The Technological Innovation Capabilities in Asian Latecomers: Patenting Evidence from the Solar Photovoltaic Industries of Taiwan, Korea, and China

By

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Abstract

This Thesis builds on work previously undertaken by scholars in industries such as semiconductors and flat panel displays to investigate innovation performance and knowledge flows as these industries diffuse from advanced countries (US, Japan and Europe) to catch-up follower countries (Taiwan, Korea and China). The aim is to investigate the emergent solar photovoltaic industry by updating and applying the arguments developed in the earlier studies. The solar photovoltaic industry is of particular interest in that its exploitation is poised between first generation crystalline silicon technologies and the newer technologies based on thin films and organic compounds. This study is distinctive in that it exploits two patent datasets for solar PV technologies, from the US Patent and Trademark Office and from the Europe Patent Office; it approaches these datasets in two stages, singling out three generations of technology and four technology platforms underpinning the evolving knowledge flows and innovative technological capabilities of the solar photovoltaic industry in the Asian latecomers. A set of stylized facts is identified and used to frame the research contribution of this Thesis. The main results demonstrate that the knowledge sources for building innovation capabilities in the three latecomer countries are gradually shifting from a principal reliance on exogenous technological forerunners (US, Japan et al.) towards a greater dependence on indigenous knowledge and internalization capability, while accommodating to diverse national innovation systems. This illustrates the latecomers' transition and transformation from imitators to innovators in the setting of the global solar photovoltaic industry. Clear policy implications for other latecomer countries and future research are also elaborated.

Keywords**:** industry knowledge flows; catch-up development; patents; solar photovoltaic technology; Taiwan; China; Korea

Statement of Candidate

I certify that the work in this Thesis entitled "**The Technological Innovation Capabilities in Asian Latecomers: Patenting Evidence from the Solar Photovoltaic Industries of Taiwan, Korea, and China**" has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the Thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the Thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the Thesis.

Ching-Yan Wu

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List of Abbreviations

Abbreviations	Definitions
1G	First Generation
2G	Second Generation
3G	Third Generation
a-Si	Amorphous Silicon
AUO	AU Optronics Corporation (Taiwan)
BIPV	Building-integrated photovoltaic
CdTe	Cadmium-Telluride
CF	Citation Frequency
CIGS	Copper-Indium-Gallium-Selenide
CMOS	Complementary Metal Oxide Semiconductor (technology)
CN	China
CPV	Concentrated Photovoltaic
c-Si	Crystalline Silicon
DE	Germany
DRAM	Dynamic Random Access Memory
DSSC	Dye Sensitized Solar Cell
EMS	Electronics Manufacturing Service
EPO	European Patent Office
FDI	Foreign Direct Investment
FIT	Feed-in Tariff
FPD	Flat Panel Display
GaAs	Gallium Arsenide
GW	Gigawatt

Abbreviations	Definitions
IBM	International Business Machines Corporation (US)
IC	Integrated Circuit
IP	Intellectual Property
IEK	Industrial Economics & Knowledge Center (Taiwan)
IPC	International Patent Classifications
IT	Information Technology
ITRI	Industrial Technology Research Institute (Taiwan)
JP	Japan
KIST	Korea Institute of Science and Technology (Korea)
KR	Korea
LED	Light-Emitting Diode
MIC	Market Intelligence & Consulting Institute (Taiwan)
MNE	Multi National Enterprise
NBER	The National Bureau of Economic Research (US)
NPL	Non-Patent Literature
ODM	Original Design Manufacturer
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PC	Personal Computer
PECVD	Plasma Enhanced Chemical Vapour Deposition
PV	Photovoltaic
R&D	Research and Development
RDGR	Relative Development of Growth Rate
RPA	Revealed Patent Advantage
RPP	Relative Patent Position

Abbreviations	Definitions
SME	Small and Medium Enterprise
TFT-LCD	Thin Film Transistor-Liquid Crystal Display
TP1	Technology Platform One (defined in this Thesis)
TP2	Technology Platform Two (defined in this Thesis)
TP3	Technology Platform Three (defined in this Thesis)
TP4	Technology Platform Four (defined in this Thesis)
TSMC	Taiwan Semiconductor Manufacturing Company (Taiwan)
TW	Taiwan
UK	United Kingdom
UMC	United Semiconductor Corporation (Taiwan)
UPC	US Patent Classifications
US	United States of America
USPTO	United States Patent and Trademark Office
WIPO	World Intellectual Property Organization
WTO	World Trade Organization

Chapter 1

Introduction

1.1 Overview and Motivation

Knowledge flows are central to the evolution of industries, in shaping our understanding of the convergence by latecomers on advanced country performers. For both first-movers and latecomers the processes of knowledge transformation, value creation, and the transitions of industrial co-evolution are central to firm and country performance and the emergence of new industrial sectors. In recent decades, East Asian latecomers such as Taiwan, Korea, and China have demonstrated mastery of the processes of catching-up, utilizing knowledge diffusion, technological interactions, and the building of innovative capabilities, enhancing their inter-dependence in relation to the advanced country in many technology and knowledge intensive industries. These relationships between Asian latecomers and advanced first-movers (i.e. the US, Japan, and other OECD countries) have been demonstrated in such sectors as semiconductors (Hu & Jaffe, 2003; Lee & Wang, 2011), mobile phone (Lee & Jin, 2012), DRAM (Dynamic Random Access Memory) (Lee & Yoon, 2010) and flat panel displays (Hu, 2008; Jang, Lo, & Chang, 2009). Now we see the same dynamics of catch-up driven by knowledge flows in the renewable energy sector, and particularly in the solar photovoltaic (PV) sector (Mathews, Hu, & Wu, 2011; Wu & Mathews, 2012a, 2012b) which is the subject of this Thesis.[1]

The technological interactions between and amongst knowledge-based innovations are multidisciplinary, so that they provide a shareable input that may be used in research on

[1] The essential parts of this Thesis have been published in Wu and Mathews (2012a) at Research Policy, Wu and Mathews (2012b) at IAMOT 2012, and Mathews, Hu, and Wu (2011) at Industry & Innovation, full papers see Appendix I1-3.

various technologies and innovations (Henderson & Cockburn, 1996). In terms of evolutionary trajectory, accumulated capacity in various related technologies certainly provides one of the critical innovation infrastructures, especially valuable for a start-up in an emerging industry, as well as for a nation intending to reinforce its innovative capacity. This accumulated capacity can either be highly specialized in certain technologies (e.g. information technology in East Asian latecomer countries) or rather diversified (as in large OECD countries). Either trajectory, if utilized effectively, can provide access to many other technological fields (Hu & Mathews, 2005; Hu & Tseng, 2007; Leten, Belderbos, & Van Looy, 2007). For example, the current success of solar PV manufacturing is restricted on the one hand by shortages of primary raw materials, and on the other by limits to the maturity of transformative manufacturing techniques. In general, manufacturing processes in the solar PV are heavily dependent on technologies in related fields (e.g. semiconductors and optoelectronics technologies), by way of knowledge generation, diffusion, combination and extraction.[2]

The solar photovoltaic industry is of particular interest, firstly because it is the latest setting for the catch-up development process, with Korea, Taiwan and China all demonstrating capacity to catch-up with technological leaders. It also is of interest in that it is poised between first generation crystalline silicon (1G), new second generation thin-film (2G) and organic-compound third generation (3G) technologies, entailing distinct evolving knowledge flows and technological innovation capabilities, which can be measured by various patenting activities such as citations and scientific linkage. Incremental technological

[2] Almost every country is putting a great deal of effort into the development of a range of renewable energies, such as wind, hydroelectricity, tide, solar, and biomass. Amongst these, the solar cell technologies are strongly related to semiconductors and flat panel displays. Countries such as Taiwan, China, and recently Korea, all of whom have specialized in these two areas, demonstrate an aggressive investment in solar cell production.

innovation plays an important role in developing and transforming user contexts, markets, or operational environments (Abernathy & Clark, 1985; Christensen, 1997; Geels, 2005; Schumpeter, 1943). In some environments, however, non-incremental innovations predominate, because the accumulation of incremental technical changes may not be appropriate, possibly because of lower effectiveness or greater expense. Significantly, non-incremental innovations are qualitatively different from incremental ones (Dahlin & Behrens, 2005; Freeman & Soete, 1997). Most non-incremental innovations are partitioned, discontinuous events accompanying ‘new connections’ and need intense efforts to develop innovations in latecomer environments. Though the effects on existing products or services may be minor, they are indispensible for building institutional contexts and innovative infrastructures.

Many studies attribute East Asian success in high-tech industries to macroeconomic trends and to their reliance on input-driven growth or their close links with Japanese and American networks (e.g., Borrus & Zysman, 1997; Krugman, 1994). However, such factors are not concerned with the technological and industrial achievements apparent in particular sectors, such as those of the Korean business groups (known as *chaebols*) in DRAM production and of the Taiwanese small and medium enterprises (SMEs) in semiconductors and information technology (IT) products, which have enabled these catch-up countries to strengthen their indigenous innovation capabilities and overcome ‘technological gaps’. These factors underlay the ruling paradigm for East Asian latecomers in making the transition from imitators to innovators (Hobday, 1995; Hu & Mathews, 2005; Kim, 1997). This study intends to show how innovation capabilities and knowledge flows have spread from advanced countries (US, Japan and Europe) to catch-up followers (Taiwan, Korea and China) and how the results and arguments proposed by earlier studies can be applied to investigate the emergent solar PV industries of the three Asian major latecomers, which have become serious players only in the early 2000s. This Study thus pursues a greater understanding not only of knowledge sources within the specific technologies of the emerging solar PV industry, but also of the overall capabilities for technological innovation, at country and industry levels.

The catch-up strategies used by industrial latecomers have increasingly been the subject of scholarly analysis. In addition to studies of production activities and process innovations that have been accomplished, as well as of the investment strategies used in dominant technologies, it is of great interest to understand the knowledge flows involved, taking patent data as proxy for knowledge flows and innovation capability. Since the path-breaking study of Hu and Jaffe (2003), a rich stream of literature has grown, examining knowledge flows from the advanced countries (US, Japan and European countries like Germany) to latecomer catch-up countries (Taiwan, Korea. and now China). This literature, comprised of studies of the semiconductor industry (Lee & Wang, 2011; Lee & Yoon, 2010), flat panel displays (Hu, 2008; Jang et al., 2009) and mobile communications (Lee & Jin, 2012), has established a number of 'stylized facts' regarding the catch-up process and its dependence on knowledge sources in the advanced countries for launching assaults on the industries themselves. The key question here is the rate at which latecomers can switch from external knowledge flows to their own knowledge generation (or build-up of absorptive capacity) – as reflected in citations of external patents compared with internal ones – as well as the effects on this process of the industrial dynamics involved.

Whilst, in general, innovation consists of moving and diffusing technological information from advanced to latecomer countries, those 'stylized facts' suggested by prior studies are still open to interpretation and sometimes to controversy. In particular, little is yet known about how well innovative practices are applied in the Asian latecomer countries, and so how effective they have been. In response to these gaps in knowledge, this Study is pursuing a greater understanding not only of the sources of knowledge flows and technological innovation capabilities at overall country and industry levels in the emerging solar PV industry, but also of the inter-company variations within specific technologies.

1.2 Research Objectives and Research Questions

Since the mid-2000s, the rapid rise of the solar PV industry in Taiwan, China, and Korea has produced an astonishing success, securing more than 50% of the global solar PV market share since 2009. The solar PV industry thus represents the latest such industrial contest, in which Korea, Taiwan and China enter as fast followers, and then establish themselves as major players in the industry as producers, investors and exporters. Taiwanese firms became established in first-generation crystalline silicon (c-Si) solar cell production in the 2000s, followed by Chinese firms crowding into this space, while the entry by Korean majors is judged to be imminent, mostly into the more advanced second and third generation technology solar cells that use alternative semiconductor materials. [3]

The goal of this Study is to explore the evolution of the sources and flows of knowledge by taking the solar PV industries of the latecomers – Taiwan, Korea, and China – as examples, and assessing the impacts of the various innovation capabilities built into technology platforms. The accumulated resources and capabilities and national strategies are critical in

[3] Samsung has already announced an impressive patent portfolio in clean energy, for which the company ranked second in the world in 2011 (Cleantech Group, 2012) and within the top four for solar patents in 2008 (EE Times, 2008). For details, see '*2011 Clean Energy Patent Growth Index Year in Review*', available at http://cepgi.typepad.com/files/cepgi-4th-quarter-2011.pdf, and 'Report: '*Samsung among top patent holders in solar'*, available at: http://www.eetimes.com/design/power-management-design/4006319/Report-Samsung-among-top-patent-holders-in-solar.

shaping the evolution of these industries. The major research questions raised in this Study deal with two aspects:

(1) This Study is designed to explore the extent, in terms of the evolution of knowledge sources and knowledge flows, to which patterns established in earlier industries are replicated, and to what extent fresh patterns may be arising in the emerging industries such as solar PV.

(2) Given that the technological trajectory of solar PV has been established by the US, Germany, and Japan – the leading countries in recent decades – to what extent have the Taiwanese, Chinese and Korean followers developed their technological innovation capabilities since the mid-2000s, with the aim of surpassing the US and Japan and acquiring leading production positions?

1.3 Research Methodology

The greatest impediment to analysing industrial evolution over time has been the lack of systematic and comprehensive longitudinal data-bases (Kuznets, 1962). To explore the two research questions of concern here, this Study adopts separate analytical methodologies in two stages, by first accessing (1) the USPTO (United States Patent and Trademark Office) data to explore the knowledge sources and flows for the solar PV industries developed in Taiwan, Korea, and China over the 25 years from 1984 to 2008; and, in the second stage (2) the EPO (European Patent Office) worldwide databases (esp@cenet) to examine the variations of innovation capabilities developed by Taiwanese, Korean, and Chinese new entrants for the solar PV-related technology platforms built during the period 1978 to 2008.

The USPTO requires patent applicants to list all patent references when filing applications, and the patent examiners also add applicable references during their examinations. The US patents thus contain the most complete patent citation data, which are the most appropriate source for such analysis of knowledge flows. Therefore, the first stage of this study needs only to refer to the solar PV-related US patents granted to Taiwan, Korea, and China in order to examine the evolving knowledge sources and knowledge flows involved in the development of the solar PV industry in these countries.

Overall, the first stage of this study has extracted 19,105 patents taken out at the USPTO over the 25 year period from 1984 to 2008 by Taiwanese, Korean, and Chinese applicants, covering three generations of solar PV technologies (the silicon-based first generation, the thin-film based second generation, and the organic-based third generation).

The second stage is meant to verify the insights from the knowledge flows revealed in these patents as well as to explore the second research question. It examines technological innovations of solar PV industries in Taiwan, China, and Korea, using measures such as relative development of growth rate (RDGR), relative patent position (RPP), and revealed patent advantage (RPA) to investigate patents relevant to solar PV granted to the three latecomers. A new dataset of 75,540 solar PV patents retrieved from the EPO worldwide patent database (*esp@cenet*) granted to Taiwanese, Korean and Chinese applicants over the 31 years from 1978 to 2008 is used to analyse the technological innovation capabilities revealed, by way of a set of four constructed technology platforms involved in various catch-up strategies.

1.4 Research Contribution

Jaffe, Trajtenberg and Henderson (1993) pioneered a widely-used statistical technique that attempts to correct for factors (other than knowledge spillovers) that might affect technological specialization of regions, and hence the pattern of patent citations. However, Thompson and Fox-Kean (2005) have shown that this technique can over-estimate knowledge flows. Accordingly, this study proposes a comprehensive set of measures to explore the evolving knowledge flows over time as well as a systematic portfolio to better examine the various levels of technological innovation capabilities. In addition, this study uses a combination of econometric techniques with additional robustness checks using the European Patent Office (EPO) worldwide patent database (esp@cenet) for comparisons of three solar PV latecomers, to counter concerns about using data solely from the US Patent Office (USPTO).

This study aims not only to identify a more comprehensive patent dataset for solar PV technologies but also to differentiate the three technology generations and the four technology platforms through a novel and deliberate methodology for extracting patents. This method has created 12 International Patent Classifications (IPC) categories for solar PV-related patents, principally using them to allocate patents to the first, second or third technology generations and four technological platforms.[4] In this way, this study seeks to construct an alternative methodological contribution to the use of patent statistics in measuring knowledge flows as well as technological innovation capability successively, from the two stages of the research design. Stage One of this study investigates the knowledge flows according to the different technology generations while Stage Two compares the technological innovation capabilities created by the three Asian latecomer countries in the four technology platforms. Finally, in

[4] The IPC is an international standard to classify technologies in patent applications, it divides technologies into eight sections with approximately 70,000 subdivisions. (See WIPO for the details, available at: http://www.wipo.int/classifications/ipc/en/general/preface.html)

this study, seven stylized facts derived from the first stage and four stylized facts derived from the second stage are identified. In total, seven substantive contributions (four from stage one and three from stage two) are claimed. The main results show that the knowledge sources for building innovation capabilities in the three latecomer countries are gradually shifting from chiefly relying on exogenous technological forerunners (US, Japan) to depending on indigenous knowledge and internalization capability accommodated to their particular national innovation systems. This demonstrates their transition and transformation from imitators to innovators, as reflected in their entry into the global solar photovoltaic industry.

1.5 Outline of the Research

The Thesis is organised as follows.

- The characteristics of the emerging global solar PV industry and the major solar PV players in the three Asian latecomers are described in Chapter 2.
- Chapter 3 outlines the theoretical background and earlier studies relevant to the research propositions.
- Chapter 4 presents the methods of using patent data to extract the sources of knowledge flows and principal technology platforms to build up the relevant technology portfolios of the major Asian producers in the solar PV industry.
- In Chapter 5, the key empirical results of the two-stage research are applied to country-level and company-level analytical comparisons.
- An overall discussion of the research questions in line with the two stages of research propositionsis presented in Chapter 6.
- Conclusions, along with claimed contributions and policy implications applied follow in Chapter 7.

Since international patenting activity is a critical indicator of national innovation performance, Chapter 2 aims to provide an outline of the development of the global solar PV industry, particularly for the major emerging Asian producers. An account of this industry is set out in Sections 2.1 and 2.2. The emergence, since the 2000s, of the three Asian latecomer countries – Taiwan, China, and Korea – is addressed in Section 2.3, with a focus on identifying the importance of the three Asian latecomer countries to the global solar PV industry and the significance of studying these latecomer countries. Recent technological developing trends in the global solar PV industry are reported in Section 2.4.

Chapter 3 offers a review of the existing literature on industrial evolution and the extended relationships between industry cycle and knowledge flows in the Asian latecomers, as well as their technological innovation capabilities. Sections 3.1 and 3.2 point out the importance of understanding how the knowledge flows and innovation capabilities in Asian latecomers are catalysed and diffused and why they are focused particularly on production activity over the industry cycle. Patents are widely recognised as one of the clearest and critical indicators for measuring knowledge diffusion and innovation performance, so it is appropriate to review the literature on their use in these ways in Section 3.3. Since earlier studies argue that the trajectories of knowledge diffusion and innovation capability differ from country to country and region to region, an important part of the literature review in Sections 3.4 and 3.5 aims to discuss what aspects of knowledge flows and technological innovation capability have already been empirically explored, particularly for the Asian latecomers. Hence some critical prior works have been chosen for discussion in greater detail in Sections 3.4.2 and 3.5.1. Consequently, **seven research propositions** regarding the evolving knowledge flows in the three Asian latecomer countries are elaborated in Section 3.4.3 while **four research propositions** concerning technological innovation capabilities are presented in Section 3.5.2. The related literature and debates are then summarized in Section 3.6.

Chapter 4 deals with the research data, measures, and methods adopted in this study. Section 4.1 describes a three-stage filtering approach for the two research datasets, in which the twelve IPCs were used to extract solar PV-related patents registered by Taiwan, Korea, and China in the USPTO and EPO (esp@cenet) patent databases respectively, to explore the evolving knowledge flows and innovation capabilities for solar PV-related technologies in the three latecomers. Section 4.2 discusses the econometric logic of four indicators – international knowledge flows via backward citation, intra-national knowledge flows through local-citation, scientific knowledge linkage, and relative citation propensity – in exploring the three latecomers' evolving knowledge flows from 1984 to 2008. Section 4.3 explains quantitative analytical techniques in measuring the three countries' innovation capabilities from 1978 to 2008, whilst factor analysis is the main technique applied to assemble technology portfolios, in terms of technology attractiveness, relative patent position, and revealed patent advantage.

Chapter 5 reports the results of the data analysis. The overall trend of knowledge flows in the three latecomer countries is presented in Section 5.1.1, while Sections 5.1.2 to 5.1.5 report the results of the evolving knowledge flows, in terms of the four indicators – international knowledge flows, intra-national knowledge flows, scientific linkage, and relative citation propensity – from 1984 to 2008. The results demonstrate some commonalities in patterns of knowledge flows between solar PV and earlier industries, but also suggest differences, such as the rising reliance of the catch-up countries on their own intra-national knowledge generation and flows, indicating their shift from imitation to innovation. Section 5.2 presents the comparisons of technological innovation capabilities, at country and company levels, in the solar PV industries of Taiwan, China, and Korea over the 31 years from 1978-2008. These results partially verify the 'stylized facts' derived from the knowledge flows of the first stage while also demonstrating the patent portfolios of the three latecomers and exploring the extent to which the Taiwanese, Korean and Chinese followers have developed their technological innovation capabilities so as to surpass the US, Germany, and Japan and acquire the lead positions in production since 2008; and how the variations of technological innovation capabilities among the major producers have influenced their business activities in the global solar PV industry.

Section 6.1 discusses, as stage one of the research, **seven research propositions** derived from knowledge flows and Section 6.2 captures the second stage in **four research propositions** derived from technological innovation capabilities, confirming and shedding additional light on the findings presented in Chapter 5. Consequently, for the emerging solar PV industries of Taiwan, China, and Korea, **seven 'stylized facts'** are derived from the evolving knowledge flows and **four 'stylized facts'** are extracted from the analysis of technological innovation capabilities. These stylized facts taken together reflect the evolving and corresponding relationships between and amongst knowledge flows and diffusion and technological innovation capabilities in Taiwan, China, and Korea over the last decades.

Finally, Chapter 7 summarises this study's main findings and contributions to the literature in respect of the two stages of this study. Section 7.1 concludes that the contemporary patterns of knowledge leverage exercised by Taiwan, Korea and China in the solar PV industry are seen as strategies by the firms and institutions in these countries, accounting for their knowledge flows and indicating their shift from imitation to innovation. In addition, the evolving strategies of knowledge acquisition, together with the national approach to industrial structure and accumulated resources, are strongly influencing the magnitude and stature of technological innovation capabilities. Finally, contributions, policy implications and future research are also suggested in Sections 7.2 and 7.3.

1.6 Research Limitations and Caveats

There are many limitations and caveats to be considered when using patenting perspectives to explore the evolution of knowledge flows and innovation capabilities of the Asian latecomers. Let us highlight three of them.

First, the precise rates of knowledge flows and technological innovation capabilities are inaccessible because only certain types of formations can be measured (see for example, Arundel & Kabla, 1998; Griliches, 1990; Mansfield, 1986). This study mainly employs patenting activity as a proxy for examination of evolving knowledge flows and technological innovation capabilities. However, these flows and capabilities are embedded within and across many other practices and mechanisms, such as manpower mobility, business trading and investment, formal and informal collaboration, mergers and acquisitions, and so on. Even though some of them are either unavailable, lack comparability of data, or are often highly confidential to the private sector, one should be aware that various types of knowledge flows and innovation capabilities and their principal-agent interactions are indeed effective.

Second, since patents can vary enormously in their importance or value, simple patent counts are unlikely to entirely capture the innovative output of companies (see for example, Jaffe & Trajtenberg, 2002; Jaffe et al., 1993; Trajtenberg, 1990). The alternative measure is patent citations rate, which, recognised as an indicator reflecting true innovations, is often used to measure the impact of knowledge flows (e.g. the NBER studies). Innovation activities in Taiwan and Korea mostly emerged in the 1990s (particularly in the second half of that decade) while China only kicked off from the early 2000s, so measurements using patent counts as indicators of innovation capabilities may have truncation problems. However, if it is taken that the solar PV industry emerged in the Asian latecomer countries starting from the early 2000s, a caveat of this kind can be expected to have minimal effect.

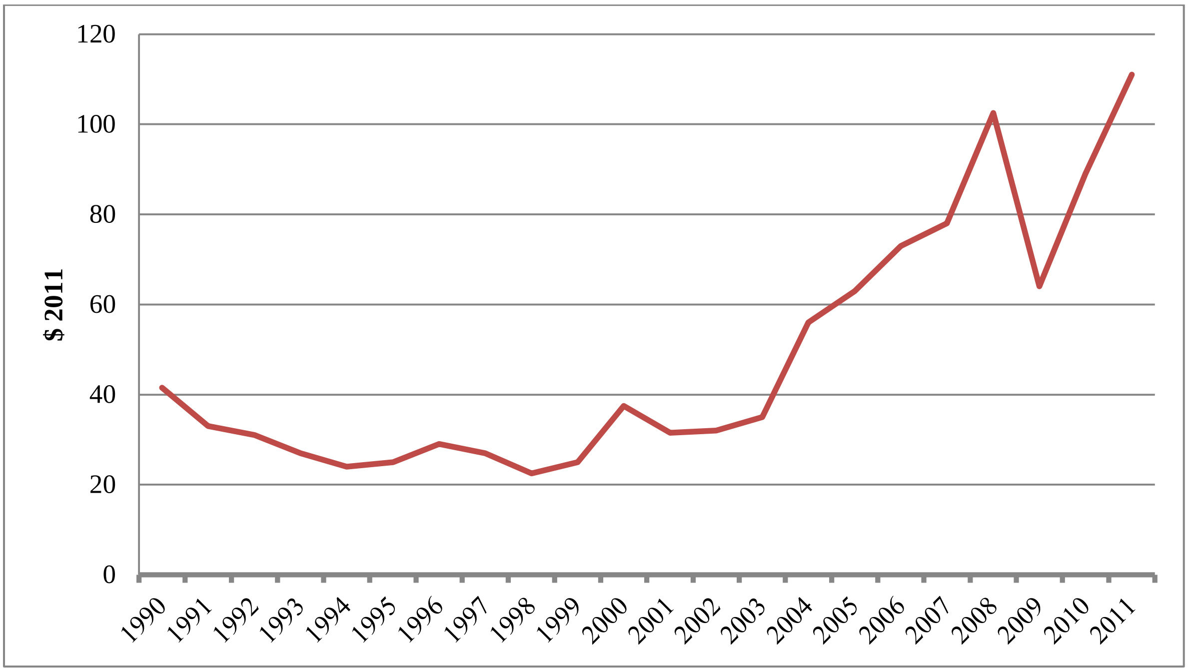
Third, classification problems have arisen with patent data in strategic and financial analysis (Evenson, 1984; Vertova, 1999). The most obvious way to categorise patents is by the patent classifications assigned by the patent examiners. However, there are hundreds of major classes and many thousands of subclasses covering the valuable field of technology that are used by the worldwide patent offices. Within these, the US patent classes (UPC, US Patent Classifications) in the USPTO are based on invention-art, rather than application-specific. To overcome this difficulty, this study has chosen to employ the four-digit international patent classes (IPC, International Patent Classifications) assigned to the specific coverage of solar PV technologies, in which only ‘Utility Patents’ are extracted, so as to ensure a significant connection with innovative activities. So these results – while not exhaustive – can still provide contributions to the literature and its methodologies, as well as insights into policy implications for the remaining latecomer countries in deploying their industrial strategies.

Chapter 2

The Global Solar Photovoltaic Industry

2.1 The Revival of the Global Solar Photovoltaic Industry in the 2000s

Many have claimed that the evolution of an industry is greatly shaped by market-oriented innovations in processes and reinforced by the institutional environment, including government policy (e.g. Antonelli, 1994; Baldwin & Scott, 1987; Dosi, 1997; Hoffman, 1999; Hu & Mathews, 2005, 2008; Hung, 2002; Kallinikos, 2006). Since the late 1990s and particularly in the early 2000s, the rise of fossil fuel prices and societal changes toward a low-carbon ecology have stimulated the demand for clean energy and for the rapid development of the renewable energy industries. As shown in Figure 2.1, oil prices stayed below US$ 40 per barrel before 2003 (2011 US dollars), then underwent a dramatic increase to above US$ 110 per barrel in 2011. Although Maugeri (2012) suggests that the oil price may yet experience a ‘steep dip’ due to the unprecedented upsurge of oil production in recent years, the increasing demand for oil and its consumption in the emerging countries such as China, India, Russia and Brazil have still markedly accentuated world concern about oil prices (Bleischwitz & Fuhrmann, 2006; Hirsch, Bezdek, & Wendling, 2006; Noreng, 2006; Winebrake, 2002). Consequently, the pressure to seek energy substitutes has led to greater investment in the renewable energy sector, triggered mostly at various levels of the public sector, and has intensified the development of renewable energy as a global industry. Along with various kinds of renewable energy, such as hydro power, bio fuels, and wind turbines, the solar PV sector has been one of the chief priorities in many countries due to its relative ease of application and commercialization in almost all the geographic areas with plentiful resources of sunshine.



Source: BP Statistical Review of World Energy 2012, US dollars per barrel

Figure 2.1 Crude Oil Prices, 1990-2011

On the other hand, global warming is endangering the sustainability of the Earth and has imposed global institutional change. Evidenced by the melting of glaciers and icebergs (European Renewable Energy Council, 2004) and the rise of sea level (Rahmstorf, 2007; WBGU, 2007), there is no doubt that global warming is threatening civilized human life (Greenpeace, 2006).[5] Emissions of greenhouse gases are blamed for global warming, among which the CO_2 discharged from the burning of fossil fuels contributes a great proportion (Watts, 2002). According to the Kyoto Protocol and the Copenhagen Accord, reducing CO_2 emission has been listed as the top priority for the governments involved.[6] Various degrees of

[5] According to Greenpeace, once all the ice in Greenland, North Pole and South Pole melts, many cities along the coast such as New York and London as well as small countries in the Pacific Ocean like the Maldives will go under water and disappear from the map; for details, see '*See level rise*', available at: http://www.greenpeace.org/international/campaigns/climate-change/impacts/sea_level_rise.

[6] The Kyoto Protocol is a legally binding agreement under which industrialized countries will reduce their collective emissions of greenhouse gases by 5.2% compared to the level of 1990. The goal is to lower overall emissions from six greenhouse gases - carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs. For details, see: http://unfccc.int/resource/docs/convkp/kpeng.pdf. Similarly to the Kyoto Protocol, the Copenhagen Accord recognizes that "deep cuts in global emissions of greenhouse gases are required according

support policy have been introduced to speed up the deployment of clean energy so as to foster the development of renewable energy industry, including solar, wind, biomass, hydro, and others.

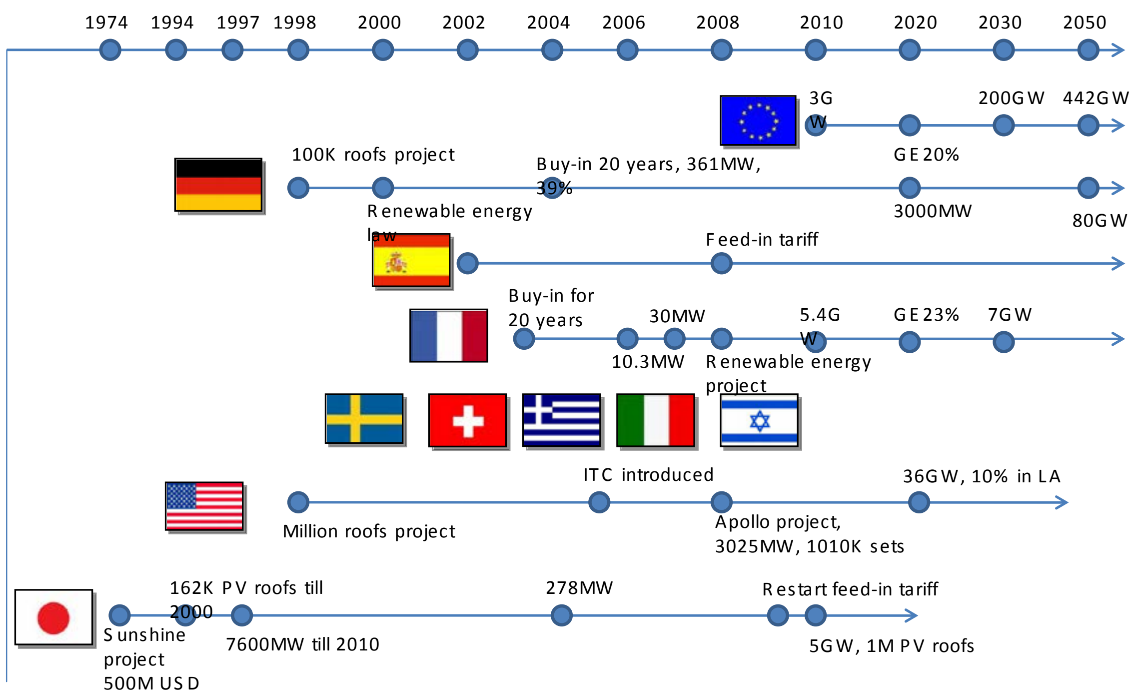
2.2 The Development of the Global Solar Photovoltaic Industry

In 1954, the first practical solar cell was produced by Bell Laboratories (Goetzberger & Hebling, 2000; Green, 2005; Strobl, LaRoche, Rasch, & Hey, 2009). Since then, the global solar cell industry based on PV technology has now moved into its sixth decade. Commercial-style solar PV for rooftop installations was first introduced in the 1960s, but the costs were so high compared with conventional power sources generated from fossil fuels that growth was very slow; hence solar PV technology was mostly applied for power generation in space probes in the early stages. It was only in the 1970s, as a result of the two oil shocks, that governments in Europe, Japan and North America started to actively promote solar PV as a realistic energy source; but the wave of policy-driven changes, as shown in Figure 2.2, such as the Sunshine Program in Japan, came to an end with the dramatic fall in oil prices in the 1980s. In the 1990s there was a revival of interest, and new policy instruments – particularly the 'feed-in tariffs' (FITs) introduced in Germany – have helped to drive growth in the industry, in the expectation that costs would fall sufficiently fast that 'grid parity' between electricity generated from solar cells and from conventional sources would eventually be achieved. Finally, in the 2000s, the industry started to show the sharp growth that had always been anticipated, with annual production output breaking the 1 GW barrier in 2004, increasing to 20.5 GW in 2010.[7] PV industry revenues have been rising quickly on a global

to science" (FCCC/CP/2009/11/Add.1). For details, see http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf.

[7] SolarBuzz reports that global solar cell production reached 20.5 GW in 2010; see: '*Industry Prepares for Significantly Lower Growth over Next Two Year*s', available at: http://www.solarbuzz.com/our-research/recent-findings/solarbuzz-reports-world-solar-photovoltaic-market-grew

basis as well, increasing from US$40 billion in 2009 to US$82 billion by 2010 and anticipated to be over $100 billion very soon.[8] It is thus approaching the earlier industries of semiconductors and flat panel displays in terms of its significance (also in the extent of its consumption of silicon).



Source: IEK (2009)[9]

Figure 2.2 History of Solar Energy Stimulating Policy in Major Countries

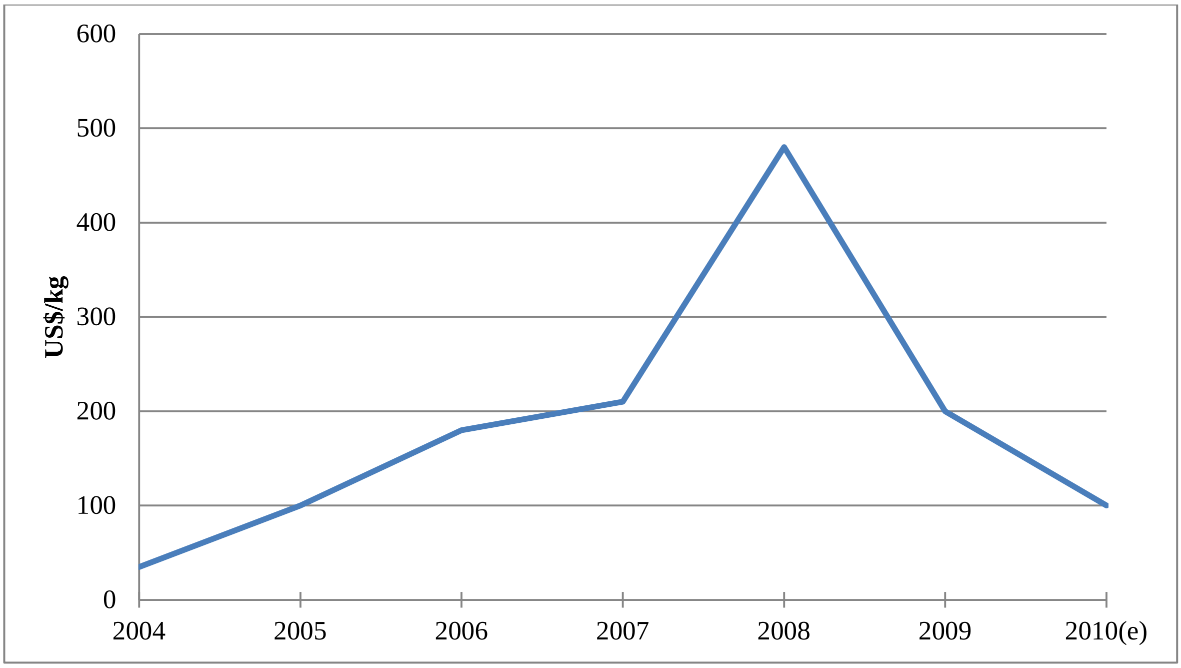
The dominant technology for PV solar remains c-Si (first generation or thick-film solar cells), both in its earlier monocrystalline form and its later polycrystalline (multicrystalline) form (Bruton, 2002; Swanson, 2006; Tiwari & Dubey, 2009: 107). The material 'polysilicon' constitutes a great proportion of thick-film solar cells, so that the supply and market price of polysilicon heavily affects the production of thick-film solar cells. As shown in Figure 2.3,

-182-gigawatts-20.

[8] SolarBuzz indicates the global solar PV industry revenues reached US$ 82 billion in 2010, see: '*Global PV Market*', available at: http://solarbuzz.com/facts-and-figures/market-facts/global-pv-market.

[9] Data derived from IEK (Industrial Economics & Knowledge Center, Taiwan),'*New trend of photovoltaic industry after global financial crisis*'. Presentation by Jay Wang on 26th May 2009, Hsinchu, Taiwan.

the spot market price for polysilicon remained below US$ 50 per kg before 2004, followed by a serial of dramatic price increases attributed to supply shortages, and eventually reached the peak of US$ 480 per kg in 2008. Ultimately, the research foci for solar PV technologies are not only the improvement of the conversion efficiency of solar cells but have also extended to a reduction in material use, and the discovery of new substitute materials.



Source: iSupply (2009)[10]

Figure 2.3 Spot Market Prices for Polysilicon, 2004-2010(e)

Second generation ('thin film') technologies, largely using amorphous silicon (a-Si) and microcrystalline silicon as semiconductor materials, but also other semiconductor materials such as cadmium-telluride (CdTe), copper-indium-gallium-selenide (CIGS), and gallium-arsenide (GaAs, so-called III-V semiconductor or high concentrated PV) are now starting to assert themselves, driven by the much lower materials requirements involved in

[10] Data extracted from iSupply, '*Sellers Market for PV Raw Materials to Shift in Buyers Favor in 2009*'. Retrieved from the Nikkei Business Website: http://techon.nikkeibp.co.jp/english/NEWS_EN/20081117/161329/

thin film production (where the semiconductor material is 'painted' on glass) (Green, 2004). The term 'third generation' is used to refer to organic compounds (such as dye-sensitized solar materials), which have the advantages of low production costs at high volumes and of flexibility (Grätzel, 2003). Patents on the fundamental technologies of first generation 'thick film' solar cells have now largely expired, leaving the field open to newcomers and latecomers, such as companies from Taiwan and China that are now crowding into this space. Key patents on thin-film, second-generation solar cells are also now nearing the end of their lives, again allowing new entrants from countries such as Taiwan, China and Korea, kick-starting process innovation in the new generation technologies.

Solar PV is one of the key applications in semiconductor technology, in which the materials are mainly based on silicon or various semiconductor materials (Wenham, Green, Watt, & Corkish, 2007: 31). The intimate relationships between and amongst the solar PV, semiconductor, and thin film transistor liquid crystal display (TFT-LCD) industries are recognized broadly in terms of their similarity in materials and manufacturing platforms. For example, first generation c-Si solar cells, semiconductor devices such as integrated circuits (IC), complementary metal oxide semiconductors (CMOS), and DRAM are all made from the same material – c-Si (Ferrazza, 2005; Ravi, 2005), while second generation thin-film solar cells use plasma-enhanced chemical vapour deposition (PECVD) technology to deposit semiconductor materials on glass, metal, or polymer substrates, the identical technology platform that is embodied in TFT-LCD products (Mauk, Sims, Rand, & Barnett, 2005). This common technology platform thus enables equipment suppliers, such as Applied Materials Inc, to provide turnkey solutions to assist Taiwanese, Korean, and Chinese fast followers to enter the global solar PV industry rapidly. Like the semiconductor and FPD industries, innovation activities amongst solar PV producers and equipment suppliers are progressive and complementary. Whereas turnkey suppliers rely on standardized technology platforms in their equipment, the main tasks of the solar PV producers are focused on investing in R&D to raise the yield and increase the energy conversion rate of the turnkey equipment that is supplied.

The early solar PV producers were located in the advanced countries of the Triad (Europe, North America, Japan), but as the technology of first-generation devices has diffused to the rising industrial powers, such as Taiwan and China, so the centre of gravity of the industry is shifting eastward – as happened with the earlier semiconductor and flat panel display (FPD) industries. Table 2.1 shows how the major advanced countries accounted for 71.7% of cell production up to 2006, but since then the rise of Taiwan, and most spectacularly China, has changed the situation completely, with China leaping since 2008 to become the No.1 producer. Up to 2010, it was China (42%), followed by Taiwan (17%) that accounted for more than half of the total solar cell production worldwide, and the firm trend is towards this proportion rising further. Within just a five-year period (2006-2010), solar PV production activity in China and Taiwan rose together, forcing the shares of the technology first-movers, such as Japan and Germany, to be halved. Although Korea has not yet seen large advances in production in the global solar PV market, Samsung has announced that solar cells will be one of its new growth engines. Samsung has been engaging in relevant R&D since 2005, in clear preparation for its entry into production, with the goal of raising its technological independence in solar cells to 85% by drawing on its expertise in semiconductors and TFT-LCD.[11] Korea's capability in production and innovation in its well-established semiconductor and optoelectronics industries has been widely acknowledged.[12]

[11] For the details: see The Chosun Ilbo: '*Samsung launches solar cell testing facility*', available at: http://english.chosun.com/site/data/html_dir/2009/09/15/2009091500765.html for the details.
[12] Indeed, Displaybank (2010) noted, "the entry of large Korea-based companies' market participation such as Samsung and LG would accelerate the mass production era for thin film solar cell applied with various technology". For details, see: '*2009 Global Thin Film Solar Cell Market Share Show Increase Y/Y to 19.8%*',

Table 2.1 Global Solar Cell Productions, by Company and Region Share, 2006-2010

Company Rank	2006	2007	2008	2009	2010
1	Sharp (JP)	Q-cell (DE)	Q-cell (DE)	First Solar (US)	Suntech (CN)
2	Q-cell (DE)	Sharp (JP)	Sharp (JP)	Suntech (CN)	JA Solar (CN)
3	Kyocera (JP)	Suntech (CN)	Suntech (CN)	Sharp (JP)	First Solar (US)
4	Suntech (CN)	Kyocera (JP)	First Solar (US)	Q-cell (DE)	Q-Cells (DE)
5	Sanyo (JP)	First Solar (US)	JA Solar (CN)	Yingli Solar (CN)	Motech (TW)
6	Mitsubishi (JP)	Motech (TW)	Kyocera (JP)	JA Solar (CN)	Gintech (TW)
7	Motech (TW)	Deutsche Cell (DE)	Motech (TW)	Kyocera (JP)	Kyocera (JP)
8	Schott Solar (DE)	Sanyo (JP)	Sunpower (US)	Trina Solar (CN)	Sharp (JP)
9	Deutsche Cell (DE)	Yingli Solar (CN)	Yingli Solar (CN)	Sunpower (US)	Trina Solar (CN)
10	BP solar (UK)	JA Solar (CN)	Gintech (TW)	Gintech (TW)	Sunpower (US)
Worldwide rest	17.60%	6.50%	3.90%	2.3%	14%
European rest	2.70% (5)	7.00%	8.10%	5.7%	2%
Germany	24.2% (2)	19.8% (3)	17.8% (3)	12.2% (5)	11% (3)
US	8% (4)	10.2% (4)	10.5% (5)	12.3% (4)	8% (5)
Taiwan	0.7%	9.90% (5)	13.2% (4)	15.3% (3)	17% (2)
Japan	36.8% (1)	24.6% (1)	22.5% (2)	18.5% (2)	9% (4)
China	10% (3)	22% (2)	24% (1)	33.7% (1)	42% (1)

Source: MIC (2009); Displaybank (2010); SolarBuzz (2011)[13]

http://www.displaybank.com/eng/info/sread.php?id=5730

[13] Data in 2006-2009 are extracted from '*The Trend of Global Photovoltaic Industry Development (Chinese version)*'. Presentation by Sean Kuo MIC (Market Intelligence & Consulting Institute, Taiwan) on 23rd April 2009, Taipei, Taiwan;Data in year 2009 is extracted from Displaybank (2010), '*2009 Global Thin Film Solar Cell Market Share Show Sharp Increase Y/Y to 19.8%*', available at: http://www.displaybank.com/eng/info/sread.php?id=5730; Data in year 2010 is extracted from Solar Buzz, '*Industry Prepares for Significantly Lower Growth over Next Two Years*', available at: http://www.solarbuzz.com/our-research/recent-findings/solarbuzz-reports-world-solar-photovoltaic-market-grew-182-gigawatts-20

In the case of solar PVs, China and Taiwan are competing to become significant players. Korea has long been preparing to enter the global solar PV market. Outside of China, all the developing countries that are ensnared in fossil fuel industrialization paradigms are looking for a way out, by way of building renewable energy industries – whether wind, bio-energy, solar, or other means such as hydro, tidal or geothermal. The catching-up latecomers, such as the solar PV industries in Taiwan, China, and Korea, can once again provide a model for what can be accomplished around the rest of the developing world – in India, Brazil, South and Central America, central Asia, and elsewhere (Mathews, 2002b, 2006a, 2006b, 2008).

2.3 **The Emergence of the Three Asian Latecomers in the Global Solar Photovoltaic Industry**

Competition from Taiwanese and Chinese firms, with their dedicated production and their innovations in process, has reduced the solar PV market share of the former technological leaders dramatically. The catch-up innovation capabilities of Taiwan, China, and Korea have forced the leading Japanese and US firms to focus almost exclusively on creating new technology-driven niche markets – for instance, US First Solar is focused on the CdTe, while Japanese Aisin Seiki concentrates on dye-sensitized solar cells (DSSC) – to compete with their Taiwanese, Chinese, and Korean rivals. In such a dynamic and competitive market, the technological competitive advantages of the solar PV industries in the three Asian latecomers demand investigation.

The numbers of major players in the solar PV industrial value chain, in relation to Taiwan, China, and Korea, are illustrated in Figure 2.4, where the numbers of Chinese players across the value chain are much greater than those of Taiwan and Korea. One exception is the new generation of solar PVs (such as thin film a-Si and Copper-Indium-Gallium-Selenide (CIGS), dye-sensitized solar cells (DSSC), and concentrated solar PV (CPV)), where the number of Chinese players is fewer than the other two, as a consequence of technology uncertainties such as low conversion efficiency and poorer production feasibility, restraining the production-oriented Chinese players from crowding into these new territories.

<table>
<tr><th>Polysilicon</th><th>Wafers</th><th>Cells</th><th>Modules</th><th>Systems</th></tr>
<tr><td colspan="5">Taiwan</td></tr>
<tr><td rowspan="5">7</td><td rowspan="5">11</td><td>c-Si: 18</td><td>20</td><td rowspan="5">35</td></tr>
<tr><td colspan="2">a-Si: 13</td></tr>
<tr><td colspan="2">CIGS: 18</td></tr>
<tr><td colspan="2">DSSC: 2</td></tr>
<tr><td colspan="2">CPV: 3</td></tr>
<tr><td colspan="5">China</td></tr>
<tr><td rowspan="5">30 - 40</td><td rowspan="5">30 - 40</td><td>20 - 30</td><td>150 - 200</td><td rowspan="5">200 - 300</td></tr>
<tr><td colspan="2">a-Si: 8</td></tr>
<tr><td colspan="2">CIGS: 6</td></tr>
<tr><td colspan="2">DSSC: 0</td></tr>
<tr><td colspan="2">CPV: 5</td></tr>
<tr><td colspan="5">Korea</td></tr>
<tr><td rowspan="5">7</td><td rowspan="5">2</td><td>11</td><td>6</td><td rowspan="5">7</td></tr>
<tr><td colspan="2">a-Si: 7</td></tr>
<tr><td colspan="2">CIGS: 4</td></tr>
<tr><td colspan="2">DSSC: 6</td></tr>
<tr><td colspan="2">CPV: 5</td></tr>
</table>

Source: MIC (2009)

Figure 2.4 Numbers of Companies in the Solar PV Industrial Value Chain, Taiwan, Korea, and China, 2009

2.3.1 Taiwanese Players

As latecomers, the Taiwanese early movers generally entered by way of the first generation c-Si solar cell sector, where the technology was relatively mature and where production equipment is supplied on a ‘turnkey’ basis; three such firms in Taiwan are Motech, Gintech, and E-Ton Solar. This allows firms with little experience in solar cell activity or R&D to enter the market, competing on the strength of their low costs and production efficiencies. Taiwan’s firms started entering the solar PV industry in a serious way in the early 2000s, just as world demand was stepping up. However, the second surge entrants flowed in after 2006, when German and Spanish FIT incentives started to take effect. Whilst many small-medium size companies were entering into the solar PV supply chain, some technology-based giant firms from the semiconductor industry (such as Taiwan Semiconductor Manufacturing Corp. (TSMC) and United Microelectronics Corp. (UMC)), the flat panel displays sector (FPDs, such as AU Optronics (AUO) and ChiMei Electronics), or the electronics manufacturing sector (such as Inventec, Delta Electronics, and Hon Hai) weighed up their options and elected to take the plunge into solar cells using their capabilities in semiconductors and FPDs. To break out from being ‘locked-in’ within the traditional c-Si solar cell technology trajectory, many of these Taiwanese companies sought a niche opportunity by forming the CIGS Alliance (based on an alternative thin-film solar cell technology) in 2009, while the dominant c-Si technology was being secured through strategies such as joint ventures, mergers and acquisitions, and technology licences and transfers.[14]

2.3.2 Chinese Players

Like Taiwan, Chinese players entered the global solar PV industry in the early 2000s and are now overwhelmingly relying on the c-Si ‘turnkey solution’ for first generation solar PV.

[14] See Mathews et al. (2011) for a detailed discussion on the industrial dynamics for Taiwan’s solar PV industry.

Up to 2010, China had secured a 42% market share in the global solar PV market, while its production capacity is still rapidly increasing. Even though thousands of players are emerging within and around China's provinces, three major firms are listed among the global top-10 solar PV producers in 2010. Suntech, founded in 2001, is China's first large-scale solar PV company. It became the global No. 4 producer in only five years, in 2006, and has risen to No. 1 in 2010. Following the lead of Suntech, JA Solar was established as a joint venture by Chinese and Australian companies in 2005. In just five years, JA Solar has become the world's No. 2 solar cell producer. In the first decade of the 21st century, China's solar cell producers have overtaken the sophisticated leading western companies and grasped a significant portion of global solar cell market share. By focusing on the dominant technology of c-Si solar cells and relying on turnkey solutions, China's solar PV industrial value chain was able to be built up extremely quickly. The success of China's solar PV production activity has to be attributed to the fast-follower strategy practiced by Taiwan and Korea in the semiconductor and electronics industries (Mathews et al., 2011).

