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Differences in Science Based Innovation by Technology Life Cycles: The case of solar cell technology

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Summary

This paper analyzes the role of university research in industrial innovation by different phases of the technology life cycle (TLC) and by patent analysis of solar cell technology. It is found that, in the early phase of TLC, the role of academic research is to broaden the technology scope to provide a variety of technologies to the market. Industry can be benefited directly from universities as a source of new technology. In contrast, in the later phase of TLC where both product and process innovation are important, university industry collaboration (UIC) patents are greater in patent quality as measured by normalized forward citation. In addition, scientific paper citations and the experience of UIC by firms' inventors are beneficial to high impact inventions. Therefore, the impact of academic research comes into play in a more indirect way, using scientific knowledge embodied by industry researchers in the later phase of TLC.

Keywords: Technology life cycle; University industry collaboration; Solar cell technology; Patent data analysis

JEL Classification: O33, L63

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1. Introduction

There are many studies that deal with the importance of the role of the science sectors, such as universities and public research institutions, in the national innovation system. The contribution to technological innovations in industry and economic growth by scientific research (university research) activities themselves has been identified (Griliches, 1979; Mansfield, 1991; Cohen et al. 2002; Feller et al., 2002; Arundel and Geuna, 2004). Mansfield (1991) found that about 10% of new products and processes would not have been developed in the absence of recent scientific research in a survey conducted on 76 U.S. firms in seven industries. Countries where researchers successfully generate important technological knowledge through science have greater potential for economic growth by diffusing their technological knowledge to their local firms through a variety of channels to link to science-like published papers and reports, public conferences and meetings, informal information exchange, and consulting (Mansfield, 1998; Beise and Stahl, 1999; Motohashi, 2005). Furthermore, at the micro level, Cassiman et al. (2010) confirmed that patents from firms engaged in science are more frequently cited and have a broader technological and geographical impact.

However due to its multi-faceted nature, technology transfers from the public research sector to the private one are not so simple as in-sourcing of ready-made technological contents to be plugged into innovation processes at firms. Gilsing et al. (2011) reviewed this nature by the type of transfer mechanism, i.e., either indirect knowledge flow through publications and patents or direct interactions between universities and firms by joint research programs. It was found that the former mechanism is relevant in “science-based regimes”, where the nature of scientific knowledge is basic, while the latter mechanism is important for “development based regimes”, based on more applied knowledge jointly created by universities and industry. This study is based on the past literature of cross industry that looks at the nature of innovation (Breschi et. al, 2000; Marsili and Verspagen, 2002), and is rooted in a seminal paper on the taxonomy of innovation by Pavitt (1984), but we are looking at the contribution of scientific findings to industrial innovation by the technology life cycle (TLC) of a specific product, solar cells.

Technological development of solar cells gives us a unique example for research, since various competing technologies, such as crystalized silicon, amorphous silicon, compound type, and organic material base, co-exist and are in different phases of TLC.

For example, a silicon-based solar panel has been introduced to the market for more than 30 years, while a dye-sensitized one, one of organic material solar photovoltaic (PV), is still under development and has not been introduced into the market yet. In addition, solar cell technology is progressed by the active participation of the science sector such as universities and public research institutions (Tomozawa, 2013). Therefore, a detailed look at UIC by different technologies allows us to figure out the different roles of scientific findings in industrial innovation by TLC.

This paper is organized as follows. The next section provides the concept of TLC and the analytical frameworks for our empirical analysis. This is followed by a section for reviewing the developments of solar cell technologies using a patent database. Then, we provide the results of our empirical analysis, based on the same database. This section is followed by discussion on the results with case studies of solar cell technological development. Finally, we conclude this paper with a summary of findings and some implications, particularly for open innovation managers at firm and UIC policy makers.

