2008 financial crisis, R&D efforts of small and medium-sized Taiwanese module producers became more passive and the cooperation with other sectors decreased. In particular, before the financial crisis, the Taiwanese photovoltaic module makers promoted long-term contracts for the stable procurement of polysilicon, and this discouraged the R&D efforts of the module manufacturers. Polysilicon prices peaked in 2010, but long-term contracts during this period rather had a negative impact on securing research capacity. Moreover, before the financial crisis, Taiwan's module producers failed to create continuous innovation performance because they invested in expanding production facilities and reducing production costs rather than technology development (New Growth Inititative Industry Information Technology Research Group, 2013).

Taiwan's case emphasizes the need to expand its production capacity and to continue to invest in R&D to maintain a virtuous cycle of continuous innovation creation.

Table 25. The influence on innovation performance among Taiwanese assignees

	Correlation to innovation performance		
	1996–2000	**2001–2010**	**2011–2015**
University and public institute			
to University and public institute	0.067	0.748	0.629
to Material (silicon, ingot, and wafer) manufacturer	-0.495	-0.133	0.394
to Solar cell and module manufacturer	0.663	0.054	-0.156
to Solar inverter and storage battery manufacturer		0.740	0.561
Material (silicon, ingot, and wafer) manufacturer			
to University and public institute	0.571	0.772	0.784
to Material (silicon, ingot, and wafer) manufacturer	-0.067	-0.007	0.674
to Solar cell and module manufacturer	0.829	-0.731	0.039
to Solar inverter and storage battery manufacturer		0.661	0.803
Solar cell and module manufacturer			
to University and public institute	0.092	0.630	0.708
to Material (silicon, ingot, and wafer) manufacturer	-0.807	0.029	0.851
to Solar cell and module manufacturer	0.487	-0.859	-0.935
to Solar inverter and storage battery manufacturer		0.567	0.682
Solar battery and generator manufacturer			
to University and public institute	0.450	0.707	0.758
to Material (silicon, ingot, and wafer) manufacturer	-0.680	-0.013	0.204
to Solar cell and module manufacturer	0.699	-0.488	-0.863
to Solar inverter and storage battery manufacturer		0.844	0.691

4.5 Conclusion

In this chapter, we analyzed patent citation network using patent data for China, Germany, Korea, and Taiwan. After categorizing each technology by value chain of the industry, we examined the patent citation network and analyzed the status of the manufacturing companies in each network. We also examined the relative influence of the manufacturing companies in the knowledge network and the characteristics of the network structure that can continuously generate innovation.

We found that during the growth period of photovoltaic knowledge network, innovation performance of companies with cell and module manufacturing capacity grew more significantly compared with public research institutes or materials manufacturing companies, and that they often utilized knowledge from companies with manufacturing capability in solar cell, module, batteries, and generators. On the other hand, innovation activities in public research institutes were more active in the formation period of knowledge network, and their knowledge was used more in other parts of the industry. Therefore, it can be seen that public research institutes play a hub of knowledge in the formation period, and manufacturing companies play a hub of knowledge in growth period. However, in the growth period, if the knowledge of each production sector does not spread to other sectors and is only used within the same sector, industrial innovation stagnated. Moreover, since knowledge embodied at the production site does not lead to the public sector, there is a gap between the innovation performance of public research institutes and that of manufacturers. Although knowledge that can create new innovations should be constantly supplied through the public sector, if not, it is not possible that innovation congestion can be intensified throughout the industry. Therefore, strengthening of knowledge exchange and cooperation with production sites and public research institutes is necessary not only in the formation period of the knowledge network but also in the growth period.