2.3.3 Korean Players

Samsung, LG, and Hyundai are without doubt the crucial big players in Korea's solar PV industry. Samsung has been active in thin-film solar PV research and has built a complete solar PV industrial value chain, from upstream to downstream; Samsung Fine Chemicals is in charge of securing polysilicon materials; while Samsung Corning Precision Materials is responsible for ingots and wafers. Meanwhile, Samsung Electronics is involved in the field of c-Si and a-Si solar cells; Samsung SDI leads advanced research in dye-sensitized solar cells, Samsung Everland takes charge of the solar PV integration systems, and Samsung C&T provides the appropriate services for solar PV plants. The other Korean *chaebol*, LG, designed a similar deliberate division of labour as Samsung, where LG Chem, LG Siltron, and

LG Display in the LG Group are assigned to secure the upstream polysilicon materials, wafer and epitaxy activity and module production activity respectively. In 2010, LG's first solar cell production line with an annual production capacity of 120MW was officially inaugurated.[15] In addition, the world's largest shipbuilder, Korean Hyundai Heavy Industries, has also announced its investment in the biggest solar cell production plant in Korea, aiming to become the world's fifth-largest solar cell producer by 2015.[16] Other Korean players, such as Shinsung Holdings and Hanwha Chemical are seen to be actively involved in the global solar PV market since 2010, through their production activities.

2.4 Recent Patenting Trends in the Global Solar Photovoltaic Industry

With awareness of global warming and the rise of fossil-fuel energy prices, the patenting rate in the renewable energy sectors has rapidly increased since the 2000s. The patents in relation to the 13 climate-mitigation fields have surged since the late 1990s, right after the Kyoto Protocol in 1997 (Bauer & Neuhaus, 2008; Glachant, Dechezleprêtre, Hascic, Johnstone, & Ménière, 2009). Out of these, Solar PV is one of the rapid growth alternative-energy technologies to be adopted (Mowery, Nelson, & Martin, 2010). Likewise, as reported by Lee, Iliev and Preston (2009) (Chatham House), the patent grants of solar PV technology have risen from less than 200 per year prior to 1998 to more than 1,400 per year in 2007.[17] While earlier studies attribute the surge of the solar PV patenting rate to the Kyoto Protocol, Bauer and Neuhaus (2008) asserted that this phenomenon is simply a trend of global high technology development toward renewable energy, a development trajectory that is identical to that of the semiconductor sector in the 1980s.

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15 For the details, see: '*LG Electronics to start production on 120MW solar-cell line in January*', available at: http://www.pv-tech.org/news/lg_electronics_to_start_production_on_120mw_solar-cell_line_in_january

16 For the details, refer to the report: '*Hyundai to build biggest solar cell plant in Korea*', available at: http://www.koreatimes.co.kr/www/news/tech/2010/10/129_74364.html

17 For the details, see '*Who Owns Our Low Carbon Future? Intellectual Property and Energy Technologies, A Chatham House Report*', available at: http://www.chathamhouse.org.uk/files/14699_r0909_lowcarbonfuture.pdf

EPO expert Visentin (2010) reported that granted patents annually grew 400% in the solar PV technology field in ten years (from around 1,800 in 1999 to around 7,900 in 2008), compared with the average 60% increase for all industries. In addition, Japan took the leading position in the patenting rate, followed by the US, China, Korea, Germany, Australia, the UK, and France. Among the seven solar PV technology fields that Visentin identified, the organic solar cell technology field has the greatest share (49%), followed by thin-film solar cells (14%), crystalline solar cells (13%), dye-sensitive solar cells (9%), CPV and architectural integration (6%), and other III-V solar cells (3%). In particular, the massive growth rate of patent applications during the period for the emerging organic solar cell (754%) and dye-sensitized solar cell (740%) technology fields reveals the recent R&D highlights and predicts a potential for the above two technologies in the near future.[18]

Tseng, Hsieh, Peng and Chu (2011) used the USPTO database to investigate the a-Si thin-film solar cells niche sector. Their results show that the Japanese company Canon owns the largest share of patents while the US Energy Conversion Devices company comes next, followed by another Japanese company, Sanyo Electric. At the country level, Japan is in the leading position for a-Si solar PV technology, followed by the US, the UK, Germany and Australia.

The recent report published by Clear Energy Group (a German solar PV specialized company) reveals that global solar patenting activities in 2010 were double that of 2009, in

[18] For the detailed discussion, refer to '*Recent trends in the PV industry: lessons from the patent application filing figures*', available at: http://legacy.pv-tech.org/?ACT=54&url=1&linklocker=NjYuMjQ5LjcyLjEzMw==MC43NjY3MTQwMCAxMjk3NzU4NTIz

that the number of solar PV patents related to second generation led the first and third generations in 2010.[19] In terms of global top-10 solar PV patentees, the Korean chaebol Samsung emerged as the only player from the three Asian latecomers in 2010, demonstrating its ambition to enter the global solar PV market with a strong patent portfolio. It is interesting to notice that none of the Asian latecomers except Samsung are listed in the top patentees, despite the fact that both Taiwan and China have already become top producers in the global solar PV industry. This gap between patent grants and productions demonstrates the fast-follower strategy pursued by Taiwan and China in the growth stage of global solar PV industry (Mathews et al., 2011).

[19] For the details, please refer to '*Shine on Solar edition of CEPGI*', published by Cleantech Group (2011), available at: http://cepgi.typepad.com/files/solar-updated-2011-05a.pdf

Chapter 3

Literature Review and Research Propositions

A rich body of empirical evidence, spanning numerous countries and time periods, has provided sufficient evidence for several leading scholars to infer stylized facts and stylized relationships about the basic elements concerning firm/industry dynamics and industry evolution (Caves, 1998; Geroski, 1995; Hargadon & Sutton, 1997; Schumpeter, 1943), knowledge flows (Hu & Jaffe, 2003; Hu, 2008; Jaffe & Trajtenberg, 1998; Jaffe et al., 1993; Lee & Yoon, 2010; Wu & Mathews, 2012), and technological innovation capabilities (Furman, Porter, & Stern, 2002; Hu & Mathews, 2005; Nelson & Winter, 1982). At the centre of the evolutionary process is knowledge-centric innovation, because the potential of knowledge-driven innovative activity shapes the evolution pattern of industries. It is innovative activity that explains why the pattern of industry evolution varies from one country to another, depending on the underlying knowledge conditions, or what Nelson and Winter (1982) called 'technological regimes'. However, these stylized facts do not reconcile, particularly, the fact that the roles of first-movers evolving over the industry life cycle are closely linked but different from that of post-entrants or latecomers (Agarwal & Audretsch, 2001). These arguments are discussed below, followed by the derived research propositions corresponding to the two research questions of this study.

3.1 Industry Evolution

Industry evolution refers to cumulative change in industry characteristics, notably the processes of a firm's entry, exit, and growth (e.g. Audretsch,1995; Dunne, Roberts, & Samuelson, 1988; Jovanovic, 1982; Klepper, 1996; Nelson, 1994; Orsenigo, Pammolli, & Riccaboni, 2001). Industry evolution is of particular interest because anticipating and exploiting environmental change is one of the greatest difficulties in the real business world, and the literature on industry evolution provides insights into the interdependencies among industry change, a firm's strategic choices, and changes in the basis of competitive advantage.

Although much of the early work on industry evolution was rooted in economics, sociological approaches have emphasized the worth of the theory of industrial structure and the role of legitimacy over competition that began in the late 1970s (e.g. Hannan & Freeman, 1977, 1984). Following that line, strategy scholars have devoted increasing attention to the heterogeneity of the landscape within an industry. One stream of research has investigated the role of pre-entry experience as a predictor of post-entry success. Several studies found that, compared to specialized *de novo* firms, diversifying entrants have greater success rates in terms of survival (e.g. Agarwal, Echambadi, Franco, & Sarkar, 2004; Klepper, 2002a, 2002b; Klepper & Simons, 2000; Sharma & Kesner, 1996), even if their products are technically inferior to those of new entrants (Khessina & Carroll, 2008). In a related study, Tripsas (1997) proposes that there is a post-technological-shock in the balance of power between incumbent and entrant over scarce complementary assets. If incumbents continue ownership of key assets that retain their importance post-innovation, then they will continue to dominate the industry. Conversely, if the assets are devalued, then the incumbents will be overwhelmed by the entrants. However, static presentation is not enough, hence the competence perspective of a resource-based view (RBV) (e.g. Barney, 1986), evolutionary theory (Nelson & Winter, 1982), and the knowledge-based view of the firm (Kogut & Zander, 1992) need to be expanded to address the changes in vertical scope induced by technological uncertainty, including routines, knowledge, skills, learning activities, and networks, in which industry-level behaviour is described by a computation of the interaction and aggregation of individual firms' decisions and outcomes. In an update of a previous argument, the study of

Malerba, Nelson, Orsenigo and Winter (2008) particularly brings to attention the effect of innovation, derived from technological change, on industry dynamics in a sector's vertical scope.

In a high-tech or knowledge-intensive industry, such as solar PV, the dynamics of the industry is not only significantly driven by patenting activities at the levels of country, industry, and firm, but has also essentially co-evolved along with the various developmental stages of the industrial cycles (Hu, 2012). These co-evolving relationships have been verified and demonstrated in the process of building innovation capabilities in many high-tech industries, such as semiconductors (Tan & Mathews, 2010a, 2010b), flat panel displays (Mathews, 2005), light-emitting diodes (Hu, 2012), and solar PV (Mathews et al., 2011). In particular, understanding the evolving industry cycle is essential for latecomers, so as to move themselves away from imitators and fast-followers and toward innovators, through resources deployment, activities designation, and routines formulation (Mathews, 2003, 2010; Mathews & Cho, 1999).

3.2 Industry Cycle

Life-cycle studies provide a comprehensive insight into comparative innovation behaviour and innovation constants, in which the basis of competition is shifted between and amongst the complementary capabilities from product innovation to process innovation (Adner & Levinthal, 2001; Klepper, 1996; Teece, 1986; Utterback & Abernathy, 1975) and extended to service or system innovations (Barras, 1990; Cusumano, Kahl, & Suarez, 2006; Drejer, 2004; Gallouj & Weinstein, 1997; Hertog, 2000; Hipp & Grupp, 2005; Spohrer & Maglio, 2008) over the progress of the industrial cycle. As Utterback and Anthony (1975) point out, in the emerging/introductory stage of the life-cycle no singular product design or concept dominates the industry. A high degree of uncertainty characterizes business experience at this stage. Thus, in the emerging/introductory stages of the life-cycle, competition is principally for the dominant product design in that industry. In contrast, as the industry evolves towards its mature and declining stages, product design becomes more standardized and uniform, and the premium attached to technological superiority recedes.

Agarwal (1998) finds that patenting activity increases in the initial stages of the life-cycle, and subsequently declines during the mature period. While this is a general picture of the observed surface of the industry cycle, more subtle and cause-effect analyses are needed nevertheless for the different roles played by first-movers and latecomers in some of the emerging industries, such as the light-emitting diode (LED) industry (Hu, 2012). As for the characteristics of latecomers, most of the LED latecomers enter the industry in the growth stage and are aggressively involved in patenting activity through *process innovation*. It is noted that the first-movers or international leaders in the stage of growth, are also consistently keen on patenting activity for *system innovation* or *platform innovation.* This is based on their prior accumulated knowledge and capabilities so as to retain their first-mover advantage in the global market through resources bundling (such as cross-licensing and joint ventures) with the *process innovation* specialized by latecomers (Hu, 2012).

Accordingly, the building of technology platforms is a generic and essential catalyst for the evolving industrial cycle to move into the rapid growth stage. A technology platform enables the creation of products and processes that support present or future development by sharing components and production processes, also allowing a company to develop differentiated products faster and more cheaply, increasing the flexibility and responsiveness of the manufacturing processes (Kim & Kogut, 1996). For example, computer hardware serves as a platform for an operating system, which in turn becomes a platform for a range of application software, in which the interactions between hardware and software mutually reinforce the dependent path of the platform while bringing about another wave of growth. In addition, technological discontinuities or critical emerging technology may re-start the industry life-cycle (Anderson & Tushman, 1990), as in an example from the personal computer (PC) industry. The PC industry is driven by the cumulative innovation of hardware setting by IBM’s framework, Microsoft and Intel’s ‘Wintel’ system in the 1980s and 1990s. When the industry was moving into the mature stage in the 2000s, software innovation along with internet integration re-started the industry cycle of the personal computer sector for the new generation of personal customization in the post-personal computer era. It is innovation and knowledge diffusion which play a critical role in driving growth over the industry as a whole, where the growth rates highly sensitive to the ease with which knowledge diffuses (Eaton & Kortum, 1999; Grossman & Helpman, 1991; Romer, 1990).

3.3 Use of Patent Statistics as Indicators of Knowledge Flows and Technological Innovation Capabilities

The establishment of technological innovation capabilities is an extremely important step in building a successful industry in a country. These capabilities are reflected in a country’s patenting activity, and depend to a large degree on the trajectory of global industrial development, which can be measured in terms of technological and economic value (Kogut & Zander, 1992; Zucker, Darby, & Armstrong, 1998). That patent data analysis can serve as an indicator for technological innovation performance has been widely recognized, especially in high-tech industries (Amsden & Mourshed, 1997; Archibugi, 1992; Hagedoorn & Cloodt, 2003; Hu, 2012; Mahmood & Singh, 2003; Pavitt, 1982; Wu and Mathews, 2012b). On the other hand, some researchers have observed that many important innovations are not patented, while some patents are awarded for very modest technological discoveries (e.g. Arundel & Kabla, 1998; Griliches, 1990; Mansfield, 1986). It follows, therefore, that patents are a poor measure of innovativeness in such production sectors as food and tobacco, petroleum refining, basic metals, automobiles, and other transport equipment, where the great majority of innovations are not patented. However, even as they criticize the overall use of patents as an innovation performance indicator, these scholars still recognize their appropriateness in the context of high-tech industries.

Campbell (1983) indicates that patent indicators can be a very useful forecasting tool, especially as a signal for entering or leaving a technology. Ashton and Sen (1988) further stress that patent information can serve as a unique planning resource for managing a firm's technology or product development. By analysing the technological life-cycle (S-curve), strategic R&D decisions can be made (Ernst, 1997). In the emerging stage of a new technology, relatively lower R&D investments can be expected, due to technological uncertainty. In contrast, the return to R&D can be expected in the growth stage, which demands higher R&D expenditures and attracts new players to enter this field. It's clear that the technological changes revealed by patent grants are in line with the industrial cycle in predicting future technology and production directions.

High-tech and knowledge-intensive industries, such as biotechnology, semiconductor production, flat-panel displays (FPD), and even solar PV production, are increasingly called upon to focus on intellectual property (IP) issues. This is particularly the case for first movers who attempt to secure an advantage, as well as for latecomers who intend to compete with the international leaders in the global market (Hu & Mathews, 2008; Park & Lee, 2006). Since the latecomers – Chinese, Taiwanese, and Korean solar PV companies – have put a great deal of effort into building up their own technological capabilities through strategic patenting activities, the analysis of their patenting activities is an effective way to understand their present innovative capabilities and future production directions.

3.4 Knowledge Flows

Many studies have revealed that the scope of knowledge flows is influenced and restricted by direct and indirect channels, such as foreign direct investment (FDI), collaboration networks, mergers and acquisitions, personnel mobility, geographic proximity, trades, OEM, ODM, licensing, and so on. Agrawal, Cockburn and McHale (2003) show that patents by inventors who move from one geographic region to another continue to be cited by former collaborators from their original region, reflecting that direct ties resulting from past collaborations can continue to be a mechanism for knowledge flows even across regions. Balconi, Breschi and Lissoni (2002) find the association between patent citations and geographic co-location in Italy to be greater for socially connected patent teams, suggesting that there might be important interaction effects between geographic co-location and collaborative links. Nevertheless, other studies focused on the emerging Asian latecomer countries have found different empirical results in the process of building their national innovation system (e.g. Hu & Tseng, 2007; Lee & Yoo, 2007; Lee & Park, 2006). This is evidence that knowledge *diffusion* might be as important as knowledge *creation* in ensuring the effective working of a national innovation system (Lundvall, 1988). In this respect, knowledge diffusion is aimed at stimulating economic development and innovation capability within and across firms, industries and nations (Hu & Jaffe, 2003; Nerkar, 2003; Romer, 1986; Scherer, 1984). In addition, Dechezleprêtre, Glachant and Ménière (2008) argue that the North-South knowledge spillovers for climate-friendly technologies reinforced the development mechanism of green technologies so as to mitigate global warming. However, knowledge is not automatically transmitted across country boundaries, pointing out the necessity and importance for the emergence of an industry such as the solar PV industry of understanding the effects of knowledge diffusion generated through the various capabilities built into a nation, particularly from the perspective of technology and appropriability (Teece, 1986; Winter, 1984).

3.4.1 Knowledge Diffusion in the Asian Latecomers

Not all knowledge diffusion generates benefits, and even when it does, the diffusion rate and speed are often variable and difficult to maintain (Davis & Greve, 1997; Hansen, 1999; Teece, Pisano, & Shuen, 1997). Various attempts have been made to characterize knowledge variation across contexts (Kogut & Zander, 1992; Teece, 2000; Winter, 1984). When knowledge diffusion plays a part as a critical agent in building innovation capability for the latecomers as they are catching up, the evolution of knowledge sources, delivery processes, interactions, and technology/institutional actors become essential dynamic elements. The importance of knowledge diffusion is particularly to be observed in the East Asian latecomer countries through their evolving development of strategic high-tech industries, starting from PCs in the 1980s, to semiconductors and electronics in the 1990s, to optoelectronics (particularly LCDs, liquid crystal displays) in the 2000s, and now, since mid-2005, it seems be moving on to solar PV.

Internalization of foreign technology was an indispensable factor in the achievements of latecomer countries during the 1990s, described as the “*East Asian Miracle*”, which were achieved through intense efforts at internalizing advanced technologies and becoming integrated into the world technological mainstream (World Bank, 1993). Foreign technology acquisition and internalization have become embedded in a variety of institutional channels that have evolved over recent decades as latecomers sought to build up their own technological capacity and to compete more closely to the technology frontiers. Therefore, knowledge diffusion could be regarded as a major factor in keeping R&D costs low and times short, for SMEs as well as for large corporations, which is particularly essential for those countries late to industrialize – the catch-up latecomers.

Taiwan and Korea have been moving from passive learning (production capability) to active learning (improvement capability) and then to innovation, as demonstrated in various studies (Hu & Mathews, 2008; Jung & Imm, 2002; Kim, 1997; Mathews et al., 2011; Viotti, 2002). China is catching up quickly, aiming to leapfrog from building production capability to innovation, with strong regional and national support (Hu & Mathews, 2008; Lee & Wang, 2011; Zeng & Williamson, 2007). Knowledge diffusion from advanced countries to latecomers exhibits quite varied individual patterns (Coe, Helpman & Hoffmaister, 1997). Some studies reveal that technological capabilities are diverse within latecomer countries such as Taiwan and Korea, in particular differing greatly in their extent of innovation due to varying knowledge sources (Hu & Jaffe, 2003; Mahmood & Singh, 2003). The role of global sources of knowledge as well as national sources (techno-globalism as distinct from techno-nationalism) in developing innovation capabilities is thus important (Miller, 1994; Montresor, 2001). However, these observations are based on examining the effects of innovation capability in latecomer countries, rather than looking for its causes and catalysts. This study has hence chosen to investigate the solar PV industry, which exploits the old knowledge of mature silicon-based technology, as well as exploring new knowledge of the emerging technologies of thin film or organic compounds, for instance by tracing the sources and evolving flows of knowledge. The attempt in this study consists of re-examining the origins of knowledge diffusion and the catalysts of innovation capability in the emergence of an industry sector such as solar PV, and further exploring the diverse evolving industrial development strategies in the three latecomers, Taiwan, Korea, and China.

3.4.2 Previous Findings Concerning Knowledge Flows for the Asian Latecomers

While some studies have found that patent citations are a noisy indicator of knowledge flows (Hall et al., 2001; Jaffe & Trajtenberg, 1999; Jaffe et al., 2000), the use of patent citations to analyse the knowledge flows involved is still broadly recognized and adopted. A number of studies have investigated the relation between knowledge diffusion and internalization of innovation capability, using patent citation data; some of them by comparing the evolving trajectories of technological development of Korea and Taiwan at either the country or industry level. Amongst these, the works of Hu and Jaffe (2003); Hu (2009); Hu (2008); Jang et al. (2009); Lee and Yoon (2010); Lee and Jin (2012); Lee and Wang (2011); Lee (2010), might give us a first look at the origins and catalysts of sources of knowledge for innovation capability in Taiwan, Korea, and China, in industries such as semiconductors (particularly DRAM), flat panel displays and mobile telephones.

Hu and Jaffe (2003)

NBER scholars have studied the broad interrelationships between knowledge diffusion and patent citations. In particular, Hu and Jaffe (2003) opened up the field of studies of latecomer strategies by demonstrating the international diffusion of knowledge between technology first-movers (US and Japan) and latecomers (Korea and Taiwan). They used backward citation data derived from the utility patents registered by Korea and Taiwan in the USPTO from 1977 to 1999, within which they explored four stylized facts regarding the mechanism of international knowledge flows. The four stylized facts are: (1) the US and Japan are the most important international knowledge sources for both Korea and Taiwan, accounting for more than 70% of total patent citations for Korea and Taiwan; (2) both Korean and Taiwanese inventors cite more patents from the US than from Japan; (3) for both Korea and Taiwan, there is a convergent trend in citing the US and Japanese patents, the trend being particularly clear for Korea; (4) compared with Taiwan, Korea tends to cite more Japanese patents, while Taiwan tends to cite more US patents.

Hu and Jaffe argue that imported capital goods and communications amongst researchers are two distinct channels of knowledge diffusion used by latecomers to gain great benefit from technologically advanced countries. They suggest that, since the 1970s, both Korea and Taiwan have established close economic relationships with the US and Japan through FDI and manpower migration. They also propose that, in Korea and Taiwan, the stronger the economic connections with the US and Japan, the higher the degree of knowledge diffusion.

Hu (2009)

Using the utility patents granted by USPTO from 1963 to 2004, Hu (2009) investigates the regionalization of knowledge diffusion within East Asia, noting that East Asia has made significant technological progress over the past decades, especially as Taiwan and Korea have surpassed Britain and France and become the fourth and fifth largest patentees respectively in the USPTO. Despite that the US and Japan are two dominant international knowledge sources for East Asia, Hu (2009) introduces a novel idea of regionalization of knowledge flows by using the notion of ‘intensity of knowledge diffusion’ and concludes that: (1) the US, Japan, Korea, and Taiwan are relative important knowledge sources for East Asia; (2) Singaporean and Korean patents cite Taiwanese patents more extensively than patents registered by the US; (3) Taiwan cites Korea’s patents more extensively than those from Japan and the US; (4) Malaysia and China cite Taiwanese and Korean patents more extensively than the US and

Japan; (5) except for Thailand, the G5 countries (UK, Canada, France, Germany, and Italy) have been the least frequently cited sources for East Asia.

Hu (2008)

Hu (2008) used the USPTO patent database and retrieved TFT-LCD related patents granted to Taiwan’s top five major players by the USPTO – AU Optronics, Chi-Mei Optronics, ChungHwa Picture Tube, Quanta and HannStar – so as to analyse the knowledge flows within and across Taiwan. The three-digit International Patent Classifications (IPCs) related to TFT-LCD technologies were selected to track the trends in new technology and the specializations in the TFT-LCD industry across Taiwan and the leading countries. The backward citation information contained in the patent bibliographies were utilised as a proxy for the knowledge flows. The results show that Taiwan’s TFT-LCD industry has successfully internalized external knowledge from the US and particularly from Japan, on specific core technologies.

Hu (2008) further found that Taiwan's top five TFT-LCD manufacturers have different knowledge sources and technology foci. This specialized capability is most likely the reason for their positions in the market. Traditionally, the public research institutes (PRI) such as Industrial Technology Research Institute (ITRI) are the knowledge catalysts, however Hu (2008) found no evidence that PRI has had a major impact on the development of Taiwan’s TFT-LCD industry

Jang et al. (2009)

Jang et al. (2009) used the indices RTA (Revealed Technology Advantage), CF (Citation Frequency), and “relative generality and originality” to assess the innovative capability and international knowledge flows amongst technological forerunners (US and Japan) and latecomers (Taiwan and Korea) in the FPD industry. Jang et al. analysed the patents published in the USPTO between 1976 and 2005, using the keywords: 'flat panel display' appearing in the patent abstracts. They found that: (1) significant knowledge flows are diffused from the technological leaders (US and Japan) to the latecomers (Korea and Taiwan); and (2) that knowledge flows in the FPD industry within and between Taiwan and Korea are not clear.

In terms of FDI, imported capital goods, and manpower migration, a number of studies have confirmed that both the US and Japan are the major sources of international knowledge flows for Korea and Taiwan. However, the findings of Jang et al. (2009) are in contrast to those of Hu and Jaffe (2003), stating that the US is the No.1 knowledge source for both Taiwan and Korea while Japan is listed as the second. In the case of the FPD industry, Japan overwhelmingly dominates the international knowledge flows in Korea, where, in the years 1987 to 2005, 56% of total citations referred to Japan and only 20% to the US. Moreover, Taiwan also showed similar results in the FPD industry, in which the share of citations referring to Japan (39%) was greater than that to the US (34%) over the same period. This result may indicate that Japan has replaced the US to become the major knowledge source for both Taiwan and Korea, especially in the most recently developing high-tech sectors. It is thus worthwhile to further investigate the international knowledge flows in the emerging solar PV industry in order to shed more light on the flows of knowledge between technological leaders and latecomers.

Lee and Yoon (2010)

By examining the industry-level knowledge flows, Lee and Yoon (2010), Lee and Jin (2012) and Lee and Wang (2011) used the notion of relative citation propensity to examine the international knowledge flows between the technology forerunners and latecomers in three industrial sectors.

Relative citation propensity is defined by Lee and Yoon (2010: 559) as "*the share of country A's citations made to country B*" as a proportion of "*the share of other countries' citations made to country B*". Using this measure, Lee and Yoon (2010) investigated the patterns of knowledge flows between and amongst the advanced countries (US and Japan) and latecomer countries (Korea and Taiwan) in the global DRAM industry. Analysing the US patents published between 1985 and 1999, using the search keyword 'DRAM' appearing in either the titles or abstracts of patent documents, Lee and Yoon (2010) conclude that: (1) with regard to international knowledge flow, the order of patent citation follows precisely the sequence of entry into the DRAM industry, in which Taiwanese firms tend to cite Korean patents, Korean firms tend to cite Japanese patents, and Japanese firms tend to cite US patents; (2) the prevalence of intra-national knowledge diffusion is similarly closely related with the level of technological capability or order of entry, while Japan shows the highest degree of intra-national knowledge diffusion in the DRAM industry. However, due to organizational differences, the intra-national knowledge diffusion in Taiwan (SMEs) is higher than that in the Korean *chaebols*.

Lee and Yoon (2010) suggest complementary interpretations to explain these phenomena. Firstly, they point out Taiwanese firms might have scouted and hired Korean engineers as a quick catch-up strategy. Secondly, Taiwanese firms have tended to learn the technologies from the immediately previous entrants (Korean firms) because they are most up-to-date and have proven competitiveness. In addition, Taiwanese firms' tendencies to cite DRAM patents from Korean firms might be because the technological gaps between them are the smallest. Lee and Yoon (2010) also suggest that the organizational difference between Korea and Taiwan is the major reason that Korea's large enterprises localize their knowledge flows primarily through internalization within their own organization. In contrast, localization of knowledge flows for Taiwanese SMEs is carried out not only within but also across organizations.

Lee and Jin (2012)

Lee and Jin (2012) also applied relative citation propensity to examine knowledge flows in the mobile phone industry. The proposition, constructs and methodology are identical with those of Lee and Yoon (2010). The difference is that China has been included for the comparisons in the mobile phone industry. It is not surprising that the concluding remarks made by Lee and Jin (2012) closely resemble those of Lee and Yoon (2010). Their findings are: (1) In terms of international knowledge flows, the order of patent citation matches the sequence of entry into the mobile phone industry; while Japanese firms tend to cite US patents, Korean firms tend to cite Japanese patents, Taiwanese firms tend to cite Korean patents, and Chinese firms tend to cite Taiwanese patents; (2) the degree of intra-national knowledge flows is proportional to the level of technological capability or the order of entry in the mobile phone industry; Japan shows the highest technological capability, following by Taiwan, Korea, and China, the lowest.

As before, the above two findings can be explained by the same arguments used by Lee and Yoon (2010), especially in the case of China. The close relationship between Taiwan and China is built not only through a common language and culture but also through intensive capital flows and manpower migration. For example, the world's largest EMS (Electronics Manufacturing Service) provider, the Hon Hai Group (Foxconn Tech in China) has recruited numerous engineers from Taiwan and deployed them to China. It is not unusual or surprising to see Taiwanese names listed as the inventors and Taiwanese patents cited as prior arts in Chinese patents. Lee and Jin (2012) have clearly explained the reason why China shows the lowest intra-national knowledge flows amongst the latecomers being compared; that it is understandable, since China is the latest entrant and has not yet built its own innovative capability.

Lee and Wang (2011)

Utilizing the same approach as Lee and Yoon (2010) and Lee and Jin (2012), an extension study by Lee and Wang (2011) aimed to investigate the knowledge flows in China's semiconductor industry. Identical findings to those of Lee and Yoon (2010) and Lee and Jin (2012) emerged: (1) Chinese firms tend to cite Taiwanese patents, since Taiwan entered the industry immediately ahead of China; (2) China exhibits the lowest degree of intra-national knowledge flows, demonstrating its lower level of internalization of technological capability.

Lee and Wang (2011) state that the close relationship between Chinese and Taiwan semiconductor firms is, no doubt, the primary reason that Chinese inventors tend to cite Taiwan's patents. Many Taiwanese semiconductor firms have set up large-scale production subsidiaries in China and dispatch their experienced Taiwanese engineers there, so it is reasonable for Chinese patents to cite Taiwanese patents as prior arts. This intimate relationship between Chinese and Taiwanese semiconductor industries has been highlighted by Hu and Jefferson (2008), stating that the development of China's semiconductor industry is essentially reliant on Taiwan's investment and technology transfer. Regarding the low degree of intra-national knowledge flows, Lee and Wang (2011) indicate that most companies setting up R&D departments aim at the domestic market by offering localized products, rather than by strengthening their technological capability in China.

The use of ‘relative citation propensity’ to interpret the international knowledge flows and assess the order of entry into the industry has been proven successful in the DRAM, semiconductor and mobile phone industries by Lee and Yoon (2010), and associated studies. However, one concern regarding the interpretation of ‘relative citation propensity’ applied into this study may need to be clarified. For example, relative citation propensity, as defined by Lee and Yoon (2010:559), can become infinite if a single country, A, in the world cites only one patent registered by country B, while other countries do not cite *any* patents registered by country B. Even in this case, the interpretation of relative citation propensity, following the style of Lee and Yoon, would become ‘*country A tends to cite country B*’, while the true situation would be ‘*country A only cites one patent from country B*’, ignoring the fact that country A may have cited thousands of patents from countries other than country B. This may be an exceptional case or an outlier, but may still need to be clarified in interpretation.

One example from the FPD industry may highlight the concern as to whether the measure used by Lee and Yoon (2010) and associated studies is always valid in all the industries. If this measure is applied to the work of Jang et al. (2009), the order of patent citations is *not* the same as the order of entry into the FPD industry for Taiwan and Korea. This is evidenced from the dataset generated by Jang et al. shown as Table 3.1 below (Jang et al.,2009: 580); Korean firms made 12 citations to Taiwan while Taiwanese firms only made one citation to Korea during the early entry period between 1987 and 1996. By using the measure of relative citation propensity, Korea would show a very high relative citation propensity toward Taiwan’s patents and the result, according to Lee and Yoon (2010), would be taken to mean that *'Korean firms tend to cite Taiwanese patents in the FPD industry'*. This interpretation obviously violates the order of entry into the industry, since Korea was ahead of Taiwan in entering the FPD industry and it ignores the fact that Korea made only 12 citations to Taiwan, but made 296 citations to Japan and 196 to the US, as shown by Jang et al. (2009: 580).

Table 3.1 Number of Patent Citations of FPD Patents Granted, 1987–2005 (reproduced from Jang et al. (2009: 580))

Citations Made To	Citations in FPD Patents Originating From:							
	United States		Japan		Korea		Taiwan	
	No.	%	No.	%	No.	%	No.	%
Panel A: 1987–1996								
United States	5,264	60.7	3,152	30.3	196	32.1	146	48.7
Japan	2,059	23.7	5,842	56.1	296	48.5	89	29.7
Korea	26	0.3	39	0.4	44	7.2	**1**	0.3
Taiwan	38	0.3	27	0.3	**12**	2	19	6.3
Others	1,286	14.8	1,355	13	63	10.3	45	15
Totals	8,673	100	10,415	100	611	100	300	100
Panel B: 1997–2005								
United States	17,774	60.8	8,340	20.2	2,754	19.5	1,636	33.9
Japan	7,213	24.7	28,245	68.3	7,916	56.1	1,919	39.7
South Korea	357	1.2	1,720	4.2	2,493	17.7	470	9.7
Taiwan	503	1.7	384	0.9	255	1.8	458	9.5
Others	3,393	11.6	2,663	6.4	693	4.9	347	7.2
Totals	29,240	100	41,352	100	14,111	100	4,830	100

Source: Jang et al. (2009: 580)

As discussed above, the validity of relative citation propensity in interpreting international knowledge flows and whether the order of patent citations can always precisely reflect the order of entry into the industry warrant further examination. In order to accurately reflect international knowledge flows, in this study I have preferred to rely on absolute numbers of patent citations to trace the evolution of knowledge sources for the solar PV industries in Taiwan, Korea, and China. Nevertheless, this study continues to compare the results derived using relative citation propensity and absolute patent citation counts, to clarify the issues arising from the Lee and Yoon (2010) and associated studies involving order of entry into the industry and order of patent citations.

Lee (2010)

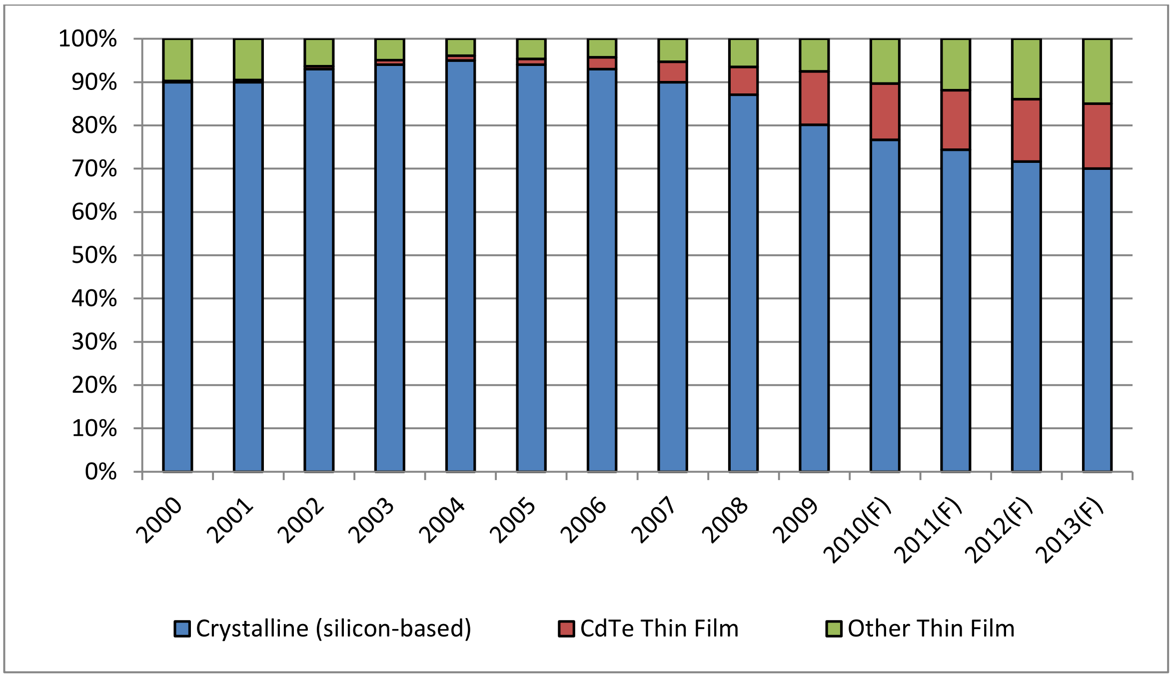
The study by Lee (2010) focused on investigating the occurrence and effectiveness of knowledge flows for the latecomers who are catching up in one technology field after another. This study used patent data in the USPTO and developed eight indicators to analyse the technological regimes amongst the ten technological catch-up countries over the period 1980-1995. Using these eight indicators – technological opportunity, appropriability (i.e. imitability or reproducibility) of innovation, cumulativeness of technical advances, properties of knowledge bases, technological cycle time, accessibility to external knowledge, initial stock of accumulated knowledge, and uncertainty of technology – Lee (2010) compares technological catch-up rates between and among the two first-tier latecomers (Taiwan and Korea), the four Asian second-tier latecomers (China, India, Malaysia, and Thailand), and the four Latin America second-tier latecomers (Brazil, Argentina, Mexico, and Chile). Amongst the eight indicators, appropriability is defined here as the extent of local-citations in a country, representing not only lesser reliance on external knowledge but also internalization of the R&D capability of latecomers by concentrating their limited resources on a specific technology area. From the resource-based view, Lee (2010) suggests that the degree of appropriability is related to the size of firms, so that Taiwan (composed of SMEs) exerts a higher and more significant degree of appropriability than Korea (dominated by large *chaebols*) (Park & Lee, 2006). While Lee (2010) shows that technological catch-up is most likely to occur in sectors with shorter technological cycle times and a higher initial stock of accumulated knowledge, the local-citation rate also demonstrates its importance in technology specialization and internalization capabilities in the latecomer countries.

Thus there are rich findings already reported for high-tech industries in which latecomer countries leverage knowledge flows from advanced firms in advanced countries to drive their catch-up efforts – and which provide a theoretical setting for this study that extends this series of efforts to the now-emerging solar PV industry. It is concerned in particular to verify the significance of Japan and the US as principal sources for these knowledge flows and their relative balance in the case of solar PVs, distinguishing between first generation c-Si technology, and second generation technologies using alternative semiconductor materials such as CIGS or Cd-Te, as well as third generation technologies like organic solar cells, where no technology has yet to emerge as dominant.

3.4.3 Derived Research Propositions

Although previous studies have tried to explore the knowledge flows between and among technology leaders and latecomers, the evolving international knowledge flows and the variations of endogenous innovation capability for latecomers such as Taiwan, Korea and China still remain indefinite. The questions derived from the evolving and dynamic industrial relationships between advanced and latecomer countries not only persist but also inspire new issues, such as: to what extent are the major knowledge sources for the latecomers such as Taiwan, Korea and China able to switch from external knowledge flows to internal knowledge generation (or the construction of absorptive capacity)? Are the innovation capabilities of the three latecomers capable of advancing the old and existing knowledge of the technology leaders and building knowledge at the cutting edge?

For updating the dynamic industrial development in the latecomer countries, the solar PV industry thus offers a perfect proxy to bridge this gap through examination of the evolving strategy of knowledge acquisition and diffusion in the Taiwan, Korea, and China latecomers; because the old technology (silicon-based first generation solar PV) has been developing for more than six decades and the emerging new technologies (the new generations of thin film or organic compounds) have only been flourishing significantly since the early 2000s. As shown in Figure 3.1, the thin film technologies took a 20% market share in 2009 and are expected to reach 30% by 2013 (Displaybank, 2010). At this cross-roads of technology, the solar PV industry thus presents an excellent example for re-examining the evolving knowledge flows and their dependent paths, in terms of knowledge utilization and internalization, in order to build the emerging industry in the technology catch-up countries.



Note: The data from 2010 to 2013 is a forecast by Displaybank (2010).

Source: IEK (2009); Displaybank (2010).

Figure 3.1 Production Shares of Various PV Technologies, 2000-2013 (with forecasts)

In order to clarify the research questions mentioned earlier, as well as to further understand the evolving dynamics of knowledge flows for the three Asian latecomers, six research propositions derived from the stylized facts concluded by Hu and Jaffe (2003), Hu (2009), Hu (2008), Jang et al. (2009), Lee and Yoon (2010), Lee and Jin (2012), and Lee and Wang (2011) are constructed, along with one additional proposition for investigating scientific linkage – with which I wish to advance the previous studies for Asian latecomers' knowledge flows. Applying the previous findings to the development of solar PV industries in Taiwan, Korea, and China, in total **seven research propositions** are derived accordingly from the four constructed indicators, those relating to international knowledge flows, intra-national knowledge flows, relative citation propensity, and scientific linkage, addressed as follows.

International Knowledge Flows

NBER scholars have investigated the patterns of knowledge diffusion from technologically advanced countries to latecomers. By analysing all the utility patents registered in the USPTO by Korean and Taiwanese inventors between 1977 and 1999, Hu and Jaffe (2003) have found that both Korea and Taiwan rely heavily on knowledge diffused from the US and Japan in the process of building innovative capability. Moreover, their study also demonstrates that the proportion of citations made to the US and Japan converges over time. Since Taiwan, China, and Korea latecomers are historically accustomed to having strong ties with the US and Japan in terms of trading, manpower, and technological licensing, this study proposes the following:

- ***Research Proposition 1-1:*** *The US and Japan are the major sources of international knowledge flows for Taiwan, China, and Korea in building innovation capability in the* *solar PV industry.*

- ***Research Proposition 1-2:*** *The shares of patent citations made to the US and Japan by Taiwan, Korea and China converge in the development of the solar PV industry.*

Intra-national Knowledge Flows

Lee and Yoon (2010) and Lee (2010) suggest that intra-national knowledge flows frequently occur in countries with a superior technology internalization capability and that both Taiwan and Korea have developed high-tech industries, such as semiconductors, for over 20 years and secured their competitive advantages in these areas. It is reasonable to assume that the degree of intra-national knowledge flows (represented by the degree of absorptive capacity and internalization of innovation capability) is higher in first generation solar PV than in later generations. In the emerging new generation solar PV, mass production activity still requires the exploration of advanced basic technology. This study thus assumes that the three latecomers still tend to cite the US and Japanese patents in the new generation solar PV, because it is in the area of basic technology that the US and Japanese patents own the most advanced basic technologies (Lee & Wang, 2011).

- ***Research Proposition 1-3:*** *In the first generation solar PV, both Taiwan and Korea tend to have a higher degree of intra-national knowledge flows, while that in China is relatively lower, resulting from the internalization capability previously built in the semiconductor industry.*
- ***Research Proposition 1-4:*** *In the new generation solar PV sector, Taiwan, China, and Korea latecomers tend to cite US and Japanese patents more than local-citations.*

The fifth proposition investigates the endogenous knowledge diffusion hub with respect to Taiwan, Korea, and China. As described in Lee and Yoon (2010) and Lee (2010), the Korean economy and its innovation activities are spearheaded by a small number of large diversified business groups, whereas the Taiwanese economy is dominated by a large number of specialized small-medium size firms along with assistance in technology upgrading from the public research institute (Amsden & Chu, 2003; Mahmood & Singh, 2003; Mathews, 2002a, 2005; Mathews & Cho, 2000; Saxenian & Hsu, 2001). Lacking stronger absorptive capability in the private sector, China is integrating both large companies and SMEs along with the external knowledge into an innovation system, in which the university is acting as a hub and vertical integration network for the large companies, while the small-medium size firms help to build and reinforce the strength of the industrial value chain (Hu & Mathews, 2008; Xue, 1997). Therefore, this study proposes the following:

- ***Research Proposition 1-5:*** *The intra-national knowledge flows of solar PV technologies in Taiwan is mainly derived from the public research institute, while that in Korea is secured from the chaebol, and in China is acquired from the university.*

Relative Citation Propensity

Lee and Yoon (2010) use 'relative citation propensity' to illustrate that the preferences for international knowledge sources of the memory chip industry in the US, Japan, Korea, and Taiwan exactly follow the order of entry into the industry. They conclude that Japanese firms tend to cite US patents; Korean firms tend to cite Japanese patents; and Taiwanese firms tend to cite Korean patents. Corresponding findings between industry entry order and international knowledge flows are also identified by Lee and Jin (2012) in the mobile phone industry as well as by Lee and Wang (2011) in the semiconductor industry.

In the solar PV industry, the three latecomers' entry was initiated by China, the first Chinese solar cell producer, Ningbo solar, which was founded in 1978 – followed by Taiwan's Motech, which established its solar PV section in 1998, and lastly Korea's LG – has been preparing to enter the solar PV industry since 2004 and announced that mass production will start in 2010.[20] However, the technological evolution in the mass production of solar PV largely relies on the applied technologies derived from the semiconductor and flat panel display industries, while the US is a technology initiator and Japan takes the lead in realizing mass production, and they are followed in turn by Korea, Taiwan, and China entering the industry. Thus, the international knowledge flows of the solar PV industry in Taiwan, China, and Korea may be inclined to follow the order of entry into the semiconductor and flat panel display industries. So this study proposes the following:

- ***Research Proposition 1-6:*** *Regarding the international knowledge flow, Korean inventors tend to cite Japanese patents, Taiwanese inventors tend to cite Korean patents, and Chinese inventors tend to cite Taiwanese patents in the solar PV industry, in accord with relative citation propensity.*

Scientific Linkage

Extending the previous study of knowledge flows for the Asian latecomers, the seventh proposition is aimed at exploring the extent to which latecomers, such as Taiwan, Korea and China, are able to switch from acquiring external knowledge to generating internal knowledge (by building absorptive capacity) so as to build innovation capability at the cutting edge of the

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[20] For the details, see Korea IT Times: '*LG Electronics commences production of solar cells and modules*', available at: http://www.koreaittimes.com/story/6228/lg-electronics-commences-production-solar-cells-and-modules

solar PV industry. To answer this question, this study uses scientific linkage in patenting activity as an indicator.

The first generation technology of solar PV is mature, having been developed for more than six decades. So the best opportunity for latecomers in pursuing higher value-added innovations, as well as gaining competitive advantage in the global market, is through the development of emerging new technologies. Taking this perspective, process innovation in the latecomer countries not only has to build on internalizing existing production knowledge but also has to take cutting-edge scientific knowledge into account (e.g. scientific papers, as judged by their degree of linkage with sciences). Proposition 7 is thus:

- ***Research Proposition 1-7:*** *The knowledge flows of the emerging new generation solar PV in Taiwan, Korea, and China are likely to have a higher degree of scientific linkage than the first generation.*

By comparing variations in knowledge acquisition between existing, first generation, knowledge and latest, new generation, knowledge of solar PV, the aim of this study is to explore the three latecomers' knowledge acquisition strategies for developing their solar PV industries, in relation to their overall business strategies and prevailing business conditions.

In this study, I seek to build on the contributions from previous studies on knowledge flows for Asian latecomers, by Hu and Jaffe (2003), Hu (2009), Hu (2008), Jang et al. (2009), Lee and Yoon (2010), Lee and Jin (2012), and Lee and Wang (2011), where the emphasis is on the knowledge flows involved in pursuing latecomer strategies. Taking the solar PV industry as the object, this study extends their work by utilizing a very large dataset of patents in the solar PV industry, examining the patents secured by China, Taiwan and China and using prior patents acquired by advanced firms in the US, Japan and Europe as a source; by utilizing a more nuanced and discriminative tool for patent selection through the three-stage filter involving technology classifications employed by global patent offices; by verifying many of the patterns of latecomer strategies previously identified in the studies of earlier industries; and by pointing out difficulties involved in utilizing the indicator ‘relative citation propensity’ as a source for drawing conclusions as to citation patterns. One of the goals of this study is to clarify the reasoning involved when a latecomer country decides to switch from external knowledge flows to internal knowledge generation (or building of absorptive capacity). By examining the four indicators (international and intra-national knowledge flows, scientific linkage, and relative citation propensity) in terms of the solar PV industries in Taiwan, Korea, and China, this study tests the seven research propositions advanced previously and aims to shed light on the evolving knowledge flow trends for the three latecomers. It will pay particular attention to Taiwan's and Korea's knowledge acquisition strategies relative to their overall business strategies and prevailing business conditions in developing their solar PV industries, which will be examined in detail in the discussion chapter.

Given that the technological trajectory of solar PV is created by the US, Germany, and Japan as leading countries in the past decades, the continuing question is presented by the second goal of this study: to what extent have the Taiwanese, Chinese and Korean followers developed their technological innovation capabilities so as to surpass the US and Japan and acquire leading production positions since the mid-2000s? Furthermore, how do the variations of technological innovation capabilities among the major technological players shape their competitive status in the global solar PV industry? It will then be worthwhile to discuss the importance and the role of technological innovation capability in Taiwan, China, and Korea latecomers.

3.5 Technological Innovation Capabilities

Technological innovation capabilities as indicated by patenting activity are greatly dependent on industry evolution and are measured by technological and economic value. For example, Hall and Ziedonis (2001) argued that the economic advances of the US semiconductor industry are mostly due to the management of patenting as an increasingly important strategic tool, especially in high-tech industries, rather as the outcomes of patenting itself. However, previous studies have overwhelmingly emphasized the economic/market value of patenting activity (Arundel & Kabla, 1998; Cohen, Nelson, & Walsh, 2000; Levin et al., 1987). Although the building of technology capabilities in the catch-up latecomer countries acts as a catalyst for industrial transition, only a little extant literature (for example, Hu, 2012; Jung & Lee, 2010) discusses the significance for patenting activity of variations in technology. Given the multidisciplinary technological interactions involved in knowledge-based innovations, technological knowledge serves as a shareable input in research on various technologies and innovations (Henderson & Cockburn, 1996), as evidenced not only in semiconductor and TFT-LCD industries (e.g. Hu, 2008; Lee & Yoon, 2010; Mathews & Cho, 2000) but also in the solar PV industry (Wu & Mathews, 2012). The second stage of this study aims to examine the catching-up of technological innovation capabilities in the emerging solar PV industry in the potentially leading production countries – China, Taiwan, and Korea – and goes on to elicit the technology portfolios of the major producers for each principal platform.

3.5.1 Relevant Studies Concerning the Technological Innovation Capabilities in the Three Latecomers

Using patent data, a number of studies have investigated the technological innovation capability for the Asian latecomers. Among these, the works of Mahmood and Singh (2003), Park and Lee (2006), Lee (2012), Hu and Mathews (2008), Hu (2012), and De la Tour, Glachant and Ménière (2011) might give us a first look at the evolving technological innovation capability in Taiwan, Korea, and China. However, this study is the first to examine their respective technological innovation capabilities in developing the solar PV industry. These six works are summarised as follows.

Mahmood and Singh (2003)

Mahmood and Singh (2003) used US patent data to investigate the innovation capabilities of five Eastern countries. In comparing the three latecomers, their results show that Taiwan and Korea have a higher patenting rate than China. The overall patenting activity of Taiwan and Korea was very low during the 1970s, but has increased dramatically in the late 1980s for Taiwan and in the 1990s for Korea. In contrast, China's patenting activity remains at a very low level, suggesting that China has not yet built its technology innovation capability. Moreover, the catalyst of technology innovation capability is mostly drawn from *chaebols* in Korea, while individuals and SMEs act as the main innovators in Taiwan and China. In addition, public research institutes, including universities, also play an important role in building indigenous innovation capability in the three latecomers.

Park and Lee (2006)

Park and Lee (2006) used US patents to examine the relationship between the technological regime and the technological catch-up for Taiwan and Korea. Their dataset comprises more than 19,000 patents for Taiwan and 14,000 patents for Korea, spanning 266 and 232 technology categories respectively. Among these, about two-thirds of Korean-held US patents are applied by the top five *chaebols*, Samsung accounting for almost one-third of the total. In contrast, about two-thirds of US patents held by Taiwanese are applied by individuals.[21] That work suggests that technological catch-up would mostly occur in those technologies that have shorter cycle time and higher knowledge stocks. Furthermore, the speed of catch-up relies on technological appropriability (the possibilities of protecting innovations from imitation and of reaping profits from innovative activities) and knowledge accessibility. They also found that the competitiveness of catch-up firms is determined by their capability to quickly enter a new market segment, their manufacturing excellence, and their ability to integrate design for products.