2. Conceptual framework: Science based innovation by technology life cycle

The concept of TLC is based on the technology evolution within certain industries or product categories over time. An emergence of a new product often comes with a breakthrough or a radical innovation which makes technological discontinuity. In Utterback's seminal work, presenting the Dynamics of Innovation Model, this first phase of TLC is called "fluid", where product innovation dominates and a variety of products and technologies are introduced to the market (Utterback, 1994). Then, in a process of market competition by a variety of technologies, a dominant design, i.e., the winner of a market competition, gradually emerges. This phase is called "transitional" where the transition from product innovation to process innovation can be observed. After the dominant design is determined, the TLC moves to "specific", where incremental innovations based on the dominant design drive market competition. In the specific stage, process innovation to improve product performance becomes important.

(Figure 1)

It should be noted that TLC is different from the product life cycle (PLC), although these two concepts are closely related to each other. TLC is often confused with PLC, and PLC is more widely used as a term in empirical studies, even while analyzing TLC (Taylor and Taylor, 2012). TLC is how technological activities changes over time, while PLC focuses on the market development of a particular product. Therefore, patent counts are the most conventional indicator for TLC, while sales volume is used for PLC (Chang et. al, 2009). Campbell (1983) is a pioneer work that presents the methodology of patent data to analyze TLC, by dividing a whole cycle into: (1) emerging, (2) growing, (3) maturing, and (4) obsolescence. The first three can be matched to “fluid”, “transition”, and “specific” stage in Utterback’s framework, respectively. This methodology is extended by Haupt et al. (2007) and is applied to pacemaker technology. It is shown that the number of backward citations increases from the introduction (emerging) to the growing phase while that for forward citations decreases over time.

In the fluid (introduction) stage, the beginning of a new technology’s development, fundamental scientific and technological problems have to be resolved (Campbell, 1983). Therefore, universities play an important role as a new technology provider to firms. Coping with basic technological problems as a precondition for developing marketable products can last so long that innovations (patent applications) stagnate or even decline toward the end of the technology’s introduction stage. The possible reasons for a temporary stagnation or decline are that innovative products are still too expensive, customer acceptance is still low, and the range of technology application possibilities is not clear yet. Therefore, a wider selection of new products in the market is important to go through this tough process, and UIC is supposed to contribute directly to such firm’s product innovation.

Towards the end of the introduction stage of TLC, the basic technological and market uncertainties will vanish. In the growing (transition) stage, instead of technological development per se, application-oriented activities toward market penetration dominate. Therefore, incremental innovation to improve product specification becomes critical, and process innovation also plays an important role in lowering the cost of new products. As a result, the role of UIC in the technological development for market competition changes from that in the previous stage. Instead of taking out new technological seeds, a firm puts more weight on application-oriented research with universities. Therefore, joint research and development (R&D) programs are shown to be more important relatively in development-based regimes than in science-based regimes because of the comparatively more systemic nature of knowledge and a greater need for intensive interaction (Gilsing et al., 2011). A broad range of market applications of the technology can be developed subsequently.

Finally, at the mature (specific) stage of TLC, innovation activities are dominated by process innovation to improve the efficiency of production based on a specific dominant design. Here, the role of academic research becomes quite limited, and firms compete against each other in the market with their own resources. This is because mature technology also has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development. Regarding mature technology, creating scientific general knowledge is not necessary because this scientific background is well understood.

3. Review of solar PV technology by patent data

In general, solar cell technology can be classified into three types: silicon, chemical compound, and organic compound. Silicon type solar panels have the longest history and can be further divided into subcategories, such as monocrystalline, polycrystalline, and amorphous. Chemical compound type is based on crystalline compound formed from non-silicon material such as cadmium tellurium (CdTe). Finally, organic compound solar cells are made by organic material, and dye-sensitized technology has emerged recently as a special type of organic compound solar cell. Tomozawa (2013) conducted cluster analysis by using scientific publications on solar cell technology, and has identified four major clusters, i.e., (1) silicon, (2) chemical compound, (3) organic compound, and (4) dye-sensitized.