This chapter analyzed the influence and importance of manufacturing companies with production capacity in the process of formation and diffusion of knowledge network through a patent citation network. For this purpose, US patent data were used to construct the innovation performance and knowledge network. However, there is a limitation that the filing of US patents does not represent all innovation activities of the country. de la Tour, Glachant, & Ménière (2011) point out that the proportion of Chinese patent applications filed overseas is lower than other countries such as Germany, Japan, and the US. However, they also explain that measuring foreign patent activity can estimate activities that are more valuable than domestic patents. Therefore, utilizing US patents' data has limitations in the measurement of total innovation activity in each country; but, on the other hand, it was useful to measure relatively high-value innovation in the knowledge network. In addition, the types of production activities were divided into materials, solar cell and module, solar inverter and storage battery according to value chain. Through this, it is confirmed that companies with production capacity are important in the growth period of knowledge network. Through the cases of Germany, Korea, and Taiwan, we can see that if we have a strong innovation base, such as public research institutes, in the formation period of the knowledge network, we can achieve feedback reinforcement of innovation creation capacity through production. On the other hand, through the case of China, it can be seen that production without the formation of the innovation-based knowledge network cannot create continuous innovation. In the analysis, China has achieved innovation only in the module sector which has production capacity, but not in other sectors. The result of this study emphasizes the fact that accumulated knowledge should flow smoothly through cooperative exchange among the industrial sectors in each part of the value chain for a virtuous cycle between production and innovation. Specifically, it emphasizes that building partnerships with manufacturing companies, universities, and research institutes plays a key role in creating sustainable innovation performance.

Chapter 5. Overall conclusion

5.1 Summary and policy implications

In this study, we examined the relationship between production and innovation. In particular, network analysis was used to complement the limitation of qualitative methodology mainly used by existing researches. Through network analysis, this study emphasized the role of production in innovation creation and aims to offer suggestions for the industrial structure that can continuously generate innovation. For this purpose, we conducted an empirical analysis of the Korean manufacturing industry and various empirical analyses on the high-tech solar industry, and made a general conclusion on the effect of production on innovation.

In Chapter 2, we discussed the theoretical and empirical studies on the relationship between production and innovation. Although the role of production has been perceived as one of the components of innovation capability in the past, recently, there is a trend that production is being described as an important factor for creating innovation. However, previous studies have pointed out the limitations of quantitative analysis. Particularly, we point out that despite its importance, many studies neglect the structure of technological learning that can strengthen the link between innovation and production. Based on this, the contribution of this study was presented.

In Chapter 3, we looked at the correlation between production and innovation through

Korean manufacturing cases. In order to overcome the limitation of using survey data that most of the previous empirical studies on the relationship between production and innovation used, we used the FDI data. As a result, we found that the decrease in domestic production capacity due to the internationalization of production in Korea since the 1990s had a negative effect on the innovation performance of the Korean manufacturing industry in the same period. In particular, as FDI in China increased, innovation performance was more negative. In other words, the transfer of production facilities to reduce costs can be negative for innovation performance. These results refute the findings of previous studies that offshoring can reallocate resources to more valuable activities and therefore be favorable to innovation.

In Chapter 4, we analyzed the solar industry, which is attracting attention as a high-tech manufacturing industry, and confirmed the importance of production capacity in technology-intensive emerging industries, and examined a desirable virtuous cycle structure between production and innovation. As a result of the analysis, we found that the production without the period of forming the innovation-based knowledge network cannot create continuous innovation, and that the innovation-generating knowledge capacity can be strengthened through production if based on the period of forming the innovation-based knowledge network. Therefore, knowledge exchange and cooperation with manufacturing companies, universities, and research institutes are necessary to create the knowledge network and continuous innovation performance.

To sum up, production activity has a positive effect on innovation capacity and performance, but if knowledge exchange and cooperation with other sectors of industry cannot be achieved, innovation performance will stagnate. This result suggests various implications for policymakers who attempt to solve social problems and economic growth through advanced manufacturing industries.

5.2 Contribution and limitations of study

This study on the effects of production on innovation is different from the previous studies in the following aspects. First, the previous studies on the relationship between the production and innovation used case studies or surveys. Therefore, it was not possible to perform a dynamic analysis of the effect of production on innovation, and only the analysis at a specific time point was possible. However, in this study, time series data were constructed and analyzed using various statistical data. In particular, we used qualitative citation networks to evaluate innovation performance. In this study, we proposed and applied a more accurate method for analyzing the relationship between production and innovation.

Second, we applied the network analysis methodology to reflect the interactions among various types of participants in the industry. In addition, companies were classified according to the types of production activities and value chain, and the relationship between production and innovation was divided into stages of development of the industry. This provides new implications for policymakers on industrial policy making. In addition, we explain the interactions among the actors, and therefore set up a framework for suggesting various implications in the future policy formulation and promotion process.