Lee (2012)

The work of Lee (2012) further used ‘technology cycle time’ to explain how middle-income developing countries could sustain their economic growth after successful entry and subsequent leapfrog into similar status to high-income developed countries. From the perspective of patenting activity, technology cycle time is a measure of technological progress defined as the median age of the patents cited for a certain technology. Industries such as automobile and pharmaceuticals are usually regarded as long-cycle technologies, whereas Information Communication Technology (ICT) industry is a short-cycle technology (Narin, 1994; 1995). Lee (2012) argued that short-cycle or low-originality technologies provide new entrants or latecomers ‘windows of opportunity’ for building technological capabilities and localizing knowledge creation and diffusion. It is due to short-cycle

[21] According to Park and Lee (2006), the US patents applied by Taiwanese companies but unassigned or assigned to individuals are regarded as patents applied by SMEs (Park and Lee, 2006: 742).

technologies' lower reliance on the existing technology and to the nature of rapidly changing and frequent emergence of new technologies. Indeed, the middle-income latecomers such as Taiwan and Korea have demonstrated this in the short-cycle technological sectors of semiconductors, electronics, and communications. Though not all new entrants benefited from developing short-cycle time technologies, localization and diffusion of knowledge creation and accumulated technology capabilities are important pre-determinants for detour strategies of sustained catch-up.

Hu and Mathews (2008)

Hu and Mathews (2008) applied the USPTO patent datasets to examine China's innovative capacity over the period 1976 to 2005. China's overall patenting activity in the USPTO was minor and only surged in the 2000s. The public research institutes (PRIs) along with universities were China's most important innovation drivers before 2002, while their role as innovator has been replaced by the private sector since 2002. The emergence of the private sector in patenting activity is attributed to the university-run enterprises or PRI spin-offs, while the rise of patenting rate in individuals is ascribed to the emergence of SMEs. That work reveals that China's national innovation capability has begun to shift gradually toward the private sector since the 2000s.

Hu (2012)

Hu (2012) used US Patent and Trademark Office data to assess variations in technological innovation capabilities and their influence on market performance, among leading TFT-LCD producers in Japan, Korea, and Taiwan. The empirical results suggest that TFT-LCD producers in Korea and Taiwan built innovation capabilities by creating complementary knowledge for Japanese firms, whose technologies lead the way in the industry. The results also show that latecomers sought to expand production by selecting certain technological fields, but that they exploited these fields in different ways. This enabled Japan's technology-push innovation and Korea's and Taiwan's demand-pull innovation to evolve sequentially and interactively. That work also confirms that inter-*keiretsu* collaborations may be seen as an evolution of Japanese industrial organization, in that they have allowed the Japanese TFT-LCD industry to reinforce its technological portfolio, while protecting itself from the risks inherent in a technological and capital-intensive industry.

De la Tour et al. (2011)

De la Tour et al. (2011) surveyed the Chinese solar PV industry, finding that Chinese producers have acquired the technologies and skills needed to manufacture solar PV products by (1) purchasing manufacturing equipment (turn-key solutions) from global suppliers; (2) recruiting experienced overseas Chinese executives and engineers; and (3) through the FDIs by MNEs which induces a transfer of knowledge through joint ventures with Chinese firms. De la Tour et al. (2011) also used a keyword-combining-IPC approach (e.g. keywords PV or solar or photovoltaic and module in IPC H01L) to retrieve the solar PV patents published during 2006-2007 in the EPO esp@cenet database. Four technology platforms – silicon, ingot, cell, and module, from upstream to downstream, in line with the solar PV value chain are identified for the comparison of technological innovation capabilities amongst Chinese and other global players. Their results show that China's performance, in terms of patent counts, is remarkable, as it ranks third in all the technology platforms. However, De la Tour et al. noticed that although Chinese companies exhibit a higher propensity to patenting, they tend to file more patent applications for an equivalent innovation output, finding that the Chinese patents are minor inventions in their intensive field investigations in China. The main reason for patenting for Chinese firms is to send a signal to public authorities for the allocation of subsidies, rather than to protect their intellectual property. It's also interesting to see that only 1% of Chinese patents are also filed abroad, comparing with 26% for Japan, 15% for Germany, and 7% for the US.

3.5.2 Derived Research Propositions

To verify the empirical results derived from the USPTO as well as to explore the second research question on the variations of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea, the research propositions of the second stage are constructed from the previous literature and are a partial attempt to verify the seven stylized facts derived from the knowledge flows in the first stage. Applying the previous findings to the development of solar PV industries in Taiwan, Korea, and China, **four research propositions** are accordingly derived, addressed as follows.

The solar PV production activities in the global market are essentially derived from the implementation of renewable energy policy pioneered by some European countries, such as Germany and Spain, in the early 2000s, which led the global solar PV industry to move into the early growth stage. The innovation capabilities seen in latecomer countries, such as China, Korea and Taiwan, may be regarded as *process innovation*, the creation of non-incremental complementary knowledge built on the incremental but under-used knowledge of technology leaders such as the US and Japan.[22] This complementary knowledge was either overlooked by the technology leaders or was seen as extraneous to their business strategies, especially in the new market (Helfat & Lieberman, 2002; Nerkar, 2003; Teece, 1986). Thus, it is reasonable to propose that the demand of large-scale production activity in the global solar PV industry

[22] The non-incremental creation of complementary knowledge can be regarded as one of the dynamic capabilities in organization theory; it defines the capacity of a latecomer firm to adapt purposefully its resource base to fit industry-specific needs (Helfat et al., 2007).

catalysed the technological innovation capability built on *process innovation* by the latecomers in Taiwan, China, and Korea.

Research Proposition 2-1: *The solar PV technological innovation capabilities in Taiwan, China, and Korea were mostly built for production activity, while the global solar PV industry was emerging significantly after the 2000s.*

The different compositions of industrial structure with respect to the Taiwanese SMEs, the unique Chinese '*forward engineering'* model diffused from universities, and the Korean *chaebols* respectively, gave rise to different types of innovation hub. Consequently, the building of technological innovation capability in the solar PV industries of Taiwan, China, and Korea latecomers tends always to use their specific national resources.

The empirical results derived in Stage One from the evolving knowledge flows demonstrated that innovation capability is critically built on prior accumulated knowledge, for which semiconductors act as a fundamental knowledge base, not only for the development of Si-based first generation solar PV technologies but also for the thin film-based second generation and organic compound-based third generation devices. This is especially true for the large-scale production activity in the solar PV industry. To test and verify this contention from the *esp@cenet* patent database, we claim:

Research Proposition 2-2: *The technological innovation capabilities of solar PV industries in Taiwan, China, and Korea are significantly reliant on accumulated knowledge stock.*

The propensity to innovation is related to a country's technological specialization, which is one of the major drivers for national industrial clusters (Vertova, 1999). In particular, powerful spillovers and external influences in high-tech industries act rapidly to turn new ideas into reality, hence technology specialization is vital to the rate of innovation (Lim, 2000). As resources for latecomers are limited, technology specialization over the industrial value chain is not merely an industry strategy but also generates the maximum catch-up effect (Hu & Mathews, 2005). In addition, the different national approaches and accumulated resources in the latecomers Taiwan, China, and Korea may lead to various formulations of specialization niche in developing their solar PV industries. Thus, research propositions 3 and 4 are formulated as:

Research Proposition 2-3: *With successful technological catching-up experience and resources, the SMEs-centric Taiwanese and chaebol-dominated Korean solar PV latecomers tend to pursue more advanced technologies, whereas the relatively poorer endogenous innovation capability of Chinese latecomers tends to focus on mature technologies.*

Research Proposition 2-4: *Given the differences in national resources, the specialisation of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea tends to be diverse.*

Summary: While the two-stage methodologies and research propositions are aimed at exploring different research questions, as stated in Chapter 1, the research propositions of the second stage are to some extent designed to verify the empirical results of the first stage. By doing so, the patent data sets of solar PV industries in Taiwan, China, and Korea extracted from the USPTO can be cross checked against that of EPO worldwide (*esp@cenet*) so as to strengthen the robustness of this study.

3.6 Summary of Literature Review

A brief summary of the literature concerning the research questions and propositions is given in Table 3.2 While patenting activities represent a proxy for understanding the innovation capability of firms/countries, previous relevant studies give a fundamental understanding of the interrelationship of technological changes and industry evolution, as well as the ways in which knowledge flows play a critical role in industrial development.

Table 3.2 Summary of Relevant Literature

Subject	Author(s)	Suggestions
Methodology		
Concerns for patent relevant researches	Hu (2008) Taylor et al. (2007) Fabry et al. (2006)	● Using keyword search alone on patent datasets is likely to be of limited value, because many patent documents do not contain expected keywords, while those patents containing them are not always relevant.
	Alcácer (2006)	● Using patenting citation as an indicator for measuring knowledge flows may causes biases for the true knowledge flows and diffusion.
	Vertova (1999) Evenson (1984)	● Classification problems have arisen with patent data in strategic and financial analysis.
	Wu and Mathews (2012) Alcácer (2006) Thompson and Fox-Kean (2005) Jaffe and Trajtenberg (1998)	● Using patent citations to trace knowledge flows often leads to over-estimation.
	Jaffe and Trajtenberg (2002) Jaffe et al. (1993) Trajtenberg (1990)	● Simple patent counts are unlikely to totally capture the innovative output of companies; not all innovations are patented.
	Arundel and Kabla (1998) Griliches (1990) Mansfield (1986)	● The precise rates of knowledge flows and technological innovation capabilities are unreachable because only certain types of formations can be measured.
Patent search technique	De la Tour, Glachant and Ménière (2011)	● Applying related solar PV keywords combining with a range of IPCs to extract China's PV patents.

Subject	Author(s)	Suggestions
	Lee and Yoon (2010) Bettencourt et al. (2008) Kaiser, Kaur, Castillo-Chávez and Wojick (2008) Wong et al. (2007) Bengisu and Nekhili (2006)	● Using Keyword search for patents in patent-related research.
Patenting strategy	Chen and Chang (2010) Criscuolo (2006) Lai and Wu (2005) Tijssen (2001) Brockhoff et al. (1999)	● The US has been one of the critical technology and product markets, filing patent applications at the USPTO are of great interest to inventors.
Factor analysis	Hair, Anderson, Tatham and Black (1995)	● Factor analysis is a statistical method used to recognize the interdependencies between variables and reduce the set of variables in a dataset.
Concerns for analysing industry evolution	Kuznets (1962)	● The greatest impediment to analysing industry evolution over time has been the lack of comprehensive and systematic longitudinal data bases.
Solar Photovoltaic Industry		
Threats from global warming and oil prices	Bleischwitz and Fuhrmann (2006) Hirsch et al. (2006) Noreng (2006) Winebrake (2002)	● The increasing demand and consumption for oil in the emerging countries such as China, India, Russia and Brazil significantly highlight the world's concerns on the oil price.
	Rahmstorf et al. (2007) WBGU (2007) Greenpeace (2006) European Renewable Energy Council (2004)	● Natural disasters caused by global warming.
	Watts (2002)	● CO_2 discharged from the burn of fossil fuel contributes a great portion of greenhouse gas emissions.
Development of solar PV industry	Mowery et al. (2010)	● Solar PV is one of the rapid growth alternative-energy technologies to be adopted.
	Strobl et al. (2009) Green (2005)	● The first solar cell was practically produced by Bell Laboratories.

Subject	Author(s)	Suggestions
	Goetzberger and Hebling (2000)	
	Tiwari and Dubey (2009) Swanson (2006) Bruton (2002)	● The dominant technology for PV solar remains c-Si, both in its earlier monocrystalline form and its later polycrystalline forms.
	Green (2004)	● Second generation 'thin film' technologies, utilizing amorphous silicon and microcrystalline silicon as semiconductor material, but also other semiconductor materials such as cadmium-telluride (CdTe), copper-indium-gallium-selenide (CIGS), and gallium-arsenide (GaAs), driven by the much lower materials requirements involved in thin film production.
	Grätzel (2003)	● Third generation is used to refer to the organic compounds (such as dye sensitized solar cell) which have the advantages of low production costs in high volumes and flexibility
Patenting trends of solar PV technologies	Clear Energy Group (2011)	● The global solar patenting activities in 2010 doubled that of 2009, in which the number of solar PV patents related to second generation led the first and third generations in 2010
	Tseng et al. (2011)	● The Japanese company Canon owns the largest share of patents while the U.S. Energy Conversion Devices company comes next, followed by another Japanese company, Sanyo Electric.
	Glachant et al. (2009) Bauer and Neuhaus (2008)	● The patents in relation to the 13 climate-mitigation fields have surged since the late 1990s, right after the Kyoto Protocol in 1997.
	Lee et al. (2009)	● The patent grants of the solar PV technology have risen from less than 200 patents per year prior to 1998 to more than 1,400 patents per year in 2007.
	Visentin (2009)	● the annual granted patents grew 400% in the solar PV technology field in ten years (from around 1,800 in 1999 to around 7,900 in 2008), compared with the average 60% increase for all industries.
Asian latecomers' solar PV industries	De la Tour et al. (2011)	● Chinese solar PV producers have acquired the technologies and skills needed to manufacture solar PV products through (1) the purchasing of manufacturing equipment (turn-key solutions) from global suppliers; (2) the recruitment of experienced overseas Chinese executives and engineers; and (3) the FDIs by MNEs which induces a transfer of knowledge through joint ventures with Chinese firms. ● The main reason to patenting for the Chinese firms is to send a signal to public authorities for the allocation of subsidies, rather than to protect their intelligent properties.
	Mathews et al. (2011)	● Chinese solar PV firms are competing in the global market through low cost, large scale production. ● Fast follower strategies pursued in the development of Taiwan's solar PV industry.
Inter-relationship of solar PV technology and other industries	Ferrazza (2005) Ravi (2005)	● Applications of silicon in semiconductor industry.
	Wu and Mathews (2012) Mauk et al. (2005)	● Commonality of solar PV and TFT-LCD manufacturing equipment.

Subject	Author(s)	Suggestions
Oil price	Maugeri (2012)	● The oil price may experience a 'steep dip' due to the unprecedented upsurge of oil productions in recent years.
Patenting		
Patent serves as a useful strategic tool	Hall and Ziedonis (2001)	● The economic advances of the U.S. semiconductor industry are mostly derived from the management of patenting as an increasingly important strategic tool, especially in high-tech industries, rather than the consequences of patenting behavior.
	Ernst (1997)	● By analyzing the technological life cycle (S-curve), strategic R&D decisions can be made.
	Ashton and Sen (1988)	● Patent information can serve as a unique planning resource for managing a firm's technology or product development.
	Campbell (1983)	● Patent indicators can be utilized as a very useful forecasting tool, especially to signal for entering or leaving a technology.
	Narin (1994) Narin (1995)	● Technology cycle time is a measure of technological progress and defined as the median age of the patents cited for a certain technology.
Technological innovation capabilities and patenting activity	Hu (2012) Mahmood and Singh (2003) Hagedoorn and Cloodt (2003) Amsden and Mourshed (1997) Archibugi (1992) Pavitt (1982)	● Patent data analysis can serve as an indicator for technological innovation performance.
	Zucker et al. (1998) Kogut and Zander (1992)	● Technological innovation capabilities are reflected in a country's patenting activity, and depend to a large degree on the trajectory of global industrial development, which can be measured in terms of technology value and economic value.
	Arundel and Kabla (1998) Griliches (1990) Mansfield (1986)	● Many important innovations are not patented, while some patents are awarded for very modest technological discoveries.
Value of patenting	Cohen, Nelson and Walsh (2000) Arundel and Kabla (1998) Levin et al. (1987)	● The economic/market value of patenting activity.
China patenting activity	Hu and Jefferson (2009)	● China's patenting activity began to surge in 2000.
Industry Evolution		
Social changes and industry evolution	Hu and Mathews (2008) Kallinikos (2006) Hu and Mathews (2005) Hung (2002) Hoffman, 1999	● The evolution of an industry is greatly shaped by the market-oriented innovation in the process and reinforced by the institutional environment such as government policy

Subject	Author(s)	Suggestions
	Dosi (1997) Antonelli (1994) Baldwin and Scott (1987)	
	Geels (2005) Christensen (1997) Abernathy and Clark (1985) Schumpeter (1943)	● Incremental technological innovation plays an important role in developments that transform user contexts, markets, or operational environments.
	Hannan and Freeman (1984) Hannan and Freeman (1977)	● Industry evolution was rooted in economics, sociological approaches emphasized the topic on the theory of industrial structure and the role of legitimacy over competition
The processes of firm entry, exit, and growth	Orsenigo, Pammolli and Riccaboni (2001)	● Technological conditions induce distinguishable patterns of change in industry structure and evolution.
	Klepper (1996) Audretsch (1995) Dunne, Roberts and Samuelson (1988) Jovanovic (1982)	● Industry evolution refers to cumulative change in industry characteristics, notably the processes of firm entry, exit, and growth.
	Nekar (2003) Helfat and Lieberman (2002) Teece (1986)	● The complementary knowledge is either overlooked by the technology leaders or is extraneous to their business strategies, especially in the new market.
	Geroski (1995)	● The catalyst of market entry, and the effect that entry has on markets.
	Nelson (1994)	● Economic development at a sectoral level deploys the growth, development of a manufacturing sector.
		● A new technology develops along a relatively standard track, companies and industry co-evolve with the technology.
		● The development of institutions response to the changes in economic conditions, incentives, and pressures.
	Mathews et al. (2011) Williamson (2010)	● Chinese firms are competing in the global market through low cost, large scale production.
Pre-entry experience	Khessina and Carroll (2008)	● Pre-entry experience is a predictor of post-entry success, compared with specialized de novo firms, diversifying entrants have greater success rates in terms of survival, even if their products are technically inferior to those of new entrants.
	Agarwal, Echambadi, Franco and Sarkar (2004) Klepper (2002a)	● Pre-entry experience is a predictor of post-entry success, compared with specialized de novo firms, diversifying entrants have greater success rates in terms of survival.

Subject	Author(s)	Suggestions
	Klepper (2002b) Klepper and Simons (2000) Sharma and Kesner (1996)	
	Tripsas (1997a) Tripsas (1997b)	● If incumbents continue to own key assets that retain their important post-innovation, then the incumbents will continue to dominate the industry.
Process and product innovation	Dahlin and Behrens (2005) Freeman and Soete (1997)	● Definitions and measurements of non-incremental innovations.
	Adner and Levinthal (2001)	● A demand based view of technology evolution which is focused on the interaction between innovations and market demands.
	Klepper (1996)	● "Over time firms devote more effort to process innovation but the number of firms and the rate and diversity of product innovation eventually wither."
	Teece (1986)	● When imitation is easy, the profits from innovation may accrue to the owners of certain complementary assets, rather than to the developers of the innovation. Innovating firms without the requisite manufacturing and related capacities may fail, despite they are the best at innovation.
	Utterback and Abernathy (1975)	● In the emerging stage of the life cycle, no singular product design can dominates the industry.
Vertical integration and specialization	Malerba et al. (2008)	● The pattern of vertical integration and specialization in an industry change is a function of the evolving levels and distribution of firms' capabilities over time.
		● The patterns depend on the co-evolution of the upstream and downstream sectors.
	Hu and Mathews (2008) Park and Lee (2006)	● High-tech and knowledge-intensive industries, such as biotechnology, semiconductor production, FPD, and even solar PV production, are increasingly called upon to focus on intellectual property (IP) issues.
Life-cycle and patenting	Agarwal and Audretsch (2001)	● The stage of industry life cycle shapes the relationship between firm size and the likelihood of firm survival.
	Agarwal (1998)	● Patenting activity increases in the initial stages of the life-cycle, and subsequently declines during the mature period.
	Anderson and Tushman (1990)	● Technological discontinue or critical emerging technology may re-start the industry life cycle.
Knowledge-based view	Kogut and Zander (1992)	● Knowing how to create and transfer knowledge efficiently within an organizational context is the central competitive dimension of firms.
Resource-based view	Barney (1986)	● Firms seeking greater than normal economic performance should pursue its unique skills and capabilities (resources), rather than its competitive environment.
	Helfat et al. (2007)	● The non-incremental creation of complementary knowledge can be regarded as one of the dynamic capabilities in organization theory; it defines the capacity of a latecomer firm purposefully to adapt its resource base to fit industry-specific needs.
Learning from Asian	Mathews (2008)	● Taiwan, China and Korea, can once again provide a model for

Subject	Author(s)	Suggestions
latecomers	Mathews (2006a) Mathews (2006b) Mathews (2002)	what can be accomplished around the rest of the developing world – in India, Brazil, South and Central America, central Asia, and elsewhere.
Essential for fast-followers toward innovators	Mathews (2010) Mathews (2003) Mathews and Cho (1999)	● Understanding the evolving industry cycle is essential for latecomers to move themselves away from imitators and fast-followers, and toward innovators through resources deployment, activities designation, and routines formulation.
Knowledge Flows		
Importance of knowledge diffusion	Hu and Jaffe (2003) Nekar (2003) Romer (1986) Teece (1986) Scherer (1984) Winter (1984)	● Knowledge diffusion is aimed at stimulating economic development and innovation capability within and across firms, industries and nations.
	Eaton and Kortum (1999) Grossman and Helpman (1991) Romer (1990)	● The innovation and knowledge diffusion play a critical role in driving the growth over the industry as a whole, in which the growth rate is highly sensitive to how easily knowledge diffuses.
	Hansen (1999) David and Greve (1997) Teece, Pisano and Shuen (1997)	● Not all knowledge diffusion generates benefits, and when it does, the diffusion rate and speed are often varied and difficult to maintain.
	Henderson and Cockburn (1996)	● Technological knowledge serves as a shareable input that is used in research on various technologies and innovations.
	Lundvall (1988)	● Knowledge diffusion might be as important as knowledge creation in ensuring the effective working of a national innovation system.
Intra-national Knowledge spillover	Lee (2010) Park and Lee (2006)	● SMEs (in Taiwan) are more likely to generate a higher local-citation rate than large companies (in Korea).
Relative citation propensity	Lee and Jin (2012) Lee and Wang (2011) Lee and Yoon (2010)	● The order of patent citations is identical to the order of entry to an industry.
Collaboration ties and knowledge flows	Agrawal, Cockburn and McHale (2003)	● Patents by inventors who move from one geographic region to another continue to be cited by former collaborators from their original region, reflecting that direct ties resulting from past collaborations can continue to be a mechanism for knowledge flows even across regions.
	Balconi, Breschi and Lissoni (2002)	● The association between patent citations and geographic co-location in Italy to be greater for socially connected patent teams.
	Jaffe (1993)	● Knowledge spillovers are geographically localized.
Scientific linkage	Harhoff et al. (2003)	● Scientific linkage is the count of patent references citing papers

Subject	Author(s)	Suggestions
	Tijssen (2001) Narin and Olivastro (1998)	from the scientific literature.
	Schmoch (1993)	● The reasons for patents to cite scientific literature as prior arts.
Close relationship with the US and Japan	Jang et al. (2009) Hu (2008) Hu and Jaffe (2003)	● The US and Japan are the major knowledge sources for Taiwanese and Korean.
	Palit (2002)	● Taiwan's close relationship with the US in relation to political and economic activities.
	Borrus and Zysman (1997) Krugman (1994)	● East Asian success in high-tech industries are associated macro phenomena and their reliance on input-driven growth or close links with Japanese and American networks.
	Mathews (1997) Chang, Shih and Hsu (1994)	● The building of Taiwan's semiconductor industry relies on the support from the US.
	Coe, Helpman and Hoffmaister (1997)	● Knowledge diffusion from advanced countries to latecomer countries exhibits quite varied individual patterns.
	Grajdanzev (1942)	● Taiwan was one of Japan's colonies between 1895-1945.
Technological catch-up of Asian latecomers	Lee (2010)	● The occurrence and effectiveness of knowledge flows for the latecomers who are catching up in one technology field after another. ● Technological catch-up is most likely to occur in sectors with shorter technological cycle times and a higher initial stock of accumulated knowledge.
	Park and Lee (2006)	● The degree of appropriability is related to the size of firms, so that Taiwan (composed of SMEs) exerts a higher and more significant degree of appropriability than Korea (dominated by large *chaebols*).
Knowledge variation	Teece (2000) Kogut and Zander (1992) Winter (1984)	● Characterize knowledge variation across contexts.
East Asian Miracle	World Bank (1993)	● Internalization of foreign technology was an indispensable factor in the achievements of latecomer countries during the 1990s, described as the “East Asian Miracle”, which were achieved through intense efforts at internalizing advanced technologies and becoming integrated into the world technological mainstream
Regionalization of knowledge flows	Hu (2009)	● The regionalization of knowledge flows within East Asia has been evidenced by the patent backward citations where the US, Japan, Taiwan, and Korea are the primary sources of knowledge diffusion for East Asia.
Knowledge diffusion	Hu and Jefferson (2008)	● Taiwanese semiconductor industry investing in and transferring technology to China plays an important role in the development of China’s semiconductor industry.

Subject	Author(s)	Suggestions
	Dechezlepretre et al. (2008)	● There are North-South knowledge spillovers of climate-friendly technologies.
Limitations of use patent citations to measure knowledge flows	Hall et al., (2001) Jaffe and Trajtenberg, (1999) Jaffe et al., (2000)	● Patent citations are a noisy indicator of knowledge flows
Technological Capability		
National innovative capacity	Hu (2011) Hu and Mathews (2005)	● Under strong national policy, China is active in building technological innovation capabilities through strategic industrial sectors, such as chemical related technologies in the 1990s.
	Lee (2010)	● The emerging Asian latecomer countries have been found different empirical results in the process of building their national innovation system.
	Hu and Mathews (2008) Wu (2007) Xue (1997)	● China is integrating both large companies and SMEs along with the external knowledge into an innovation system, in which the university is acting as a hub and vertical integration network for the large companies, while the small-medium size firms help to build and reinforce the strength of the industrial value chain.
	Eun et al. (2006) Hu and Mathews (2008) Jung and Lee (2007)	● 'Forward engineering' mode in China's innovation system.
	Hu and Tseng (2007)	● The public resources of Taiwan are focused on accelerating the development of emerging sectors and technologies, the chemical industry serves as an effective linkage and catalyst in problem-solving.
	Mathews (2005) Amsden and Chu (2003) Mahmood and Singh (2003) Mathews (2002) Saxenian and Hsu (2001) Mathews and Cho (2000)	● Korean economy and its innovation activities are spearheaded by a small number of large diversified business groups, whereas the Taiwanese economy is dominated by a large number of specialized small-medium size firms along with assistance in technology upgrading from the public research institute.
	Faber and Hesen (2004) Furman et al. (2002)	● National innovative capacity depends on the overall strength of a nation's common innovative structure.
Technological capabilities of Asian latecomers	Mathews et al. (2011) Hu and Mathews (2008) Jung and Imm (2002) Viotti (2002)	● Taiwan and Korea have been moving from passive learning (production capability) to active learning (improvement capability) and then to innovation.
	Lee and Wang (2011)	● China is catching up quickly, aiming to leapfrog from building production capability to innovation with strong regional and

Subject	Author(s)	Suggestions
	Hu and Mathews (2008) Zeng and Williamson (2007)	national support.
	Hu and Jaffe (2003) Mahmood and Singh (2003)	● The technological capabilities are diverse within latecomer countries such as Taiwan and Korea, in particular differing greatly in extent of innovation.
The dynamic and technological innovation capability of firm/industry/country	Hu (2012) Mathews et al. (2011) Tan and Mathews 2010a) Tan and Mathews (2010b) Mathews (2007) Mathews (2005)	● The dynamics of a knowledge-intensive industry is not only significantly driven by patenting activities at the levels of country, industry, and firm, but has also essentially co-evolved along with the various developmental stages of the industrial cycles
Technology portfolios	Hu (2012) Ernst (1998) Schmoch (1995) Ernst (1995) Grupp (1994) Schmoch and Schnöring (1994) Brockhoff (1992)	● Using patent data to introduce the concept of technology portfolios, demonstrating the viability of various indicators including relative growth rate, relative patent position, and revealed patent advantage.
Technological advance of East Asian latecomers	Hu and Mathews (2005) Kim (1997) Hobday (1995)	● The transition of East Asian latecomers from imitators to innovators.
Fast follower strategy	Mathews (2006)	● The technology leverage effect in latecomers and the strategies used by fast followers, took off only after 1994.
Technology platform	Kim (2003) Tushman et al. (1997) Kim and Kogut (1996)	● Technology platform enables the creation of products and processes that support present or future development by sharing components and production processes, which also allows a company to develop differentiated products faster and more cheaply, increase the flexibility and responsiveness of the manufacturing processes.
Patent stock and endogenous knowledge sources	Altenburg, Schmitz and Stamm (2008) Hu (2004)	● Taiwan's patent stock has accumulated and already become the major endogenous knowledge source for Taiwan's industrial development.
Technological diversification	Leten et al.(2007)	● Firm's Technological diversification is linked to its technological performance.
Supplier network	Sutton (2005)	● Supplier relations are used to accelerate technological capability enhancement, combined sometimes with a 'local content' rule to force advanced firms into closer relations with their suppliers.
Evolutionary theory of the capabilities and behavior of firms	Nelson and Winter (1982)	● "Evolutionary theory is useful in analyzing a wide range of phenomena associated with economic change stemming either from shifts in product demand or factor supply condition, or innovation on the part of firms."

Subject	Author(s)	Suggestions
Technology diversity	Lin, Chen and Wu (2006)	● It is effective for firms with high technology stocks to diversify their R&D activities to a broad spectrum of technology fields and vice versa
Technology cycle time	Lee (2012)	● Short-cycle or low-originality technologies provide new entrants or latecomers 'windows of opportunity' for building of technological capabilities and localization of knowledge creation and diffusion.
Techno-globalism and techno-nationalism	Miller (1994) Montresor (2001)	● Understanding the techno-globalism is equivalent to or not less than the techno-nationalism in developing innovation capabilities.

Chapter 4

Data, Measures, and Methodology

To achieve the research goal of this study, to explore the evolving knowledge flows and technological innovation capabilities of the solar PV industries in Taiwan, Korea, and China, two separate analytical methodologies are applied here, using the USPTO and EPO worldwide (esp@cenet) databases. The first stage is aimed at aggregating the numerous solar PV-related patent data in the USPTO into a comprehensive and systematic dataset detailing the evolving solar PV technology generations from the first to the second and third generations over the period 1984-2008. According to Kim (2003) and Tushman, Anderson and O'Reilly (1997) on the evolving industrial cycle from emergence to growth, the innovation activity in the global solar PV industry is realised in a consolidated technology platform, for which a key successful factor in the market is the creation of products and processes that support present or future development. Thus, the results derived from the first stage are then further verified by the comparisons of technological innovation capabilities, in terms of solar PV technology platforms built in the three countries in the second stage, using the *esp@cenet* worldwide patent database from 1978-2008 to cross check and confirm the validity and robustness of the earlier results. In addition, the second stage methodology is aimed at shedding light on the possible dominant solar PV technology, because of the critical role of production in driving the development of the global solar PV industry. In summary, this study tends to explore the evolution paths of knowledge flows and to verify the innovation capabilities built on the technology platform in the solar PV industries of Taiwan, Korea, and China, for which the accumulated resources and capabilities and national strategies are critical.

4.1 The Data

To achieve the goals of this study, it is necessary to extract the solar PV-related technologies as precisely as possible from the patent database. Keyword search has been the most popular and convenient method to locate a certain technology in patent-related research (for examples, see Bengisu and Nekhili, 2006; Bettencourt, Kaiser, Kaur, Castillo-Chávez and Wojick, 2008; Lee and Yoon, 2010; Wong, Ho and Chan, 2007). However, using keyword search alone on patent datasets is likely to be of limited value, because many patent documents do not contain the expected keywords, while those patents containing them are not always relevant (Fabry, Ernst, Langholz, & Köster, 2006; Hu, 2008; Taylor et al., 2007:67-68). De la Tour et al. (2011) applied related solar PV keywords combined with a range of IPCs to extract China’s PV patents and group them into four value-chain sectors (silicon, wafers, cells, and modules). However, the aim of this study is to explore the evolving technological innovation capability and knowledge sources, rather than to build value chain innovation capability, the target of De la Tour et al. (2011). Thus, in order to extract the related solar PV patents as precisely as possible, this study adopts and implements a novel three-stage filtering approach as follows.

(1) This study checked the correspondence in meaning between the **solar PV keywords –** solar cell, PV, thin film solar, CdTe, CIGS, BIPV, high concentration solar, organic solar, and dye sensitized solar cell **–** across various technology generations and the **International Patent Classifications (IPCs)** defined by the World Intellectual Property Organization (WIPO). In total, 43 four-digit IPCs were derived from the solar PV-related keywords (see Appendix A for details).[23]

[23] The details of keywords and IPCs search are available at : http://v3.espacenet.com/eclasrch?classification=ecla&locale=en_V3.

(2) To test whether the 43 IPCs so extracted are used in practice, this study investigated the patenting activities of 76 international solar PV specialization companies from 1977 to 2009 (see Appendix B for company list). In total, 828 patents containing 80 four-digit IPCs granted to these companies were extracted from the EPO worldwide database. This study further sets out to cross-check the extracted 80 four-digit IPCs with the 43 IPCs derived from the keyword matching in stage one and so to identify the 13 most significant four-digit IPCs, as seen in Appendix C.

(3) To further verify the accuracy of the 13 identified IPCs, this study continued to seek help from solar PV technology experts to verify the reliability of the datasets. As they suggested, this study excluded IPC F24J02 (solar heat applications) and IPC B23K26 (laser welding), which are regarded as less relevant to solar PV technology. Meanwhile, they advised the addition of one IPC, H01G09/028 (organic semiconductor electrolytes), which is highly relevant to third generation solar PV. Consequently, 12 IPCs associated with the later stages of the solar PV technology were appeared up to the last year 2009 in the investigation period.

It is found that some of the resulting groups are either fundamental or relevant to various generations of solar PV technologies due to technological interdependence and co-evolution. For example, IPC H01L31 is defined as PV semiconductor devices generally, which is the elementary technology for 1G/2G/3G, so that it applies to all three generations. This becomes an interpretation limitation for this study, because five of the 12 IPCs (i.e. E04D13/18, H01L21, H01L27, H01L31, and H02N6) form a technological platform and can be attributed to any one of the three generations. However, in order to test the research propositions in this study, the IPCs classified in the first generation solar PV include dedicated technologies for silicon based first generation, as well as the applicable technologies for all the three generations; while those IPCs falling into the second and third generations clearly and specifically refer to thin film and organic compound solar PV technologies respectively. Accordingly, this study identifies three different solar PV generations as shown in Table 4.1

Table 4.1 Twelve Solar PV Related IPCs and Technological Generations

Technology Generation	IPC	Technology Function
Silicon Based First Generation	C30B15	Single-crystal growth
	C30B28	Production of polycrystalline material
	C30B29	Single crystals or polycrystalline materials
	E04D13/18	Solar panel roof
	H01L21	Semiconductor manufacturing
	H01L27	Semiconductor devices on a common substrate
	H01L31	PV semiconductor devices
	H02N6	PV generators
Thin-film Based Second Generation	C23C14	Coating by vacuum evaporation
	C23C16	Chemical vapour deposition
Organic Compounds Third Generation	H01L51	Organic solid state devices
	H01G09/028	Organic semiconducting electrolytes

Note: See Appendix D for the official definitions of the twelve identified solar PV IPCs.

Ultimately, these twelve IPCs were used to extract the solar PV-related patents registered by Taiwan, Korea, and China from the USPTO and the *esp@cenet* worldwide patent database respectively to explore the evolving knowledge flows and innovation capabilities for the solar

PV-related technologies in the three latecomers.[24] Altogether, this study extracts 19,105 patents from the USPTO and 75,540 patents from the *esp@cenet*, granted to the applicants from Taiwan, China, and Korea in relation to solar PV technologies. The two-stage data measures and methodologies in respect of the two research questions and corresponding research propositions of this study are addressed below.

4.2 Stage One –Knowledge Flows

The evolving path of knowledge flows in solar PV first generation, second generation, and third generation technologies uses the patenting datasets extracted from the USPTO over the period of 1984-2008 by way of four dimensions: international knowledge flows, intra-national knowledge flows, relatively propensity citations, and scientific knowledge linkage. The definitions, datasets, and measures of the four dimensions are addressed below.

4.2.1 International Knowledge Flows Measured via Backward Citations

Patent backward citation reveals the "prior art" upon which later patent knowledge is based. In terms of aggregate country level in patent backward citations, the fact that country X is cited by country Y indicates that country X is the origin of international knowledge flows to country Y. By analysing the country of origin of patent backward citations, this study traces the sources of knowledge as well as the developmental trajectory of technology capability at country level. Hu and Jaffe (2003) found that both Korea and Taiwan rely heavily on knowledge diffused from the US and Japan in the process of building innovative capability. Moreover, their study also demonstrates that the proportion of citations made by Korea and Taiwan to the US and Japan converges over time.

[24] The esp@cenet is a network of EPO databases. It contains over 60 million patent documents from all over the world and offers the general public free access to worldwide patent information via the Internet. See their website http://www.epo.org/patents/patent-information/free/espacenet.html for details.

4.2.2 Intra-national Knowledge Flows Measured via Local-citations

Intra-national knowledge flows are regarded as a country's local-citations (defined as citations of patents registered by firms from the same country), which indicates the absorptive or internalization capability within the country. In order to clarify the innovation capability in constructing various drivers of the internal innovation capability, this study allocates solar PV innovators into four sectors: (1) private sector; (2) public research institute; (3) university; and (4) individuals. Lee and Yoon (2010) suggest that intra-national knowledge flows frequently occur in a country with a superior technology internalization capability, and that it is reasonable to assume that the degree of intra-national knowledge flows (represented by the degree of absorptive capacity and internalization of innovation capability) is higher in the first generation solar PV than in later generations. In the emerging new generation solar PV, mass production activity still requires the exploration of advanced basic technology sourced from the US and Japan. This study thus focuses on the different impacts of intra-national knowledge flows in respect to the first, second and third generations in the four sectors.

4.2.3 Scientific Linkage Measured via Scientific Paper References

Scientific linkage is measured by counting patent references citing papers from the scientific literature (Harhoff, Scherer, & Vopel, 2003; Narin & Olivastro, 1998; Tijssen, 2001). The reasons for patents to cite scientific literature as prior arts are various (Schmoch, 1993), nevertheless, it is a critical indicator of the quality of knowledge for building internalization capability, and is particularly essential for the technology latecomers (Hu & Mathews, 2008). Increasingly, particularly in the emerging new technology, patents cite scientific literature. A high level of scientific linkage thus indicates that a patent is building on a technology base grounded in advances in science. The first generation technology of solar PV is mature, so the best opportunity for latecomers to pursue higher value-added innovations, as well as to gain competitive advantage in the global market, is through the development of emerging new generation technologies. Taking this perspective, process innovation in the latecomer countries not only has to build on internalizing existing production knowledge but also has to take cutting-edge scientific knowledge into account. It is believed that China may be following a leapfrog strategy in the building of solar PV industry, therefore the scientific linkage of its patents might be high, whereas Taiwan is probably adopting a fast follower strategy, focused on the dominant technology, and therefore its scientific linkage might not be as high.

4.2.4 Relative Citation Propensity Measured via Citation Comparison with other countries

The relative citation propensity compares patent citing behaviours amongst the countries selected – a concept introduced by Lee and Yoon (2010). A notion of relative citation propensity similar to that of Lee and Yoon (2010: 559) is used in this study, where the relative propensity of country i’s patents to cite country j’s patents is defined as:

$$\frac{N_{ijt}/N_{it}}{N_{jt}/N_t}$$

where

N_{ijt}: citations made by country i to country j in year t.

N_{it}: all citations made by country i in year t.

N_{jt}: citations made to country j in year t, excluding those by country i.

N_t: all citations made in year t, excluding those by country i.

This formulation means that the greater the value, the higher the citation tendency of the correspond country. For example, if the relative citation propensity of country i to cite country j is greater than its propensity to cite any other comparable countries, it indicates that, in comparison, country i has the highest tendency to cite country j out of all the selected countries.

4.3 Stage Two – Technological Innovation Capabilities

To verify and extend the results derived from stage one in the USPTO, the second stage is mainly focused on the exploration and variation comparisons of the solar PV technological innovation capabilities in the three latecomer countries Taiwan, China, and Korea by examining the *esp@cenet* worldwide patent database from 1978-2008.

4.3.1 Factor Analysis

There are several methods for selecting the most important factors in the present context that can help to reduce the complexity of the results, of these, factor analysis is a statistical method used to recognize the interdependencies between variables and reduce the set of variables in a dataset (Hair, Anderson, Tatham, & Black, 1995). Factors are considered significant and retained for rotation only if they have an eigenvalue equal to or greater than 1 and a factor loading equal to or greater than 0.50. In other words, the larger the factor loading, the greater the identified significance of the factor in a given technology field. Consequently, the significant factors are classified into groups, and each group is given the name of a technology platform according to the common attributes. The verified technology platforms are then taken as a base to measure technological innovation capabilities through technology portfolios, in terms of technological attractiveness (relative growth rate and relative development of growth rate), relative patent position, and revealed patent advantage.

4.3.2 Measures of Technological Innovation Capability

Technology Portfolios

Brockhoff (1992) first used patent data to introduce the concept of technology portfolios, while researchers such as Ernst (1995); Hu (2012); Schmoch (1995) followed this and demonstrated the viability of various indicators, including relative growth rate, relative patent position, and revealed patent advantage. Even though their targets are different, it is widely recognized that technology portfolios measured by patent data contain useful information to estimate either a nation's technological innovation capacity or a company's R&D strategy in a specific industry.

Technological Attractiveness

Technology attractiveness is measured by relative growth rate (RGR), which refers to the average growth rate of patents granted for a particular technology platform relative to the average growth rate of all patents granted for all the technology platforms over the total period of analysis. However, even though the global solar PV industry has been developing for half a century, it was not profitable until the late 1990s, when countries such as Germany, Japan, and Spain sequentially launched the "feed-in tariffs" (FITs) policies (Ren21, 2009). Alternatively, it is appropriate to use the previous 21-year period (1978-1998) and the latter 10-year period (1999-2008) to calculate the relative development of growth rate (RDGR) in terms of the average growth rate of patents granted for the specific technology platform during the period 1999 to 2008 relative to the average growth rate of patents granted for the same technology platform in the preceding period (1978-1998).

Relative Patent Position (RPP)

Brockhoff (1992), H. Ernst (1998), Brockhoff (1992) and Ernst (1998) applied relative patent position (RPP) for patent portfolios to illustrate a company's R&D strategy. This study refers the RPP of a country/company in a particular technology platform to measure the number of patents owned by the country/company relative to the number of patents of the most active competitor country/company in that particular technology platform. That is, in this case the most prolific patentee acts as a benchmark, with the maximum value of the RPP in each technology platform being set as unity. This RPP acts as an indicator of the scale and intensity of R&D for the country/company in the specified industry.

Revealed Patent Advantage (RPA)

A number of studies have applied RPA in the comparison of company or country level technological innovation capabilities (e.g. Grupp, 1994; Hu, 2012; Schmoch & Schnöring, 1994). RPA is analogous to the concept of Revealed Comparative Advantage (RCA) and used to evaluate comparative advantage on the basis of a country's/company's relative specialization in exports. The higher the value of RPA in a certain technology platform for a country/company, the more that the country/company produces a higher level of technological specialization. That is, a country/company is operating at a higher level of technological efficiency when it produces a certain level of output with the least amount of input. RPA thus represented the relative technological efficiency of a country/company in relation to its technology platform. This study adopts RPA to measure the relative strength of different technological platforms for each country/company, and is thus able to represent the relative technological efficiency of a country/company in relation to the specific technology platform. RPA is defined by the following formula:

$$\mathrm{RPAij} = 100 \times \tanh\left(\ln\left(\frac{P_{ij} / \sum_i P_{ij}}{\sum_j P_{ij} / \sum_{ij} P_{ij}}\right)\right)$$

P_{ij} refers to the number of granted patents for the technology platform j in country/company i.

Chapter 5

Empirical Results

5.1 Stage One - Knowledge Flows

5.1.1 Overall Trends

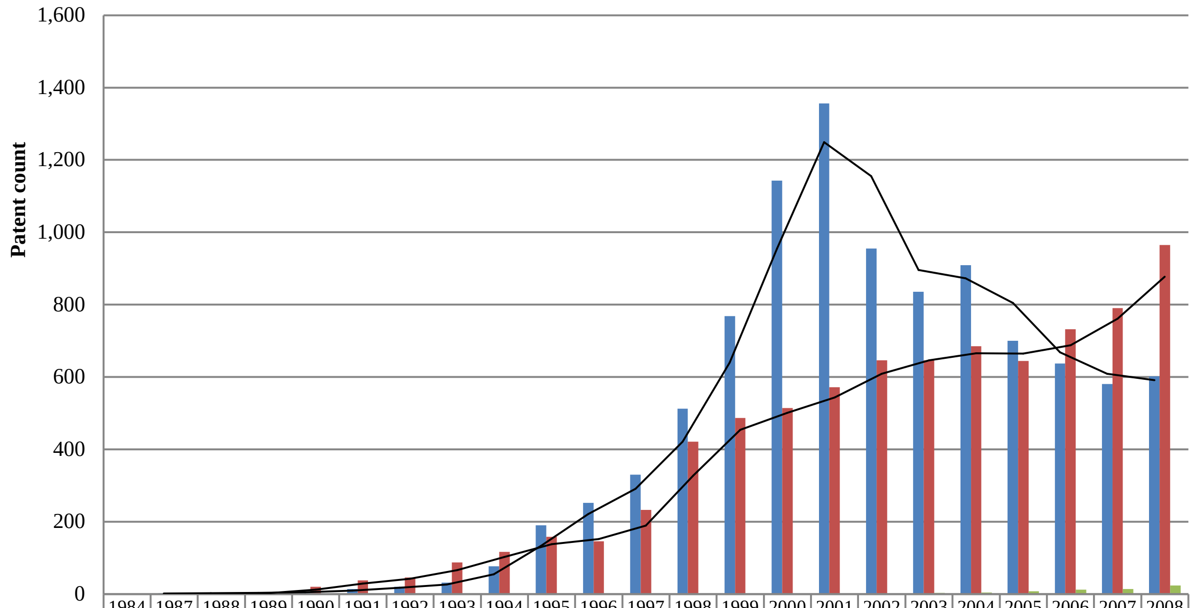
In total, this study has further extracted 19,105 patents related to solar PV granted to Taiwan, Korea, and China by the USPTO from 1984 to 2008. As shown in Table 5.1, the dataset includes 17,952 patents for silicon-based and common applicable first-generation technologies, and 1,153 patents for technologies in the emerging new generations (thin film and organic compounds). Amongst these are 10,351 patents for Taiwan, 8,671 for Korea, and 83 for China. In terms of backward citation, 117,998 patent citations in total are derived from the above 19,105 solar PV-related patents. Of these, 59,419 backward citations were made by Taiwan, 58,091 by Korea, and 488 by China.

Table 5.1 Patents Granted and Backward Citation Counts in the Solar PV for Taiwan, Korea, and China in the USPTO, 1984 - 2008

	Granted patent counts			Backward citation counts		
	First generation	New generations	Total	First generation	New generations	Total
Taiwan	9,929	422	10,351	56,697	2,722	59,419
Korea	7,952	719	8,671	52,519	5,572	58,091
China	71	12	83	414	74	488
Total	17,952	1,153	19,105	109,630	8,368	117,998

Source: USPTO: compiled by the author.

Based on the development trajectory of the solar PV industry in the three latecomers, the dynamics of the knowledge flows between Taiwan's and Korea's solar PV industries may be divided into three periods: (1) before 1994; (2) 1995-2004; and (3) 2005-2008 (Mathews et al., 2011). Before 1994, the development of Korea's solar PV technology was more active than that of Taiwan, as shown in Figure 5.1, which may be due to its earlier engagement in the global semiconductor and flat panel display industries. During the period 1995-2004, it may be seen that Taiwan's solar PV patent counts increased dramatically over time and were well in advance of those of Korea (and certainly of China), while Taiwan was putting a great deal of effort into the development of the two strategic industries (semiconductors and flat panel displays). After Taiwan's patenting rate reached a historically high point of 1,356 in 2001, it then decreased significantly and since 2004 has been overtaken by Korea. It is interesting to see that, while the global solar PV market has rapidly expanded since the 2000s, process innovation (as measured by patents) in Taiwan is essentially decreasing, while Korea (without mass production as yet) is still continuously growing. Although the degree of China's patenting activity in first generation solar PV is low relative to that of Korea and Taiwan, China seems to have started to build its own internal technological capability in response to the demands for solar PV becoming obvious in recent years.



	1984	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Taiwan	1	2	2	5	5	14	20	32	77	190	252	330	512	768	1143	1356	955	836	909	700	637	581	602
Korea	0	1	0	4	20	38	46	87	117	158	146	233	421	487	514	572	646	646	685	644	732	790	965
China	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	1	3	4	8	12	14	24

Source: USPTO, and compiled by the author.

Figure 5.1 Annual US Patents Granted to Taiwan, Korea, and China in First Generation Solar PV, 1984-2008

The significant decrease since 2001 of patenting activity in Taiwan's first generation solar PV indicates a strategic shift in Taiwan's evolving industrial development. This is derived particularly from Taiwan's semiconductor sector, which dominates more than 60% of Taiwan's total patenting activity in the USPTO (Hu, 2004). Three factors driving this decline have been identified: (1) Taiwan's entry into the WTO in 2002; (2) the nature of resource-limited SMEs; and (3) accumulation and building of technological capability, especially in the semiconductor sector. These three aspects are discussed in greater detail below.

When China entered the WTO in 2001, Taiwan followed, joining in 2002, so that Taiwanese firms certainly face greater pressure from international competition, especially from low-cost countries such as China, so that many of them have been forced to become aware of the importance of intellectual property management, either to build entry barriers or to increase their competitive advantages in the global market, especially in patents for high-tech products, leading subsequently to a series of revolutions in patents and patenting strategy in Taiwan. A critical milestone in this strategic movement was the patent auction platform set up by ITRI in 2003, aimed at improving the management and commercialization of patents for all industries in Taiwan.

Such a turning point in the early 2000s came about due to the nature of Taiwan's SMEs, and because accumulated technological capability had already reached a threshold. Indeed, starting in the 2000s, Taiwanese firms began initiating active patent litigation in the global market.[25] Hall and Ziedonis (2001) state that patent stock is a useful and effective bargaining power for the US semiconductor firms but, because patenting costs are heavy, these firms can only benefit from such "patent portfolio races" through increased efficiency in managing intellectual property rights.[26] This study offers an explanation for this as follows: as Taiwan's patent stock has accumulated and already become the major endogenous knowledge source for Taiwan's industrial development, the resource-limited Taiwanese firms started to quit the expensive game of "patent portfolio races" to shift their focus to pursuing the quality of patents rather than merely accumulating a number of patents as a bargaining power. This argument is also supported by the decline in patent numbers awarded to Taiwan's semiconductor giants TSMC and UMC (as well as to the largest public research institute,

[25] For the first time, TSMC successfully filed an active claim to invalidate a US Syndia patent in 2003, implying a stronger patent portfolio and an advance in TSMC's IP management. Since then, many more Taiwanese companies have started active but defensive patent litigation.

[26] According to USPTO, each patent application must pay a filing fee ranging from USD 220 to over USD 1000, an examination fee of USD 140~650, a patent issue fee of USD 860~1510 if the application is successful, and various patent maintenance fees, depending on the patent types, number of claims, and years since issue (USPTO, www.uspto.gov).