This category is used in this paper, and patent analysis is conducted to see the difference in TLC of each technology (Campbell, 1983; Haupt et. al, 2007). We have extracted relevant patent information from PATSTAT with an IPC code of “H01/L31/04”, and the patent of which the title or abstract contains the keywords is shown in Table 1. It should be noted that patent analysis in this paper is based on patent family, instead of individual patents, including all patent application information in PATSTAT.[2]

(Table 1)

Figure 2 shows that the patent family counts for four kinds of technology used for solar cells. The modern solar cell, using a diffused silicon p-n junction, was developed in 1954 at Bell Laboratories, while the PV effect was first recognized in 1839 by French physicist A. E. Becquerel, and the first solar cell was built in 1883 by Charles Fritts, who coated the semiconductor selenium with an extremely thin layer of gold to form the junctions (Perlin, 2004). In the space development era from the 1950s to the early 1970s,

[2] PATSTAT provides patent filing information from around 90 patent offices worldwide, including the European Patent Office (EPO), the Japan Patent Office (JPO), and the U.S. Patent and Trademark Office (USPTO).

improvements were slow in this era, and the only widespread use was in space applications where their power-to-weight ratio was higher than any competing technology (Perlin, 2004).

(Figure 2)

In the oil shock era from 1973 to the early 1980s (the first oil shock occurred in 1973 and the second one in 1979), the number of patents in silicon and chemical compounds solar cells increased, as governments all over the world started investing in R&D in this area. Especially in the silicon solar cell field, the number of patents applications had dramatically increased. The outputs in organic and dye-sensitized solar cell area began to be recorded, but did not occupy a high share. In this era, major oil companies also started a number of solar firms and, for decades, were the largest producers of solar panels. Exxon, ARCO, Shell, Amoco (later purchased by BP), and Mobil all had major solar divisions during the 1970s and 1980s. After governments made the policy to make PVs diffuse in the power generation market in the early 1990s, silicon solar cells (especially crystalline silicon solar cells) started to diffuse. While the number of patent application in silicon solar cells shows periods of up and down, the number of scientific publications has increased sharply after the 1990s, suggesting that scientific research did not lose its momentum even in the recent period (Tomozawa, 2013).

Patent applications of organic and dye-sensitized solar cells, which are an alternative design to silicon solar cells, have also increased for two reasons. One is the potentiality of cost reduction. The production of silicon solar cells has realized cost reduction, but this is not sufficient. Organic solar cells are made of conductive organic polymers or small organic molecules for light absorption and charge transport, which themselves have low production costs in high volume. After the epoch-making invention by Oregan and Gratzel (1991), suggesting that the new concept of dye-sensitized solar cells to be composed of a porous layer of titanium dioxide nanoparticles, patent applications on dye-sensitized solar cells have been increasing sharply. The conversion efficiency of dye-sensitized solar cells was about 11% in late 1990s. However, this figure can reach above 30%. There are many issues to improve the conversion efficiency, which can be contributed by scientific and industrial R&D.

Regarding the stage of TLC, silicon solar cells have passed the “fluid stage” and moved into the “transitional stage”, since the dominant design of various types of solar cell technology has been determined. However, fundamental research for a new concept of solar cells is still ongoing, thus silicon types have not reached maturity stage yet. As well as scientific research on new types of PV mechanism being conducted, substantial efforts of industrial R&D are devoted to incremental innovation to improve efficiency of the energy conversion rate. In contrast, dye-sensitized solar cells are still in the "fluid stage", where new technology solutions for electrolytes to increase energy conversion efficiency are proposed. Since conversion efficiency has not reached a sufficient level for commercial production, this type of solar cells has not been introduced to the market yet. Chemical and organic compound solar cells are in-between, in terms of the stage of TLC, silicon type, and dye-sensitized type.