Lastly, unlike the previous studies which only covered developed countries, we analyzed the cases of Korea, Taiwan, and China and suggested various implications for both developed and developing countries In particular, we emphasized the role of manufacturing companies in the early stages of knowledge network formation as well as cooperation and knowledge exchange with public research institutes. We pointed out that pursuing technological catch-up based only on cheap production cost has limitations on innovation and industrial capacity advancement.

However, this study has some limitations. First, the proxy variables are used because of limitations of data on production facilities and production activities of companies. As mentioned above, because there was a limitation to the data at the firm level, this study performed the analysis in the subdivision unit of the manufacturing industry. However, the impact of production activities on innovation performance may vary by firm size. Therefore, it is necessary to accurately estimate the production capacity at an individual firm level in order to perform a more accurate analysis.

Second, US patent data are used to analyze the formation of the knowledge network. There is a difference in the tendency to apply for foreign patents in each country, and the pattern of applying patents to innovation activities in different phases of industrial development will also be different. Furthermore, a technology that can change the current technological platform is likely to come from the initial stage of research, even though it has not reached the stage of commercialization. Therefore, for a more accurate analysis, it is necessary to utilize not only the patent data, but also other data, such as journal publications, to reflect the innovation activity in the basic research stage.

In spite of these limitations, this study established a framework for analyzing the relationship between production and innovation, and therefore has laid a foundation for future studies on various application topics.

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Appendix

Table A1. Definition and ISIC classification of industries in this study

Industry	ISIC Rev.3	ISIC Rev.4
Manufacture of food products and beverages	D1500	C1000 C1100
Manufacture of textiles	D1700	C1300
Manufacture of wearing apparel	D1800	C1400
Manufacture of leather and related products	D1900	C1500
Manufacture of wood and of products of wood and cork, except furniture	D2000	C1600
Manufacture of paper and paper products	D2100	C1700
Printing and reproduction of recorded media	D2200	C1800
Manufacture of coke and refined petroleum products	D2300	C1900
Manufacture of chemicals and chemical products	D2400	C2000 C2100
Manufacture of rubber and plastics products	D2500	C2200
Manufacture of other non-metallic mineral products	D2600	C2300
Manufacture of basic metals	D2700	C2400
Manufacture of fabricated metal products, except machinery and equipment	D2800	C2500
Manufacture of computer, electronic and optical product	D3000 D3200	C2600
Manufacture of electrical equipment	D3300	C2700
Manufacture of machinery and equipment not elsewhere classified	D3100	C2800
Manufacture of motor vehicles, trailers and semi-trailers	D2900	C2900
Manufacture of other transport equipment	D3400	C3000
Manufacture of furniture	D3500	C3100
Manufacture of furniture; manufacturing not elsewhere classified	D3600	C3200 C3300

Table A2. Major characteristics of Chinese photovoltaic networks

	Number of nodes	**Number of links**	**Network density**	**Average degree**	**Average path length**	**Clustering coefficient**
2002	23	36	0.071	3.130	1.000	0.000
2003	27	39	0.056	2.889	1.000	0.000
2004	27	41	0.058	3.037	1.000	0.000
2005	35	53	0.045	3.029	1.000	0.000
2006	55	92	0.031	3.345	1.000	0.000
2007	86	174	0.024	4.047	1.000	0.000
2008	119	245	0.017	4.118	1.000	0.000
2009	168	438	0.016	5.214	1.000	0.000
2010	215	712	0.015	6.623	1.089	0.001
2011	268	940	0.013	7.015	1.069	0.001
2012	321	1,228	0.012	7.651	1.063	0.003
2013	341	1,289	0.011	7.560	1.059	0.003
2014	358	1,357	0.011	7.581	1.060	0.004
2015	361	1,390	0.011	7.701	1.130	0.007