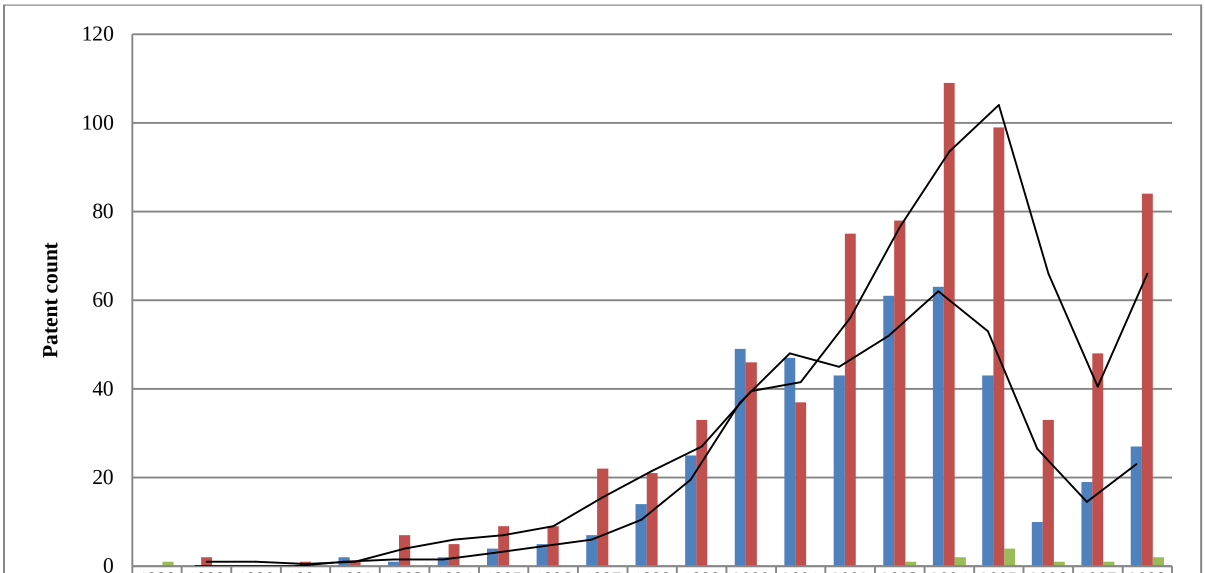
ITRI) since 2001 while they were involved in setting up internal regulations for managing intellectual property rights and were forming a patents evaluation committee (Hu, 2004: 138).[27]

Meanwhile, the steady growth of Korea's patenting activity in the first generation solar PV over recent decades could be due to its abundantly resourced *chaebols*, with its national technology strategy toward patents stressing quantity rather than quality. The contrasting patenting rates between Taiwan and Korea indicate their different technology development strategies in developing the first generation solar PV sector. Note that Korea has not yet begun production of solar PV cells and panels.

Figure 5.2 shows the annual patents granted to the three latecomers in the emerging new generation solar PV. Although Korea has not yet entered the global solar PV industry, its early involvement in the technological development of the emerging new generation solar PV can be seen to be in advance of Taiwan, particularly since the 2000s, while Samsung and LG are believed to be in their preparation stage.[28] In 2004, the number of patents granted to Korea in the emerging new generations of PV technology reached a historical high, being awarded 109 patents while Taiwan had 63 patents and China had only two patents. On the other hand, China's patenting rate has emerged only in recent years and is not impressive at all in the USPTO. These datasets imply that Taiwan's innovation capability in the solar PV industry tends to be built on the dominant silicon-based technology while Korea may adopt a different entry strategy by focusing on the emerging generations of new technologies. Despite

[27] This argument is based on the conducted interviews with Taiwan's TSMC and ITRI in 2004, and recorded by Hu (2004) for her doctoral thesis.
[28] For details, see DisplaySearch, '*Quarterly PV Cell Capacity Database & Trends Reports*'. Available at: http://www.displaysearch.com.tw/press_releases/20090812.aspx

its No.1 position in global solar PV production, China's lower degree of patenting rate in the emerging new generations implies a relatively weaker innovation capability in the complementary technology areas, such as semiconductors or FPDs.



	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Taiwan	0	0	0	0	2	1	2	4	5	7	14	25	49	47	43	61	63	43	10	19	27
Korea	0	2	0	1	1	7	5	9	9	22	21	33	46	37	75	78	109	99	33	48	84
China	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	1	1	2

Source: USPTO, and compiled by the author.

Figure 5.2 Annual US Patents Granted to Taiwan, Korea, and China in New Generation Solar PV (2G+3G), 1988-2008.

Summary: The most striking phenomenon, as shown in Figure 5.2, is the dramatic decline in the numbers of patents granted to both Taiwan and Korea during 2005 and 2006 and the bounce back to a rising track since 2007 (even though the numbers are smaller, China has shown the same pattern as Taiwan and Korea). The dramatic decline from 2005-2006 is most likely derived from new policy instruments in the European countries, particularly the aggressive solar PV investments that have been announced by some European countries and the 'feed-in tariffs' (FITs) enforced in Germany since 2002. In order to respond to immediate market demands, the firms in Taiwan chose to incorporate 'turnkey equipment' of the first generation solar PV into their production activity. As the R&D crowding out effect rises, patenting activity for new generation solar PV with low manufacturing feasibility or poor transfer efficiency decreases (recalling that there are two to three year time lags for patents to be awarded).

However, the patenting activity in the **new generation solar PV** has started to increase again since 2007. This is seen as a trade-off effect with the silicon-based first generation solar PV, because the price of polysilicon materials has increased rapidly from US$10/kg in 2002, to US$66/kg in 2005, skyrocketing to a high of US$480/kg in 2008 (iSupply, 2009). This shortage of polysilicon materials, is suggested to have promoted the growth of patenting activity in the new generation solar PV since 2008.

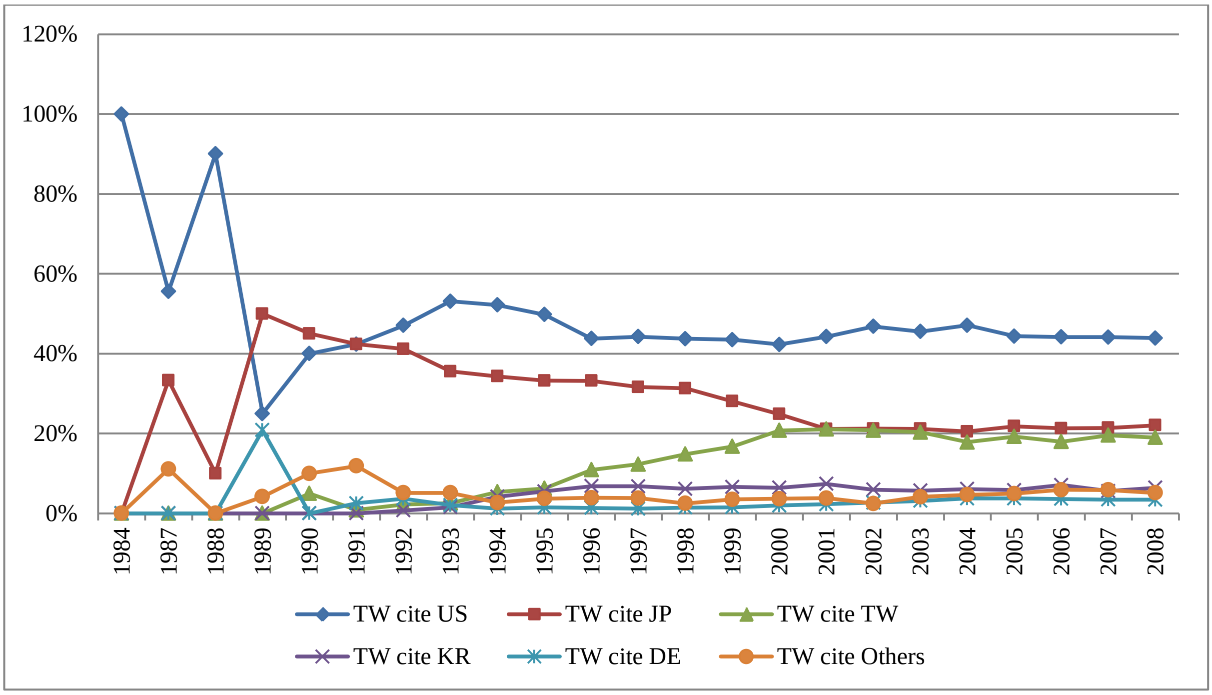
5.1.2 International Knowledge Flows

This study uses backward citations to examine international knowledge flows for the three solar PV latecomers. In total, 117,998 backward citations were traced and categorized according to the country of origin – US, Japan, Taiwan, Korea, and Germany. The remaining patents not belonging to the above countries are grouped as 'others' (see Appendix E-1 to Appendix E-6 for the detailed country list and the counts of backward citations). Interestingly, the patterns of international knowledge flows in relation to Taiwan, Korea, and China are dissimilar. This study reports these below.

Taiwan

The technology of Taiwan's involvement in first generation solar PV relies heavily on internalization capability sourced from both US and Japan, as shown in Figure 5.3, showing that solar PVs are following the same overall catch-up pattern as registered earlier in industries like semiconductors and flat panel displays. These two technically advanced countries contributed over 70% of the total international knowledge spillover to Taiwan before the year 2000 and still provide over 65% today. Notably, the US contributes over 40% of total international knowledge flows to Taiwan and clearly remains its most important source of knowledge. The increasing volume of local-citations, namely citations of patents registered by firms from the same country, confirms success in establishing R&D capacity by the latecomers. Taiwan has been citing patents registered by Taiwanese firms since 1990; the local-citation rate kept increasing during the 1990s, reaching as high as 20%, and converging in 2001 to a share equivalent to that of Japan (at the same time that Taiwan's patenting activity for the first generation solar PV was significantly declining, as shown in Figure 5.3). Notably, Taiwan's reliance on Japanese knowledge has gradually decreased from 40% in the early 1990s to only a half of that, 20%, by the 2000s. This declining share has been largely made up by local-citations from Taiwan itself, while those from the US remained at the same level (around 50%). This implies a substitution effect, in terms of codified patent knowledge, from Japan and from Taiwan's internal knowledge sources, as well as revealing that sources for Taiwan are different from those for US and Japan. This interesting distinction is examined in greater detail in the discussion section below.

Apart from the patent citations from US, Japan and Taiwan itself, Korea and Germany, since the 2000s, have contributed only a small fraction, constituting less than 10% in total of the first generation solar PV knowledge to Taiwan.

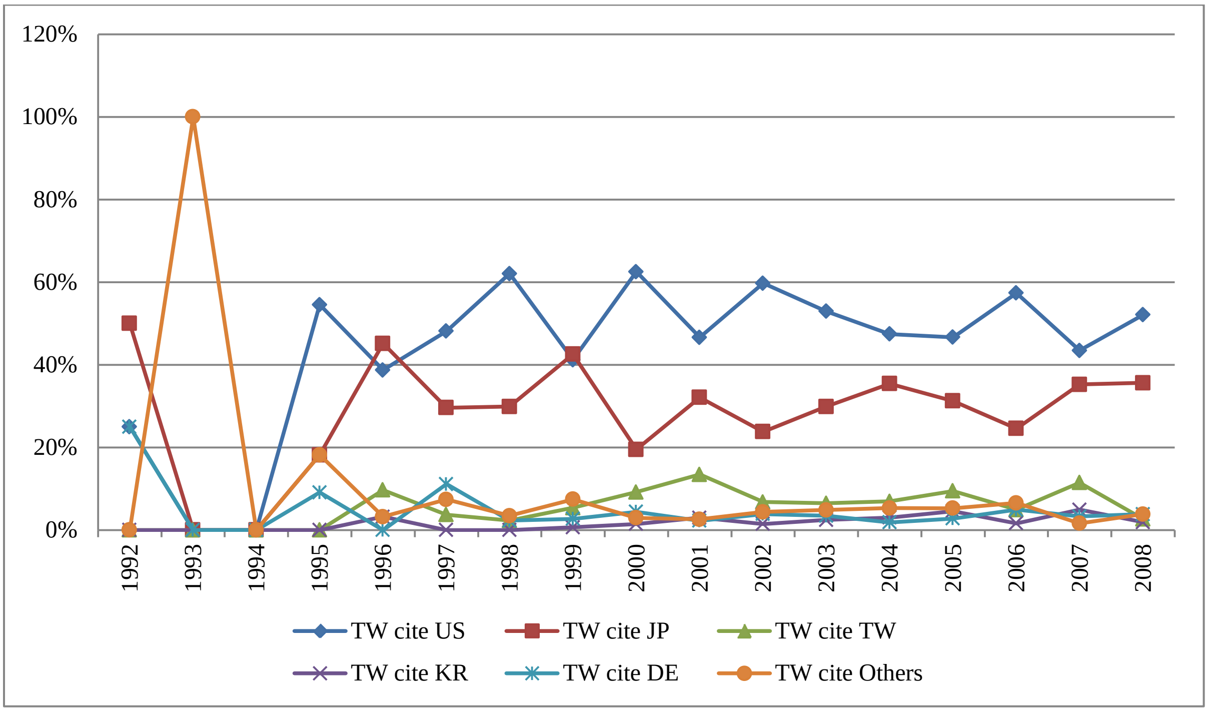


Source: USPTO and EPO, and compiled by the author.

Note: JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.3 Share of Country Origins of Backward Citations for Taiwan's First Generation Solar PV, 1984-2008

Figure 5.4 shows that the international knowledge flows in Taiwan's emerging new generation solar PV have been continuously active since 1994. It is clear that the innovation capability in the emerging new generations is particularly heavily reliant on the knowledge diffused from both the US and Japan, which account for more than 70% of total citations. Impressively, the US dominates around 50% of knowledge sources for Taiwan, which is equivalent to that for Taiwan's first generation solar PV. While local-citation has not become significant in Taiwan's emerging new generation solar PV technologies, Japan still retains its influence on the second place with a 20-40% share of total citations made by Taiwan. This, again, provides evidence to support the argument of this study for the substitution effect between knowledge sources from Taiwan and Japan.



Source: USPTO and EPO, and compiled by the author.

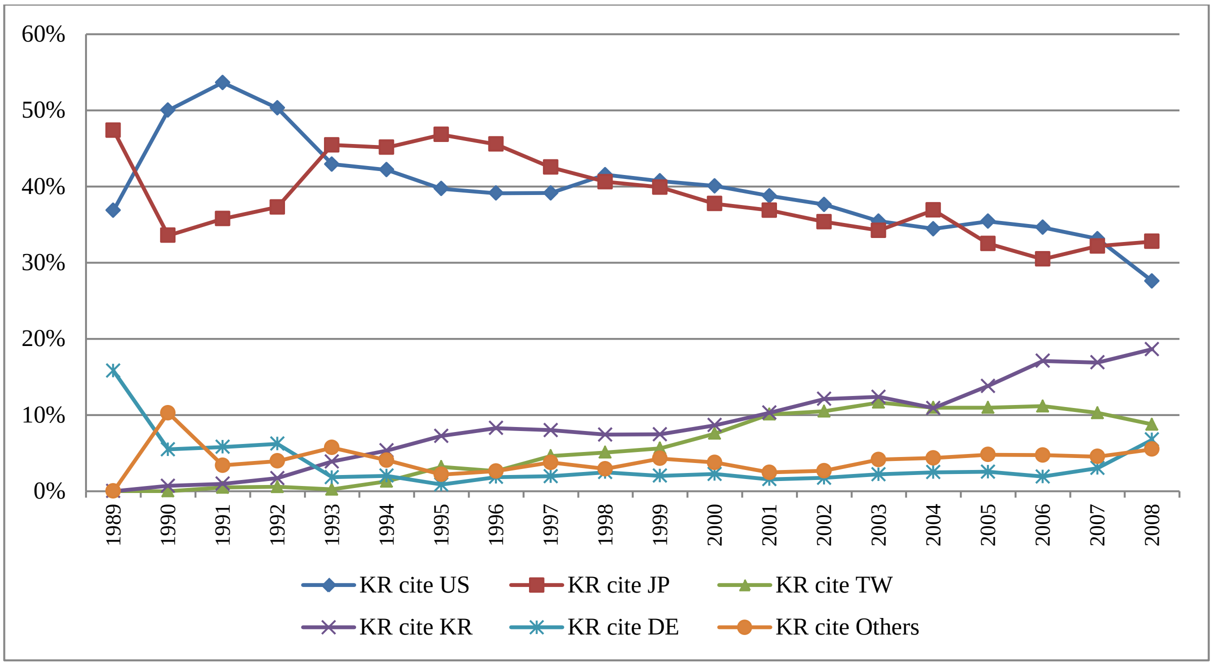
Note: JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.4 Share of Country Origins of Backward Citations for Taiwan's Emerging New Generation Solar PV (2G+3G), 1992-2008

Korea

As with Taiwan, the US and Japan are the most important knowledge sources in building Korean innovation capability in the first generation solar PV industry, as shown in Figure 5.5 The US contributed more than 50% of international knowledge for Korea before the 1990s, with Japan ranked as the second knowledge source, but it then jumped to become Korea's main knowledge source during 1993-1997. The share of the US in contributing to Korea's international knowledge flows halved, from 54% in 1991 to only 27% in 2008, while that of Japan decreased from 46% in 1993 to 32% in 2008. It is interesting to see that Korea has reduced its reliance on knowledge sources from both the US and Japan in the first generation solar PV over recent decades. Notably, the decline in the share from the US and Japan have been substantially replaced by an increasing share from Korea's internal knowledge source

(19% local-citation rate in 2008) as well as from Taiwan (around 10% since 2001). Compared with Taiwan, this substitution effect of Korea's international knowledge sources in the first generation solar PV applies not only to Japan but also to the US. Together with the case of Taiwan, these substitution effects may be interpreted as deriving from a range of technology strategies adopted by the technology latecomers so as to generate variations in their international knowledge flows. This argument will find further support when examining the evolution of scientific linkage, in Section 5.4 below.

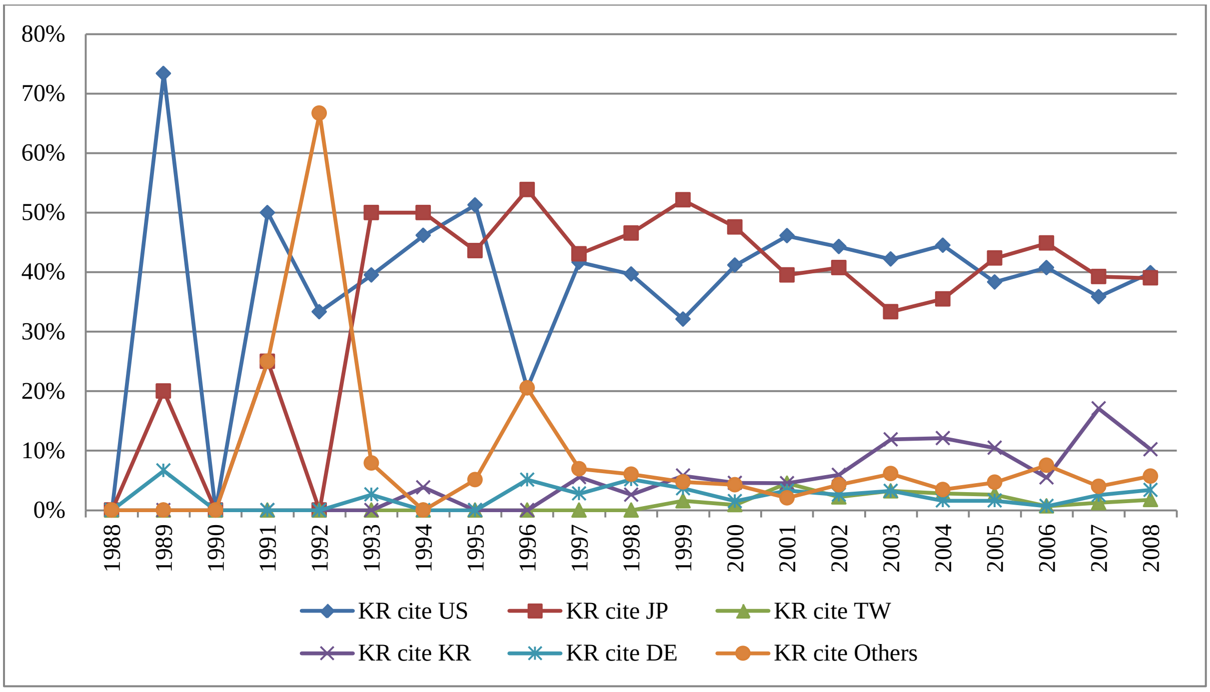


Source: USPTO and EPO, and compiled by the author.

Note: JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.5 Share of Country Origins of Backward Citations for Korea's First Generation Solar PV, 1989-2008

Like Taiwan, Korea's knowledge sources in the emerging new generation solar PV technologies (2G + 3G) are mainly from the US and Japan, as shown in Figure 5.6. In this emerging sector, US has constantly dominated around 40% of the total inbound knowledge flows for Korea since the 2000s, while Japan has also provided around 40% and has become the No.1 knowledge source for Korea's new generation solar PV technologies since 2005. It is noted that Korea's local-citations have only became significant since the 2000s, reaching 10% only in 2003, indicating that the building of innovation capability in the new generation solar PV was just kicking off at that time. Indeed, the media reported that LG announced its investment in the solar PV business in 2004, followed by Samsung in 2005. As this is an emerging sector, it is not surprising that the international knowledge flows from other countries for this emerging generation remain at a low level.



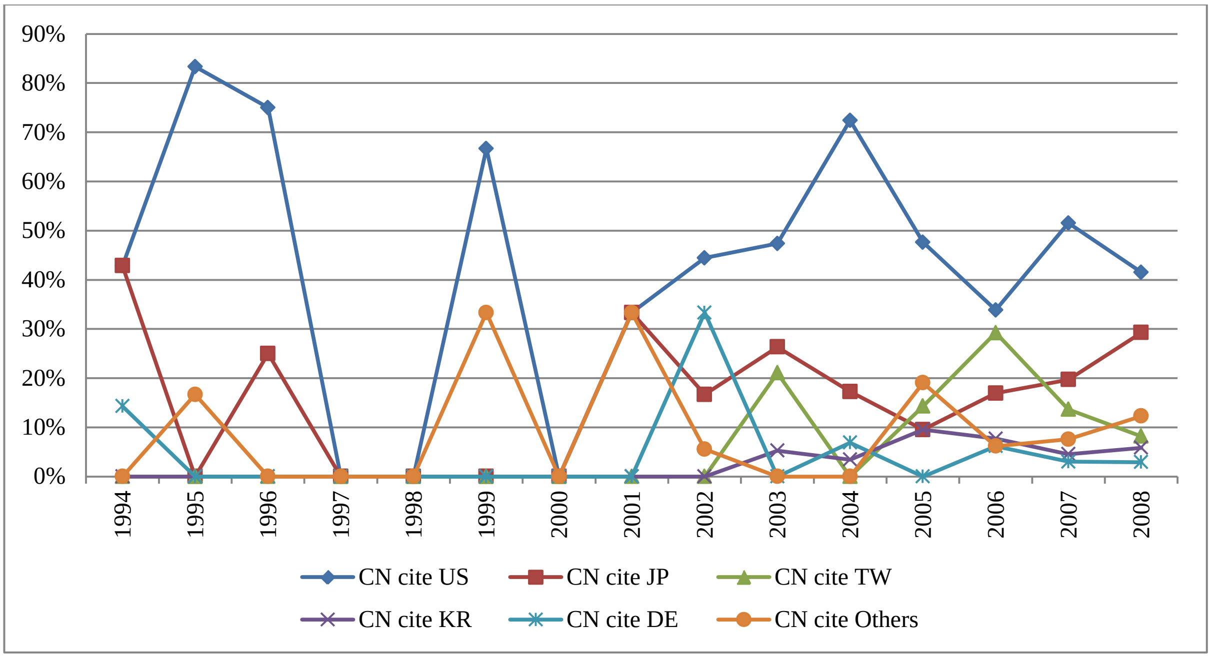
Source: USPTO and EPO, and compiled by the author.

Note: JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.6 Share of Country Origins of Backward Citations for Korea's Emerging New Generation Solar PV (2G+3G), 1988-2008

China

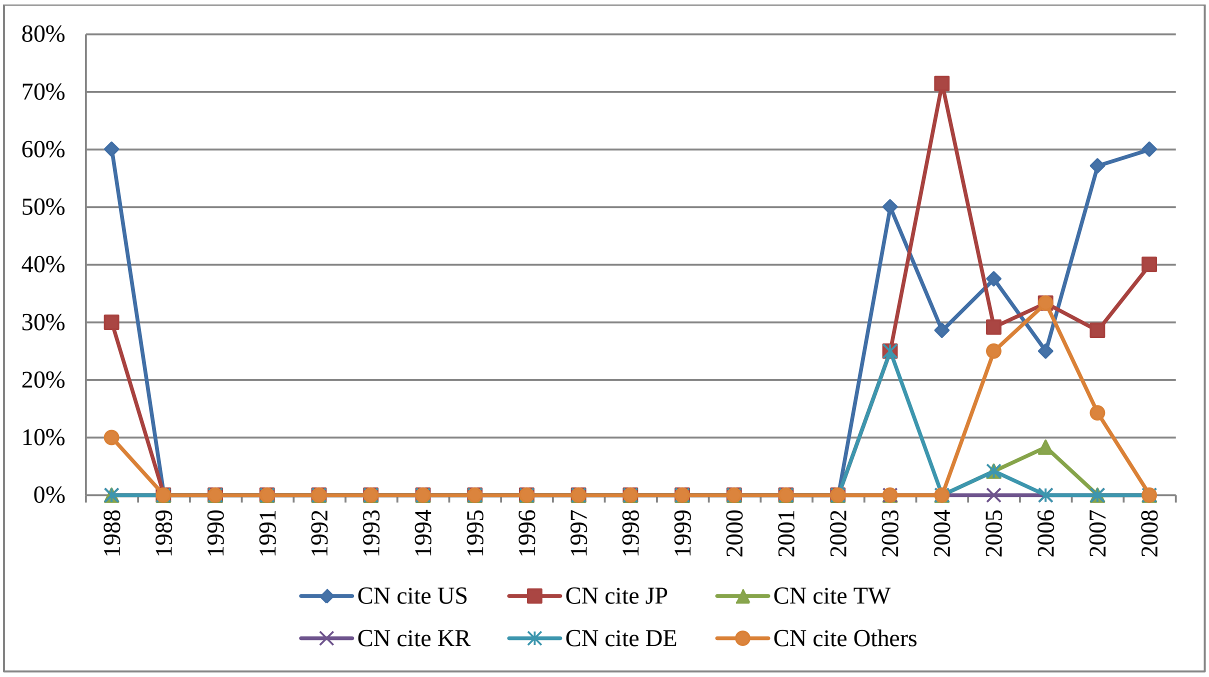
As seen in Figures 5.7 to 5.8, China's patenting activity has emerged only since the 2000s, with patenting rates relatively lower than Taiwan and Korea. Although the knowledge sources have fluctuated, China's main knowledge sources, like Taiwan and Korea, are the US and Japan. Innovation activity of China's first generation solar PV started in 1994 and has only been active since the early 2000s with the second generation. As late arrivals, the first and later generation solar PV technologies in China actively developed at almost the same time at the beginning of the 2000s. The US is clearly the main knowledge source for China's first generation solar PV (making up 32-70% of total citations), followed by Japan (10-30%) and Taiwan (starting in 2002 and reaching 30% of total citations in 2005). One thing that needs to be noted is that local-citations (China citing its own patents as prior arts) in China's both first and new generations solar PV are scarce, implying that the endogenous innovation capability of China's solar PV industry may not yet be fully developed.



Source: USPTO and EPO, and compiled by the author.

Note: CN – China, JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.7 Share of Country Origins of Backward Citations for China's First Generation Solar PV, 1994-2008



Source: USPTO and EPO, and compiled by the author.

Note: CN – China, JP – Japan, TW – Taiwan, KR – Korea, DE – Germany.

Figure 5.8 Share of Country Origins of Backward Citations for China's New Generation Solar PV (2G+3G), 1988-2008

Summary: It is clear that the US and Japan are both important knowledge sources for the three latecomers (Taiwan, Korea, and China) in developing their solar PV industries, as shown in Table 5.2. Taiwan tends to cite US patents more than others (46% of total citations), while Korea gives its preferences evenly to US (36.1%) and Japan (35.8%). Although China shows a diverse and fluctuating patent citation behaviour, the US emerges as the main knowledge source (at 45%), followed by Japan (23.7%) and Taiwan (17.9%). Other European first-movers such as Germany are historically distant from these three latecomers and only show a minor influence on their knowledge sources, despite the European market having been critical since the 2000s. Local-citation has become one of the essential knowledge sources for Taiwan and Korea, particularly in the first generation solar PV, indicating a rise in each country's absorptive capacity. However, in the emerging new generation solar PV, Korea's internalization capability (as shown in local-citation rate) is outperformed by that of Taiwan, since Korea has not clearly entered the global solar PV industry. The knowledge characteristics of the technology forerunners (US and Japan) seem to be different, in their emphases on science as opposed to technology (to be discussed in a moment); the variation in use of knowledge sources by the technology latecomers (Taiwan, Korea, and China) thus may be due to the various technology strategies they have adopted in developing their first and new generation solar PV technologies. This argument will be further supported by their scientific linkages as will be seen in Section 5.4 and addressed in the discussion section.

Table 5.2 Country Origins of Backward Citations in All Generations for Taiwan, Korea, and China, 1984-2008

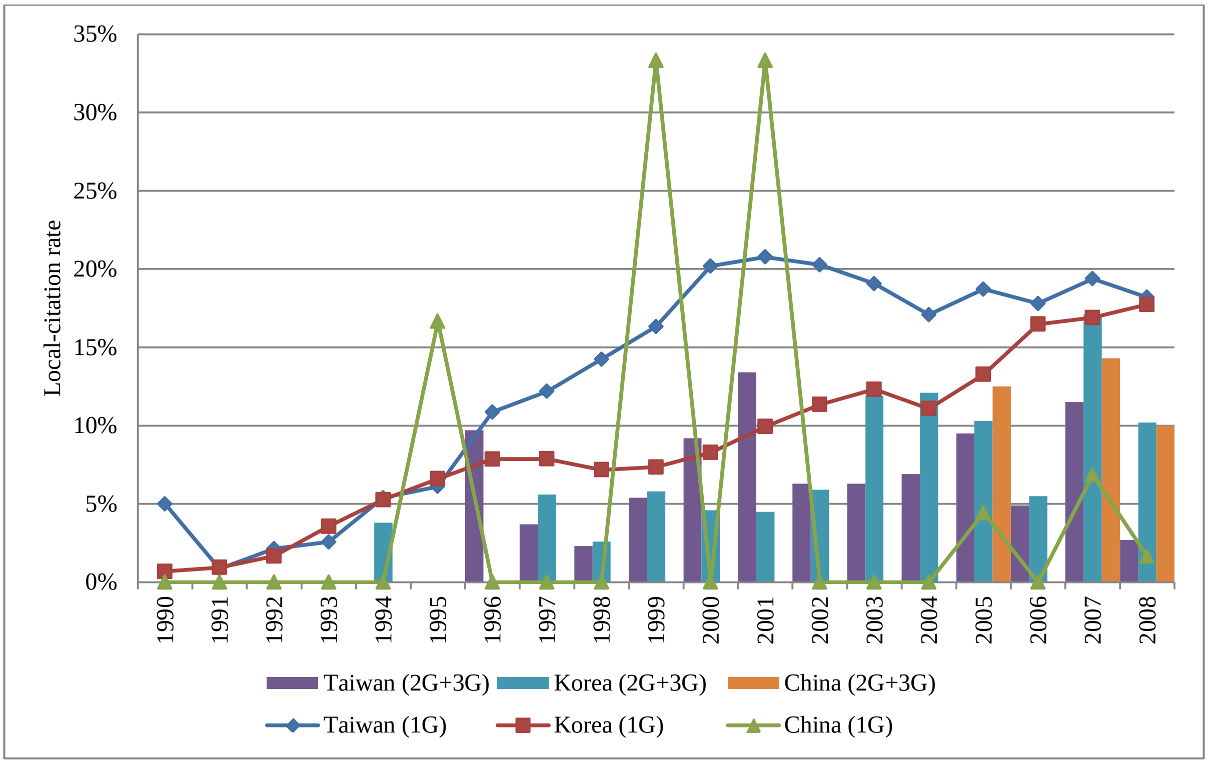
	Cited countries for China, Korea and Taiwan (all generations)									
	US		Japan		China		Korea		Taiwan	
	citation count	share (%)	citation count	share (%)	citation count	share (%)	citation count	share (%)	citation count	share (%)
Taiwan	26,782	**45**	14,103	23.7	16	0.02	3,622	6	10,641	17.9
Korea	20,972	**36.1**	20,793	**35.8**	42	0.07	7,241	12.4	4,897	8.4
China	223	**46**	120	24.5	12	2.4	22	4.5	51	10.4

Source: USPTO and EPO: compiled by the author

As demonstrated in Taiwan's and Korea's high-tech industries since the 1990s, internalization capability is one of the critical knowledge sources for innovation activity. Although China's internalization capability is still relatively low compared with that of Taiwan and Korea, it is using mature 'turnkey solution' equipment for its silicon-based first generation, while competing in the global solar PV market through low cost, large scale production (Altenburg, Schmitz, & Stamm, 2008; Mathews et al., 2011; Williamson, 2010). However, internalization capability is not only an indispensable catalyst in pursuing competitive advantages beyond mass production activity for the first generation solar PV industry, but is also essential for developing the emerging new generation of this industry. Hence the role of internal knowledge agents through intra-national knowledge flows is investigated, as follows.

5.1.3 Intra-national Knowledge Flows

With respect to Taiwan, Korea, and China, the evolving trajectories of intra-national knowledge flows between the first and emerging new generations (thin film and organic compounds), in terms of local-citation rates, match their international knowledge flows, as shown in Figure 5.9. The local-citation rates in Taiwan's and Korea's first generation solar PV were comparable before the mid-1990s. The trend then diverged after 1995, as Taiwan obviously exercises a higher local-citation rate than does Korea. However, Korea has been catching up, while Taiwan's local-citation rate reached a historical peak at 21% in 2001– a time when Taiwan's patenting strategy was being altered. Since then, the local-citation rate in Taiwan's first generation solar PV has remained at around 20% of total citations, whereas that of Korea becomes comparable again in 2008. With the proportion of external knowledge sourced from the US and Japan remaining significant (even though the share is decreasing), this finding implies that the technology latecomers such as Taiwan and Korea still need external knowledge to upgrade their innovation capability, even though the first generation solar PV has become a mature technology. China's local-citation rate, on the other hand, presents an irregular and fluctuating pattern (the raw data of sources of local-citations are included in Appendix F-1 to Appendix F-6).



Source: USPTO and EPO, and compiled by the author.

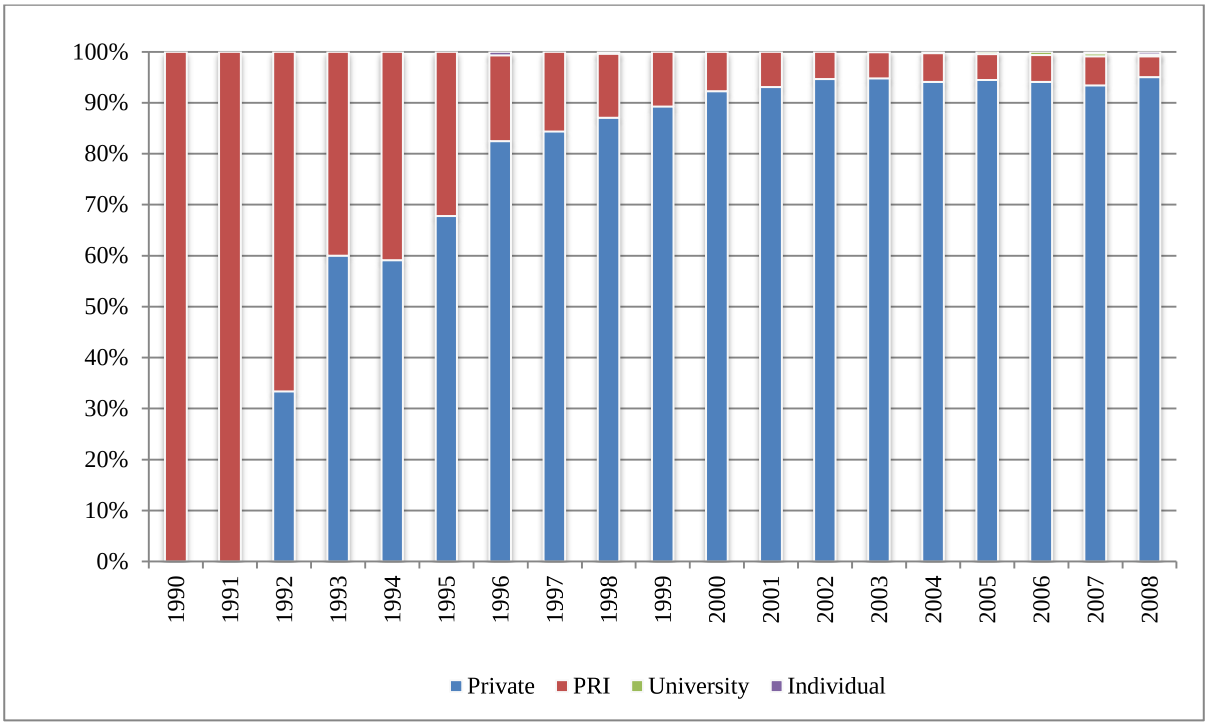
Figure 5.9 Local-citation Rates for the Three Latecomers' Solar PV in the Different Technological Generations, 1990-2008

In the emerging new generation solar PV, Korea and Taiwan are seen to have started to build their internalization capability in the late 1990s, while maintaining their local-citation rates; China appears on the scene in 2005. Even though patent counts are few, China's local-citation rate in the new solar PV generation is impressive – overtaking Taiwan and reaching more than 10% very quickly. Again, the local-citation rate in Korea essentially rose more than 100% from 6% in 2002 to 13% in 2003, when the large Korean *chaebols*, LG and Samsung, were about to announce their entry into the industry. Corresponding to the finding of this study that the new generation solar PV patenting activities declined in 2006-2007 in Taiwan and Korea, as shown in Figures 5.4 and 5.6, the decreased local-citation rates in 2006 in the three latecomers reflect a crowding-out effect generated by the increase in market demand for first generation solar PV. However, both Korea and China are seen to have put great effort into building the endogenous innovation capability in the emerging new solar PV generations since the mid-2000s, while Taiwan seems to have had relatively less involvement. This, again, raises interesting issues of why the technology strategies might be so dissimilar among the three latecomers.

Given the importance of internalization capability and public sector institutions in catalysing knowledge diffusion in developing innovation capability for the emerging industry in the Asian latecomer countries, the question to be posed is: what are the principal knowledge sources for the three latecomer countries?

Taiwan

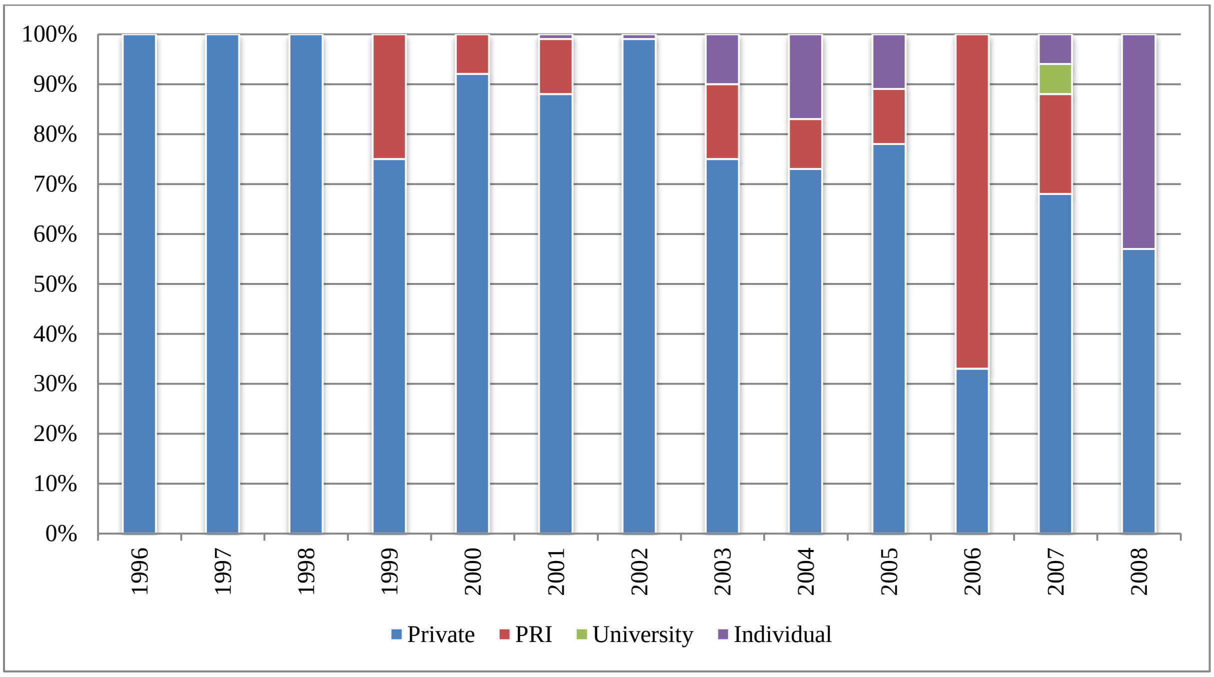
The data in Figure 5.10 shows that, in the early 1990s, the public R&D institute was responsible for 100% of intra-national knowledge flows in Taiwan's first generation solar PV. Remarkably, the private sector since then has successfully built its internalization capability and taken over the role from the public R&D institute as a major knowledge source in Taiwan's first generation solar PV technologies. Within only 5 years (1991 to 1996), the private sector came to dominate more than 80% of Taiwan's intra-national knowledge flows in the first generation solar PV technologies. Up to 2008, the private sector provided more than 95% of intra-national knowledge sources, as the contribution of the public R&D institute dropped to only 4%.



Source: USPTO and EPO, and compiled by the author.

Figure 5.10 Intra-national Knowledge Flows for Taiwan's First Generation Solar PV, by Sector, 1990-2008

However, a different pattern is found for the intra-national knowledge flows in Taiwan’s emerging new generation solar PV, as shown in Figure 5.11. The intra-national knowledge drivers in the emerging new generation solar PV have been initiated by the private sector since 1996. The public research institute and universities appear not to be involved in intra-national knowledge flows until 1999, there being no clear pattern in which PRIs are more significant than the private sector, evidence that the innovation capability in Taiwan’s private sector is well established.

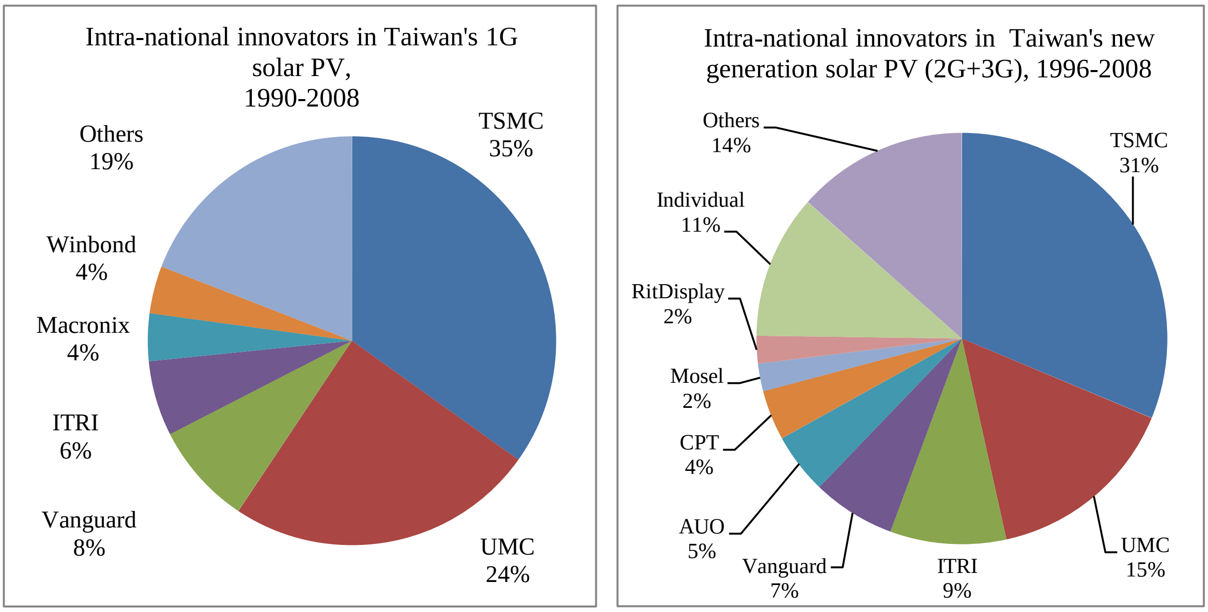


Source: USPTO and EPO, and compiled by the author.

Figure 5.11 Intra-national Knowledge Flows for Taiwan's New Generation Solar PV (2G+3G), by Sector, 1996-2008

Figure 5.12 indicates that the intra-national knowledge flows of Taiwan's solar PV industry are largely derived from the semiconductor industry, dominating 78% of total intra-national knowledge sources, while Taiwan's No.1 and No.2 semiconductor foundries TSMC and UMC take 35% and 24% respectively.

The second intra-national knowledge source for Taiwan's emerging new generation solar PV is the optoelectronics industry (especially the TFT-LCD sector), which generates 16% of internal knowledge, while the public R&D institute contributes 6%. The late involvement of Taiwan's public research institutes in developing the emerging technologies for the new generation solar PV implies that industrial transition and policy instruments may need to be re-positioned for the development of emerging industries.

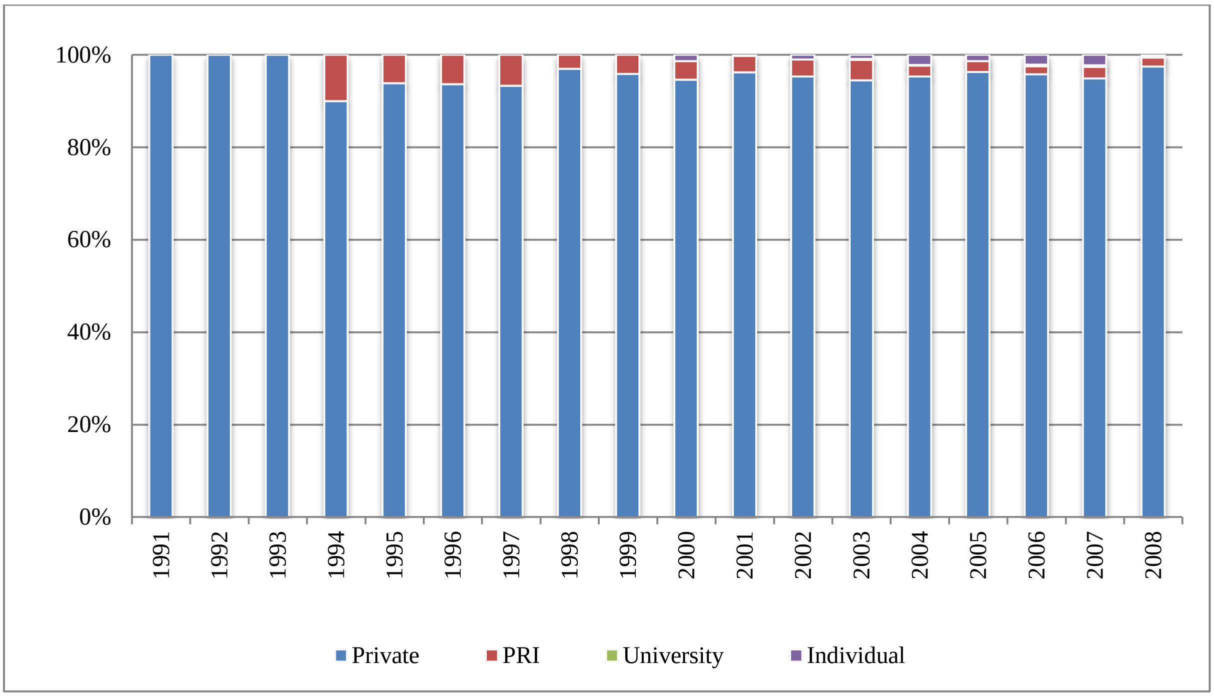


Source: USPTO and EPO, and compiled by the author.

Figure 5.12 Intra-national Knowledge Flows for Taiwan's Solar PV Industry, 1990s-2008

Korea

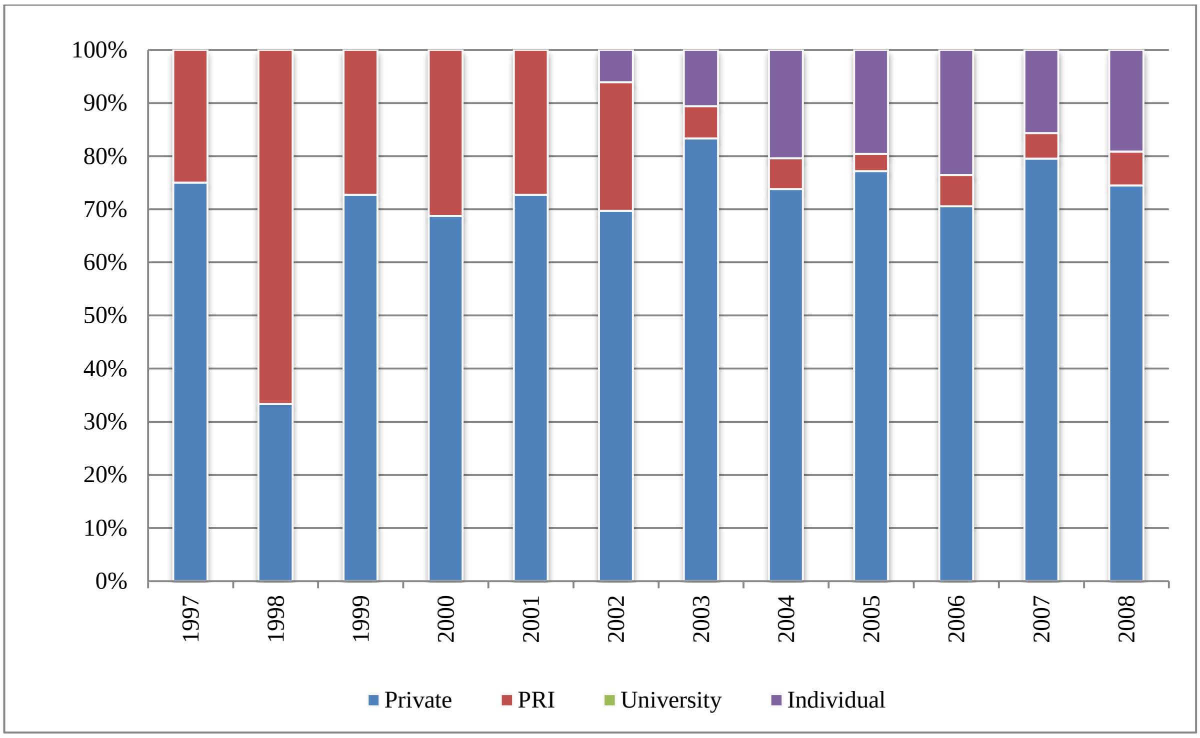
Since the early 1990s, Korea's private sector has included groups of *chaebols*, which have been playing the most important role in Korea's solar PV intra-national knowledge spillover, as shown in Figure 5.13. In fact, three *chaebols*, Samsung (48%), LG (19%), and Hyundai (13%) have been taking more than 90% of Korean internal knowledge sources in the first generation solar PV technologies. The impact of the public sector on development for Korea's first generation solar PV is minimal, contributing at an average rate of only 7.8% over the last 20 years.



Source: USPTO and EPO, and compiled by the author.