4. Empirical analysis

In this section, we conducted an empirical analysis on the impact of UIC on innovation performance by TLC. Concretely, we used citation-based indicators as a dependent variable to compare the difference in how UIC activities matter across different stages of TLC (Campbell, 1983; Haupt et. al, 2007). It should be noted that patent statistics are biased by changes in science and technology policy, such as the promotion of UIC. For example, the number of patent filings by universities increased sharply in the 1980s after the Bayh-Dole Act was introduced in 1980 in the United States. Furthermore, there are a substantial number of studies investigating whether patent quality has decreased due to this patent surge (Henderson et al., 1998; Rosell and Agrawal, 2009). A similar study was conducted for Japan, when the Japanese government introduced several UIC promotion policies after the late 1990s (Motohashi and Muramatsu, 2012). Some of these studies found that the patent quality measured by forward citations changes significantly after these UIC promotion policies were introduced.

In order to control for potential bias in patent citation indicators by the differences in the institutional framework related to UIC across time periods and countries, we focused on one country and a particular time period. As for country selection, we used patent data filed by Japanese firms and public research institutions including universities, since Japanese applicants have the largest share of patents in our datasets as shown in the previous section. In addition, we have identified that all of the top 10 applicants are Japanese firms such as Sharp Corporation, Canon Inc., and Panasonic Corporation. As for the time period, we used the data from 1998 to 2007. This period starts in 1998 when active Japanese UIC policy began with the introduction of the Technology Licensing Organization (TLO). Therefore, we assumed a possible bias is associated with UIC policy changes. For this time period, we compared silicon type (already in the transitional phase) and dye-sensitized solar cells (still in the fluid phase) to see the differences by TLC.

We have extracted the patent family data from the datasets used in the previous section under the following conditions:

- Patent family allied by Japanese applicants with JPO filing patents as its priority patent.
- JPO filing dates are within the period of 1998-2007, and technology fields are classified as either silicon or dye-sensitized.

There are 1,298 patent families in total with 549 silicon type and 749 dye-sensitized type. Table 2 shows the sample size by the technology field and the types of applicants. We split all applicants into two types, i.e., industry (firm) and universities including public research institutions such as the Agency for Industrial Science and Technology. In the dye-sensitized type, a larger portion of patents are filed by universities (79 out of 749), and the share of university-industry joint applications is also larger than the silicon type. This is consistent with the corresponding TLC phase for each technology category, in the sense that direct academic contribution to whole innovation is greater in the earlier stage of TLC.

(Table 2)

We use normalized forward citation counts as a patent quality indicator, and a dummy variable of examiner citation as an indicator of newness in invention as dependent variables, which are regressed by the following independent variables.[3]

- UI dummy: a dummy variable for university and industry joint application (base=industry patent)
- U_dummy: a dummy variable for university patent (base=industry patent)
- NPL: the number of non-patent literature citations (the degree of science linkage)
- UI_exp: a dummy variable for at least one of inventors with university industry

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[3] Normalization of patent citations is conducted by dividing the average number of forward citations by the application year. It should be noted that the sample is selected only for a narrowly defined technology field (H01/L31/04), so that technology specific bias in forward citation count is already controlled for.

experience (invented any patent of UI joint application)

- International: a dummy variable for international inventor within inventor team
- Inventor: Log of number of inventors
- Past_patent: log of sum of all patents invented by inventors in the past
- Past_cited: average normalized forward citation of all inventors in their past patents
- Silicon: a dummy variable for silicon technology (base=dye sensitized)

Descriptive statistics for these variables are provided in Table 3.