Table A3. Major characteristics of German photovoltaic networks

	Number of nodes	Number of links	Network density	Average degree	Average path length	Clustering coefficient
1981	25	43	0.072	3.440	1.133	0.043
1982	41	78	0.048	3.805	1.625	0.064
1983	52	107	0.040	4.115	2.062	0.075
1984	70	196	0.041	5.600	2.041	0.128
1985	83	229	0.034	5.518	1.981	0.114
1986	96	288	0.032	6.000	2.029	0.099
1987	109	325	0.028	5.963	1.969	0.100
1988	135	421	0.023	6.237	1.989	0.077
1989	151	495	0.022	6.556	2.179	0.075
1990	156	525	0.022	6.731	2.192	0.069
1991	166	566	0.021	6.819	2.241	0.078
1992	188	645	0.018	6.862	2.286	0.074
1993	193	663	0.018	6.870	2.297	0.073
1994	217	748	0.016	6.894	2.341	0.076
1995	228	818	0.016	7.175	2.217	0.074
1996	246	900	0.015	7.317	2.257	0.068
1997	273	981	0.013	7.187	2.340	0.061
1998	300	1,152	0.013	7.680	2.450	0.060
1999	321	1,276	0.012	7.950	2.548	0.061
2000	353	1,475	0.012	8.357	2.607	0.060
2001	409	1,725	0.010	8.435	2.603	0.059
2002	451	2,001	0.010	8.874	2.663	0.057
2003	483	2,197	0.009	9.097	2.697	0.056
2004	524	2,443	0.009	9.324	2.707	0.053
2005	561	2,741	0.009	9.772	2.761	0.051
2006	584	2,954	0.009	10.116	2.773	0.051

(continued)

	Number of nodes	Number of links	Network density	Average degree	Average path length	Clustering coefficient
2007	633	3,259	0.008	10.297	2.820	0.048
2008	676	3,482	0.008	10.302	2.995	0.046
2009	732	4,220	0.008	11.530	3.045	0.044
2010	770	4,448	0.008	11.553	3.054	0.041
2011	804	4,709	0.007	11.714	3.565	0.040
2012	843	5,005	0.007	11.874	3.706	0.039
2013	871	5,341	0.007	12.264	3.721	0.037
2014	875	5,401	0.007	12.345	3.731	0.037
2015	884	5,471	0.007	12.378	3.736	0.036

Table A4. Major characteristics of Korean photovoltaic networks

	Number of nodes	Number of links	Network density	Average degree	Average path length	Clustering coefficient
1990	10	9	0.100	1.800	1.000	0.000
1991	18	22	0.072	2.444	1.000	0.000
1992	21	26	0.062	2.476	1.000	0.000
1993	26	34	0.052	2.615	1.000	0.000
1994	40	63	0.040	3.150	1.000	0.000
1995	44	82	0.043	3.727	1.179	0.039
1996	49	117	0.050	4.776	1.184	0.069
1997	69	175	0.037	5.072	1.299	0.041
1998	79	231	0.037	5.848	1.493	0.039
1999	93	268	0.031	5.763	1.477	0.034
2000	102	327	0.032	6.412	1.543	0.049
2001	129	409	0.025	6.341	1.541	0.037
2002	154	604	0.026	7.844	1.943	0.049
2003	195	885	0.023	9.077	2.348	0.049
2004	253	1,363	0.021	10.775	2.447	0.049
2005	298	1,952	0.022	13.101	2.407	0.049
2006	347	2,585	0.022	14.899	2.363	0.054
2007	403	3,106	0.019	15.414	2.386	0.054
2008	453	3,595	0.018	15.872	2.416	0.052
2009	516	4,401	0.017	17.058	2.409	0.051
2010	573	4,868	0.015	16.991	2.497	0.049
2011	626	5,374	0.014	17.169	2.512	0.047
2012	663	5,872	0.013	17.713	2.507	0.049
2013	707	6,354	0.013	17.975	2.554	0.046
2014	733	6,913	0.013	18.862	2.565	0.044
2015	741	7,132	0.013	19.250	2.562	0.043

Table A5. Major characteristics of Taiwanese photovoltaic networks

	Number of nodes	Number of links	Network density	Average degree	Average path length	Clustering coefficient
1992	8	10	0.179	2.500	1.000	0.130
1993	11	14	0.127	2.545	1.000	0.064
1994	21	27	0.064	2.571	1.179	0.094
1995	24	31	0.056	2.583	1.235	0.071
1996	31	43	0.046	2.774	1.233	0.055
1997	38	57	0.041	3.000	1.241	0.044
1998	50	84	0.034	3.360	1.167	0.036
1999	79	168	0.027	4.253	1.792	0.059
2000	91	218	0.027	4.791	1.761	0.059
2001	113	331	0.026	5.858	1.956	0.061
2002	157	524	0.021	6.675	2.095	0.068
2003	233	873	0.016	7.494	2.237	0.057
2004	264	1,215	0.017	9.205	2.529	0.070
2005	306	1,462	0.016	9.556	2.574	0.063
2006	319	1,666	0.016	10.445	2.535	0.063
2007	371	2,179	0.016	11.747	2.594	0.057
2008	419	2,435	0.014	11.623	2.537	0.056
2009	474	2,832	0.013	11.949	2.683	0.057
2010	567	4,108	0.013	14.490	2.978	0.050
2011	614	4,744	0.013	15.453	3.083	0.048
2012	696	5,729	0.012	16.463	3.028	0.045
2013	744	6,899	0.012	18.546	2.976	0.042
2014	764	7,510	0.013	19.660	2.986	0.042
2015	773	7,944	0.013	20.554	2.984	0.041