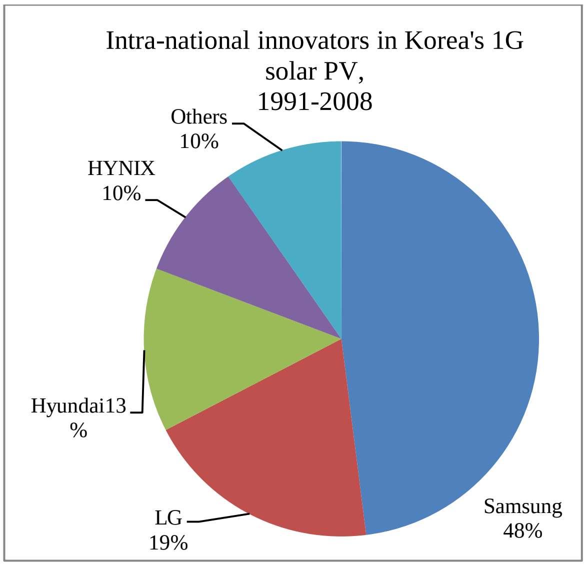
Figure 5.13 Intra-national Knowledge Flows for Korea's First Generation Solar PV, by Sector, 1991-2008

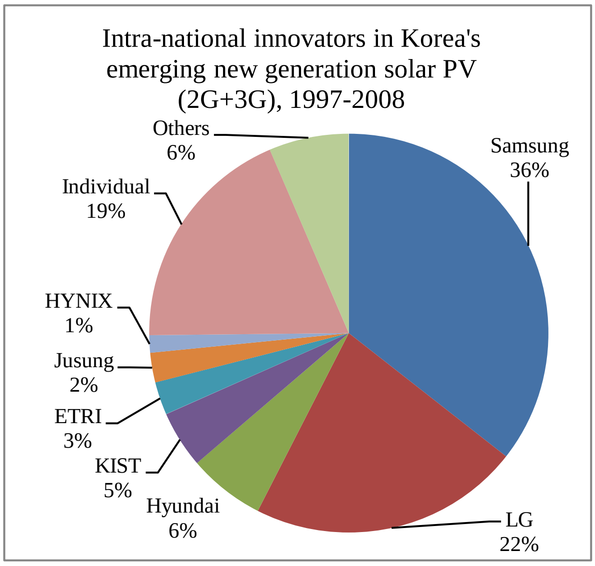
The influence of the public research institutes, such as KIST and ETRI, has shown up, however, mostly in the emerging new solar PV technologies, especially at the early stages in the late 1990s, while the private sector has not taken it into serious account (see Figure 5.14). Interestingly, apart from the *chaebols*, 19% of Korea's emerging solar PV technologies was taken up by individual inventors, as shown in Figure 5.15, implying that some Korean small-medium size companies have entered into the new generation solar PV sector industrial network, competing in the emerging new technologies by using their innovation capability.



Source: USPTO and EPO, and compiled by the author.

Figure 5.14 Intra-national Knowledge Flows for Korea's New Generation Solar PV (2G+3G), by Sector, 1997-2008





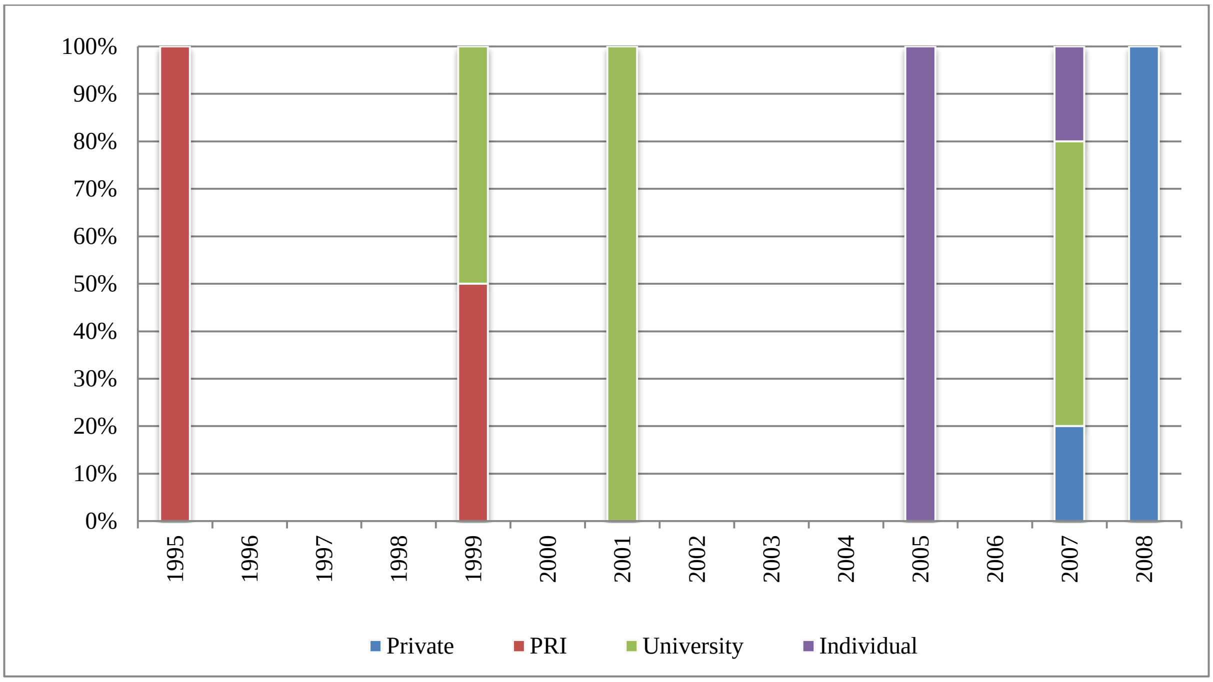
Source: USPTO and EPO, and compiled by the author.

Figure 5.15 Intra-national Knowledge Flows for Korea’s Solar PV Industry, 1990s-2008

China

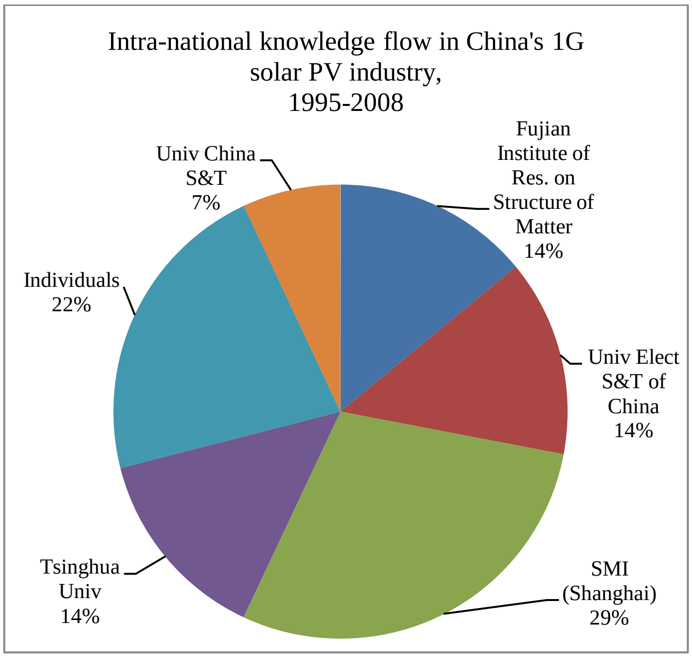
Compared with Taiwan and Korea, China registered relatively few solar PV patents in the USPTO, and only a small amount of intra-national knowledge flows (only 2.8% or 14 local-citations out of a total number of 488 backward citations). The first local-citation – to the public R&D centre, the Chinese Academy of Sciences – in solar PV technology was made in 1995. As reported in many Chinese studies (for example, see Hu and Mathews, 2008; Wu, 2007; Xue, 1997), the public sector (particularly the universities) had been the essential driver and innovator in China's national innovation system, until the private sector began emerging as an efficient and productive player in the 2000s. As shown in Figures 5.16 and 5.17, the internal knowledge sources for developing China's solar PV technologies are, without exception, heavily reliant on the public sector and especially on the universities (49% in total) over the years.[29] It can be seen that the dependence on the private sector (51% in total) only started in 2005, if individual sectors are categorised along with the private sector as SMEs. The single large company, SMI (Semiconductor Manufacturing International) is China's largest semiconductor player, taking 29% of internal knowledge sources.[30]

[29] This study doesn't use any patenting data from China for the new generation in this study, because only 3 local-citations were found during 1988 to 2008.
[30] It is worth noting that the technology capability developing in SMI is largely supported by the state as a whole, including universities and research institutes (Hu and Mathews, 2008).



Source: USPTO and EPO, and compiled by the author.

Figure 5.16 Intra-national Knowledge Flows for China's First Generation Solar PV, by Sector, 1995-2008



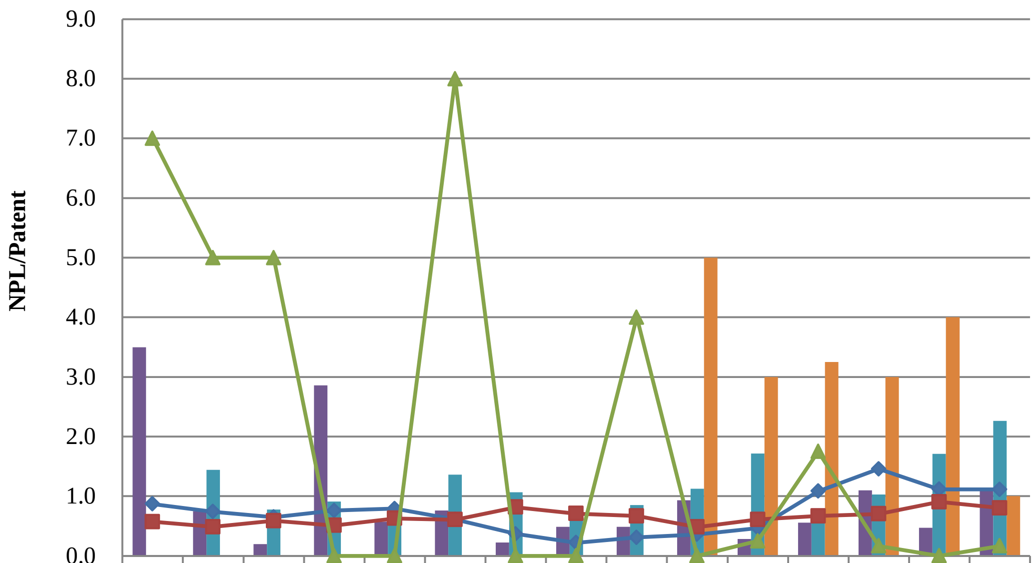
Source: USPTO and EPO, and compiled by the author.

Figure 5.17 Intra-national Knowledge Flows for China's First Generation Solar PV, 1995-2008

Summary: Most of the fundamental solar PV technologies have already been developed and registered (in the form of patents) by the first-movers in advanced countries (mostly in the US, Japan, and Germany), although production-based *process innovation* is still under-developed. Thus, building internalization capability on the emerging new solar PV technologies could potentially be a great opportunity for latecomers, such as Taiwan, Korea, and China, for gaining competitive advantages over the technology forerunners in the global solar PV industry. To verify their variations of internalization capability, this study further uses scientific linkage (meaning non-patent literature, i.e. citations of scientific journal papers) to examine the quality of innovation capability for developing the solar PV industry in the three latecomers, as follows.

5.1.4 Scientific Linkage

The investigation of technology leverage and efforts in pursuing advanced knowledge in the solar PV industries in Taiwan, Korea, and China is one of the major contributions in this study, based on examination of patent citations linked to the scientific literature. As shown in Figure 5.18 (see Appendix G-1 and Appendix G-2 for the details of non-patent literature references), the scientific linkages in all three latecomers, indicating the technology leverage effect in latecomers and the strategies used by fast followers, took off only after 1994. Taiwan was most active in building the advanced capability for the first generation solar PV in the1990s, while it was overtaken by Korea in the first half of the 2000s but regained its leading position in 2005. Corresponding to the finding by Lee and Wang (2011), China's fluctuations (ranging from 0 to 8) in scientific linkage in the first generation indicate unstable catch-up efforts in the field of semiconductors, while the first generation was mostly applied to the technology of semiconductors. However, over the last 15 years, although the average numbers of scientific linkage for the solar PV first generation in the three latecomers vary, most values registered are less than 1 (except for Taiwan, which has exerted a constant level of scientific linkage above 1 since 2005). This lower scientific linkage demonstrates that the development of semiconductors in the Asian latecomers has been focused on *process innovation,* as argued by Hu and Mathews (2005). Nevertheless, the evolution of scientific linkage in the first generation solar PV reflects not only the rank order of production capabilities but also the technological standings of Taiwan, Korea, and China in the global semiconductor industry.



	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Taiwan new generation	3.50	0.75	0.20	2.86	0.57	0.76	0.22	0.49	0.49	0.93	0.29	0.56	1.10	0.47	1.11
Korea new neneration	0.00	1.44	0.78	0.91	0.52	1.36	1.07	0.78	0.85	1.13	1.72	0.59	1.03	1.71	2.26
China new generation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00	3.00	3.25	3.00	4.00	1.00
Taiwan 1st generation	0.87	0.74	0.65	0.76	0.79	0.61	0.37	0.22	0.31	0.36	0.47	1.08	1.46	1.12	1.11
Korea 1st Generation	0.57	0.49	0.59	0.51	0.63	0.61	0.82	0.71	0.67	0.48	0.61	0.67	0.70	0.90	0.80
China 1st Generation	7.00	5.00	5.00	0.00	0.00	8.00	0.00	0.00	4.00	0.00	0.25	1.75	0.17	0.00	0.17

Source: USPTO, and compiled by the author.

Figure 5.18 Comparisons of Average Scientific Linkage for First and New Generations of Solar PV Technologies in Taiwan, Korea, and China, 1994-2008

It is noteworthy to see that the technology leverage or *leapfrog* strategy has been adopted significantly by China, catalysed by the emerging new generation solar PV, while its scientific linkage suddenly increased after 2003 with a persistently high average citation rate reaching 5 for all the latecomers. Since then, China has been leading Korea and Taiwan in pursuing the cutting-edge new generation solar PV, with the average scientific citation rate ranging from 3 to 5, until it first dropped in 2008 to only 1.[31] The higher scientific linkage in the new generation solar PV in China is attributed to the fact that 83% of the patents are owned by academia, in which the Tsinghua University and Chinese Academy of Science are the most prolific patentees and own a 67% share of all patents. Even though China appears as a leader in pursuing the cutting-edge new generation solar PV in terms of scientific linkage, the fact that the technology capability is owned by the universities (rather than by the private sector) implies an urgent need for deploying further strategies on technology diffusion and commercialization.

In contrast to the first generation solar PV, the consolidation of Taiwan's scientific knowledge in the new generations is lagging behind not only China but also Korea. The lag has been particularly obvious since the 2000s, when the new generation solar PV started to emerge. This phenomenon reflects the fast follower strategy that has been seriously adopted by Taiwan, showing that the resources movements/mobility from the first generation to the new generation cannot be too fast before the new technology has signalled its potential (Mathews, et al., 2011).

Summary: Korea's pursuit of advanced knowledge in the new generation solar PV is demonstrated by its constant linkages with scientific knowledge over the last 15 years. In the

[31] The drop of China's average citation number in the thin film based new generation solar PV in 2008 may be due to the prosperous stage of the silicon-based first generation being kicked off by Germany and Spanish government announcements about solar PV investments in 2006 (Mathews et al., 2011). However, the reducing focus on the new generation solar PV is apparent since the awarded patents in the USPTO in 2008 normally have two- or three-year lag since they were filed in 2006.

last observation year of this study, 2008, the average scientific citation rate was the first to break through the historical record by a factor of 2. Indeed, although Korea has not yet started its aggressive entry into the global solar PV industry, the large *chaebols* such as LG and Samsung have been indicating their intention to do so since 2004/2005. The constant and significant scientific linkages with the new generation solar PV in both Taiwan and Korea, again reflects the behaviour of fast followers, in which the resource movement/mobility is more conservative, but partial efforts are being made to develop a new technology niche in order to avoid becoming 'stuck' in the mature technology sector. However, with relatively more abundant resources than the SMEs-dominated Taiwan, Korea can be seen to be acquiring more scientific knowledge than Taiwan in the uncertain field of new generation solar PV. The different levels of scientific linkage involved between the first and new generation solar PV of Taiwan, Korea, and China thus present the different national strategies that have been adapted and adopted in order to upgrade from imitation to innovation. These distinct variations amongst the three latecomers are examined in greater detail in the discussion section.

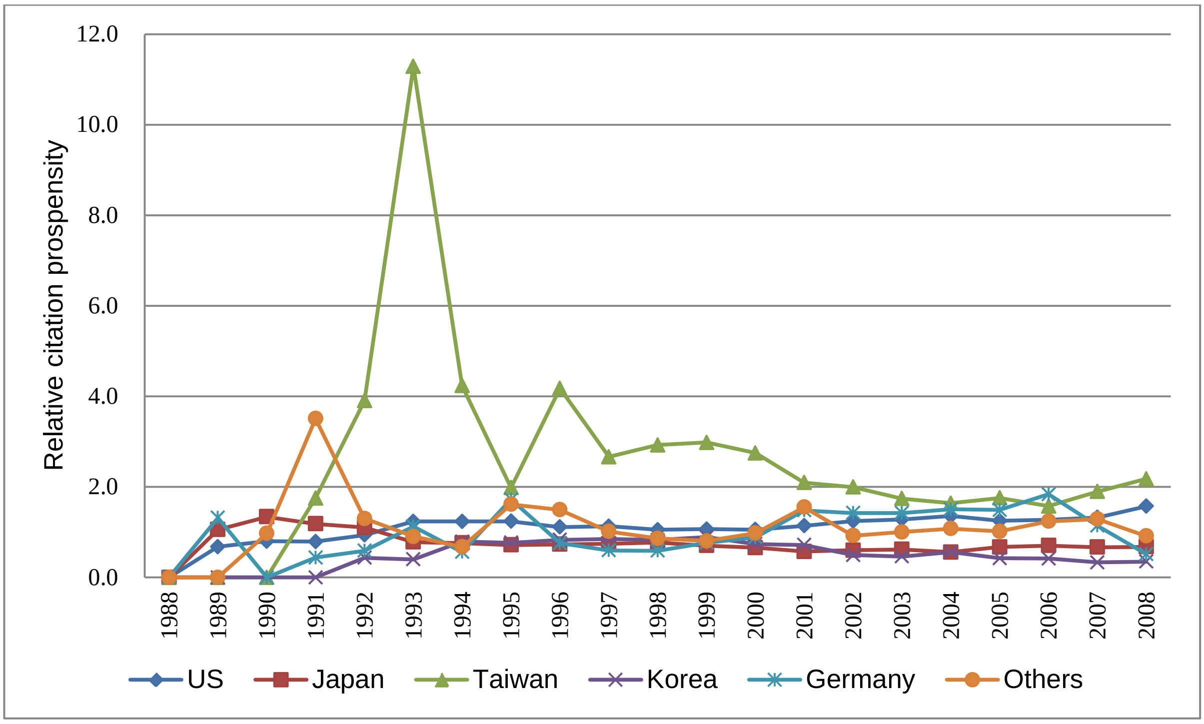
5.1.5 Relative Citation Propensity

Even though it needs caveats, as discussed in Chapter 3, I shall still use the indicator of relative citation propensity to compare the three solar PV latecomers. It should be borne in mind that the interpretation may not reflect the real situation, because the absolute number of citations made to the cited country may only be small, and yet the result generated could seem much weightier in terms of relative number of citations. However, I shall try to use the precise interpretation as much as possible to explain these results. The results from Taiwan, Korea, and China show different patterns, as follows (detailed counts are supplied in Appendix H-1 to Appendix H-6).

Taiwan

It is remarkable that the technological development of Taiwan's first generation solar PV is heavily reliant on internalization capability, reaching a peak local-citation of 3.0 in 1999, as shown in Figure 5.19. Corresponding to the most prosperous stage in Taiwan's semiconductor industry during the 1990s, local-citation has become the major knowledge source over the last 20 years, since the 1990s, for Taiwan's first generation solar PV sector. Compared with Korea and China, Taiwan tended to cite US patents more during the 1990s and then switched to citing German patents more during the first few years of the 2000s. It is notable that Taiwan's relative citation propensity regarding Germany reached a high point of 1.9 in 2006, but significantly then declined to a relatively low level, implying that either Korea or China have shown a higher preference for citing Germany than Taiwan since then. Indeed, Korea has shown a preference for citing German patents since 2007 as shown in Figure 5.20 below. Interestingly, the lower citation propensity for Japan and Korea (both are less than 1.0) indicates that Taiwan does not cite either Korean or Japanese patents as often as Korean or Chinese firms do themselves.

Compared with the absolute number of citations, as in Figure 5.3, relative citation propensity shows that, compared with Korea and China, Taiwan tends increasingly to cite more US patents for the first generation solar PV sector, even though the absolute number of citations to the US remains at the same level.

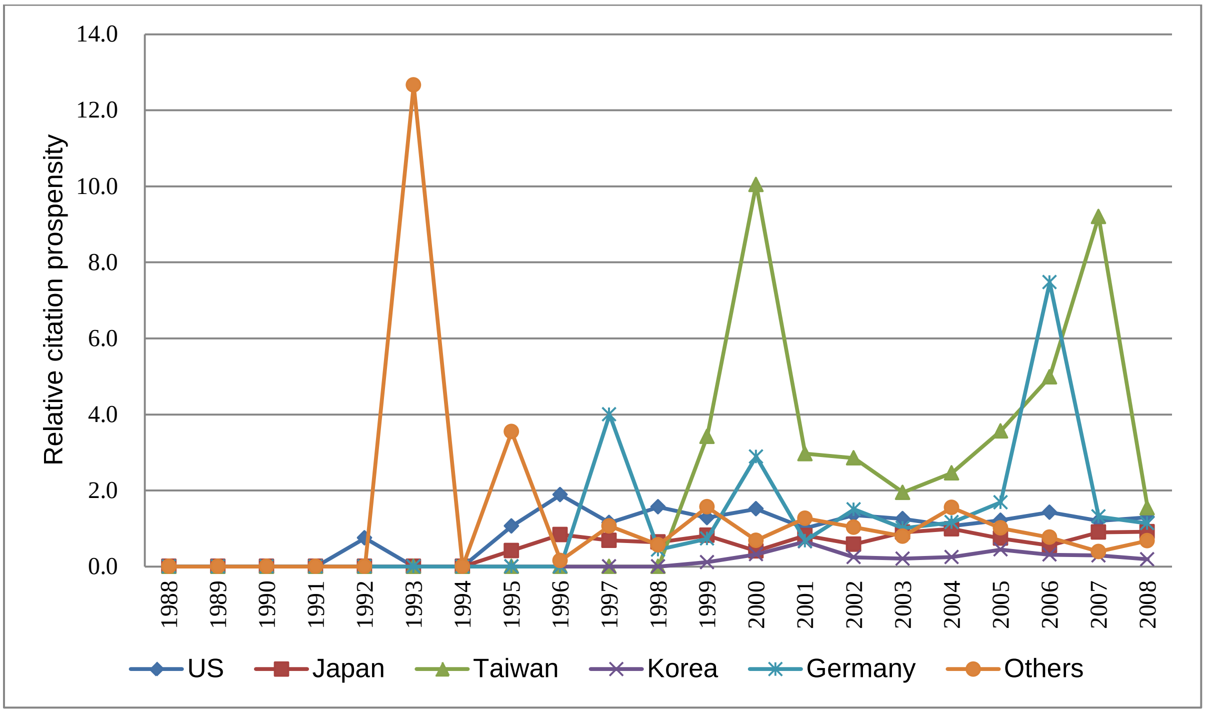


Source: USPTO and EPO, and compiled by the author.

Figure 5.19 Relative Citation Propensity for Taiwan's First Generation Solar PV, 1988-2008

Figure 5.20 shows the relative citation propensity for Taiwan's emerging new generation solar PV. As in the first generation, the innovation capability in Taiwan's emerging new generation has started relying on the endogenous knowledge base since 1998. As discussed earlier, the decline in endogenous innovation capability in Taiwan's new generation solar PV, as shown in the period of 2001-2003 and in 2008, was brought about by increasing market demand and the skyrocketing price of polysilicon materials for the first silicon-based generation (Mathews et al., 2011). In parallel with the first generation solar PV, Taiwan presents a relatively higher citation tendency for the US and Germany in the emerging new generations, with a lower tendency for Korea and Japan.

Compared with the use of absolute number of citations, as in Figure 5.4, the relative citation propensity in Taiwan's new generation solar PV sector shows that Taiwan has cited more of its own patents (as local-citations) and German patents, even though these local-citation and German patents are very sparse compared with the absolute number of citations. This raises a serious caveat about using the method of relative citation propensity to measure international knowledge flows.



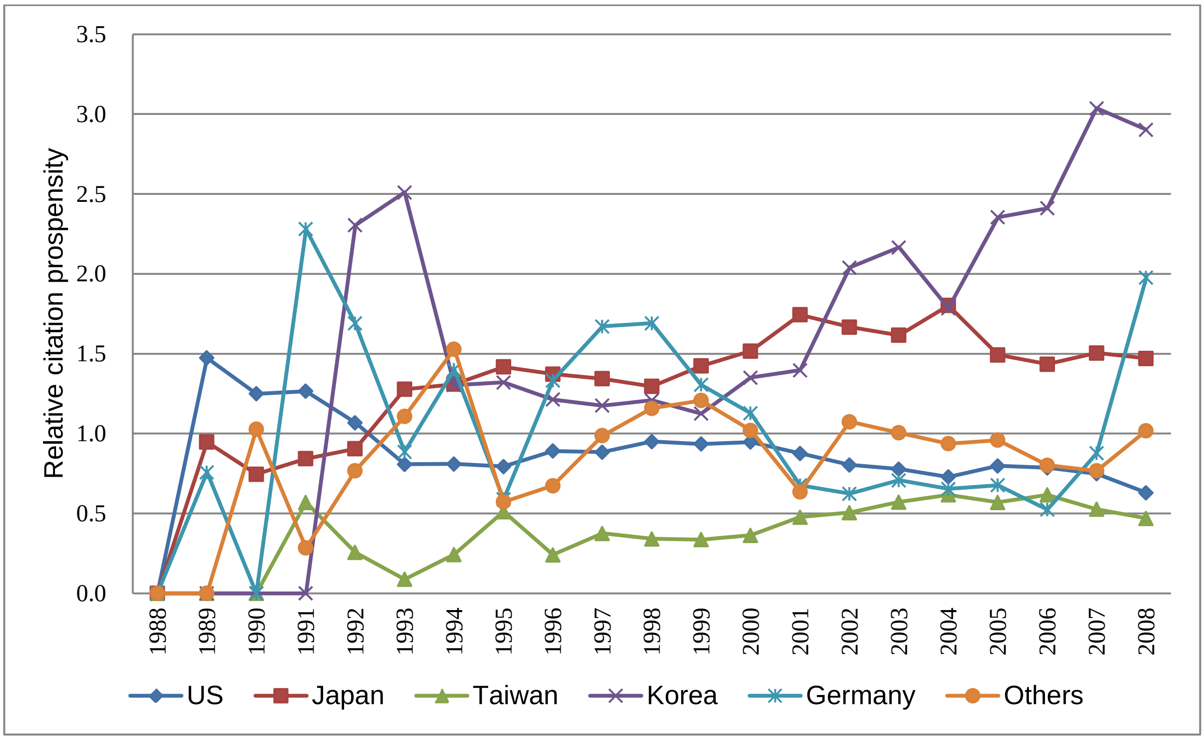
Source: USPTO and EPO, and compiled by the author.

Figure 5.20 Relative Citation Propensity for Taiwan's Emerging New Generation Solar PV (2G+3G), 1988-2008

Korea

As seen in Figure 5.21, Korea's relative citation propensity may be divided into three periods: (1) before the 1990s: the US was the most critical knowledge source for Korea's first generation solar PV; (2) during the 1990s: compared with Taiwan and China, Korea favoured Japan more as the knowledge source as Japan became the No.1 knowledge source in Korea's first generation solar PV sector ; and (3) after the 2000s: Korea's citation behaviour significantly switched to building its internalization capacity, as the local-citation propensity dramatically increased and hit a highest point of 3.05 in 2007 (double the value from Japan). In comparison, both Taiwan and Korea show a similar low preference in citing the patents from each other (both are less than 1.0). It is also interesting to find that Germany may have regained its knowledge preference in Korea's first generation solar PV in 2008 (as high as 1.9, lagging two years behind Taiwan), after losing its significant influence since the beginning of the 2000s.

Compared with the use of absolute number of citations as in Figure 5.5, the relative citation propensity in Korea's first generation solar PV shows that, compared with Taiwan and China, Korea tends to cite Japanese patents more, even though the absolute number of citations made to Japan has decreased over recent decades.

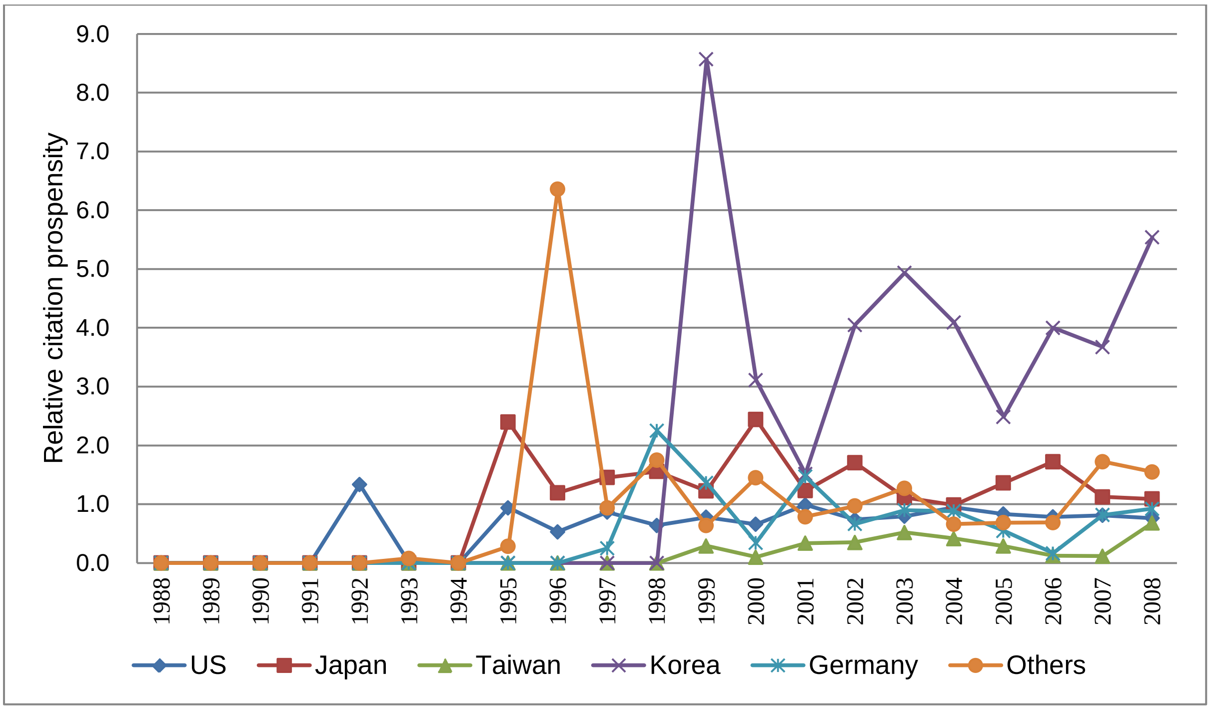


Source: USPTO and EPO and compiled by the author.

Figure 5.21 Relative Citation Propensity for Korea's First Generation Solar PV, 1988-2008

As Figure 5.22 shows, it is interesting to see that Korea's local-citation propensity for the emerging new generation solar PV started as early as 1999. Compared with Taiwan and China, Korea has shown a consistent preference for citing Japanese patents across the various solar PV generations over the decades.

Compared with the use of absolute number of citations, as in Figure 5.6, the relative citation propensity in Korea's new generation solar PV shows a particularly high local-citation rate (5.5 in 2008), even though the absolute number of local-citations (10% of total citations) is much lower than that those made to Japan and the US (around 40% each); again the serious caveat about using the method of relative citation propensity needs to be mentioned.

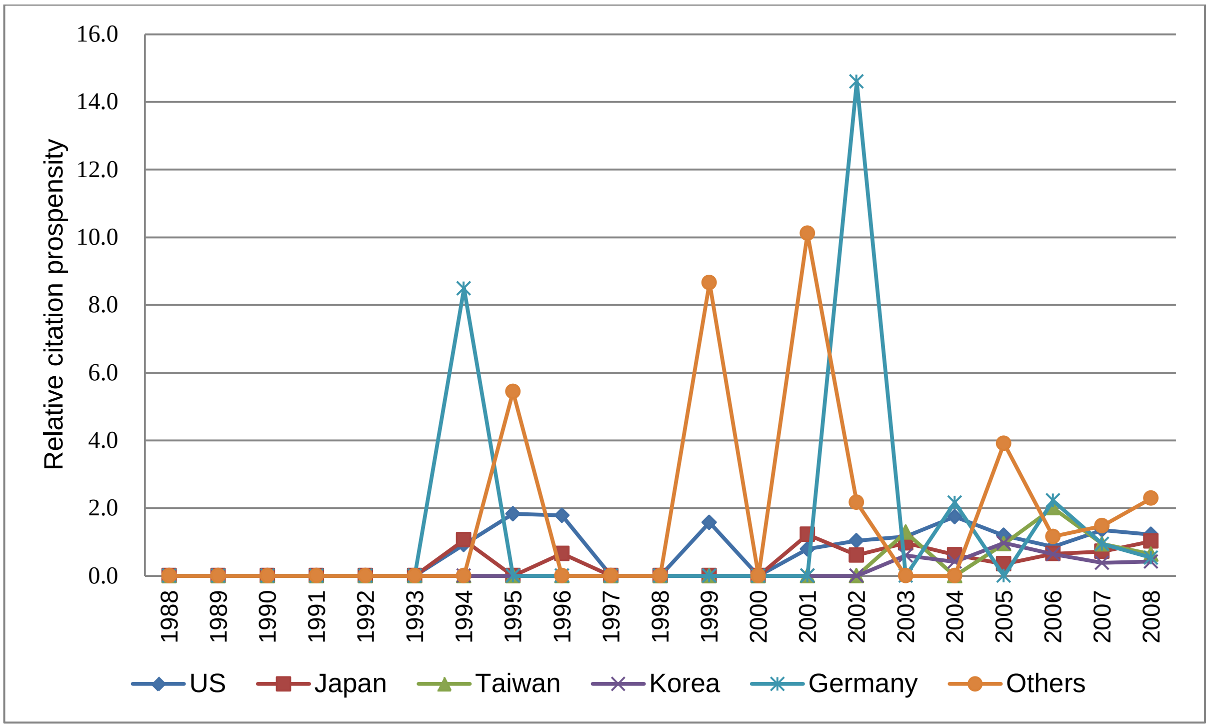


Source: USPTO and EPO, and compiled by the author.

Figure 5.22 Relative Citation Propensity for Korea's Emerging New Generation Solar PV (2G+3G), 1988-2008

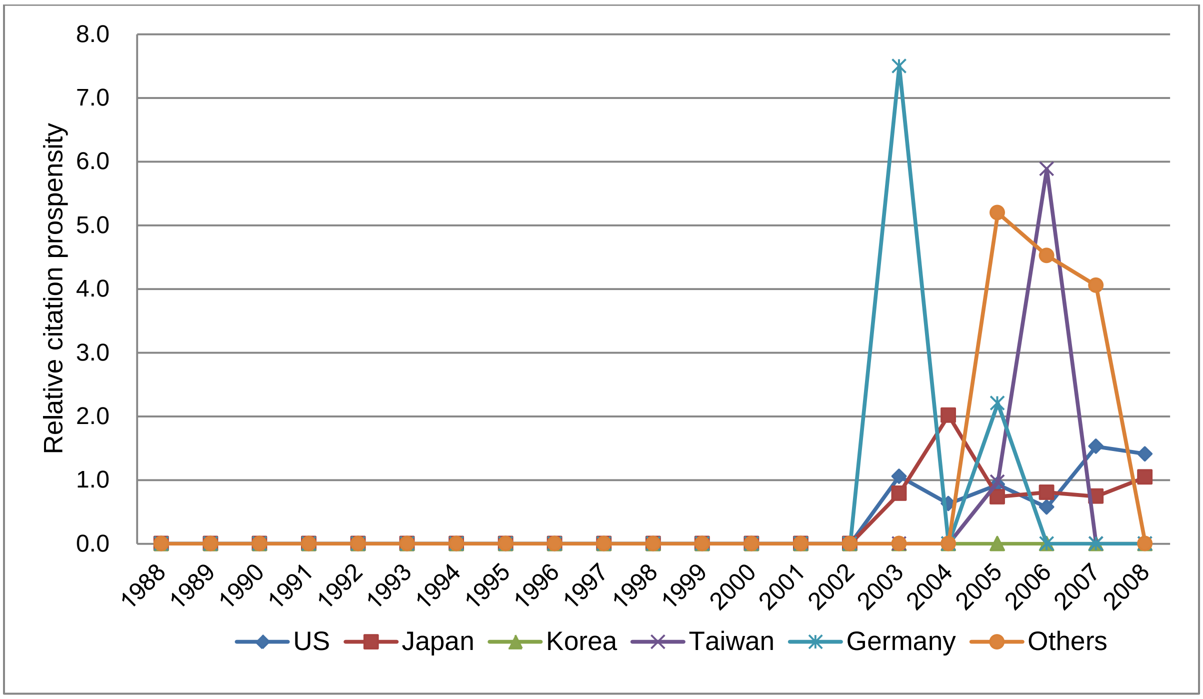
China

The caveats against relative citation propensity in measuring international knowledge flows are even clearer when this method is applied to the Chinese case. As seen in Figures 5.23 - 5.24 and compared with the absolute number of citations as in Figures 5.7 and 5.8, Germany seemed to overtake the US and Japan and become the major knowledge source in China's first generation solar PV sector since 2000s in terms of relative citation propensity, although the absolute number of citations made to Germany is far below than those of the US, Japan or Taiwan.



Source: USPTO and EPO: compiled by the author.

Figure 5.23 Relative Citation Propensity for China's First Generation Solar PV, 1980s-2008



Source: USPTO and EPO: compiled by the author.

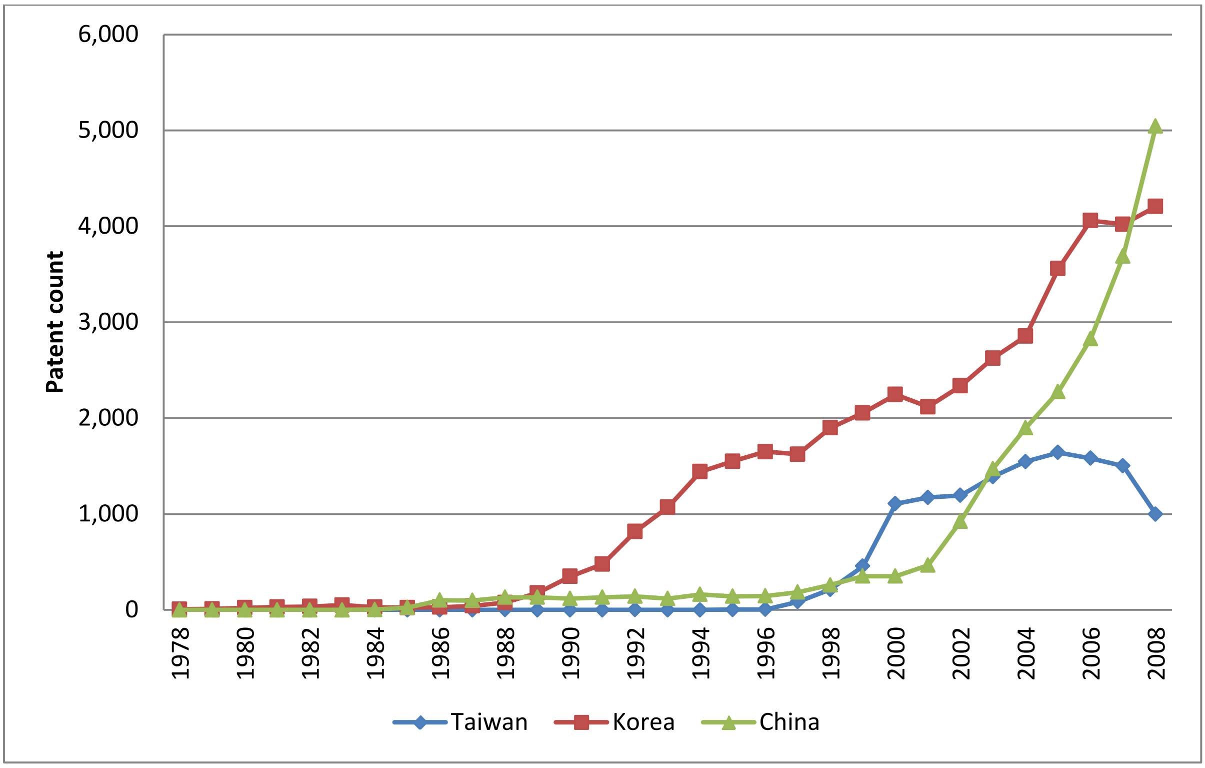
Figure 5.24 Relative Citation Propensity for China's New Generation Solar PV (2G+3G), 1988-2008

Summary: Despite the caveats about using relative citation propensity, both absolute and relative numbers of citations demonstrate that the US and Japan are the major knowledge sources for Taiwan, Korea, and China in developing their solar PV industries. In particular, Korea has a stronger tendency toward Japan while Taiwan prefers to cite the US as its knowledge source and China reveals an inconsistent and diverse citation propensity towards various countries. In terms of international knowledge flows, intra-national knowledge flows, and scientific linkage, the variations of knowledge flows from the technology forerunners, the US and Japan, imply that different national strategies were adopted by Taiwan, Korea, and China in developing their solar PV industries. These interesting issues along with discussions of the constructed research propositions are elaborated in the Discussion Chapter.

5.2 Stage Two - Technological Innovation Capabilities

5.2.1 Overall Trends

Figure 5.25 shows the overall trends in patenting activities in the solar PV industries of Taiwan, China, and Korea. Korea's patenting activity in the solar PV-related technologies started as early as 1978 and has increased significantly since 1989 to reach its historic peak in the last observation year of 2008. During the period from 1978 to 2008, Korea received 41,462 patents worldwide. Thus, its patent stock among the three Asian latecomers is clearly in the leading position. Next to Korea, China secured the second largest patent stock, at 21,192, during the same period. China's patenting activity in the solar PV technologies started in 1984, but the essential boost was not seen until the early 2000s. In 2008, China surpassed Korea to become the most active patentee among the three Asian latecomers in worldwide patent offices. On the other hand, Taiwan lags behind both Korea and China in terms of solar PV patenting rate. The first solar PV-related patent in Taiwan is found in 1988, while the critical surge only started in the late 1990s, 10 years after Korea but 2-3 years earlier than China. In total, Taiwan received 12,886 solar PV-related patents from worldwide patent offices during 1988 to 2008.



Source: EPO, compiled by the author

Figure 5.25 Solar PV-related Patents Granted to Taiwan, China, and Korea by Global Patent Offices, 1978-2008

Table 5.3 indicates the diverse nature of the development of primary technological fields (in terms of the 12 selected IPCs) in Taiwan, China, and Korea. The fundamental manufacturing processes and devices, as in the IPC H01L21 (semiconductor manufacturing processes) and H01L27 (semiconductor devices) have taken 78%, 43%, and 59% in Taiwan, China, and Korea, respectively. This demonstrates that the innovation capabilities of the solar PV industry in Taiwan, China, and Korea are intensively focusing on semiconductor manufacturing technologies. This is especially the case for Taiwan.

Table 5.3 Patent Counts in the 12 Solar PV IPCs for Taiwan, Korea, and China, 1978 - 2008

IPC	Taiwan	China	Korea
H01L31	1,417	2,211	5,526
H01L21	**6,324**	**5,977**	12,269
H01L27	3,844	3,367	**12,250**
H01L51	206	1,054	3,852
C23C14	455	2,868	2,010
C23C16	420	1,453	3,443
C30B15	19	549	246
C30B28	32	110	44
C30B29	61	1,877	736
H01G9	85	837	1,042
H02N6	20	653	28
E04D13	3	236	16
Total	12,886	21,192	41,462

Source: EPO and compiled by the author.

5.2.2 Factor Analysis

The principal-factors method is used for the initial extraction process and covers only those factors explaining at least 10% of the variance in the data. The values of KMO, the Bartlett Sphericity test, and degrees of freedom in the present study are 0.855, 2500.963, and 78 respectively, with $p<0.001$. This confirms the feasibility of factor analysis. Factor loadings were obtained by applying the promax rotation, with the purpose of deriving a simpler factor structure which can be meaningfully interpreted.

After rotation has been performed, Table 5.4 shows the relevant factor loadings; four significant factors can be identified from the 12 IPCs connected with the respective IPC variables and corresponding to the following solar PV technology platforms:

(1) Technology Platform One (TP1, energy conversion) comprises four IPCs, namely H02N6, E04D13, C30B28, and H01G9. They are related to PV generator and auxiliary fixture functions. This technology portfolio is the most essential mass production capability (process innovation) by which the energy efficiency will be greatly increased.

(2) Technology Platform Two (TP2, new generations) includes three IPCs, namely H01L51, C23C16, and C23C14. This platform refers as organic semiconductor materials and surface deposition technologies, mostly attributed to the new generation solar PV.

(3) Technology Platform Three (TP 3, epitaxy) consists of two IPCs, namely C30B15 and C30B29. Their interaction concerns the formation of crystalline semiconductor materials.

(4) Technology Platform Four (TP4, c-Si cell manufacturing) covers three IPCs, namely H01L21, H01L27, and H01L31. They are regarded as fundamental technologies for c-Si solar PV.

Table 5.4 Factor Matrix and Technology Platforms

	Factor 1	Factor 2	Factor 3	Factor 4
Technology platform	**Energy conversion**	**New generations**	**Epitaxy**	**c-Si cell manufacturing**
H02N6	0.977			
E04D13	0.931			
C30B28	0.927			
H01G9	0.892			
H01L51		0.935		
C23C16		0.925		
C23C14		0.843		
C30B15			0.92	
C30B29			0.897	
H01L31				0.953
H01L27				0.945
H01L21				0.925
Variance	68.14%	17.67%	5.88%	4.47%
Accumulation of variance	68.14%	85.81%	91.67%	96.15%

Extraction method: Principal factor analysis
Rotation method: Promax rotation

Note: Please refer to Table 4.1 for the technology functions of the twelve solar PV related IPCs and Appendix D for their official definitions.
Source: EPO and compiled by the author.

Technology Platform One (energy conversion, TP1) relates to solar PV module and energy conversion, the main focus in the production activity. It is no surprise, therefore, to find that this factor accounts for 68.14% of the variance of the total factor solution. TP1 is concerned with four IPCs, as shown in Table 5.4, in which the factor loadings greater than 0.5 are identified as H02N, E04D13, C30B28, and H01G9. These are considered to be the main concerns in the production activity of the solar PV industry.

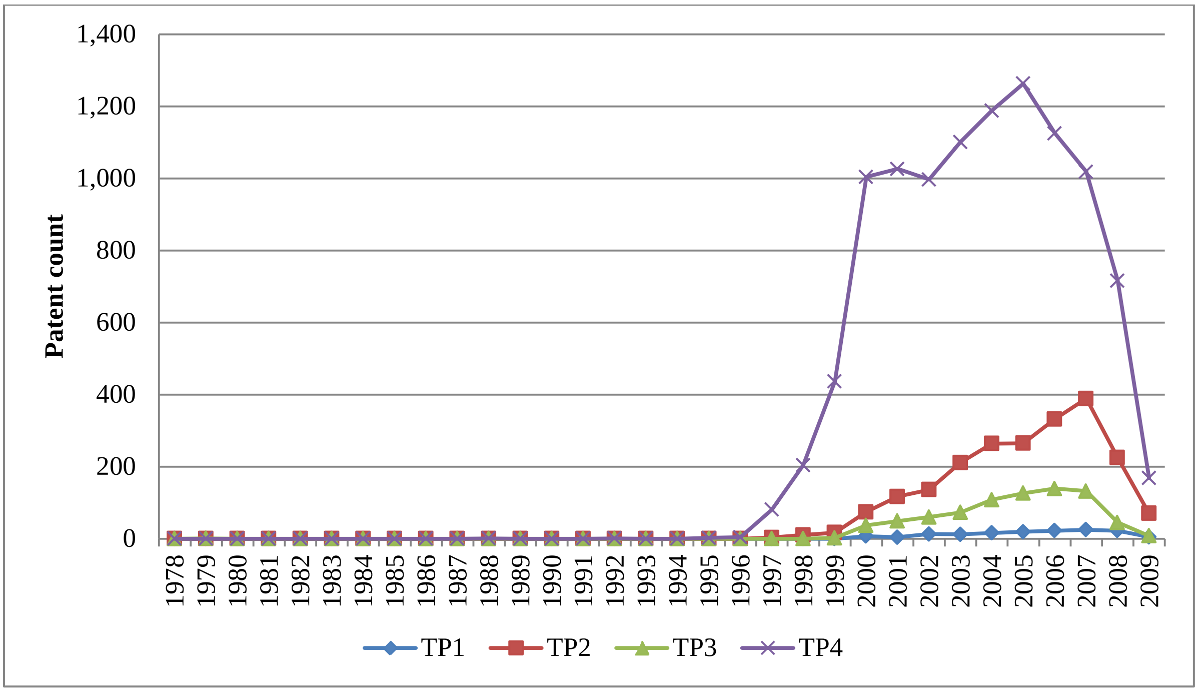
Technology Platform Two (new generations, TP2) accounts for 17.67% of the variance in the total factor solution, and has three highly loaded factors (H01L51, C23C16, C23C14). The factor relates to non-silicon-based solar PV manufacturing methods (the second and third solar PV generations such as thin-film, dye-sensitized, and organic PV). This demonstrates that the Asian catch-up latecomers Taiwan, China and Korea overwhelmingly focus on production activity, as they are used to working in the semiconductors and other electronics industries, but on the other hand, they are seeking a leverage opportunity by developing the new niche sectors (i.e., the new generation technologies) where feasible, particularly where patent protection is not too strong (Mathews, et al., 2011).

Technology Platform Three (epitaxy, TP3) accounts for 5.88% of the variance of the total factor solution, with the two loading items C30B15 and C30B29 applying to the upstream Si-based epitaxy technology, mainly on concentrated PV or III-V high efficiency solar cell. Finally, the three items H01L31, H01L27 and H01L21 in Technology Platform Four (c-Si cell manufacturing, TP4) explain 4.47% of the variance in the total factor solution, representing the Si-based cell manufacturing process and devices in the first generation. The smaller share of variance exerted by TP3 and TP4 indicates that the silicon-based technologies in the first generation are no longer the key element, because the relevant patents have largely expired. In addition, the results also imply that the building of the industrial value chain in Taiwan, China, and Korea is concentrated on downstream production activity and has not yet extended to the upstream materials and epitaxy. Indeed, upstream supply of polysilicon materials has been lacking since 2002, while solar PV flourishes and all the strategic alliances and collaborations in the global solar PV production networks are aimed at securing materials supplies.

5.2.3 Patenting Activity at Country Level

Taiwan

Corresponding to the technological diversity among the three latecomers, as shown in Table 5.3, and Figures 5.26, 5.27 and 5.28, below, the patenting activity in Taiwan, China, and Korea did not emerge until the late 1990s, while the development of solar PV technologies was being focused on different technology platforms. As shown in Figure 5.26, the significant patenting rate occurred in Taiwan, while the European countries have aggressively promoted solar PV renewable energy since 1996. Based on Taiwan's strong innovation capability in semiconductors, the development of solar PV technologies in Taiwan has overwhelmingly concentrated on the c-Si cell manufacturing process and devices in the first generation (TP4), followed by the new generation solar PV technology platform (TP2) since the emergence of new generations in the latest decade.