(Table 3)

Table 4 and Table 5 show regression results for normalized forward citations (TOBIT model) and dummy variable of examiner citations (LOGIT model), respectively. In the results of Model (1) of Table 4, we cannot find a statistically significant difference in patent quality by the type of applicants (UI_dummy and U_dummy), and there is no significant difference in university-related patents between silicon and dye-sensitized types (Model (2)). The degree of science linkage (NPL) is positively correlated with patent quality for silicon technology at the 5% significance level (Models (4) and (6)). Finally, a cross term of UI experience and the NPL has a positive and statistically significant coefficient for the silicon type (Model (6)). In sum, science linkage and the UI experience of the inventor are positively correlated for silicon type, which is already in the transitional phase, while a similar pattern cannot be found for the dye-sensitized type, which is still in the fluid phase.

(Table 4)

In contrast, it is found that the involvement of academic institutions has a significant impact on patent newness for the dye-sensitized type, while it is not found for the silicon type. In Models (1) and (2) of Table 5, UI joint application and university application patents have higher technology newness (smaller probability in examiner citation, implying newness in invention without prior important patent documents) for dye-sensitized type, but not for silicon type. In Models (4) and (6), we can find a weak but not statistically significant correlation between UI experience and newness in invention for the dye-sensitized type, implying that researchers at a firm with university collaboration experience may contribute more to inventing new types of technology. These findings are consistent with prediction that academic involvement is important particularly for broadening technology scope in the fluid phase of TLC.

(Table 5)

5. Discussion

The empirical analysis in the previous section confirms the difference in the roles of academic research in industrial innovation by TLC. In the fluid phase (dye-sensitized), the role of academic research is broadening the technology scope to provide a variety of technologies to the market. Industry can be benefited directly from universities as a source of new technology. Therefore, we have found that UIC patents are greater in terms of newness of invention, measured by the non-existence of examiner citations. In contrast, in the transition phase where both product and process innovations are important, UIC patents are greater in patent quality as measured by normalized forward citations. In addition, scientific paper citations and the experience of UIC by the firm's inventors are beneficial to high impact inventions. Therefore, the impacts of academic research come into play in a more indirect way, namely, knowledge embodied by industry researchers through past experiences of UIC does matter with the quality of patents.

In order to understand the results of the empirical analysis more deeply, we introduced some concrete examples regarding the relationship of science and industrial innovation in solar cell technology. The first example is drawn from Hara et al. (2003), where industrial researchers from Hayashibara Biochemical Laboratories Inc. collaborated with scientific researchers from the National Institute of Advanced Industrial Science and Technology in order to improve the photo-conversion efficiency of dye-sensitized solar cells. They have developed new coumarin dyes with thiophene moieties. The absorption spectra of these novel coumarin dyes are red-shifted remarkably in the visible region relative to the spectrum of C343, a conventional coumarin dye. This invention opens up new technology avenues for increasing the energy efficiency of dye-sensitized solar cells.

On the other hand, in the later stage, industrial researchers seem to try to get hints from scientific researchers in order to create commercially important inventions. At this stage, industrial researchers already have enough experience and the capability to do scientific research and assimilate scientific knowledge. Furthermore, they focus on the creation of commercially important inventions in order to build their competitive advantage. For example, Kenji Wada of Sharp Corporation experienced UIC with scientific researchers from the National Institute of Advanced Industrial Science and Technology in 2000 (patent title: "Solar cell substrate, thin-film solar cell, and multi-junction thin-film solar cell", application number: JP20000333701). Following that, he joined a similar industrial research project which created inventions that received much citation. The title of this invention is "Thin-film solar battery and its manufacturing method". This is a basic technology for process innovation, which has a significant amount of commercial value. He seems to succeed in getting hints to create commercially important inventions from his experience with previous UIC activities and his network in the scientific community.