Abstract (Korean)

1990년대 미국 등 선진국을 필두로 제조업에서 서비스업으로의 산업구조 재편이 확산되기 시작하였으며, 생산성 및 효율성 개선을 통한 산업의 고도화를 목표로 생산설비들을 개발도상국들로 이전하는 오프쇼어링이 발생하였다. 경쟁우위를 잃어가고 있는 생산시설들을 가격경쟁력을 확보할 수 있는 국가들로 이전하고, 본국은 연구개발 기지로 재편하여 경제의 체질을 개선하겠다는 노력이었다. 그러나 생산설비들이 개발도상국으로 빠져나가면서, 안정적인 고용창출 기반이 흔들리게 되었고 경제가 활기를 잃게 되었다. 최근에는 개발도상국들의 가파른 임금 상승률과 물류비용의 증가, 기술유출 우려가 대두되었다. 뿐만 아니라, 지속적인 경제성장을 위한 기반인 산업의 혁신동력이 떨어지게 되었다. 제조업 경시와 생산설비의 해외이전으로 인하여 새로운 아이디어를 구현할 수 있는 기반이 줄어들었기 때문이다.

지속적인 성장을 위한 혁신을 창출하는데 있어서 생산의 중요성이 대두됨에도 불구하고, 기존의 대다수 실증연구들에서는 산업구조개편 또는 고용창출의 측면에서 생산의 역할을 강조하는데 집중하고 있을 뿐 생산이 혁신에 미치는 영향에 대한 연구는 부족하다. 따라서 생산이 혁신에 미치는 영향에 대하여 살펴보는 것은 향후 우리 산업경제체제가 나아가야 할 방향을 설정하는데 있어 현 시점에서 매우 중요한 과제라고 할 수 있다.

본 논문에서는 혁신활동에 미치는 생산의 역할과, 혁신을 지속적으로 창출할 수 있도록 하는 산업구조에 대한 연구를 수행하고자 하였다. 이를 위해서

먼저, 생산과 혁신 간의 관계에 대한 기존의 연구들에 대한 리뷰를 통해 생산과 혁신의 연결고리를 강화할 수 있는 기술학습의 중요성에 대하여 강조한다. 실증적으로는 먼저 한국의 제조업 사례를 통하여 생산역량과 혁신성과 사이의 상관관계를 규명한 후, 미래사회의 원동력이 될 첨단산업에 있어서의 분석을 통해 지속적인 혁신창출과 성장을 위한 바람직한 생산과 혁신 간의 협력에 대한 제언을 할 수 있을 것으로 기대한다.

연구의 결과를 정리해보면 다음과 같다. 먼저 국내 제조업의 생산역량의 감소는 혁신성과의 하락을 발생시키는 것으로 나타났다. 특히 비용절감을 목적으로 하는 생산설비의 해외 이전의 경우 이러한 경향이 확연히 나타났다. 첨단 산업에 있어서도 생산역량의 보유여부는 혁신성과와 지식네트워크의 구성에 있어서 중요한 요인임을 확인하였다. 그러나 생산역량만을 보유하였다고 해서 항상 혁신의 향상으로 이어지는 것은 아니며, 생산 및 응용역량을 보유한 기업과 기초 지식연구를 진행하는 대학 및 연구소와의 협력관계를 형성하는 것이 핵심적인 역할을 한다는 점을 확인하였다. 따라서 생산과 혁신 간의 선순환을 위해서는 둘 간의 협력과 네트워크를 통해 축적된 지식이 흐름이 원활히 이루어지도록 할 필요가 있다.

주요어 : 생산, 혁신, 제조업, 지식네트워크, 네트워크 분석, 특허인용분석
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