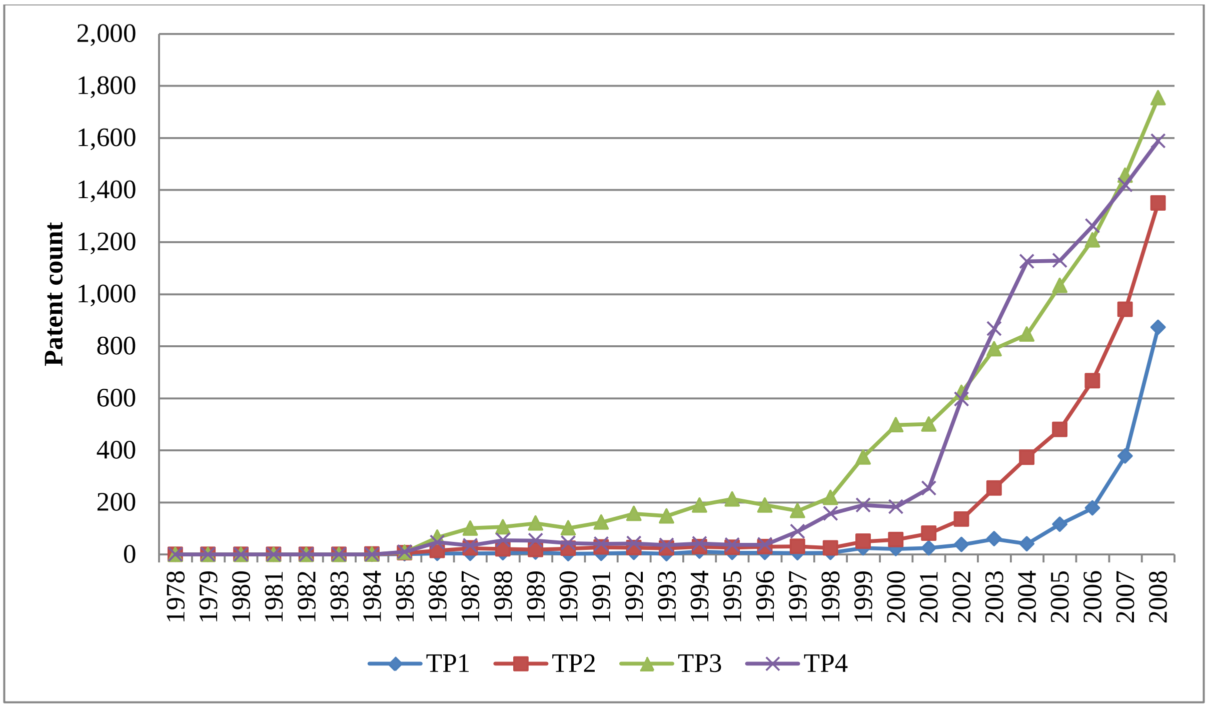
Source: EPO and compiled by the author.

Figure 5.26 Patenting Activities of Four Technology Platforms in Taiwan, 1978-2008

China

Hu and Jefferson (2009) note the surge of Chinese patenting activity since the year 2000, while the annual Chinese patent applications grew from around 140,000 in 2000 to approximately 600,000 in 2007. They identify three factors to account for this boom in China: (1) the growth of FDI inducing Chinese firms to apply for more patents; (2) amendments to the patent law so as to favour patent holders; and (3) the ownership reform of industry, the exit of state-owned enterprises and the entry of private-owned enterprises, all resulting in the propensity to patenting.

In line with the finding by Hu and Jefferson (2009), this study also demonstrates that the surge of China's solar PV patenting activity began in 2000. Interestingly, China's patenting activity in the solar PV industry is seen not to be concentrated only on certain technology areas, as it is in Taiwan (see Figure 5.27). In contrast, since the 2000s, all the four solar PV technology areas in China are essentially growing. Except for the upstream epitaxy technology (TP3) laid down as a base during the 1990s, since 2000 the innovation activity in China's solar PV industry has sequentially moved onward to the related c-Si cell manufacturing (TP4), the new generation non-silicon based technology (TP2) since 2002, and to the energy conversion (TP1) since 2004. In contrast to the 'reverse engineering' East Asian experience, as in Taiwan and Korea, initiated from the downstream product manufacturing processes, the emerging order of China's solar PV technology innovation activities is in line with the '*forward engineering*' or unique '*Beijing model*' as claimed by Park and Lee (2006).[32]



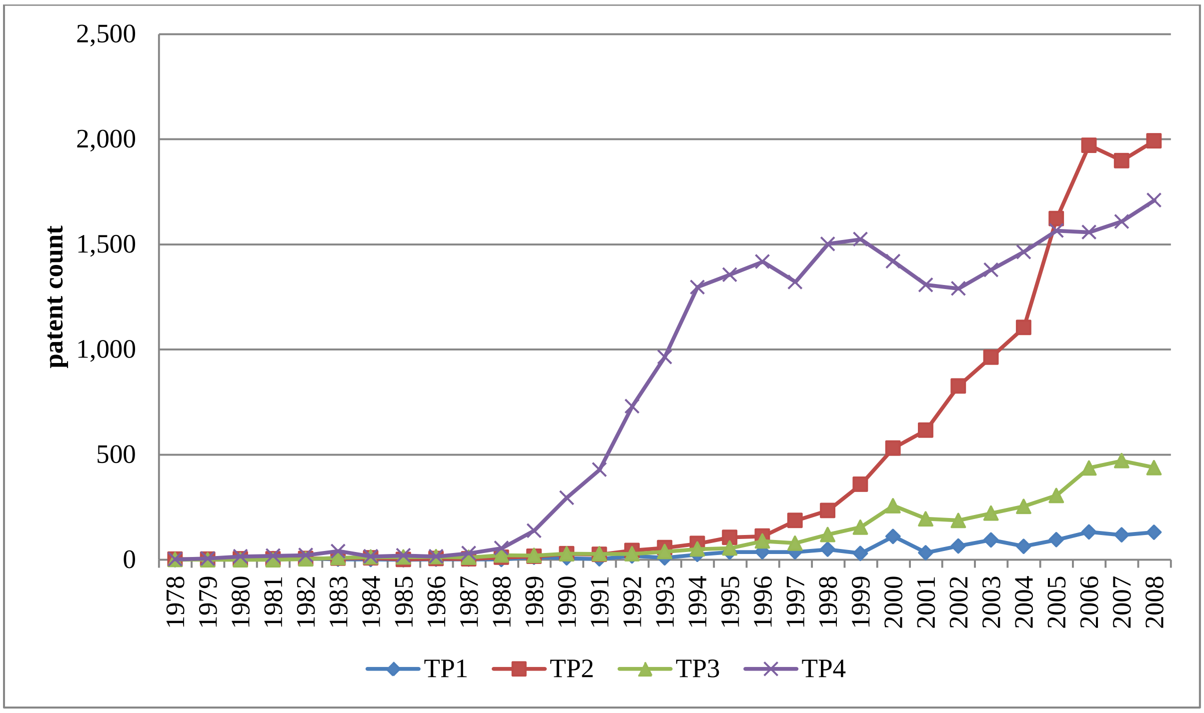
Source: EPO and compiled by the author.

Figure 5.27 Patenting Activities of Four Technology Platforms in China, 1978-2008

[32] In contrast to reverse engineering, forward engineering refers to a process of moving forward from the formulation of original idea, through basic R&D, applied R&D, to the physical implementation of commercialization. On the other hand, reverse engineering analyses an existing product or service in order to identify its components and their interrelationships.

Korea

Like Taiwan, Korea's solar PV patenting activity is mostly focused on c-Si cell manufacturing (TP4), which may be derived from its successful semiconductor industry, as shown in Figure 5.28. However, the non-silicon based new generation technologies (TP2) have been emerging rapidly since the early 2000s and have become the priority in developing Korea's solar PV technology since 2004 (despite the fact that Korea's mass production activity has not yet kicked off). Again, this corresponds to the earlier argument of this study for the latecomer strategy, in which the development of new generation solar PV (i.e. TP2) has become the new niche sector for Korea and Taiwan, while China, with its large country size, is rapidly growing in all the four technology platforms. Indeed, the patenting activity in China's solar PV industry has been increasing aggressively since the 2000s and is seen to surpass that in Taiwan and Korea, in terms of the number of patents.

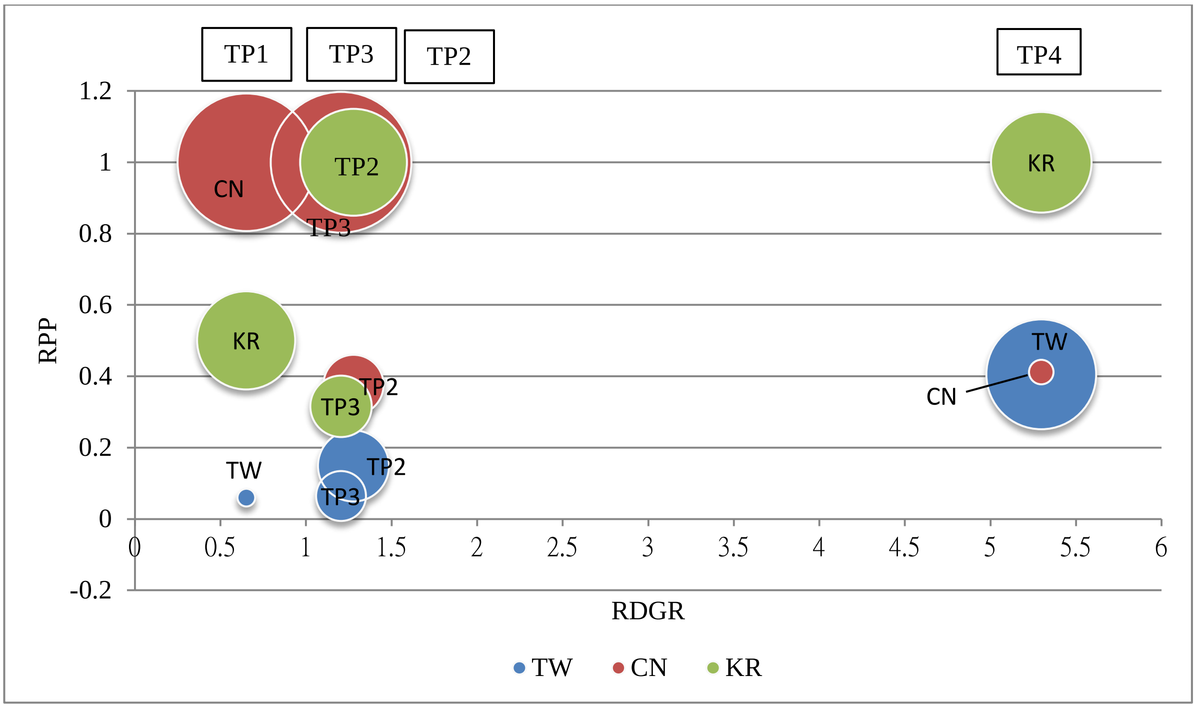


Source: EPO and compiled by the author.

Figure 5.28 Patenting Activities of Four Technology Platforms in Korea, 1978-2008

5.2.4 Technology Portfolios

Next, three-dimensional technology portfolios are used to examine country-level technological innovation capabilities among the three latecomers. Figure 5.29 shows the results, with technology attractiveness (RDGR) on the X-axis, relative patent position (RPP) on the Y-axis, and revealed patent advantage (RPA) on the Z-axis – represented by the diameter of the bubbles.



Note: the diameter of the bubbles represents the magnitude of RPA

Source: EPO and compiled by the author.

Figure 5.29 Technology Portfolios in Taiwan, China, and Korea

The results in Figure 5.29 demonstrate that the RDGR in the long-developed TP4 (c-Si manufacturing) has secured the fastest growth rate over the last 10 years (1999 to 2008), while the latest emerging TP1 (energy conversion) is the slowest among the four technology platforms. These demonstrate that the trajectory of technological development of the solar PV industry in Taiwan, China, and Korea has been heavily dependent on the growth of semiconductor technologies

The technology advantages of the solar PV industries in Taiwan, China, and Korea are divergent. As shown in Figure 5.29, China enjoys the highest RPP and RPA in both TP1 and TP3, while Taiwan has the highest RPA in TP4, and Korea has secured the highest RPP in TP4 and TP2. This result implies that different technology development strategies have been pursued in respect to the latecomers, China (pursuing both R&D scale and efficiency), Taiwan (focusing on R&D efficiency), and Korea (relying on R&D scale).

5.2.5 Patenting Activity – Company Level

Taiwanese Producers

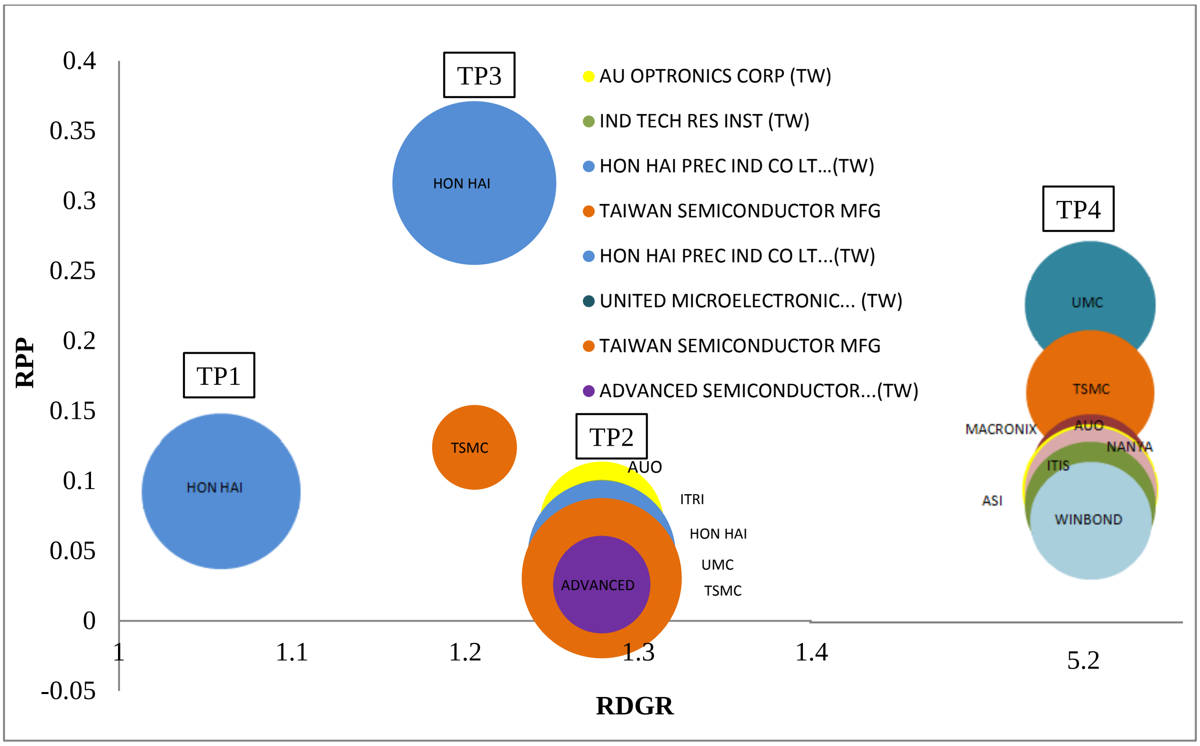
Details of the company-level technological innovation capabilities are provided in Figures 5.30, 5.31, and 5.32 below, showing the respective technology portfolios of major producers in Taiwan, China, and Korea.

The technology platform of c-Si cell manufacturing (TP4) is the major driving force for the development of Taiwan's solar PV industry, in which the leading semiconductor players such as TSMC, UMC, AUO, Macronix, Winbond, and the public research institute ITRI establish their technology position, as shown in Figure 5.30. On the other hand, Hon Hai (or Foxconn Electronics), the leader in the Electronic Manufacturing Services (EMS) industry, dominates both RPA and RPP in the fields of energy conversion (TP1) and epitaxy (TP3) technologies. Hon Hai's business units across the entire ICT industry cover such things as personal and desktop computers, mobile devices, telecommunications, flat panel displays, and LED. Its specialized technologies in connecting circuits and interface materials are the key elements for energy conversion and power devices for the solar PV technologies. Therefore, it is not surprising to see that Hon Hai specializes in TP1 and TP3. In particular, Hon Hai is Taiwan's only major technology-centred company ranked in TP1, while others are using imported solar PV turnkey equipment for module production (Mathews, et al., 2011).

Taiwan Semiconductor Manufacturing Corporation (TSMC), the No.3 global IC foundry player, dominates the RPA in the new generations (TP2) and c-Si cell manufacturing (TP4), together with other semiconductor and flat panel display players such as AUO, Winbond, ITRI, and UMC.

Even though both TSMC and Hon Hai have not yet exerted aggressive activity in the solar PV industry, both companies have set up an energy business unit aiming at investigating the entry opportunity into the solar PV industry.[33] The results thus confirm the statement by the market research company Displaybank (2010) that TSMC (in its manufacturing and process technology), Hon Hai (in its module mass production), and Formosa Plastics (in its petrochemical extraction technology for poly-silicon materials) are the three competent companies with potential for developing Taiwan's solar PV industry.

[33] In 2009, TSMC has acquired a 25% stake in Taiwan's No.1 solar PV producer Motech, while Hon Hai has announced its intention to be involved in the solar PV industry, focussing on module production (i.e. TP1) and epitaxy production (i.e. TP3) either through merger and acquisition (M&A) for the module production or collaboration activities with epitaxy players (DigiTimes, 2009; 2010).



Note: the diameter of the bubble represents the magnitude of RPA

Source: EPO and compiled by the author.

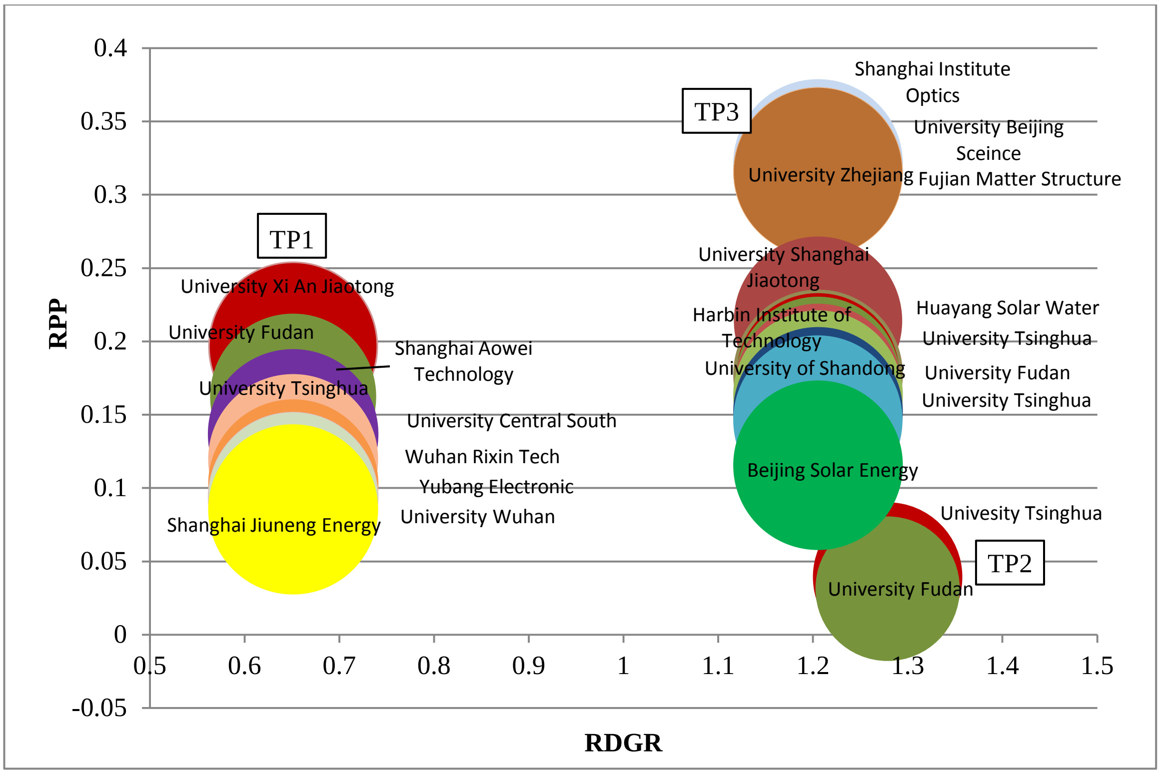
Figure 5.30 Technology Portfolios of Taiwan's Major Players

Chinese Producers

China's patenting activity in the solar PV industry is relatively smaller than that of Korea, especially in the technology platform of c-Si manufacturing (TP4). China does not have any critical player in this area, as shown in Figure 5.31.[34] The lack of active patentees in TP4 contrasts sharply with its leading position in the global c-Si solar PV production, which suggests a prevalence of turnkey solutions in China's solar PV industry. While China has listed semiconductor technology as one of its national priorities and is specialized in mass production, the upstream silicon-based epitaxy technology (TP3) and downstream energy conversion (TP1) certainly attract the most players and generate prolific patenting activities. In addition, the non-silicon based new generation technology platform (TP2) is obviously an

[34] The findings for the lack of critical players in the technology platform of semiconductor manufacturing and process devices (TP4) also reflect on China's weak market performance in the global semiconductor industry.

emerging area and growing rapidly; in this area, the RPA is dominated by Tsinghua University (Beijing) and Fudan University (Shanghai). The majority of solar PV R&D activity is conducted by Chinese universities and some of the public research institutes. The few private companies ranked among China’s solar PV technology players relate to the suggestion of ‘*forward engineering*’ mode in China’s innovation system (Eun, Lee, & Wu, 2006; Hu & Mathews, 2008).



Note: the diameter of the bubbles represents the magnitude of RPA

Source: EPO and compiled by the author.

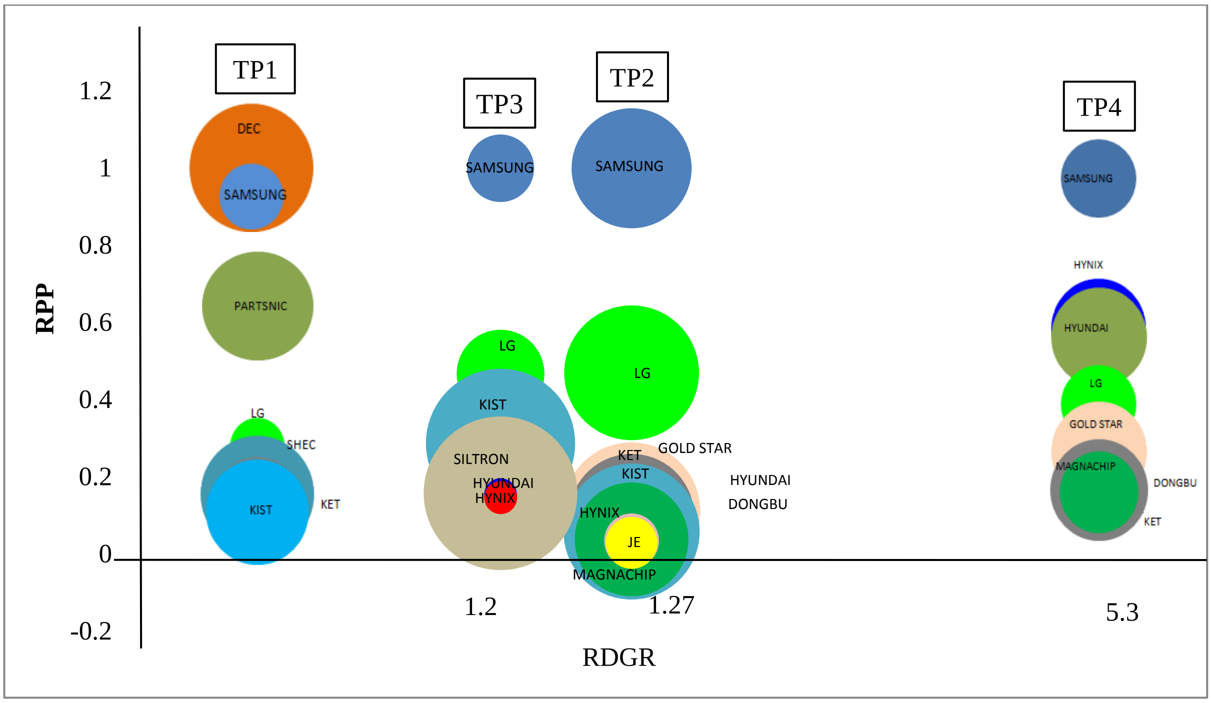
Figure 5.31 Technology Portfolios of China’s Major Players

Korean producers

Even though Korea has not yet seen large scale involvement in the global solar PV industry, it is clear that various *chaebols* dominate in the different technology platforms, which may signal an emerging and competitive tension within Korean players. As seen from

Figure 5.32, while Samsung has secured the highest RPP in the c-Si cell manufacturing and process devices (TP4), Dongbu enjoys the highest RPA in the field. Not surprisingly, DEC (Daewoo Electronics Corporation) and its affiliate Partsnic (a business unit of Daewoo Group), are found to have the strongest technological capability in energy conversion (TP1). Like other Korean *chaebols*, Daewoo is diverse and its business units DEC and Partsnic are specialized in energy storage and conversion technology, such as electrolytic capacitors.

Siltron, the business unit of LG Group, which produces semiconductor materials, and epitaxial wafers, has secured the highest RPA in epitaxy (TP3), followed by Korea's public research institute KIST (Korea Institute of Science and Technology). LG also enjoys the highest PRA in the new generation (TP2), while Samsung has the highest RPP. It is interesting to see that Samsung captures the highest RPP in all four technology platforms, comparable only with Daewoo in TP1. This may indicate that Samsung's abundant R&D resources and diverse technological guidelines make it a national champion.



Note: the diameter of the bubbles represents the magnitude of RPA

Source: EPO and compiled by the author.

Figure 5.32 Technology Portfolios of Korea's Major Players

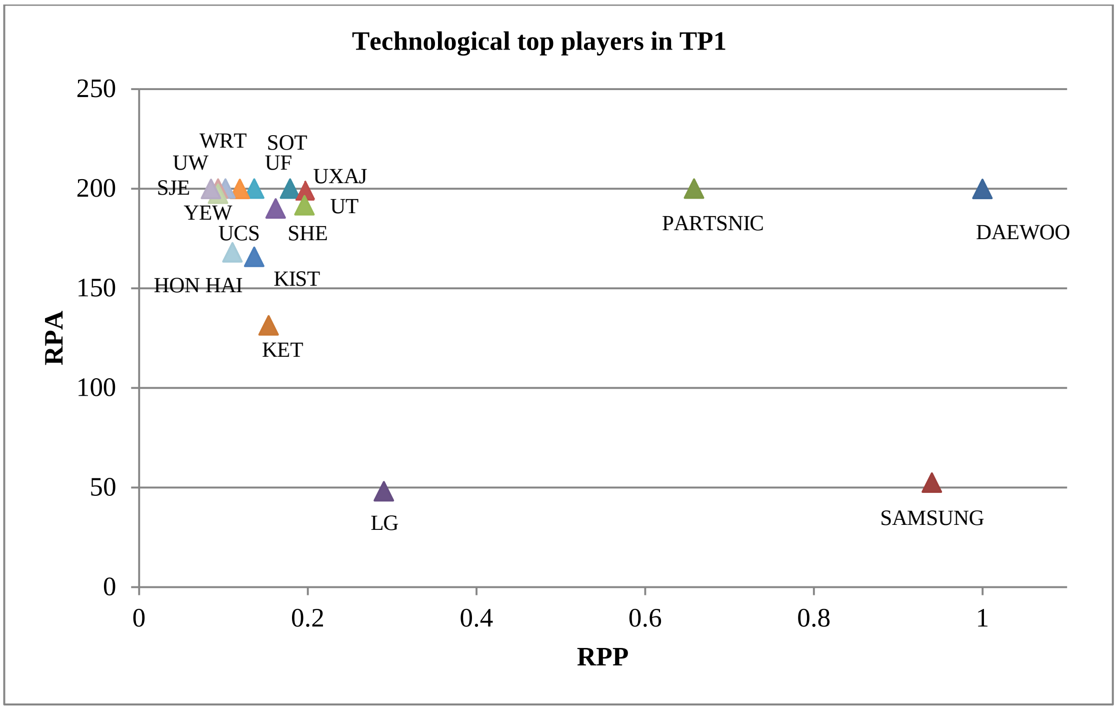
5.2.6 Asia's Technological Top Players

To illustrate the technological innovation capabilities of the top Asian latecomers in the solar PV industry, those firms from each country with the highest RPP (technology scale) and RPA (technology efficiency) have been selected. Figures 5.33, 5.34, 5.35, and 5.36 show the technological top players of the three Asian latecomers in the four technology platform fields.

Corresponding to the national approach in the three latecomers, the results show that both Taiwanese SMEs and Chinese research-oriented players are competing through R&D efficiency enhancement (i.e., higher RPA), while Korea's *chaebols* tend to compete through R&D scale increase (i.e., higher RPP). It is clear that Samsung has secured the largest R&D scale (RPP) and acts as a benchmark among the three latecomers in TP2, TP3, and TP4, while Daewoo has captured the strongest competitive advantage in both RPA and RPP in TP1. In considering the performance and technological capability for the other Korean *chaebol*, LG is seen to be moderate and mixed, using both RPP and RPA.

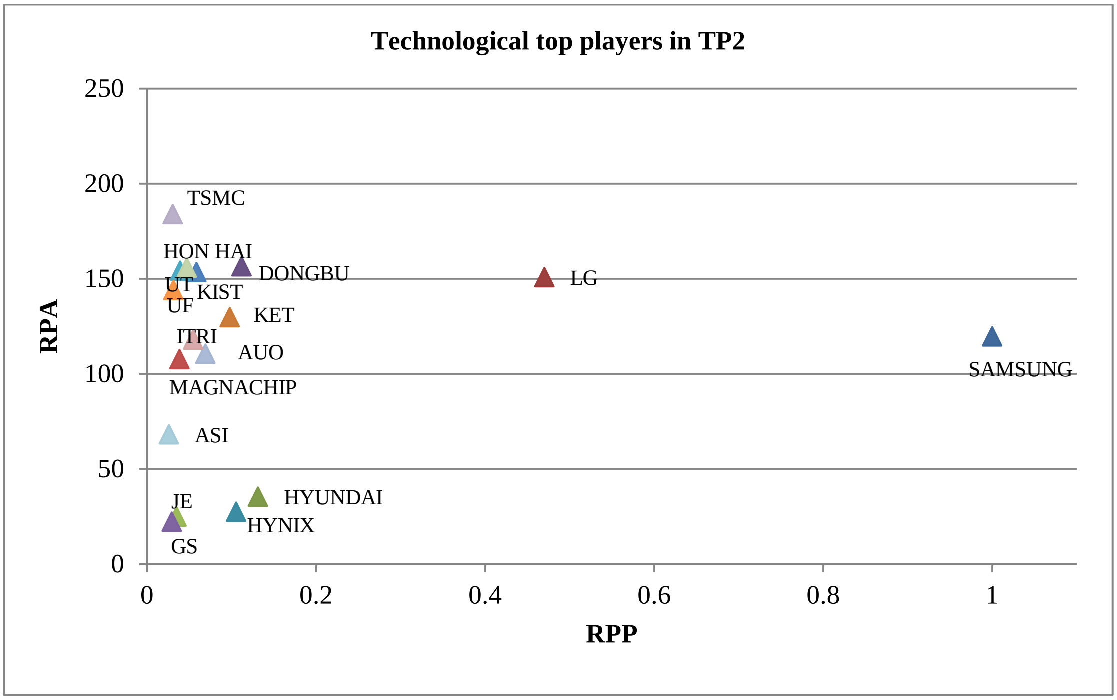
Given that the majority of Chinese solar PV technology authorities are universities, it is reasonable that their technological capability is built on technology efficiency (RPA), while the research focuses on the downstream solar PV module and energy conversion TP1 as well as the upstream epitaxial technology TP3.

In contrast to China's technological specialty, the technological capability of Taiwanese players focuses on the new generation (TP2) and on c-Si cell manufacturing (TP4), in which its semiconductor industry is already prosperous. TSMC and Hon Hai take the prime place in the solar PV new generation technology (TP2). Other semiconductor and flat panel display players such as Macronix, ITRI, and UMC are seen to be performing well in the first generation manufacturing processes, TP4.



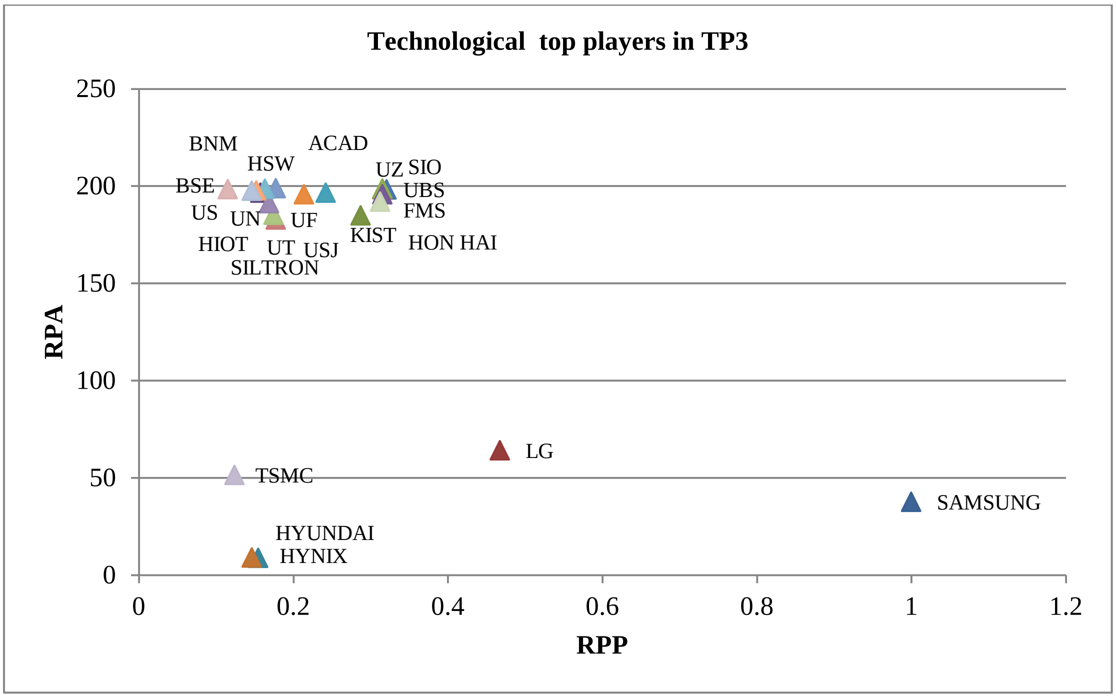
Source: EPO and compiled by the author.

Figure 5.33 Technological Top Players in TP1



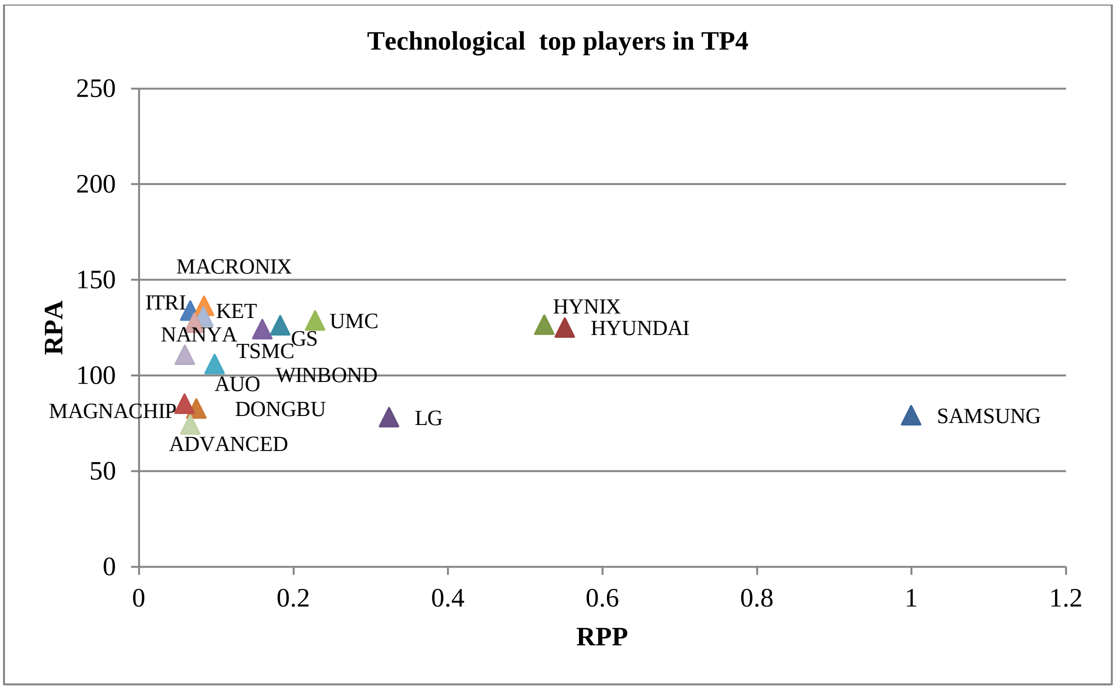
Source: EPO and compiled by the author.

Figure 5.34 Technological Top Players in TP2



Source: EPO and compiled by the author.

Figure 5.35 Technological Top Players in TP3



Source: EPO and compiled by the author.

Figure 5.36 Technological Top Players in TP4

It is worth noting that none of the current technology authorities in Taiwan, China, and Korea has been ranked as the top producer in the global solar PV industry. As discussed in Chapter 2, the global solar PV market is currently dominated by silicon-based first-generation products. Patents for these products have largely expired, so that the competitive advantage is based on large-scale mass production and the availability of polysilicon materials. While the conversion technology of the second or new generations, such as thin-film based and organic PV, has not yet matured, all the new entrants – including Taiwanese firms (such as TSMC, Hon Hai, and AUO) and Korean firms (such as Samsung and LG) – are carefully analysing the cost-benefit economics along with the roadmap of technological progress, particularly for the new generations of solar PV (DigiTimes, 2009; 2010). This is confirmed by Displaybank (2010): '*the entry of large Korea based companies' market participation such as Samsung and LG would accelerate mass production era for thin film solar cell applied with various technology*'.[35]

[35] For details, please see '*2009 Global Thin film Solar Cell Market Share Show Sharp Increase Y/Y to 19.8%*', Displaybank, 2010; http://www.displaybank.com/_eng/share/press_view.html?id=210269&&startPage=2

Chapter 6

Discussion

6.1 Stage One Results – Knowledge Flows

The empirical results of this study will either confirm or contradict the assessments for Taiwan, Korea, and China. Since China is still in an intermediate stage of developing its solar PV technologies, the discussions primarily focus on Taiwan and Korea. This study elaborates the findings associated with the seven research propositions of Chapter 3, by comparing the empirical findings of this study with the previous studies by Hu and Jaffe (2003), Hu (2009), Hu (2008), Jang et al. (2009), Lee and Yoon (2010), Lee and Jin (2012), Lee and Wang (2011), and Lee (2010) as follows.

- ***Research Proposition 1-1****: The US and Japan are the major sources of international knowledge flows for Taiwan, China, and Korea in building innovation capability of the solar PV industry.*

In terms of both absolute and relative propensity of citations, the US and Japan are acting as the most important international knowledge sources for both the first and new generation solar PV industries of Taiwan, Korea, and China, demonstrating that although the technology latecomers Taiwan and Korea have built up their innovation capabilities in certain high-tech sectors, they still need external knowledge to help upgrade their *process innovation* in mature technologies, such as the first generation solar PV sector.

However, Taiwanese inventors tend to cite more patents from the US than from Japan, while Korean inventors tend to cite equally from both these countries. This finding resembles the suggestion made by Hu and Jaffe (2003), but departs from it where they argue both Taiwan and Korea tend to cite more from the US than from Japan. While both the US and Japan act as the main knowledge sources for the development of solar PV industries in Taiwan and Korea, the findings suggest a divergent pattern for knowledge flows for Taiwan in citing the US and Japan, but a convergent pattern for Korea. This implies not only that different technology development strategies have been adopted in building the evolving innovation capabilities in Taiwan's and Korea's solar PV industries but also points to the different characteristics of knowledge in the US and Japan. Indeed, the requirements for US patents are more science-oriented while for Japanese patents they are more technology-oriented.[36] For its SMEs-based industrial structure, Taiwan tends to build its innovation capability in terms of mature technology and/or product differentiation, citing more from the science-based US patents, so as to differentiate through *product innovation.* In contrast, Korea*'s chaebols* tend to cite technology-based Japanese patents to the same extent, or even more, than science-based US patents, which may be because Korea's national strategy is not only to compete on the promotion of international brands (like the US and Japan as technology forerunners) but also to secure mass production capacity (like Taiwan and China as technology latecomers). These dual aims enable Korea's knowledge flows to be built on both scientific and technological foundations.

- ***Research Proposition 1-2****: The share of patent citations made to the US and Japan by Taiwan, Korea and China converges in the development of the solar PV industry.*

[36] According to a statement by WIPO, one of the critical requirements for US patents to be granted is '*novelty*', while for Japanese patents it is '*industrial use*'.

In comparative studies on Taiwan and Korea by Hu and Jaffe (2003), a convergent citation trend from the US and Japan indicated a decreasing citation propensity for US patents (science-based) and an increasing citation propensity for Japanese patents (technology-based). The findings of this study do not agree with the argument of Hu and Jaffe (2003), suggesting a divergent citation trend between the US and Japan in Taiwan's solar PV industry and a convergent trend in Korea. While Korea's citations of US patents (science-based) have decreased over time, they are replaced by the significantly increased level of scientific linkage in building its endogenous innovation capability, especially in the new generation solar PV. However, the US remains the main knowledge source for Taiwan (and actually increases in the first generation solar PV sector as the share from Japan decreases), while the degree of scientific linkage in Taiwan's solar PV industry is relatively lower and does not demonstrate a substitution effect as Korea's does. This finding may be due to the different industrial and/or organizational structures in building the endogenous innovation capability between Taiwan (SMEs with limited resources and a niche differentiation focus) and Korea (large-scale investment and international branding activities of *chaebols*). Based on these distinct industrial and/or organizational structures and technology strategies, the adoption of diverse strategies can be seen for knowledge acquisition from the technology leaders (US and Japan) in Taiwan's and Korea's first and new generations solar PV sectors, particularly since 2000.

- ***Research Proposition 1-3**: In the first generation solar PV, both Taiwan and Korea tend to have a higher degree of intra-national knowledge flows while that in China is relatively lower, resulting from the internalization capability previously built in the semiconductor industry.*

Both Korea and Taiwan have been involved in the semiconductor industry for more than two decades and have acquired confident technological capacities, as evidenced by their intensive patenting activities (Hu & Mathews, 2005). As the first generation solar PV technologies are highly related to semiconductors, the degree of intra-national knowledge flows in the first generation solar PV is well reflected in the innovation capability in Taiwan's and Korea's semiconductor sectors. However, China exhibits a lower degree of intra-national knowledge flows in the first generation solar PV due to a relatively weak technological capability in its semiconductor industry.

- ***Research Proposition 1-4:*** *In the new generation solar PV sector, Taiwan, China, and Korea latecomers tend to cite US and Japanese patents more than local-citations.*

Although Korea and China have put great efforts into going beyond mass production activity and trying to build their competitive advantages in the new generation solar PV sector, the external knowledge sources from the US and Japan are still indispensable. The intra-national knowledge flows in Korea's and China's new generation solar PV sector have surged since its emergence in the 2000s, while Taiwan has not yet shown very much effort in building its endogenous innovation capability through local-citations. This finding is at variance with the suggestions made by Park and Lee (2006) and Lee (2010), that SMEs (in Taiwan) are more likely to generate a higher local-citation rate than large companies (in Korea). As discussed above, the diverse performance of intra-national knowledge flows, in terms of local-citation rate, between Taiwan and Korea can be interpreted as derived from their adoption of different national strategies to the three latecomers in using the fast follower strategy.

Jaffe et al. (1993) proposed that patentees who live in the same country are more likely to cite each other, because of their geographic proximity. However, the findings of this study for the solar PV industries demonstrate that this argument does not necessarily apply in the case of the three latecomers (Taiwan, Korea, and China), where different assumptions may prevail. In the cases of latecomer countries, the effects of geographic proximity of knowledge flows can only be validated once the internalization capacity has been built or the technology threshold reached. For cases such as the new generation solar PV sector in Taiwan and Korea and both generation solar PV sectors in China, the building of innovation capabilities and internalization capacities are still overwhelmingly reliant on external knowledge from the US and Japan.

- ***Research Proposition 1-5:*** *The intra-national knowledge flows of solar PV technologies in Taiwan is mainly derived from the public research institute, while that in Korea is secured from the chaebols, and in China is acquired from the universities.*

The empirical results show that Taiwan's public research institute played a critical role in developing the first generation solar PV technologies in the very early 1990s. However, the role has been quickly taken over, since the mid-1990s, by semiconductor players, such as TSMC, UMC, and Vanguard. In contrast, the development of the new generation solar PV sector has been initiated by the private sector since 1996. The late involvement of Taiwan's public research institutes in developing the emerging technologies for the new generation solar PV imply that the role of public research institutes may need to be re-positioned for developing these emerging industries. In contrast to Taiwan's experience, the development of the first generation solar PV in Korea has been nearly entirely dominated by the large *chaebols*, while the public research institute was significantly involved in the new generation solar PV sector as early as 1996, but withdraw its participation after 2002, when the *chaebols* Samsung and LG were about to enter the sector. China's intra-national knowledge sources have, not surprisingly, been secured by the *forward engineering* knowledge hub universities in both solar PV generations, signalling their concern with technology commercialization and absorption capability in the private sector.

- ***Research Proposition 1-6:*** *Regarding international knowledge flow, Korean inventors tend to cite Japan's patents, Taiwanese inventors tend to cite Korea's patents, and Chinese inventors tend to cite Taiwan's patents in the solar PV industry in terms of relative citation propensity.*

Turning to relative citation propensity, the results are at variance with the arguments made by Lee and Yoon (2010), Lee and Jin (2012), and Lee and Wang (2011), since they show that Taiwanese inventors tend mostly to cite US (not Korean) patents. This is evidence that the order of patent citations does not necessarily follow the order of entry into the solar PV industry. One may criticize the proposed constructs regarding the entry order for Taiwan following Korea to enter the solar PV industry. Although Korea has not yet started mass production activity in the global solar PV industry, the technology origins and relevance between the first generation solar PV and semiconductors, and second generation (thin film) solar PV and FPDs are widely recognized. Thus, this study provides compelling reasons to believe that Korea is ahead of Taiwan in entering the solar PV-related technologies, because they indeed entered the semiconductor and FPD industries ahead of Taiwan. Nevertheless, even if the concern for technology interdependence between and amongst semiconductor, FPD, and solar PV sectors is disregarded and Korea is assumed to be the latest entrant amongst the three latecomers in the global solar PV industry, the results still do not conform to the conclusions of Lee and Yoon (2010), Lee and Jin (2012), and Lee and Wang (2011) regarding the order of patent citations. This implies that the order of patent citations may be difficult to assess from industry to industry and is possibly influenced by many other factors, rather than merely by the order of entry into the industry.

In terms of relative citation propensity, and in comparison with Taiwan and China, Korea exhibits a high propensity to cite Japanese patents and a low propensity to cite US patents in all generations of solar PV technologies. This result is very likely to be interpreted as Korean inventors tending to cite Japanese patents and being reluctant to cite US patents. However, Korean inventors actually cite patents equally from both the US and Japan, according to the absolute number of patent citations. Another issue is that both Taiwan and Korea exhibit high relative citation propensity for German patents in certain years, but the absolute number of citations of German patents is, in fact, very low. The measure of relative citation propensity is very useful to compare patent citation behaviour within a group of selected countries, but the interpretation may need to take the comparison base into consideration, as discussed in Section 3.2.

The results of this study demonstrate that the order of patent citations may be difficult to assess and may not always follow the order of entry into the industry, at least in the solar PV sector, as in this study, and in the flat panel display sector, as in the work by Hu (2008) and Jang et al. (2009). Rather, other societal, political, and historical factors influencing knowledge flows need to be considered. For example, the US company, RCA, built its offshore manufacturing site in Taiwan in 1969. This assisted Taiwan’s manpower growth in the semiconductor professions, while related technologies along with manufacturing equipment were transferred to Taiwan soon afterwards. Relying on the knowledge provided by RCA, the first Taiwanese semiconductor firm – United Microelectronics Corporation (UMC) – was able to be established in 1980, kicking off the era of prosperous semiconductor industry for Taiwan (Chang, Shih, & Hsu, 1994; Mathews, 1997). Apart from the technological cooperation at firm level, Taiwan received a great deal of military and financial support from the US government during the 1950s and 1960s, enabling a close relationship with the US in relation to political and economic activities (Palit, 2002). Since then, foreign direct investments, joint ventures, and technology licensing sourced from the US have deeply influenced the development of Taiwanese industry. Besides, skilled returnees from the US have promoted the cooperation in various aspects between the US and Taiwan (Shih, Wang, & Wei, 2007). After the US, Japan is the second most important knowledge source for Taiwan, reflecting a long colonial heritage going back to 1895 (Grajdanzev, 1942). Thus, Taiwan had established tight cultural and economic relationships with Japan since then. Due to these intimate historical and economic relationships, Taiwanese firms tend to cite both the US and Japanese patents. Furthermore, considering the technology advance and abundant knowledge stock shown by the US and Japan in the past century, technological catch-up latecomers are most likely to learn from these two countries. It is believed that these historical, cultural, and economic factors may have more bearing on patent citation than order-of-entry into industries. In conclusion, the above examples imply that the order of patent citations may be influenced by many factors, in addition to the order of entry into the industry.

- ***Research Proposition 1-7:*** *The knowledge flows of the emerging new generation solar PV in Taiwan, Korea, and China are likely to have a higher degree of scientific linkage than of the first generation.*

Except for Taiwan, the extent of scientific linkages in the new generation solar PV in both Korea and China is higher than that of the first generation. As late arrivals, the emerging new generation solar PV technologies have become the opportunity for China to leverage or *leapfrog* into the list of international technology leaders, so that its scientific linkage has been leading Korea and Taiwan since its inception in 2003. Korea's pursuit of advanced knowledge in the new generation solar PV is demonstrated by its persistent linkage with scientific knowledge over the last 15 years. The average scientific citation rate in Korea broke through the historical level for the first time in 2008 (nevertheless the scientific linkage is still lower than China's). Taiwan's scientific knowledge for the new generations lags behind not only China but also Korea. This may due to the fast follower strategy having been seriously adopted by Taiwan, because the mobility of resources from the first to the new generation cannot be too fast until a potentially new technology is signalled (Mathews, et al., 2011).

Summary: Seven stylized facts derived from applying the three indicators (namely international knowledge flow, intra-national knowledge flow, and scientific linkage) for examining the evolving knowledge flows in developing solar PV industries in Taiwan, Korea, and China have been identified, as follows.

International Knowledge Flows:

(1) Both the US and Japan are major sources of international knowledge flows for Korea and Taiwan in the solar PV industry.

(2) The patent citations made to the US and Japan are convergent in Korea but divergent in Taiwan, especially when the technology is mature (as in the first generation solar PV sector).

(3) Korea tends to cite both US and Japanese patents equally, while Taiwan tends to cite US

patents more (due to various industrial strategies).

(4) The international knowledge flows between and amongst technology latecomers in the solar PV industry are not apparent, not even in the mature technology of the first generation solar PV sector.

Intra-national Knowledge Flows:

(5) Only in the mature technology sector (as in the first generation solar PV), would Taiwan generate a higher degree of intra-national knowledge flows than Korea (because the SMEs can only put their resources into the dominant technology or have to wait until it emerges).

(6) Korea's intra-national knowledge flows are mainly derived from the large *chaebols*, Taiwan counts on the SMEs, and China relies on the universities.

Scientific Linkage:

(7) The strategies of knowledge acquisition for developing the solar PV industries in Taiwan, Korea, and China correspond to their accumulated resources of national strategies (SMEs in Taiwan, *chaebols* in Korea, and '*walking on three legs*' in China, even though that is not stabilized yet).

6.2 Stage Two Results – Technological Innovation Capabilities

The research findings of the second stage for the technological innovation capabilities of solar PV industries in Taiwan, China, and Korea have proved interesting, providing better understanding for the evolving industrial dynamics in the latecomer countries. Based on the research propositions elaborated in Chapter 3, their cause and effect relationships are discussed as follows.

- ***Research Proposition 2-1:*** *The solar PV technological innovation capabilities in Taiwan, China, and Korea were mostly built for production activity, while the global solar PV industry has significantly emerged after the 2000s.*

The finding of the second stage corresponds to the results derived from the knowledge flows of the first stage, and generally confirms Research Proposition 1 for the linkage of technological innovation capability and production activity in latecomer countries. However, it is found that different strategies are employed by each latecomer country. Technology Platform One (energy conversion, TP1) is the main focus in the production activity of all the three solar PV technology generations, taking 68% explanation power in factor analysis for all the three latecomers. The significant presence of TP1 thus demonstrates the importance of *process innovation* in the production-specialized latecomers.

Even though production technology is the main concern in developing technological innovation capabilities in Taiwan, China, and Korea, the focus of developing such capability has been diverse since the early 2000s, while the industry was entering the growth stage. The prior studies have revealed that the current mainstream products in the global solar PV market are dominated by the mature c-Si first generation technologies, as stated in Chapter 2, but Visentin (2009) clearly states that organic solar cell technology (49% of share) represents the majority of all solar PV patent applications from 1999 to 2008, followed by thin-film technology (14%). The results of this second stage show that Korea's technological innovation capability since the 2000s, as measured by patenting rate, corresponds most with this trend and the focus on the emerging TP2 thin-film and organic compound advance technologies. However, Taiwan and China remain focussed on the current dominant production technology (TP4 c-Si technology). This finding is in line with their significant market shares (both Taiwan and China together secure over 60%) owned in the global solar PV market since 2008.

This finding sheds a light on the evolving role of latecomers in seeking opportunities to become innovative first-movers in the emerging new niche after their successful catching up (Mathews et al., 2011). Even though not yet significantly present in the global solar PV industry, Korean latecomers are seen to be preparing aggressively to leverage its advanced technological capability from TP2 into new generation production activity, rather than involving the already mature c-Si technology. On the other hand, it is interesting to see that China has found no major innovation players in the presence of c-Si cell technology (TP4), thus not conforming to its leading position in global solar cell production. It suggests implicitly that the utilization of turnkey solutions in China accounts for the major production activities. Indeed, it is seen that China has already been standing at the leading position in global solar cell production activity since the year 2008. Furthermore, the massive production capacity expansions fuelled by Chinese IPOs in overseas stock markets have led to economic scale and low-price advantage, contributing to China's success in global solar cell production, by means of c-Si first generation solar PV products. In sum, the findings suggest that Taiwan and China are seriously adopting the fast-followership strategy while Korea is aggressively leveraging its national resources to leapfrog as a leading innovator in terms of advanced technology.[37]

- ***Research Proposition 2-2:*** *The technological innovation capabilities of solar PV*

[37] Even though Taiwan's latecomers are also aggressively pursuing the 2G/3Gadvanced technologies such as the formation of the 'CIGS alliance' in 2010, the patenting rate of such efforts is not yet as significant as Korea up to 2012.

industries in Taiwan, China, and Korea are significantly reliant on accumulated knowledge stock.

Research Proposition 2-2 holds well for all the three latecomers. The first generation, second generation, and third generation solar cell products share identical manufacturing process with those of semiconductors, but the third generation (III-V materials such as GaAs, and organic compound) technology tend to require more chemically-based knowledge. The success of the semiconductor industry in both Taiwan and Korea has long been recognized. Therefore, Taiwanese and Korean technological advantages in respect to first generation c-Si technology and second generation thin-film solar cell technologies reflect the significant impact of semiconductors for which they have accumulated essential knowledge stock. In particular, Taiwanese firms perform better in c-Si cell manufacturing (TP4, highly relevant to semiconductor technologies) and moderately in new generations (TP2) due to the nature of SMEs, which are able to quickly grasp onto the new technologies. Accordingly, it is chemical technology that has been the core in building China's national innovation system over the last two decades (Hu & Mathews, 2008). It is thus not surprising to see China's technological strength in developing the solar PV industry, apart from the TP4 production technology, has relied on TP3 chemical-based upstream epitaxy technology. China's endogenous national innovative capacity is mainly provided by universities and PRIs. Under strong national policy, they are active in building technological innovation capabilities through strategic industrial sectors, such as chemically-related technologies in the 1990s (Hu & Mathews, 2005; Hu, 2012) and extending to TP3, the chemically-based solar PV technology in the 2000s.

- ***Research Proposition 2-3**: With successful technological catch-up experience and resources, the SMEs-centric Taiwanese and chaebol-dominated Korean solar PV* *latecomers tend to pursue more advanced technologies, while the relatively lower endogenous innovation capability Chinese latecomers tend to focus on mature technologies.*

The empirical results do not fully support this research proposition in general, particularly since the 2000s. Before then, the technological innovation capabilities in all the three latecomers were indeed overwhelmingly focused on the TP4 production technology. However, the early 2000s become a critical divergent point for the three latecomers in developing their technological innovation capabilities, thus demonstrating the evolving effects of different national resources in each country. Since the 2000s, it is clear that Korea was aggressively pursuing the thin-film and organic compounds advance technologies (TP2), while the focus of Taiwan lay in the mature c-Si technology (TP4) and China had switched concentration to the cutting-edge upstream epitaxy technology (TP3). The inherent resource-scarcity of SMEs (which dominate in Taiwan) tend to reduce their ability to invest massively in R&D to pioneer highly uncertain new technologies, so they only focussed on *process innovation* during the growth stage of the industry cycle since the 2000s (Mathews, et al., 2011). While Chinese endogenous innovation capability is led by universities, it is expected that the technological innovation capability is linked more with basic science such as TP3 the upstream epitaxy technology, which has only significantly emerged since the 2000s. In contrast, Korean *chaebols* possess abundant resources and, having secured prolific accumulated capabilities over the past decades, are able to start to pursue leverage opportunities on emerging advanced technologies.[38]

[38] SNE Research reports that the commercialization of dye-sensitized solar cells (organic technology) will be achieved in 2013, see '*DSSC Technology Trend and Market Forecast (2008~2015)*', available at: http://www.solarnenergy.com/eng/service/report_show.php?id=732

- ***Research Proposition 2-4:*** *Given the different national resources, the specialisation of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea tend to be diverse.*

The results positively support research proposition 2-4. Many have reported that Korea is pursuing its future economic growth through overall involvement in R&D, module production, and system integration activities in the global solar PV industry. Lin, Chen and Wu (2006) suggest that it's effective for firms with high technology stocks to diversify their R&D activities to a broad spectrum of technology fields and *vice versa*. Along with the aggressive investment in the renewable energy industrial promotion initiated by the Korean government, the largest Korean *chaebol* Samsung dominates in all the four technology platforms in terms of R&D scale (RPP). Samsung aims to build a complete solar PV value chain, spanning from upstream solar PV materials to downstream solar PV plant constructions. This clearly shows Korea's industrial structure, which is different from that of Taiwan. Networking of SMEs constitutes a flexible and complementary industrial structure in Taiwan. Taiwan's advantage in quick response to market demands has been proved by its success in global solar cell production. Korean companies have long been preparing to enter the global solar PV market. Their vertical-integrated industrial structure, lacking flexibility, may be blamed for their lag behind Taiwan in the incidence of global solar cell production.

In a comparison of the top technological players, Korean companies undoubtedly secure the largest number of top players. This shows that Korea has established sufficient technological innovation capabilities to potentially threaten the leading positions of China and Taiwan, even though it is not yet significantly current in the global solar PV industry. Following Korea, Chinese patentees appear more in the fields of energy conversion (TP1) and epitaxy (TP3) where universities are the major innovators. In addition, China's massive patenting activities concerning all the four technology platforms are impressive, revealing China's great national ambition as well as the numerous international and intra-national collaborations, aiming at a significant presence in the global solar PV industry.

Summary: Four stylized facts regarding the technological innovation capabilities of the solar PV industry in the three Asian latecomers are as follows:

(1) Although not yet taking a significant market share, Korean firms potentially threaten the leading positions of China and Taiwan in the global solar PV production activity.

(2) The building of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea are evolving with their accumulated resources. That is, it is mainly built on the intense semiconductor industry in both Taiwan and Korea, and on the stronger chemical industry in China.

(3) Taiwan tends to focus on mainstream mature production technology (c-Si cell), while China intends to put more efforts into large-scale production technology (energy conversion) and secure upstream cutting-edge technology (epitaxy). Korea tends to exploit the advantages of *chaebols* and aims at building comprehensive technological innovation capabilities spanning from upstream to downstream solar PV technologies.

(4) Both the innovation activities of Taiwanese SMEs and Chinese research-oriented players are focused on R&D efficiency enhancement (higher RPA), while Korea's *chaebols* tend to concentrate on R&D scale increase (higher RPP) to compete in the global solar PV industry.

Even though the two separate analytical results have demonstrated different research outcomes, the seven stylized facts derived from knowledge flows and the four stylized facts realised from technological innovation capabilities interactively reflect to one another on the evolving and corresponding relationships between and amongst knowledge flows and diffusion and the technological innovation capabilities in the three solar PV latecomer countries Taiwan, China, and Korea over the last decades. In particular, the strategies of knowledge acquisition along with the industrial structure of national approach and accumulated resources greatly influence the magnitude and altitude of technological innovation capabilities.

Chapter 7

Conclusions, Contributions, and Policy Implications

7.1 Conclusions

Taking the solar PV industry as an example, the empirical results of both knowledge flows and technological innovation capabilities in the Asian latecomers Taiwan, China, and Korea offer fruitful outcomes as they explore industry evolution from the perspective of those latecomers. This study is not only to identify a more comprehensive patent dataset for solar PV technologies but also to differentiate the three technology generations and the four technology platforms through a deliberate three-stage methodology of extracting patents. This study, then, has adopted a two-stage research methodology to investigate respectively the evolving knowledge flows and technological innovation capabilities of the three solar PV generations in the Asian latecomers, Taiwan, Korea and China over recent decades. It next briefly surveys the contributions to the literature and the policy implications derived from the two sequential research stages in turn, after which the future research is expounded.

Recalling that the two objectives of this study are:

(1) *To explore the extent to which patterns, in terms of evolving knowledge sources and knowledge flows, established in earlier industries are replicated, and to what extent fresh patterns may be in the process of being generated in the emerging industries such as the solar PV industry by the Asian latecomers Taiwan, China, and Korea.*

(2) *Given that the technological trajectory of solar PV is created by the US, Germany, and Japan as leading countries in the past decades, to find to what extent the Taiwanese, Chinese and Korean followers have developed their technological innovation capabilities so as to surpass the US and Japan and acquire leading production positions since the*

mid-2000s.

The seven stylized facts derived from evolving knowledge flows and the four stylized facts in respect of the technological innovation capabilities that have been generated from the empirical results of this study are:

- **Stage One - Evolving Knowledge Flows**

International Knowledge Flows:

(1) Both the US and Japan are major sources of international knowledge flows for Korea and Taiwan in the solar PV industry.

(2) The patent citations made to the US and Japan are contracting in Korea but diverging in Taiwan, especially when the technology is mature (as in the first generation solar PV sector).

(3) Korea tends to cite both US and Japanese patents equally, while Taiwan tends to cite more US patents (due to various industrial strategies).

(4) International knowledge flows between and amongst technology latecomers in the solar PV industry are not evident, not even in the mature technology of the first generation solar PV sector.

Intra-national Knowledge Flows:

(5) Only in the mature technology sector (as in the first generation solar PV), would Taiwan generate a higher degree of intra-national knowledge flows than Korea (because SMEs can only put their resources into the dominant technology or wait until it emerges).

(6) Korea's intra-national knowledge flows are mainly derived from the large *chaebols*, whereas Taiwan depends on SMEs, and China relies on universities.

Scientific Linkage:

(7) The strategies of knowledge acquisition for developing the solar PV industries in Taiwan, Korea, and China correspond to their accumulated resources of national strategies (SMEs in Taiwan, *chaebols* in Korea, and '*walking on three legs*' in China, even though the latter is not stabilized yet).

- **Stage Two - Technological Innovation Capability**

(1) Although not yet taking a significant market share, Korean firms potentially threaten the leading positions of China and Taiwan in global solar PV production activity.

(2) The building of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea are evolving along with their accumulated resources. That is, they are mainly built by the active semiconductor industry in both Taiwan and Korea, and by the stronger chemical industry in China.

(3) Taiwan tends to focus on mainstream mature production technology (c-Si cell), while China tends to put more effort into large-scale production technology (energy conversion) and secure upstream cutting-edge technology (epitaxy). Korea tends to utilize the strengths of *chaebols* and aims at building a comprehensive array of technological innovation capabilities spanning from upstream to downstream solar PV technologies.

(4) Both the innovation activities of Taiwanese SMEs and Chinese research-oriented players are focused on R&D efficiency enhancement (higher RPA), while Korea's *chaebols* tend to concentrate on R&D scale increase (higher RPP) to compete in the global solar PV industry.

The seven stylized facts derived from knowledge flows and four stylized facts extracted from technological innovation capabilities interactively reflect one to another in the evolving and corresponding relationships between and amongst knowledge flows and diffusion and the technological innovation capabilities in the three solar PV latecomer countries over recent decades. In particular, the strategies of knowledge acquisition combined with the industrial structure of national approach and accumulated resources greatly influence the magnitude and altitude of technological innovation capabilities.

Mathews et al. (2011) provides a framework for analysing the successes of countries and firms pursuing industrial upgrading through fast follower strategies – as well as for shedding light on sectors where such strategies have not worked. This study has sought to show how a country can successfully enter the solar PV sector as a potentially significant global player, utilizing fast follower strategies that can now be identified and characterized in canonical fashion. The rest of the world, and in particular India, Russia, and Brazil, will be taking careful note of the kinds of policies and strategies deployed in the three latecomer countries, as renewable energy industries move to become potentially the largest and most significant industries of the 21st century.

7.2 Contributions and Policy Implications

7.2.1 Knowledge Flows

Compared with previous studies of inter-national and intra-national knowledge flows, this study employed an additional indicator, viz. 'scientific linkage' to evaluate a latecomer country's internationalization capability; this is particularly suitable for investigating the development of knowledge flows for emerging technologies such as solar PVs (Schmoch, 1993). In fact, this study is concerned with patterns of *knowledge leverage* exercised by

Taiwan, Korea and China in the solar PV industry – considering that it is strategizing by the firms and institutions in these countries that accounts for the knowledge flows.

Along with the seven ‘stylized facts’ outlined above, four substantive contributions are claimed in this study: (1) Through a novel and deliberate three-stage filtering approach, this study identified the major solar PV technologies, in terms of IPCs, representing a higher degree of robustness than other approaches, such as using keyword searches alone; (2) Through examining the development of the emerging solar PV industry, this study closely observes and updates the dynamic evolution of knowledge flows in the Asian latecomers, through which Taiwan’s and Korea’s knowledge acquisition strategies in relation to their overall business strategies and prevailing business conditions in leveraging external and internal knowledge sources are more clearly explored; (3) This study extends the understanding of knowledge internalization capability by adding the indicator of scientific linkage to examine the evolving absorptive capacity and cause and effect in pursuing advanced knowledge for Asian latecomers; (4) This study presents empirical results to prove that, in the PV sector, patent citations increasingly reflect intra-national knowledge flows, reflecting the development of absorptive capacity in both Taiwan and Korea.

By using these three indicators (international knowledge flows, intra-national knowledge flows, and scientific linkage), the results of this study show that the variations of external and internal knowledge flows sourced from the technology forerunners as well as within the country, disclose the varying national strategies adopted in Taiwan, Korea, and China to develop their solar PV industries. As for international knowledge flows, the US and Japan act as the main knowledge sources for the development of solar PV industries in Taiwan and Korea, while the findings of this study suggest a divergent pattern of citing US and Japan in

Taiwan, but a convergent pattern in Korea. In contrast, the intra-national knowledge flows in developing the solar PV industries in the three latecomers indicate that the role of the public sector is evolving along with industrial development. The late involvement of Taiwan's public research institutes in developing the emerging technologies for the new generation solar PVs implies that the role of public research institutes is being re-positioned to develop the emerging industries. In contrast to Taiwan's experience, the development of first generation solar PV in Korea is nearly completely dominated by the large *chaebols*, while the public research institutes have been involved only in the new generation solar PVs. China's intra-national knowledge sources have, not surprisingly, been secured by the *forward engineering* in knowledge hub universities for all generations of solar PVs, signalling the concerns of the private sector in technology commercialization and absorption capability.

In terms of scientific linkage, China is seen to be aggressively leveraging or *leapfrogging* into the list of international technology leaders in the new generation solar PV sector, in which it is scientific linkage that has led Korea and Taiwan since its inception in 2003. Due to its weaker industrial base, it is not surprising that China presents as a leader in pursuing the cutting-edge new generation solar PV in terms of scientific linkage (even though its patent count is only 12). The technology appropriation owned by the universities (rather than by the private sector) is clear, and points to an urgent need for deploying strategies of technology diffusion and commercialization, as termed as "*forward engineering*" (Eun et al., 2006; Hu & Mathews, 2008). Korea has also taken the emergence of new generation solar PVs as an opportunity to become an international leader, despite its late entry into the global industry. Taiwan's lower level of scientific linkage in the new generations reflects the adoption of either "*reverse engineering*" mode (Kim, 1997) or a fast follower strategy focussed on the dominant technology. In this sense, this study exposed clear policy implications for other emerging latecomers, such as those found in Southeast Asia, Latin America or other countries. First, the public research institutes have been critical knowledge agents in East Asian latecomers, especially at the early stage of industrial development. The role of public research institutes may be varied but it evolves along with industrial development, moving from being an initiator and facilitator of innovation to an innovation linkage between technology and business activities. Second, depending on a country's accumulated resources (historical, cultural, technological, and economic), the knowledge acquisition strategies used by its firms rely heavily on the national approach in developing an emerging field of technology. This is particularly important at the stage when external knowledge is a critical factor in shaping a country's absorptive capacity as well as influencing the magnitude and intensity of its innovation capability.

7.2.2 Technological Innovation Capabilities

As well as the four 'stylized facts' and providing partial verification for the empirical results of the evolving knowledge flows for the solar PV industries in Taiwan, China, and Korea, three substantive contributions are claimed: (1) this study has identified the major solar PV technology platforms; (2) this study has extended various magnitude and longitude understandings for technological innovation capabilities in developing the solar PV industries of latecomers Taiwan, China, and Korea through their technological portfolios (RDGR, RPP, and RPA); and (3) this study has explained how the various technological strategies and knowledge sources employed by Taiwan, China, and Korea demonstrate that the technological innovation capabilities in the latecomers are evolving together with the national approaches and are built upon a country's collective and embedded accumulated resources.

This study identifies a more-comprehensive patent dataset for solar PV technologies, in which four technology platforms are constructed through a deliberate three-stage methodology utilizing patent extraction and factor analysis. The respective technological innovation capabilities of the four solar PV technology platforms in Taiwan, Korea and China define various niches. Chinese firms' domination over the production of solar PV is attributed to the importation of turnkey solutions, economies of scale, and lower production costs. The aggressive investment made by the Korean *chaebols* in the solar PV industry since 2006 signals an important precedent; that activities associated with abundant resources and tacit knowledge accumulated from the DRAM and FPD industries have been deployed. Compared with the large patent stocks in China and Korea, Taiwanese SMEs secure the least volume but leverage their technological capabilities accumulated and extended from semiconductors, demonstrating the focus on *process innovation* in mature c-Si technology.

The major findings of this Thesis suggest that the innovative technology capabilities of the solar PV industry in Asian latecomer countries essentially depended on the acquisition of external knowledge which built by invention and product innovation of international leaders in the first generation. When the external knowledge is diffused and internalized, the Asian latecomers are competing with the international technological leaders in the global market through production expansion. Simultaneously, the Asian latecomers are seeking niche development in the emerging second and third generations, based on their different embedded resources and national approaches.

Due to the high level of technological relatedness with semiconductors and flat panel displays, the Asian latecomers entered the solar PV industry with greater advantages of production and process innovation and were able to leverage themselves into the emerging technological frontier in the second and third solar PV generations. This study thus provides clear policy implications for other emerging latecomers, such as those found in Southeast Asia, Latin America, or other countries. First, universities and PRIs are critical sources of technological innovation capabilities, especially for the emerging technologies such as solar PV. For resource-limited latecomer countries, government-funded universities and PRIs are less sensitive to uncertainty, so that they are able to act as risk takers engaging in state-of-art technology for developing the emerging industry. Secondly, the build of technological innovation capabilities in the latecomer countries is based largely on their accumulated knowledge as well as resource endowment and mobilization. The development of Taiwan's solar PV industry is tied to a fast-follower strategy, led by the SMEs to focus on the dominated and mature c-Si technology, whose resource is mostly extended from its well-established semiconductor industry; Korea relies heavily on its *chaebols* for value chain integration and aims to secure innovation leadership in the advanced technologies*;* China depends on universities to mobilize its accumulated chemical-related knowledge and resources into the cutting-edge upstream technology while retaining a production advantage in the dominant mainstream technology.

Whether or not one agrees with the interpretations in this study, these empirical regularities exist and must be accounted for. A brief summary of the two-stage empirical study is presented in Table 7.1.

Table 7.1 Summary of the Empirical Study

	Evolving Knowledge Flows	**Technological Innovation Capabilities**
Research Questions	➢ To what extent do the patterns, in terms of evolving knowledge sources and knowledge flows established in earlier industries are replicated, and to what extent are fresh patterns in the process of being generated in the emerging industries such as in the solar PV industry by the Asian latecomers Taiwan,	➢ Given that the technological trajectory of solar PV is created by the US, Germany, and Japan as leading countries in the past decades, to what extent have the Taiwanese, Chinese and Korean followers developed their technological innovation capabilities so as to surpass the US

	Evolving Knowledge Flows	Technological Innovation Capabilities
	China, and Korea?	and Japan and acquire leading production positions since the mid-2000s?
Research Setting	➢ Three Asian countries: Taiwan, South Korea, and China (1984-2008)	➢ Three Asian countries: Taiwan, South Korea, and China (1978-2008)
Unit of Analysis	➢ Four main indicators extracted from the USPTO: inter-national knowledge flows; intra-national knowledge flows; scientific knowledge linkage; and relative citation rate.	➢ Technology portfolio composed of three elements calculated from the EPO worldwide patent database (esp@cenet): technology attractiveness (relative growth rate); technology patent position (RPP); and revealed patent advantage (RPA).
Research Design	An econometric analysis of time series for the solar PV industry relating to international patenting activity from 1984 to 2008.	➢ An econometric analysis involved in measuring performance of technological innovation capability from 1978 to 2008.
Key Findings	***International knowledge flows:*** ➢ Both the US and Japan are major sources of international knowledge flows for Korea and Taiwan in the solar PV industry. ➢ The patent citations made to the US and Japan are convergent in Korea but divergent in Taiwan, especially when the technology is mature (as in the first generation solar PV sector). ➢ Korea tends to cite both US and Japanese patents equally, while Taiwan tends to cite US patents more (due to various industrial strategies). ➢ The international knowledge flows between and amongst technology latecomers in the solar PV industry are not apparent, not even in the mature technology of the first generation solar PV sector. ***Intra-national knowledge flows:*** ➢ Only in the mature technology sector (as in the first generation solar PV), would Taiwan generate a higher degree of intra-national knowledge flows than Korea (because the SMEs can only put their resources into the dominant technology or have to wait until it emerges). ➢ Korea's intra-national knowledge flows are mainly derived from the large	➢ Although not yet taking a significant market share, Korean firms potentially threaten the leading positions of China and Taiwan in the global solar PV production activity. ➢ The building of technological innovation capabilities in the solar PV industries of Taiwan, China, and Korea are evolving with their accumulated resources. That is, it is mainly built by the active semiconductor industry in both Taiwan and Korea, and by the stronger chemical industry in China. ➢ Taiwan tends to focus on mainstream mature production technology (i.e. c-Si cell), while China tends to put more efforts into large-scale production technology (i.e. energy conversion) and secure upstream cutting-edge technology (i.e. epitaxy). Korea tends to utilize the advantages of *chaebols* and aims at building a comprehensive technological innovation capabilities spanning from upstream to downstream solar PV technologies. ➢ Both the innovation activities of Taiwanese SMEs and Chinese research-oriented players are

	Evolving Knowledge Flows	Technological Innovation Capabilities
	chaebols, Taiwan counts on the SMEs, and China relies on the universities. ***Scientific linkage:*** ➢ The strategies of knowledge acquisition for developing the solar PV industries in Taiwan, Korea, and China correspond to their accumulated resources of national strategies (SMEs in Taiwan, *chaebols* in Korea, and 'walking on three legs' in China, even though that is not yet stabilized).	focused on R&D efficiency enhancement (i.e., higher RPA), while Korea's *chaebols* tend to concentrate on R&D scale increase (i.e., higher RPP) to compete in the global solar PV industry.
Contributions	➢ This study identified the major solar PV generations, in terms of IPCs, which represents a higher degree of robustness than other approaches, such as using only keyword searches. ➢ By examining the development of the emerging solar PV industry, this study closely observes and updates the dynamic evolution of knowledge flows in the Asian latecomers, in which Taiwan's and Korea's knowledge acquisition strategies in relation to their overall business strategies and prevailing business conditions in leveraging external and internal knowledge sources are more clearly explored. ➢ This study extends the understanding of knowledge internalization capability through adding the indicator of scientific linkage to examine the evolving absorptive capacity and cause and effect in pursuing advanced knowledge for Asian latecomers. ➢ This study presents empirical results to prove that, in the PV sector, patent citations increasingly reflect intra-national knowledge flows, reflecting the development of absorptive capacity in both Taiwan and Korea.	➢ This study is the first in the literature to identify the major solar PV technology platforms through a deliberate three-stage data filter. ➢ This study extends various magnitude and longitude understanding for technological innovation capabilities in developing the solar PV industries of latecomers Taiwan, China, and Korea through their technological portfolios (i.e., RDGR, RPP, and RPA). ➢ The various technological strategies and knowledge sources employed by Taiwan, China, and Korea contribute to the literature that the technological innovation capabilities in the latecomers are evolving with the national approaches and built upon a country's collective and embedded accumulated resources.

7.3 Further Research

The empirical results of this study have suggested several future studies in order to better understand the relationships between patenting activity and evolution of industrial dynamics. First, given that the US has been one of the critical technology and product markets, filing patent applications at the USPTO is of great interest to inventors (e.g. Brockhoff, Ernst, & Hundhausen, 1999; Chen & Chang, 2010; Criscuolo, 2006; Lai & Wu, 2005; Tijssen, 2001). Future research should also pay attention to the cause and effect of the fact that very few Chinese solar PV-related patents have been registered at the USPTO, while a great number of solar PV-related patents have been granted domestically by the Chinese SIPO (State Intellectual Property Office), which is line with De la Tour (2011) that only 1% of Chinese patents are also filed abroad.

Second, using patenting citation as an indicator for measuring knowledge flows may cause biases in the true knowledge flows and diffusion, e.g. Alcácer and Gittelman, 2006, who argue that the majority of citation patents which appear in patent applications are significantly suggested by the patent examiners (who are familiar with the patenting field) rather than by the inventors themselves. Even though this may be true about the process for the patent application, it is not deniable that these knowledge flows are still treated as indirect diffusion if they are not directly cited by the inventors. However, any future study should investigate the effect of such ‘indirect knowledge flows’ for both advanced and latecomer countries.

Third, the findings of knowledge flows suggest that Taiwan’s dependence on the US and Japan is expanding, while that of Korea is contracting (and the case of China is as yet unclear). The results of this study, even those dealing with the departure from the perspectives of patenting activity in the solar PV industries of the latecomer countries in Taiwan, China, and Korea, call for policy attention not only on the technological impact but also on a country’s historical, social, cultural, and economical influence, in which the magnitude and intensity of innovation capability along with the industrial dynamics are great influences.

Fourth, it is highly aware that the developmental models amongst the three sample countries, namely Taiwan, Korea, and China are diverse. In particular, the Chinese model is highly related to its strong top-down policy and abundant resource endowments, aiming at creating a new technological regime to compete with the western countries. Each country has its unique industrial structure and technological regime which relies on a different strategy in technological catch-up andit would be worthwhile to further explore their interdependency and uniqueness.

Fifth, given that the nature of renewable energy it needs to be integrated into an eco-system; one should consider not only technological innovations but also systematic and architectural innovations in order to develop a sustainable industry such as solar PVs.

Last but not least, as well as the patenting activity as shown in this study, one should also investigate the degree of effectiveness and efficiency for various channels of knowledge flows and innovation capability mechanisms, such as licensing and/or cross-licensing, in-house R&D, collaboration, acquisitions and mergers, and manpower flows, in accordance with the different technology and social capabilities, because the interactions between and amongst these mechanisms affect the evolution of an industry.

Appendix A: International Patent Classification (IPCs) Match with Solar Photovoltaic Relevant Keywords

Keyword: <u>Solar cell</u>

Find classification(s) for keywords syringe injection

solar cell

Search

Go Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture [C0608]	H01G9
Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....	H01L51
Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof (processes or apparatus peculiar to the manufacture or treatment	H01L21
Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes (reactive sputt....	C23C16
Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate (processes or apparatus specially adapted for the manufacture or treatm....	H01L27
Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material (discharge tubes with provision for introducing objects or material to be exposed to the	C23C14
Glass compositions containing a non-glass component, e.g. compositions containing fibres, filaments, whiskers, platelets, or the like, dispersed in a glass matrix (devitrified glass ceramic....	C03C14
Use of solar heat, e.g. solar heat collectors (distillation or evaporation of water using solar energy C02F1/14 ; devices for producing me....	F24J2
Enamels; Glazes (cold glazes for ceramics [N: C04B41/48]); Fusion seal compositions being frit compositions having non-frit additions	C03C8

Source: EPO

Keyword: <u>Photovoltaic</u>

Find classification(s) for keywords syringe injection

Photovoltaic

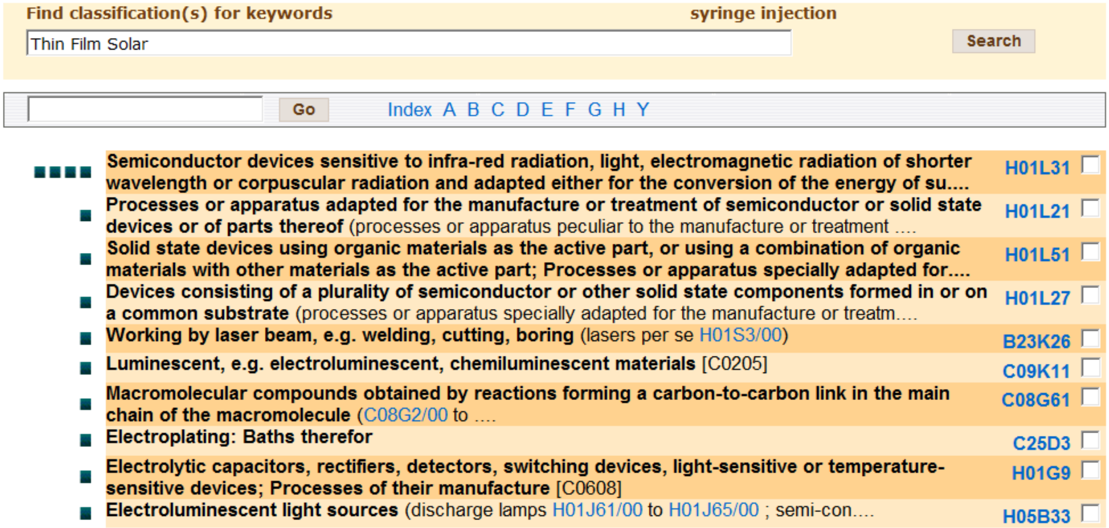
Search

Go Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Use of solar heat, e.g. solar heat collectors (distillation or evaporation of water using solar energy C02F1/14 ; devices for producing me....	F24J2
Layered products essentially comprising sheet glass, or glass, slag, or like fibres	B32B17
Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....	H01L51
Single crystals or homogeneous polycrystalline material with defined structure characterised by the material or by their shape (alloys C22C)	C30B29
Circuit arrangements for ac mains or ac distribution networks	H02J3
Burglar, theft, or intruder alarms (vehicle theft alarms B60R25/10 ; cycle theft alarms B....	G08B13
Single-crystal growth by normal freezing or freezing under temperature gradient, e.g. Bridgman-Stockbarger method (C30B13/00 , ...	C30B11
Automatic systems in which deviations of an electric quantity from one or more predetermined values are detected at the output of the system and fed back to a device within the system to restor....	G05F1
Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof (processes or apparatus peculiar to the manufacture or treatment	H01L21

Source: EPO

Keyword: <u>Thin Film Solar</u>



Find classification(s) for keywords   syringe injection

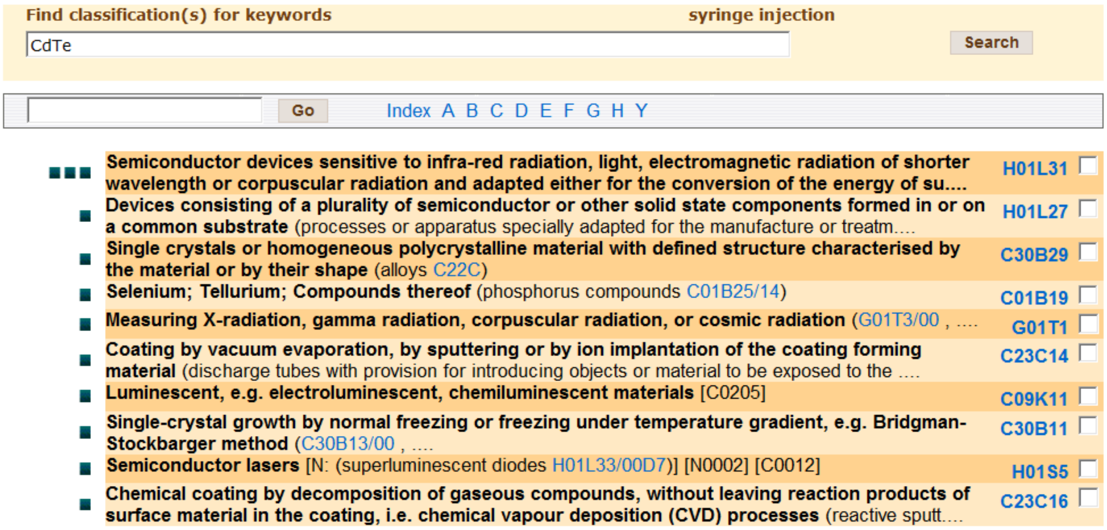
Thin Film Solar   Search

Go   Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof (processes or apparatus peculiar to the manufacture or treatment	H01L21
Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....	H01L51
Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate (processes or apparatus specially adapted for the manufacture or treatm....	H01L27
Working by laser beam, e.g. welding, cutting, boring (lasers per se H01S3/00)	B23K26
Luminescent, e.g. electroluminescent, chemiluminescent materials [C0205]	C09K11
Macromolecular compounds obtained by reactions forming a carbon-to-carbon link in the main chain of the macromolecule (C08G2/00 to	C08G61
Electroplating: Baths therefor	C25D3
Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture [C0608]	H01G9
Electroluminescent light sources (discharge lamps H01J61/00 to H01J65/00 ; semi-con....	H05B33

Source: EPO

Keyword: <u>CdTe</u>



Find classification(s) for keywords   syringe injection

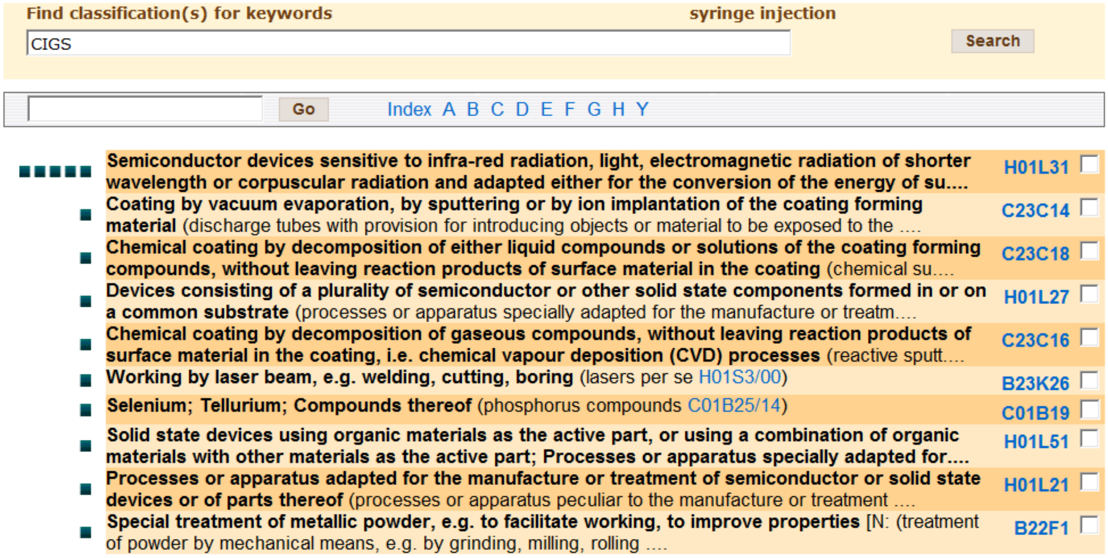
CdTe   Search

Go   Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate (processes or apparatus specially adapted for the manufacture or treatm....	H01L27
Single crystals or homogeneous polycrystalline material with defined structure characterised by the material or by their shape (alloys C22C)	C30B29
Selenium; Tellurium; Compounds thereof (phosphorus compounds C01B25/14)	C01B19
Measuring X-radiation, gamma radiation, corpuscular radiation, or cosmic radiation (G01T3/00 , ...	G01T1
Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material (discharge tubes with provision for introducing objects or material to be exposed to the	C23C14
Luminescent, e.g. electroluminescent, chemiluminescent materials [C0205]	C09K11
Single-crystal growth by normal freezing or freezing under temperature gradient, e.g. Bridgman-Stockbarger method (C30B13/00 , ...	C30B11
Semiconductor lasers [N: (superluminescent diodes H01L33/00D7)] [N0002] [C0012]	H01S5
Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes (reactive sputt....	C23C16

Source: EPO

Keyword: CIGS


Find classification(s) for keywords syringe injection

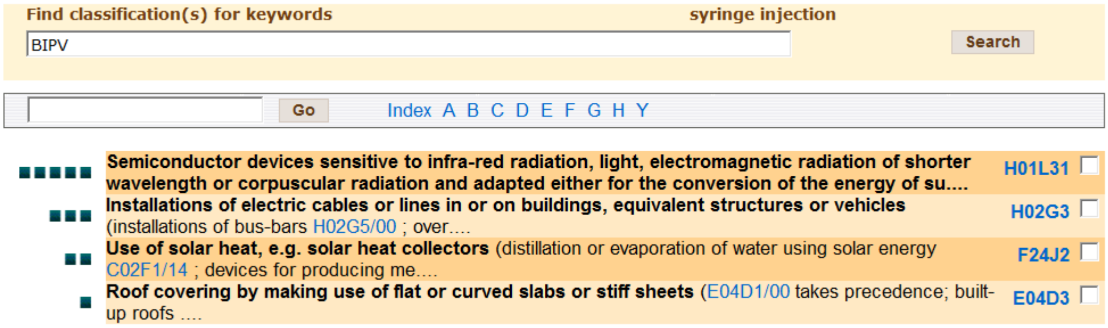
CIGS Search

Go Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material (discharge tubes with provision for introducing objects or material to be exposed to the	C23C14
Chemical coating by decomposition of either liquid compounds or solutions of the coating forming compounds, without leaving reaction products of surface material in the coating (chemical su....	C23C18
Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate (processes or apparatus specially adapted for the manufacture or treatm....	H01L27
Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes (reactive sputt....	C23C16
Working by laser beam, e.g. welding, cutting, boring (lasers per se H01S3/00)	B23K26
Selenium; Tellurium; Compounds thereof (phosphorus compounds C01B25/14)	C01B19
Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....	H01L51
Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof (processes or apparatus peculiar to the manufacture or treatment	H01L21
Special treatment of metallic powder, e.g. to facilitate working, to improve properties [N: (treatment of powder by mechanical means, e.g. by grinding, milling, rolling	B22F1

Source: EPO

Keyword: BIPV


Find classification(s) for keywords syringe injection

BIPV Search

Go Index A B C D E F G H Y

Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....	H01L31
Installations of electric cables or lines in or on buildings, equivalent structures or vehicles (installations of bus-bars H02G5/00 ; over....	H02G3
Use of solar heat, e.g. solar heat collectors (distillation or evaporation of water using solar energy C02F1/14 ; devices for producing me....	F24J2
Roof covering by making use of flat or curved slabs or stiff sheets (E04D1/00 takes precedence; built-up roofs	E04D3

Source: EPO

Keyword: High Concentration Solar

Find classification(s) for keywords — syringe injection

High Concentration Solar — Search

Go — Index A B C D E F G H Y

■■■■	**Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....**	H01L31
■■	**Use of solar heat, e.g. solar heat collectors** (distillation or evaporation of water using solar energy C02F1/14 ; devices for producing me....	F24J2
■	**Systems with reflecting surfaces, with or without refracting elements** (microscopes G02B21/00 ; telescopes, periscopes	G02B17
■	**Direction-finders for determining the direction from which infrasonic, sonic, ultrasonic, or electromagnetic waves, or particle emission, not having a directional significance, are being receiv....**	G01S3
■	**Thermo-electric devices comprising a junction of dissimilar materials, i.e. exhibiting Seebeeck or Peltier effect with or without other thermo-electric effects or thermomagnetic effects; Proces....**	H01L35
■	**Silicon; Compounds thereof** ([N: C01B6/00] , C01B21/00 , ...	C01B33
■	**Single-crystal growth by normal freezing or freezing under temperature gradient, e.g. Bridgman-Stockbarger method** (C30B13/00 , ...	C30B11
■	**Single crystals or homogeneous polycrystalline material with defined structure characterised by the material or by their shape** (alloys C22C)	C30B29
■	**Production of homogeneous polycrystalline material with defined structure** [N0102]	C30B28
■	**Printed circuits** (assemblies of a plurality of individual semiconductor or solid state devices H01L25/00 ; devices consisting of a plura....	H05K1

Source: EPO

Keyword: Organic Solar

Find classification(s) for keywords — syringe injection

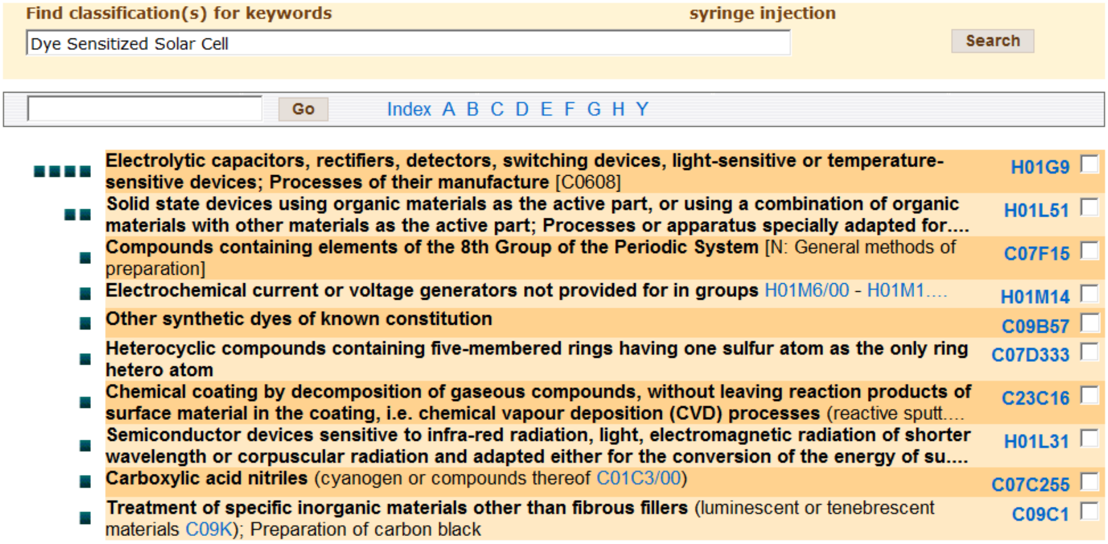
Organic Solar — Search

Go — Index A B C D E F G H Y

■■■	**Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....**	H01L51
■	**Luminescent, e.g. electroluminescent, chemiluminescent materials** [C0205]	C09K11
■	**Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....**	H01L31
■	**Macromolecular compounds obtained by reactions forming a carbon-to-carbon link in the main chain of the macromolecule** (C08G2/00 to	C08G61
■	**Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate** (processes or apparatus specially adapted for the manufacture or treatm....	H01L27
■	**Conductors or conductive bodies characterised by the conductive materials; Selection of materials as conductors** (resistors H01C ; selection of m....	H01B1
■	**Electroluminescent light sources** (discharge lamps H01J61/00 to H01J65/00 ; semi-con....	H05B33
■	**Compounds containing elements of the 4th Group of the Periodic System**	C07F7
■	**Treatment of water, waste water, or sewage** (C02F3/00 to C02F9/00 take precedence)	C02F1
■	**Compositions of macromolecular compounds obtained by reactions forming a carbon-to-carbon link in the main chain** (C08L7/00 to	C08L65

Source: EPO

Keyword: <u>Dye Sensitized Solar Cell</u>



Find classification(s) for keywords — syringe injection

Dye Sensitized Solar Cell — Search

Go — Index A B C D E F G H Y

■■■■	**Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture** [C0608]	H01G9
■■	**Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for....**	H01L51
■	**Compounds containing elements of the 8th Group of the Periodic System** [N: General methods of preparation]	C07F15
■	**Electrochemical current or voltage generators not provided for in groups** H01M6/00 - H01M1....	H01M14
■	**Other synthetic dyes of known constitution**	C09B57
■	**Heterocyclic compounds containing five-membered rings having one sulfur atom as the only ring hetero atom**	C07D333
■	**Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes** (reactive sputt....	C23C16
■	**Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of su....**	H01L31
■	**Carboxylic acid nitriles** (cyanogen or compounds thereof C01C3/00)	C07C255
■	**Treatment of specific inorganic materials other than fibrous fillers** (luminescent or tenebrescent materials C09K); Preparation of carbon black	C09C1

Source: EPO

Appendix B: Patents Granted to 76 Global Solar PV Specialization Firms, 1977-2009

Country	Company	Patent count	Country	Company	Patent count
Belgium	Photovoltech NV	0	Switzerland	Solar Swiss SM	0
Canada	Canrom Photovoltaics	0		Solibro	4
China	Canadian Solar	11		Solterra Fotovoltaico SA	0
	China Solar Energy Group	0	Taiwan	Auria Solar	0
	China Sunergy	6		Big sun energy	1
	Chint Solar	0		Chi Mei Energy	0
	Eging PV	0		Delsolar	3
	JA Solar	8		E-Ton Solar	0
	Jaco Solarsi	5		Gintech Energy	4
	Polar Photovoltaics	4		Green Energy Technology	16
	Solarfun Power	13		Ligitek Photovoltaic	1
	Suntech Power	21		Motech Industrial	2
	Trina Solar	60		Neo Solar Power	5
	Yingli Green Energy	4		NEXPOWER TECHNOLOGY	2
Germany	ANTEC Solar Energy	5		Solartech energy	3
	AVANCIS	6		Tainergy	0
	Deutsche Solar	23		Top Green Energy	3
	Ersol Solar Energy	7	UAE	Microsol International LL FZE	0
	Inventux Technologies	2	United Kingdom	BP Solar	23
	ISET (INST SOLAIRE ENERGIEVERSORGUNG)	33	US	Ascent Solar	4
	Johanna Solar	0		AVA Solar	0
	Nordic Solar	1		DayStar Technologies	10
	ODERSUN	1		EPV Solar	4
	Phototronics solartechnik	7		Evergreen Solar Inc	33
	Q-Cells	16		First Solar	38
	Schott Solar	48		Global Solar	7
	Shell Solar	32		HelioVolt	8
	Solartec	24		Miasole	18
	Sontor (Q-Cells subsidiary)	0		Nanosolar Inc	57
	SULFURCELL Solartechnik	8		PrimeStar Solar	1
	Sunfilm	0		Solar Semiconductor	0
	Sunways AG	5		Solarex Corp	107
	Wuerth Solar	6		SoloPower	36
Korea	Alti Solar	0		SUNPOWER CORP	61
	Shinsung Holdings	0		United Solar Ovonic	11
	Telio Solar	0		XsunX	0
Netherland	Soll and Solar Energy	0		Xunlight Corp	2
Spain	Isofoton	8			
				Total	828

Source: EPO: compiled by author

Appendix C: IPCs Counts in the Patents Granted to 76 Solar PV Specialization Firms, 1977-2009

IPC	Count	IPC	Count	IPC	Count	IPC	Count
H01L031	911	C25D005	9	F27B005	5	C25D017	3
H01L021	176	H02J003	8	B05C003	4	E04B002	3
F24J002	46	H02M007	8	B07B013	4	G01B011	3
C23C016	45	B28D005	7	B32B017	4	G02B001	3
C23C014	39	G01J001	7	B65G013	4	G05F001	3
C30B015	32	H02J007	7	B65G039	4	G21H001	3
E04D013	31	B05D003	6	C23F001	4	H01B001	3
C30B029	30	B08B003	6	F03D009	4	H02J013	3
B23K026	28	B32B027	6	F27D001	4	H05K001	3
H01L027	28	B65G049	6	G02F001	4	H01G09	2
H02N006	24	E04D003	6	H01L	4	A61K009	2
H01L051	20	H01L023	6	H01L025	4	B01D053	2
C30B028	19	H01Q001	6	B05D001	3	B05B013	2
C01B033	19	H05K003	6	B23K020	3	B05C009	2
F27B014	18	B05D005	5	B28D001	3	B05C011	2
H01L029	16	C07F007	5	C04B041	3	B05C013	2
C30B011	14	C09D005	5	C08L023	3	B09B003	2
G01R031	13	C25D003	5	C09D001	3	B22C001	2
C03C017	12	C25D009	5	C22C021	3	B22F003	2
C30B035	11	F03D007	5	C23C018	3	B23D057	2
						Total	1,778

Source: EPO: compiled by the author

Appendix D: WIPO Definitions and Attributes of the Twelve Identified Solar PV IPCs

IPC	Description	1 G	2 G	3 G	Technology Platform
E04D13/18	Roof covering by making use of flat or curved slabs or stiff sheets	✓	✓		TP1
H02N6	Generators in which light radiation is directly converted into electrical energy	✓	✓	✓	
H01G9	Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture			✓	
C30B28	Production of homogeneous polycrystalline material with defined structure	✓			
C23C14	Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material		✓		TP2
C23C16	Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapour deposition (CVD) processes		✓		
H01L51	Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; Processes or apparatus specially adapted for the manufacture or treatment of such devices, or of parts thereof			✓	
C30B29	Single crystals or homogeneous polycrystalline material with defined structure characterized by the material or by their shape	✓			TP3
C30B15	Single-crystal growth by pulling from a melt, e.g. Czochralski method	✓			
H01L31	Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation; Processes or apparatus peculiar to the manufacture or treatment thereof or of parts thereof	✓	✓	✓	TP4
H01L21	Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof	✓	✓		

IPC	Description	1 G	2 G	3 G	Technology Platform
H01L27	Devices consisting of a plurality of semiconductor or other solid state components formed in or on a common substrate	✓	✓		TP4

Source: WIPO, compiled by the author.

Appendix E-1: Country Origins of Backward Citations for Taiwan's First Generation Solar PV Patents, 1984-2008

Country	1984	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
US	6	5	9	6	8	50	64	103	213	469	538	754
JP	0	3	1	12	9	50	56	69	140	313	408	539
TW	0	0	0	0	1	1	3	5	22	59	134	210
KR	0	0	0	0	0	0	1	3	17	52	84	116
DE	0	0	0	5	0	3	5	4	5	14	17	20
SG	0	0	0	0	0	0	0	0	1	3	3	3
NL	0	0	0	0	0	2	0	0	0	0	0	1
FR	0	1	0	0	1	9	4	5	3	9	14	16
IT	0	0	0	1	1	0	0	1	2	8	18	17
CA	0	0	0	0	0	0	0	2	1	8	6	10
GB	0	0	0	0	0	2	2	1	4	5	2	5
IL	0	0	0	0	0	0	0	0	0	0	1	1
BE	0	0	0	0	0	0	0	0	0	0	0	0
CH	0	0	0	0	0	0	0	0	0	2	0	3
SE	0	0	0	0	0	0	1	1	0	0	2	1
RU	0	0	0	0	0	0	0	0	0	0	0	4
FI	0	0	0	0	0	0	0	0	0	0	0	0
CN	0	0	0	0	0	0	0	0	0	0	0	0
AU	0	0	0	0	0	0	0	0	0	0	2	2
PL	0	0	0	0	0	0	0	0	0	0	0	0
BM	0	0	0	0	0	1	0	0	0	0	0	0
AN	0	0	0	0	0	0	0	0	0	0	0	0
HK	0	0	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0	0	0
IE	0	0	0	0	0	0	0	0	0	0	0	0
IR	0	0	0	0	0	0	0	0	0	0	0	0
LI	0	0	0	0	0	0	0	0	0	0	0	1
VG	0	0	0	0	0	0	0	0	0	0	0	0
DK	0	0	0	0	0	0	0	0	0	0	0	0
ID	0	0	0	0	0	0	0	0	0	0	0	0
MX	0	0	0	0	0	0	0	0	0	0	0	0
MY	0	0	0	0	0	0	0	0	0	0	0	0
HU	0	0	0	0	0	0	0	0	0	0	0	0
KN	0	0	0	0	0	0	0	0	0	0	0	0
NO	0	0	0	0	0	0	0	0	0	0	0	1
NZ	0	0	0	0	0	0	0	0	0	0	0	0
GE	0	0	0	0	0	0	0	0	0	0	0	0
KP	0	0	0	0	0	0	0	0	0	0	0	0
OF	0	0	0	0	0	0	0	0	0	0	0	0
SI	0	0	0	0	0	0	0	0	0	0	0	0
TR	0	0	0	0	0	0	0	0	0	0	0	0

Continued

Country	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
US	748	1612	2151	2643	2382	2247	2642	2112	2286	2178	2161
JP	536	1040	1265	1262	1080	1044	1149	1038	1102	1056	1085
TW	254	621	1057	1260	1059	1003	1002	917	929	966	936
KR	105	246	326	440	303	282	343	278	367	275	317
DE	25	57	101	137	137	154	211	179	187	170	169
SG	16	32	56	91	105	82	104	84	101	97	84
NL	1	4	39	31	19	35	32	37	60	60	43
FR	-2	19	20	38	17	17	31	25	36	37	33
IT	10	25	31	30	29	16	20	19	24	0	14
CA	7	23	10	15	16	15	23	11	24	14	15
GB	6	8	12	9	21	9	8	13	7	7	17
IL	1	6	0	4	12	10	15	14	10	22	12
BE	0	2	4	2	6	7	7	5	12	14	10
CH	2	1	4	7	6	0	3	3	3	2	3
SE	0	1	0	2	1	3	5	3	5	12	1
RU	2	7	1	0	0	3	1	0	12	0	0
FI	0	2	0	0	0	3	1	4	3	4	4
CN	0	0	0	0	0	2	1	0	3	10	0
AU	0	0	3	0	0	1	1	1	0	0	3
PL	0	0	0	0	0	0	0	10	0	0	2
BM	0	0	0	0	0	0	0	4	0	0	3
AN	0	0	0	0	0	0	1	0	0	4	2
HK	0	0	0	0	0	0	4	2	0	0	0
AT	0	0	0	0	0	1	2	1	0	0	1
IE	0	0	1	0	0	0	0	0	1	0	0
IR	0	0	0	0	1	1	2	0	0	0	0
LI	0	0	1	0	0	0	0	0	0	0	0
VG	0	1	0	0	0	0	0	0	0	3	0
DK	0	0	0	0	0	0	0	0	0	1	1
ID	0	0	0	0	0	0	0	0	1	1	1
MX	0	0	3	0	0	0	0	0	0	0	0
MY	0	0	0	0	0	0	0	0	2	1	0
HU	0	1	0	0	0	0	0	0	0	0	1
KN	0	0	0	0	0	0	0	0	0	1	1
NO	0	0	0	0	0	0	0	0	0	0	1
NZ	0	0	1	0	0	0	0	0	0	0	1
GE	0	0	0	0	0	0	0	0	0	0	1
KP	0	0	0	0	0	0	1	0	0	0	0
OF	0	0	0	0	0	1	0	0	0	0	0
SI	0	0	1	0	0	0	0	0	0	0	0
TR	0	0	0	0	0	0	0	0	1	0	0

Note. Country codes shown in the tables, country names can be found at WIPO, see Handbook on industrial property information and documentation, available at http://www.wipo.int/standards/en/pdf/03-03-01.pdf

Appendix E2: Country Origins of Backward Citations for Taiwan's New Generation Solar PV Patents, 1984-2008

Country	1992	1993	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
US	1	0	12	12	13	54	61	170	125	123	262	205	133	35	53	136
JP	2	0	4	14	8	26	63	53	86	49	148	153	89	15	43	93
TW	0	0	0	3	1	2	8	25	36	13	31	30	27	3	14	7
KR	0	0	0	1	0	0	1	4	8	3	12	13	13	1	6	5
DE	1	0	2	0	3	2	4	12	6	8	17	8	8	3	4	10
SG	0	0	0	0	0	0	0	1	4	0	0	2	2	0	0	0
CA	0	0	1	1	1	1	2	1	0	0	3	5	1		1	6
FR	0	0	0	0	0	2	1	0	1	2	8	4	0	0	0	0
GB	0	0	3	0	0	0	1	5	0	1	4	2	7	4	0	2
FI	0	0	0	0	1	0	1	0	2	0	1	1	0	0	0	0
LI	0	0	0	0	0	0	1	0	0	2	0	0	0	0	1	0
SE	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	1
IL	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1
IT	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	0
RU	0	0	0	0	0	0	1	0	0	0	2	1	0	0	0	0
BE	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
IE	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
CH	0	0	0	0	0	0	0	1	0	1	4	0	0	0	0	0
CN	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
NL	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0
AT	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
DK	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
PL	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
UA	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
AU	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

Note. Country codes shown in the tables, country names can be found at WIPO, see Handbook on industrial property information and documentation, available at http://www.wipo.int/standards/en/pdf/03-03-01.pdf

Appendix E-3: Country Origins of Backward Citations for Korea's First Generation Solar PV Patents, 1984-2008

Country	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
US	7	73	111	89	188	229	274	298	499	941	1157
JP	9	49	74	66	199	245	323	347	542	920	1134
KR	0	1	2	3	17	29	50	63	102	168	212
TW	0	0	1	1	1	7	22	20	59	115	160
DE	3	8	12	11	8	11	6	14	25	56	57
SG	0	0	0	0	0	1	1	0	1	7	9
NL	0	1	0	1	0	3	1	3	4	1	13
FR	0	4	1	4	9	9	10	4	17	20	24
IT	0	3	3	1	7	3	1	2	7	11	13
GB	0	5	1	2	1	1	0	4	11	8	16
CA	0	0	0	0	2	3	3	3	8	6	15
CH	0	0	0	0	1	0	0	0	0	1	12
FI	0	0	0	0	0	0	0	0	0	1	0
IL	0	0	0	0	0	0	0	0	0	0	1
BE	0	0	1	0	0	1	0	2	0	0	3
RU	0	0	0	0	2	0	0	0	0	7	10
SE	0	2	1	0	0	0	0	2	0	2	1
CN	0	0	0	0	0	0	0	0	0	0	2
AT	0	0	0	0	0	0	0	0	0	0	1
AU	0	0	0	0	0	0	0	0	0	0	0
LI	0	0	0	0	0	1	0	0	0	2	0
HU	0	0	0	0	0	0	0	0	0	0	0
UA	0	0	0	0	0	0	0	0	0	0	2
MY	0	0	0	0	0	0	0	0	0	0	0
VG	0	0	0	0	0	0	0	0	0	0	0
KY	0	0	0	0	0	0	0	0	0	0	0
NO	0	0	0	0	0	0	0	0	0	0	0
IE	0	0	0	0	0	0	0	0	0	0	0
DK	0	0	0	0	0	0	0	0	0	0	0
SZ	0	0	0	0	0	0	0	0	0	1	0
HK	0	0	0	0	0	0	0	0	0	0	0
KN	0	0	0	0	0	0	0	0	0	0	0
KP	0	0	0	0	0	0	0	0	0	0	0
AN	0	0	0	0	0	0	0	0	0	0	0
AZ	0	0	0	0	0	0	0	0	0	0	0
BB	0	0	0	0	0	0	0	0	0	0	0
ES	0	0	0	0	0	0	0	0	0	0	0
IN	0	0	0	0	3	0	0	0	0	0	0
LU	0	0	0	0	0	0	0	0	0	0	0
NP	0	0	0	0	0	0	0	0	0	0	0
NZ	0	0	0	0	0	0	0	0	0	0	0
PL	0	0	0	0	0	0	0	0	0	0	0
ZA	0	0	0	0	0	0	0	0	0	0	0

Continued

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008
US	1324	1473	1464	1481	1533	1677	1773	1998	2108
JP	1247	1401	1376	1430	1643	1538	1560	1940	2504
KR	286	391	471	517	485	653	876	1018	1424
TW	250	383	408	486	488	519	571	620	669
DE	74	59	68	92	110	120	98	182	516
SG	19	20	40	49	56	78	65	0	95
NL	6	0	7	37	35	47	43	58	74
FR	25	14	15	18	23	31	30	25	47
IT	21	24	15	13	15	16	27	33	34
GB	14	13	6	14	19	8	20	28	35
CA	22	10	6	10	10	9	15	30	35
CH	2	6	1	4	7	2	3	16	25
FI	0	0	0	0	4	8	23	26	8
IL	2	0	2	1	10	10	7	15	9
BE	3	2	5	2	7	5	1	9	8
RU	1	0	0	13	1	0	0	2	2
SE	2	0	3	3	1	3	4	8	6
CN	2	1	0	0	2	7	0	6	17
AT	0	0	1	1	2	2	0	0	6
AU	1	1	3	1	0	0	0	2	0
LI	1	0	1	0	0	1	0	3	0
HU	0	0	0	0	1	1	0	2	3
UA	0	0	0	3	0	0	0	2	0
MY	0	0	0	0	0	0	0	1	5
VG	0	2	0	3	0	0	0	1	0
KY	0	0	0	0	0	0	0	2	3
NO	0	0	0	0	1	0	1	1	2
IE	0	0	0	0	1	1	1	1	0
DK	0	0	2	0	0	0	0	1	0
SZ	3	0	0	0	0	0	0	1	0
HK	0	0	0	0	0	0	1	0	2
KN	0	0	0	0	0	0	0	1	1
KP	0	0	0	1	1	0	0	0	0
AN	0	0	0	0	0	0	0	0	1
AZ	0	0	0	0	0	0	0	0	1
BB	0	0	0	0	0	0	0	0	1
ES	0	0	0	1	0	0	0	0	0
IN	0	0	0	0	0	0	0	0	0
LU	1	0	0	0	0	0	0	0	0
NP	0	0	0	0	0	0	0	1	0
NZ	0	0	0	0	0	0	1	0	0
PL	0	0	0	0	0	0	1	0	0
ZA	0	0	0	1	0	0	0	0	0

Appendix E-4: Country Origins of Backward Citations for Korea's New Generation Solar PV Patents, 1984-2008

Country	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
US	11	0	2	1	15	12	20	8	30	46	61	135	112	239	234	360	337	119	170	363
JP	3	0	1	0	19	13	17	21	31	54	99	156	96	220	185	287	372	131	186	355
KR	0	0	0	0	0	1	0	0	4	3	11	15	11	32	66	98	92	16	81	93
DE	1	0	0	0	1	0	0	2	2	6	7	5	8	14	18	13	14	2	12	31
TW	0	0	0	0	0	0	0	0	0	0	3	3	11	12	18	23	23	2	6	16
FR	0	0	0	0	1	0	0	0	1	3	2	4	1	3	6	3	4	3	0	5
FI	0	0	0	0	0	0	0	2	1	0	1	1	1	2	3	10	7	2	2	1
GB	0	0	0	0	0	0	0	2	1	0	4	4	2	4	8	3	14	6	3	20
CA	0	0	0	0	1	0	1	0	0	0	0	2	1	5	6	4	2	3	1	5
NL	0	0	1	0	0	0	0	1	1	1	1	1	0	0	1	3	4	2	3	5
LI	0	0	0	1	0	0	0	3	0	1	0	1	0	1	0	1	1	1	0	1
IT	0	0	0	0	0	0	0	0	0	1	0	1	0	3	0	1	2	3	1	2
SE	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	1	0	0	0	2
BE	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2	0	1	0	1	0
IN	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
AT	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
RU	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1
CH	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	2
SG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0
CN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2	2
ZA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MA	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
UA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
HK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
LU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
IL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
AU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
NO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
SZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
ES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
NZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Note. Country codes shown in the tables, country names can be found at WIPO, see Handbook on industrial property information and documentation, available at http://www.wipo.int/standards/en/pdf/03-03-01.pdf

Appendix E-5: Country Origins of Backward Citations for China's First Generation Solar PV Patents, 1984-2008

Country	1994	1995	1996	1999	2001	2002	2003	2004	2005	2006	2007	2008
US	3	5	3	4	1	8	9	21	10	22	34	71
JP	3	0	1	0	1	3	5	5	2	11	13	50
TW	0	0	0	0	0	0	4	0	3	19	9	14
KR	0	0	0	0	0	0	1	1	2	5	3	10
DE	1	0	0	0	0	6	0	2	0	4	2	5
CN	0	1	0	0	1	0	0	0	0	0	3	7
SE	0	0	0	0	0	0	0	0	2	0	0	0
SG	0	0	0	0	0	0	0	0	0	0	0	5
IL	0	0	0	0	0	0	0	0	0	0	0	4
NO	0	0	0	0	0	0	0	0	2	0	0	0
ZA	0	0	0	0	0	0	0	0	0	3	0	0
CH	0	0	0	2	0	0	0	0	0	0	0	0
FR	0	0	0	0	0	1	0	0	0	0	1	1
BE	0	0	0	0	0	0	0	0	0	0	0	1
AT	0	0	0	0	0	0	0	0	0	0	0	1
FI	0	0	0	0	0	0	0	0	0	0	1	0
IT	0	0	0	0	0	0	0	0	0	0	0	1
NL	0	0	0	0	0	0	0	0	0	1	0	0

Note. Country codes shown in the tables, country names can be found at WIPO, see Handbook on industrial property information and documentation, available at http://www.wipo.int/standards/en/pdf/03-03-01.pdf

Appendix E-6: Country Origins of Backward Citations for China's New Generation Solar PV Patents, 1984-2008

Country	1988	2003	2004	2005	2006	2007	2008
US	6	2	2	9	3	4	6
JP	3	1	5	7	4	2	4
TW	0	0	0	1	1	0	0
CN	0	0	0	3	0	1	0
BE	0	0	0	0	1	0	0
CH	0	0	0	0	1	0	0
NL	1	0	0	0	0	0	0
SE	0	0	0	1	1	0	0
ZA	0	0	0	0	1	0	0
DE	0	1	0	1	0	0	0
KR	0	0	0	0	0	0	0
NO	0	0	0	2	0	0	0

Note. Country codes shown in the tables, country names can be found at WIPO, see Handbook on industrial property information and documentation, available at http://www.wipo.int/standards/en/pdf/03-03-01.pdf

Appendix F-1: Intra-national Knowledge Sources for Taiwan's First Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
Private sector	
TAIWAN SEMICONDUCTOR MANFACTUR (TW)	3691
UNITED MICORELECTRONICS CORP (TW)	2592
VANGAURD INTERNATIONAL SEMICON (TW)	856
MACRONIX INT CO LTD (TW)	397
WINBOND ELECTRONIC CORP (TW)	397
MOSEL VITELI INC (TW)	287
NANYA TECHNOLOGY CORP (TW)	218
TEXAS INSTR ACER INC (TW)	209
SILICONEWARE PREC IND CO LTD (TW)	123
WORLDIWIDE SEMICONDUCTOR MFG C (TW)	121
PROMOS TECH INC (TW)	105
ADVANCED SEMICONDUCTOR ENG (TW)	94
POWERCHIP SEMICONDUCTOR CORP (TW)	88
AU OPTRONICS CORP (TW)	57
MEGIC CORP (TW)	53
SILICON BASED TECH CORP (TW)	39
SILICON INTEGRATED SYS CORP (TW)	29
HANNSTAR DISPLAY CORP (TW)	23
VIA TECH INC (TW)	23
CHI MEI OPTOELECTRNICS CORP (TW)	20
KINGPAK TECH INC (TW)	19
BRIDGE SEMICONDUCTOR CORP (TW)	15
EMEMORY TECHNOLOGY INC (TW)	15
ACER SEMICONDUCTOR MANUFACTURI (TW)	13
EPISTAR CO (TW)	13
ETRON TECHNOLOGY INC (TW)	13
SOUTH EPITAXY CORP (TW)	12
HOLTEK MICROELECTONICS INC (TW)	11
TOPPOLY OPTOELECTRONICS CORP (TW)	11
ACER INC (TW)	10
COMPEQ MANUFACTURING COMPANY L (TW)	10
PHOENIX PREC TECHNOLOGY CORP (TW)	9
FORMOSA EPITAXY INC (TW)	8
HON HAI PREC IND CO LTD (TW)	8
INTELLIGENT SOURCES DEV CORP (TW)	7
RITDISPLAY CO (TW)	7
UTRON TECHNOLOGY INC (TW)	6

Local Knowledge Source	Citation count
WALSIN ADVANCED ELECTRONICS LT (TW)	6
CAESAR TECHNOLOGY INC (TW)	5
CHUNGHWA PICTURE TUBES LTD (TW)	5
DELTA ELECTRONICS INC (TW)	5
EPITECH CORP (TW)	5
LIGHTUNING TECH INC (TW)	5
OPTO TECH CORP (TW)	5
QUANTA DISPLAY INC (TW)	5
TOUCH MICRO SYSTEM TECH (TW)	5
TSMC ACER SEMICONDUCTOR MFG CO (TW)	5
UMAX DATA SYSTEMS INC (TW)	5
UNI LIGHT TECHNOLOGY INC (TW)	5
UTEK SEMICONDUCTOR CORP (TW)	5
APACK TECHNOLOGIES INC (TW)	4
FARADAY TECH CORP (TW)	4
FOXCONN PREC COMPONENTS CO LTD (TW)	4
HIGHLINK TECHNOLOGY CORP (TW)	4
ULTRA TERA CORP (TW)	4
UNIMICRON TAIWAN CORP (TW)	4
ACER DISPLAY TECH INC (TW)	3
ACTRANS SYSTEM INC (TW)	3
ARIMA OPTOELECTRONICS CORP (TW)	3
AVISION INC (TW)	3
CHIPMOS TECHNOLOGIES INC (TW)	3
CYNTEC CO LTD (TW)	3
EPISIL TECHNOLOGIES INC (TW)	3
SOLID STATE SYSTEM CO LTD (TW)	3
VISUAL PHOTONICS EPITAXY CO LT (TW)	3
ACER COMM AND MULTIMEDIA INC (TW)	2
ADVANCED CHIP ENG TECH INC (TW)	2
ALI CORP (TW)	2
AMIC TECHNOLOGY CORP (TW)	2
ANALOG AND POWER ELECTRONICS C (TW)	2
CHAUN CHOUNG IND CORP (TW)	2
DATECH TECHNOLOGY CO LTD (TW)	2
FIRST INT COMPUTER INC (TW)	2
GENESIS PHOTONICS INC (TW)	2
GIGNO TECHNOLOGY CO LTD (TW)	2
JOHN WOLF INTERNATIONAL INC (TW)	2
LITE ON ELECTRONICS INC (TW)	2

Local Knowledge Source	Citation count
MICROTEK INT INC (TW)	2
MUSTEK SYSTEMS INC (TW)	2
NANO ARCHITECT RES CORP (TW)	2
NANOMETRICS INC (TW)	2
PAN PACIFIC SEMICONDUCTOR CO L (TW)	2
POWERCHIP SEMICONDUCTO...	2
PRIME VIEW INT CO LTD (TW)	2
PROSYS TECHNOLOGY INTEGRATION (TW)	2
SILICON PREC IND CO LTD (TW)	2
THIN FILM MODULE INC (TW)	2
TPO DISPLAYS CORP (TW)	2
UNIPAC OPTOELECTRONICS CORP (TW)	2
UNITIVE ELECTRONICS INC (TW)	2
WAFFER TECHNOLOGY CORP (TW)	2
ACER PERIPHERALS INC (TW)	1
ALCOR MICRO CORP (TW)	1
ANPEC ELECTRONICS CORP (TW)	1
APPLIED INTELLECTUAL PROPERTIE (TW)	1
CHICONY ELECTRONICS CO LTD (TW)	1
CHIPBOND TECHNOLOGY CORP (TW)	1
COMPAL ELECTRONICS INC (TW)	1
EPOCH MATERIAL CO LTD (TW)	1
ETERNAL CHEMICAL CO LTD (TW)	1
FORHOUSE CORP (TW)	1
GEM LINE TECHNOLOGY CO LTD (TW)	1
GLACIALTECH INC (TW)	1
GOODARK ELECTRONIC CORP (TW)	1
HERMES MICROVISION TAIWAN INC (TW)	1
HUALON MICROELECTRONICS CORP (TW)	1
IDEAL ELECTRONICS INC (TW)	1
INNOLUX DISPLAY CORP (TW)	1
INTEGRATED TECHNOLOGY EXPRESS (TW)	1
INVENTEC CORP (TW)	1
JAEGER IND CO LTD (TW)	1
KING BILLION ELECTRONICS CO LT (TW)	1
KINIK COMPANY (TW)	1
MEDIATEK INC (TW)	1
MEGAWIN TECHNOLOGY CO LTD (TW)	1
MUST SYSTEM INC (TW)	1
MYSON TECHNOLOGY INC (TW)	1

Local Knowledge Source	Citation count
OPTIMUM CARE INTERNAT TECH INC (TW)	1
PARA LIGHT ELECTRONICS CO LTD (TW)	1
PRIMAX ELECTRONICS LTD (TW)	1
ROCKWOOD ELECTROCHEMICALS ASIA (TW)	1
SAMPO SEMICONDUCTOR COOPERATIO (TW)	1
SCIENTEK CORP (TW)	1
SHIN JIUH CORP (TW)	1
SILITEK CORP (TW)	1
SKYMEDI CORP (TW)	1
SOLIDLITE CORP (TW)	1
STACK DEVICES CORP (TW)	1
SUNPLUS TECHNOLOGY CO LTD (TW)	1
SUPER NOVA OPTOELECTRONICS COR (TW)	1
TAI SOL ELECTRONICS CO LTD (TW)	1
TAIWAN DA LONG IND CO LTD (TW)	1
TAIWAN GREEN POINT ENTPR CO LT (TW)	1
TEAM WORLDWIDE CORP (TW)	1
TECONN ELECTRONICS INC (TW)	1
TOPCO SCIETIFIC CO LTD (TW)	1
TWIN HAN TECHNOLOGY CO LTD (TW)	1
WINTEK CORP (TW)	1
WORLD WISER ELECTRONICS INC (TW)	1
YAGEO CORP (TW)	1
Public R&D institute	
IND TECH RES INST (TW)	628
NAT SCIENCE COUNCIL (TW)	90
METAL IND RES AND DEV CT (TW)	1
NAT APPLIED RES LAB NAT CHIP I (TW)	1
CHUNG SHAN INST OF SCIENCE (TW)	1
University	
National Taiwan Unversity	1
National Yunlin University of Science and Technology (TW)	12
NAT CHUNG CHENG UNIVERSITY (TW)	1
NAT CHUNG HSING UNIVERSITY (TW)	2
UNIV NAT CENTRAL (TW)	2
UNIV NAT CHIAO TUNG (TW)	2
Individual	
LIN M S (TW)	1
KUAN YANG LIAO (TW)	1

Local Knowledge Source	Citation count
HOU JACK (TW)	1
HSI HUANG LIN (TW)	1
HSIEH HSIN MAO (TW)	1
HSU HSIEN KENG (TW)	1
WANG JACK (TW)	1
WANG YEONG JING (TW)	1
CHEN DER JONG (TW)	1
CHEN SHI-MING (TW)	3
YANG TAI HER (TW)	1
YANG WEN-KEN (TW)	1

Appendix F-2: Intra-national Knowledge Sources for Taiwan's New Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
Private sector	
Taiwan Semiconductor Manufacturing Co.	72
United Microelectronics	35
Vanguard International Semiconductor Corporation	15
AU OPTRONICS CORP	11
Chung Picture Tubes, Ltd.	9
Mosel Vitelic Inc.	5
RITDISPLAY CORP	5
MACRONIX INT CO LTD	3
Texas Instruments-Acer Incorporated	3
Worldwide Semiconductor Manufacturing Corp.	3
Asia Optical Co., Inc.	2
Delta Optoelectronics, Inc.	2
Winbond Electronics Corp.	2
Applied Vacuum Coating Technologies Co., Ltd.	1
COSMOS VACUUM TECHNOLOGY CORP	1
E-Ray Optoelectronics Technology Co., Ltd.	1
Ether Precision, Inc.	1
HIGHLIGHT OPTOELECTRONICS INC	1
Holtek Semiconductor Inc.	1
LAIBAO SCIENCE AND TECHNOLOGY	1
LIGHTRONIK TECHNOLOGY INC.	1
Luxon Energy Devices Corporation	1
MICROJET TECHNOLOGY CO LTD	1
Ritek Corporation	1
UNIVISION TECHNOLOGY INC	1
UTEK Semiconductor Corp.	1
Public R&D institute	
Industrial Technology Research Institute	21
National Science Council	1
University	
National Tsing Hua Univeristy	2
Individual	
Chung, Chia-Tin	2
Huang, Liang-Ying	2
Chen, Hsing	1
Chen; Der-Jong	1
Chen; Hsing	1
Han, Cheng-Xian	1
Hung; Min-Ling	1
Kuo, Chao-Nan	1
Lin, Ming-Der	1
Lin; Chieh-Fu	1
Lu, Tien-Rong	1
Peng; Kuan-Chang	1
Sung; Chien-Min	2
Teng, Yueh-Ming	2

Local Knowledge Source	Citation count
TU, AN-CHUN	2
Lin, Ming-Yu	1
Chen; Tsong-Maw	1
Shih; Han-Chang	1
TSAI YUNG-HSUAN	1
Wang, Wei-Hsu	1
Yang; Tai-Her	1

Appendix F-3: Intra-national Knowledge Sources for Korea's First Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
Private sector	
SAMSUNG (KR)	3496
LG / GOLD STAR (KR)	1411
HYUNDAI (KR)	976
HYNIX SEMICONDUCTOR (KR)	694
DONGBUANAM SEMICONDUCTOR INC (KR)	115
KOREA INST OF SCIENCE & TECHNOLOGY (KR)	56
DONGBU ELECTRONICS (KR)	55
KOREA TELECOMMUNICATION (KR)	26
JUSUNG ENG CO LTD (KR)	15
MIRAE CORP (KR)	12
DAEWOO ELECTRONICS CO LTD (KR)	11
PT PLUS CO LTD (KR)	11
JU SUNG ENGINEERING CO LTD (KR)	10
AMKOR TECHNOLOGY INC (KR)	9
MAGNACHIP SEMICONDUCTOR LTD (KR)	9
CHEIL IND INC (KR)	8
ANAM IND CO LTD (KR)	7
GENITECH CO LTD (KR)	7
DONG YANG CEMENT CORP (KR)	6
FAIRCHILD KR SEMICONDUCTOR LTD (KR)	5
POSTECH FOUNDATION (KR)	5
BOE HYDIS TECHNOLOGY CO LTD (KR)	4
IPS LTD (KR)	4
P K LTD (KR)	4
SILTRON INC (KR)	4
HANYANG HAK WON CO LTD (KR)	3
NESS CAPACITOR CO LTD (KR)	3
SILTRON INC (KR)	3
TONG YANG CEMENT CORP (KR)	3
ASM GENITECH KOREA LTD (KR)	2
BARUN ELECTRONICS CO LTD (KR)	2
BEYONDMICRO INC (KR)	2
DASAN C & I CO LTD (KR)	2
EO TECHNICS CO LTD (KR)	2
EPIVALLEY CO LTD (KR)	2
HAIRYOKSA SEMICONDUCTOR CO LTD (KR)	2
HAN YUL CO LTD (KR)	2

Local Knowledge Source	Citation count
HANDO IND CO LTD (KR)	2
KOREA ELECTRIC POWER CORP (KR)	2
MEMS SOLUTIONS INC (KR)	2
ACE HIGHTECH CO LTD (KR)	1
ANAPASS INC (KR)	1
APACK TECHNOLOGIES INC (KR)	1
APEX CO LTD (KR)	1
ASB INC (KR)	1
CHIPPAC KOREA CO LTD (KR)	1
CLD INC (KR)	1
DONGJIN SEMICHEM CO LTD (KR)	1
ENTIK RES CO LTD (KR)	1
EVERTEK CO LTD (KR)	1
HANWHA CHEMICAL CORP (KR)	1
ILJIN NANOTECH CO LTD (KR)	1
INTEGRATED PROCESS SYSTEMS LTD (KR)	1
KOSTAT SEMICONDUCTOR CO LTD (KR)	1
LTD ETS (KR)	1
MOOHAN CO LTD (KR)	1
PACIFIC CORP (KR)	1
PO HANG IRON & STEEL (KR)	1
PROWTECH INC (KR)	1
SANGNONG ENTPR CO LTD (KR)	1
SIGNETICS KP CO LTD (KR)	1
SILTRON INC (KR)	1
SILTRON INC (KR)	1
SK CORP (KR)	1
T & B TRONICS CO LTD (KR)	1
TAEYANG TECH CO LTD (KR)	1
TECHNO TRADING CO LTD (KR)	1
TELEPHUS INC (KR)	1
TERRA SEMICONDUCTOR INC (KR)	1
TONG YANG MOOLSAN CO LTD (KR)	1
TONGBOO ELECTRONICS INC (KR)	1
VITONET CO LTD (KR)	1
Public R&D institute	
KOREA ELECTRONICS & TELECOMMUNICATIONS RESEARCH INST	132
KOREA INFORMATION & COMMUNICATION (KR)	3
KOREA MACHINERY & METAL INST (KR)	2

Local Knowledge Source	Citation count
KOREA RES INST CHEM TECH (KR)	2
KOREA RESEARCH INSTITUTE OF CHEMICAL TECHNOLOGY (KR)	4
KOREA ELECTRONICS TECHNOLOGY INSTITUTE (KR)	1
INST ADVANCED ENGINEERING (KR)	1
University	
INST SCIENCE & TECH KWANGJU (KR)	7
KWAGJU INST OF SCIENCE AND TEC (KR)	2
CHONNAM NAT UNIVERSITY (KR)	1
KOREA UNIVERSITY FOUNDATION (KR)	1
NAT UNIV SEOUL (KR)	1
Individual	
JANG JIN (KR)	9
JOO SEUNG GI (KR)	7
LEE JONG DUK (KR)	4
BYUN JAE-SEONG (KR)	1
CHA JONG-HWAN (KR)	1
CHAI CHONG-CHUL (KR)	1
CHANG GEE KEUN (KR)	1
CHANG HAK-SUN (KR)	1
CHO DONG IL (KR)	1
CHO HONG-JE (KR)	1
CHOI BEOM-RAK (KR)	1
CHOI BYOUNG-LYONG (KR)	1
CHOI JOON HOO (KR)	1
CHOUL GUE PARK (KR)	2
CHUN BEONG SOO (KR)	1
HAN SANG HO (KR)	1
HYON MAN-SOK (KR)	1
HONG MUN-PYO (KR)	2
HWANG CHEOL SUNG (KR)	2
JUNG BAE-HYOUN (KR)	1
JEAGUN PARK (KR)	1
JEONG CHANG-OH (KR)	1
KANG MYUNG-KOO (KR)	1
KANG SANG WON (KR)	1
KANG SANG WOO (KR)	1
KANG SOOK-YOUNG (KR)	1
KANG SUNG-CHUL (KR)	1

Local Knowledge Source	Citation count
KIM JUN-YOUNG (KR)	1
KIM KI-BUM (KR)	1
KIM NAM-HUNG (KR)	1
KIM YONG TAE (KR)	2
KOH WON YONG (KR)	1
KOO SEUNG JI (KR)	5
LIM HYUN-SU (KR)	1
LYU JAE-JIN (KR)	1
LEE CHANG-HUN (KR)	1
LEE CHEOL JIN (KR)	1
LEE EUN-KYUNG (KR)	1
LEE HEUNG SOO (KR)	1
LEE JI HWA (KR)	2
LEE KI WON (KR)	2
LEE KUN-JONG (KR)	1
LEE KWANG HWAN (KR)	1
LEE SANG-KYOO (KR)	1
LEE YOUNG JONG (KR)	1
NOH TAE WON (KR)	1
PARK KYUNG WOOK (KR)	1
PARK AN-NA (KR)	1
PARK BAE HO (KR)	1
PARK BYUNG GOOK (KR)	1
PARK HONG-SICK (KR)	1
PARK PONG-OK (KR)	1
PARK YOUNG KYUN (KR)	2
RHEE SHI WOO (KR)	1
ROH NAM-SEOK (KR)	2
SEUNG KI JOO (KR)	1
SHIN KYONG-JU (KR)	1
SONG JEAN HO (KR)	1
SONG KEUN-KYU (KR)	1
WOO DONG SOO (KR)	1
YIM MYUNG JIN (KR)	1
YOUNG HEE LEE (KR)	1

Appendix F-4: Intra-national Knowledge Sources for Korea's New Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
Private sector	
Samsung	253
LG	156
Hyundai	44
Jusung Engineering Co. Ltd.	17
HYNIX SEMICONDUCTOR INC	10
IPS LTD	6
P.K. Ltd	4
Genitech Co., Ltd.	3
Ness Capacitor Co., Ltd.	3
ADVANCED DISPLAY PROCESS ENGIN	2
Apex Co., Ltd.	2
Semes Co., Ltd.	2
Tong Yang Cement Corporation	2
Anam Semiconductor Inc.	1
Daewoo Electronics Service Co., Ltd.	1
Dong Yang Cement Corporation	1
GRACEL CO LTD	1
Hanwha Chemical Corporation	1
ILJIN NANOTECH CO LTD	1
Korea Electric Power Corporation	1
MOOHAN CO LTD	1
Nessdisplay Co., Ltd.	1
Protech Inc.	1
SHINWHA OPLA CO LTD	1
SK Corporation	1
Postech Foundation	1
Public R&D institute	
Korea Institute of Science and Technology	33
Electronics & Telecommunications Research Institute	19
Korea Research Institute of Chemical Technology	3
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY	2
Korea Research Institute of Technology	2
University	
Kwangju Institute of Science and Technology	1
SEOUL NAT UNIV IND FOUNDATION	1

Local Knowledge Source	Citation count
Individual	
Bae, Sung Joon	1
Baek, Bum-Ki	1
Ban, Byeong-Seob	1
Cho, Bong-Rae	1
Cho, Sung-Woo	1
CHO; Seung-Hwan	1
Choi, Sung Yool	1
Chung, Jin-Koo	1
Hwang, Young-Nam	1
Hwang; Do-hoon	1
IHM, JI SOON	3
Jang; Jin	1
Jeon; Hyeong Tag	1
Kang, Tae-Wook	1
Kang; Min Soo	2
Kim, Bo-Sung	1
Kim, Dong-Gyu	2
Kim, Hye-Dong	1
Kim, Ji-Eun	1
Kim, Jin-Sung	1
Kim, Kong Kyeom	3
Kim, Mu-Hyun	2
KIM, YONG SHIN	1
Kim; Chang Yeon	1
Koo, Jae-Bon	1
Kwak, Won-Kyu	3
Kwon, Dong-chul	2
Kwon, Young Wan	1
LEE JIN HO	1
Lee, Hyun-Kyu	1
Lee, Jun-Yeob	1
Lee, Se-Ho	1
Lee; Hyo Young	1
Li; Jing	1
Noh; Jeoung Kwen	1
Park, Byoung-Choo	2
Park, Jae-Yong	2
Park, Joon-Young	1

Local Knowledge Source	Citation count
Park; Byoung-Choo	1
Park; Seung-Ryull	1
Park; Yong In	1
Rho, Soo-Guy	1
Sohn, Byung-Hee	1
Son, Se-Hwan	7
Song, Jang-Kun	1
Song, Seung-Yong	1
Suh, Mi-Sook	2
Suh; Min-Chul	1
Sung; Dong-Young	1
Yang, Nam-Choul	2
Yim, Jin Heong	1
Yoo, Hong Suk	1
Yoon, Jong Geun	2
Im, Young-Bin	1
Jang, Geun-Ha	1
Jeon, Jeong-Sic	1
Joo, Kwang Chul	1
Joo; Seungki	1
Jung, Soon-Jong	1
Jung, Woo-Chan	1
KANG, SANG-BUM	1
KANG, Sang-Won	1
Kim, Hong-Seub	1
Kim, Ki-Bum	1
Kim, Myung-Kyu	1
Kim, Tae-Hoon	1
KIM, YEONG-KWAN	1
KIM, YONG SHIN	1
Kim, Young Yul	1
Kim; Young-sun	1
KOH, Won-Yong	1
Kwan, Kim Yeong	1
LEE CHEOL JIN	1
Lee, Jae-Cheol	1
LEE, Ji-Hwa	1
Lee, Sang-Gon	1
Lee, Seung-Hwan	1
Lee; Jung-hyun	1

Local Knowledge Source	Citation count
Lim, You-Dong	1
Park, Jong Hyurk	1
Park, Jong-Chul	1
Song, Han Sang	1
Song, Youn-Seok	1
Sung, Gun Yong	1
Won, Seok-Jun	1
Kim, Kyong Min	3
Park, Young Hoon	3
Byun, Chulsoo	2
Cheong, Woo-Seock	2
Hur, Gwang Ho	2
Hwang, Chul-Ju	2
Kang, Sang-Bom	2
Park, Sung-Eon	2
Yang, Bee-Lyong	2
Chae, Yun-Sook	1
Cho, Byung Chul	1
Cho, Hag-ju	1
Choe, Yong Sahm	1
Chung, Jeong-hee	1
HWANG, Eui-Seong	1
Hwang; Chul-Ju	1

Appendix F-5: Intra-national Knowledge Sources for China's First Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
Private sector	
Semiconductor Manufacturing International (Shanghai) Corporation	4
Public R&D institute	
Fujian Institute of Research on the Structure of Matter, Chinese Academy	2
University	
Tsinghau University	2
UNIV CHINA SCIENCE & TECH	1
UNIV ELEC SCI & TECH OF CHINA	2
Individual	
Fan, Shoushan	1
Jiang, KaiLi	2

Appendix F-6: Intra-national Knowledge Sources for China's New Generation Solar Photovoltaic Patents, 1984-2008

Local Knowledge Source	Citation count
University	
Tsinghau University	1
Individual	
ZHANG YOUSHENG	1
Wang, Lianxiang	1

Appendix G-1: Counts of Non-patent Literature (NPL) Reference for First Generation Solar PV Patents

	Taiwan 1st Generation			Korea 1st Generation			China 1st Generation		
	NPL count	Patent count	NPL / Patent	NPL count	Patent count	NPL / Patent	NPL count	Patent count	NPL / Patent
1988	6	2	3.00	0	0	0.00			
1989	25	5	5.00	2	4	0.50			
1990	2	5	0.40	11	20	0.55			
1991	46	14	3.29	22	38	0.58			
1992	27	20	1.35	22	46	0.48			
1993	21	32	0.66	47	87	0.54			
1994	67	77	0.87	67	117	0.57	7	1	7.00
1995	141	190	0.74	77	158	0.49	5	1	5.00
1996	164	252	0.65	86	146	0.59	5	1	5.00
1997	251	330	0.76	119	233	0.51	0	0	0.00
1998	405	512	0.79	264	421	0.63	0	0	0.00
1999	471	768	0.61	296	487	0.61	8	1	8.00
2000	421	1,143	0.37	420	514	0.82	0	0	0.00
2001	299	1,356	0.22	405	572	0.71	0	1	0.00
2002	294	955	0.31	432	646	0.67	4	1	4.00
2003	300	836	0.36	312	646	0.48	0	3	0.00
2004	426	909	0.47	418	685	0.61	1	4	0.25
2005	759	700	1.08	430	644	0.67	14	8	1.75
2006	929	637	1.46	514	732	0.70	2	12	0.17
2007	648	581	1.12	714	790	0.90	0	14	0.00
2008	670	602	1.11	774	965	0.80	4	24	0.17
Total	6,372	9,926		5,432	7,951		50	71	

Appendix G-2: Counts of Non-patent Literature (NPL) Reference for New Generation Solar PV Patents

	Taiwan New Generations			Korea New Generations			China New Generations		
	NPL count	Patent count	NPL / Patent	NPL count	Patent count	NPL / Patent	NPL count	Patent count	NPL / Patent
1988							7	1	7.00
1989				0	2	0.00	0	0	0.00
1990				0	0	0.00	0	0	0.00
1991				0	1	0.00	0	0	0.00
1992	2	2	1.00	0	1	0.00	0	0	0.00
1993	0	1	0.00	10	7	1.43	0	0	0.00
1994	7	2	3.50	0	5	0.00	0	0	0.00
1995	3	4	0.75	13	9	1.44	0	0	0.00
1996	1	5	0.20	7	9	0.78	0	0	0.00
1997	20	7	2.86	20	22	0.91	0	0	0.00
1998	8	14	0.57	11	21	0.52	0	0	0.00
1999	19	25	0.76	45	33	1.36	0	0	0.00
2000	11	49	0.22	49	46	1.07	0	0	0.00
2001	23	47	0.49	29	37	0.78	0	0	0.00
2002	21	43	0.49	64	75	0.85	0	0	0.00
2003	57	61	0.93	88	78	1.13	5	1	5.00
2004	18	63	0.29	187	109	1.72	6	2	3.00
2005	24	43	0.56	58	99	0.59	13	4	3.25
2006	11	10	1.10	34	33	1.03	3	1	3.00
2007	9	19	0.47	82	48	1.71	4	1	4.00
2008	30	27	1.11	190	84	2.26	2	2	1.00
Total	264	422		887	719		40	12	

Appendix H-1: Relative Citation Propensity for Taiwan's First Generation Solar PV Technologies

	TW citing US	TW cites JP	TW cites TW	TW cites KR	TW cites DE	TW cites Others
1988	-	-	-	-	-	-
1989	0.68	1.06	-	-	1.32	-
1990	0.80	1.34	-	0.00	0.00	0.97
1991	0.79	1.19	1.75	0.00	0.44	3.51
1992	0.94	1.10	3.90	0.43	0.59	1.30
1993	1.24	0.78	11.29	0.40	1.13	0.90
1994	1.24	0.76	4.24	0.79	0.56	0.67
1995	1.24	0.72	1.98	0.77	1.72	1.62
1996	1.11	0.73	4.18	0.83	0.76	1.50
1997	1.13	0.74	2.66	0.85	0.60	1.01
1998	1.05	0.77	2.93	0.83	0.59	0.86
1999	1.07	0.70	2.98	0.89	0.77	0.81
2000	1.06	0.66	2.75	0.74	0.89	0.98
2001	1.14	0.57	2.10	0.72	1.48	1.55
2002	1.24	0.60	1.99	0.49	1.42	0.92
2003	1.28	0.62	1.74	0.46	1.42	1.00
2004	1.36	0.56	1.64	0.56	1.51	1.08
2005	1.25	0.67	1.76	0.42	1.49	1.02
2006	1.28	0.70	1.58	0.42	1.84	1.24
2007	1.32	0.67	1.90	0.33	1.14	1.29
2008	1.57	0.67	2.18	0.35	0.51	0.91

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix H-2: Relative Citation Propensity for Taiwan's Emerging New Generation Solar PV Technologies

	TW cites US	TW cites JP	TW cites TW	TW cites KR	TW cites DE	TW cites Others
1988	-	-	-	-	-	-
1989	-	-	-	-	-	-
1990	-	-	-	-	-	-
1991	-	-	-	-	-	-
1992	0.75	-	-	-	-	0.00
1993	0.00	0.00	-	-	0.00	12.67
1994	-	-	-	-	-	-
1995	1.06	0.42	-	-	-	3.55
1996	1.89	0.84	-	-	0.00	0.16
1997	1.16	0.69	-	0.00	4.00	1.07
1998	1.57	0.64	-	0.00	0.44	0.57
1999	1.28	0.82	3.42	0.12	0.73	1.57
2000	1.52	0.41	10.05	0.32	2.89	0.69
2001	1.01	0.81	2.97	0.66	0.68	1.27
2002	1.36	0.59	2.85	0.25	1.51	1.03
2003	1.26	0.90	1.95	0.21	1.01	0.80
2004	1.07	0.99	2.46	0.25	1.16	1.55
2005	1.22	0.74	3.56	0.45	1.69	1.01
2006	1.43	0.55	4.98	0.31	7.48	0.77
2007	1.20	0.90	9.20	0.29	1.31	0.39
2008	1.30	0.91	1.54	0.19	1.14	0.68

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix H-3: Relative Citation Propensity for Korea's First Generation Solar PV Technologies

	KR cites US	KR cites JP	KR cites TW	KR cites KR	KR cites DE	KR cites Others
1988	-	-	-	-	-	-
1989	1.47	0.95	-	-	0.76	0.00
1990	1.25	0.75	0.00	-	-	1.03
1991	1.27	0.84	0.57	-	2.28	0.29
1992	1.07	0.91	0.26	2.31	1.69	0.77
1993	0.81	1.28	0.09	2.51	0.89	1.11
1994	0.81	1.31	0.24	1.30	1.40	1.53
1995	0.79	1.42	0.51	1.32	0.59	0.57
1996	0.89	1.37	0.24	1.21	1.33	0.67
1997	0.88	1.34	0.38	1.18	1.67	0.99
1998	0.95	1.30	0.34	1.21	1.69	1.16
1999	0.94	1.42	0.34	1.13	1.31	1.21
2000	0.95	1.52	0.36	1.35	1.13	1.02
2001	0.88	1.74	0.48	1.40	0.68	0.64
2002	0.80	1.67	0.51	2.04	0.62	1.07
2003	0.78	1.62	0.57	2.17	0.71	1.01
2004	0.73	1.80	0.62	1.79	0.65	0.94
2005	0.80	1.49	0.57	2.35	0.68	0.96
2006	0.79	1.43	0.62	2.41	0.53	0.80
2007	0.75	1.50	0.53	3.04	0.88	0.77
2008	0.63	1.47	0.47	2.90	1.98	1.02

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix H-4: Relative Citation Propensity for Korea's Emerging New Generation Solar PV Technologies

	KR cites US	KR cites JP	KR cites TW	KR cites KR	KR cites DE	KR cites Others
1988	-	-	-	-	-	-
1989	-	-	-	-	-	-
1990	-	-	-	-	-	-
1991	-	-	-	-	-	-
1992	1.33	0.00	-	-	0.00	-
1993	-	-	-	-	-	0.08
1994	-	-	-	-	-	-
1995	0.94	2.40	-	-	0.00	0.28
1996	0.53	1.19	0.00	0.00	-	6.36
1997	0.87	1.45	0.00	-	0.25	0.94
1998	0.64	1.56	0.00	-	2.25	1.75
1999	0.78	1.22	0.29	8.57	1.36	0.64
2000	0.66	2.44	0.10	3.11	0.35	1.45
2001	0.99	1.23	0.34	1.52	1.47	0.79
2002	0.74	1.70	0.35	4.05	0.66	0.97
2003	0.80	1.11	0.52	4.94	0.90	1.27
2004	0.94	0.99	0.42	4.09	0.88	0.66
2005	0.83	1.36	0.29	2.49	0.55	0.69
2006	0.78	1.72	0.13	4.00	0.17	0.69
2007	0.81	1.12	0.12	3.67	0.82	1.72
2008	0.76	1.09	0.68	5.54	0.92	1.55

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix H-5: Relative Citation Propensity for China's First Generation Solar PV Technologies

	CN cites US	CN cites JP	CN cites TW	CN cites KR	CN cites DE	CN cites Others
1988	-	-	-	-	-	-
1989	-	-	-	-	-	-
1990	-	-	-	-	-	-
1991	-	-	-	-	-	-
1992	-	-	-	-	-	-
1993	-	-	-	-	-	-
1994	0.92	1.06	0.00	0.00	8.49	0.00
1995	1.83	0.00	0.00	0.00	0.00	5.44
1996	1.79	0.66	0.00	0.00	0.00	0.00
1997	-	-	-	-	-	-
1998	-	-	-	-	-	-
1999	1.58	0.00	0.00	0.00	0.00	8.66
2000	-	-	-	-	-	-
2001	0.79	1.22	0.00	0.00	0.00	10.11
2002	1.04	0.61	0.00	0.00	14.60	2.17
2003	1.16	0.97	1.29	0.60	0.00	0.00
2004	1.75	0.62	0.00	0.42	2.16	0.00
2005	1.19	0.35	0.94	0.97	0.00	3.91
2006	0.86	0.65	2.01	0.64	2.22	1.16
2007	1.35	0.72	0.94	0.39	0.94	1.48
2008	1.22	1.02	0.64	0.42	0.54	2.29

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix H-6: Relative Citation Propensity for China's Emerging New Generation Solar PV Technologies

China	CN cite US	CN cite JP	CN cite TW	CN cite KR	CN cite DE	CN cite Others
1988	-	-	-	-	-	-
1989	-	-	-	-	-	-
1990	-	-	-	-	-	-
1991	-	-	-	-	-	-
1992	-	-	-	-	-	-
1993	-	-	-	-	-	-
1994	-	-	-	-	-	-
1995	-	-	-	-	-	-
1996	-	-	-	-	-	-
1997	-	-	-	-	-	-
1998	-	-	-	-	-	-
1999	-	-	-	-	-	-
2000	-	-	-	-	-	-
2001	-	-	-	-	-	-
2002	-	-	-	-	-	-
2003	1.06	0.79	0.00	0.00	7.49	0.00
2004	0.63	2.01	0.00	0.00	0.00	0.00
2005	0.93	0.74	0.97	0.00	2.20	5.20
2006	0.57	0.81	5.88	0.00	0.00	4.53
2007	1.53	0.74	0.00	0.00	0.00	4.05
2008	1.41	1.05	0.00	0.00	0.00	0.00

Note. US: United States, JP: Japan, TW: Taiwan, KR: Korea, DE: Germany Country

Appendix I-1: Publication 1 - Wu, C.-Y., & Mathews, J. A. (2012a). Knowledge flows in the solar photovoltaic industry: Insights from patenting by Taiwan, Korea, and China. *Research Policy, 41*(3), 524-540.

(Appendix I-1 (page 221-237) has been removed from the Digital Thesis due to copyright issue)

Appendix I-2: Publication 2 - Wu, C.-Y., & Mathews, J. A. (2012b). *Catching-up of Technological Innovation Capabilities: The Solar Photovoltaic Industries in Taiwan, China, and Korea*. Conference paper presented at The 21st International Conference on Management of Technology, Hsinchu, Taiwan.

(Appendix I-2 (page 239-268) has been removed from the Digital Thesis due to copyright issue)

Appendix I-3: Publication 3 - Mathews, J. A., Hu, M.-C., & Wu, C.-Y. (2011). Fast-Follower Industrial Dynamics: The Case of Taiwan's Emergent Solar Photovoltaic Industry. *Industry & Innovation, 18*(2), 177-202.

(Appendix I-3 (page 270-296) has been removed from the Digital Thesis due to copyright issue)

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