UIC activities take various styles such as joint R&D, technology consulting, patent licensing, and disembodied technology spillovers from scientific papers. The impact of UICs on industrial innovation varies by their scope and means (Motohashi, 2005). Empirical findings in this paper suggest that the phase of the TLC can be an important dimension to clarify the heterogeneous nature of UIC activities. One important implication from this study is that UIC activities not only help industrial innovation per se, but also enhance the absorptive capacity of firms (Cohen and Levinthal, 1990). More specifically, the type of relevant absorptive capacity is different by TLC. Zahra and George (2002) show four components of absorptive capacity (AC): (1) acquisition, (2) assimilation, (3) transformation, and (4) exploitation. They grouped the first two as "potential AC" and the last two as "realized AC". In the fluid stage, dominated by product innovation, UIC activities contribute to "potential AC" directly, while in the later stage of TCL, such as the transition phase, "realized AC" becomes more important, which UIC experience helps to enlarge.

6. Conclusion and Implications

Our empirical analysis suggest that it is valuable to pay attention to UIC's potential to contribute to the creation of commercially important inventions in the later stage of TLC, but not in the earlier stage where broadening the technology scope is important. In evaluating the UIC policy program, one should take into account the heterogeneous nature of UIC activities. We should evaluate the UIC not only by judging the value of outputs created through it, but also by recognizing the effect on the capability building of companies. Both at the earlier and later stages, UIC seems to have positive impacts on the capability of companies. Therefore, it might be effective for policy makers to promote UIC further as a capability building opportunity as well as an output enhancement opportunity in order to promote solar cell innovation and other innovations.

For the companies, it is also valuable to utilize UIC strategically as a capability building opportunity as well as an output enhancement opportunity, and there might be more chances to apply UIC to build the competitive advantage especially in the later stage of TLC. For both the fluid and transition phases, UIC activities are important for absorptive capacity building, but in different ways. In the earlier stage, the major objective of UIC activities is to create technology acquisition and assimilation capability, while in the later stage, using researchers with UIC experience is helpful for enhancing transformation and exploitation capability.

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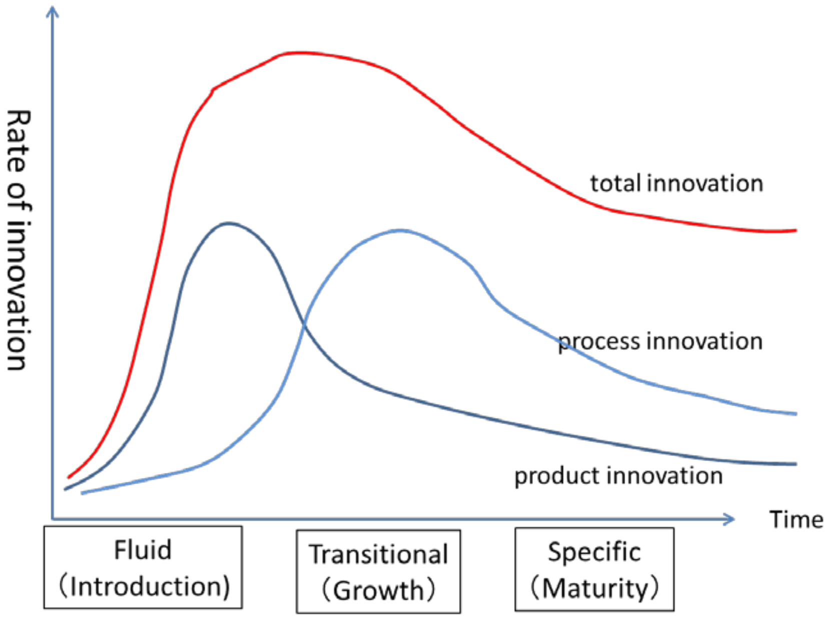
Figure 1: Rate of innovation by TLC



(Adapted from Figure 3 of Taylor and Taylor (2012)

Table 1 Keywords to extract patent data by solar cell technology type

	Keywords
Silicon	silicon,a-si,amorphous,polycrystalline si
Compounds	cds,cadmiumselenium,cigs,cdte,gaas,inp,cis,cuin,zns,cu2o,cus,agins,copper,in2o3,sns,mose2
Organic	organic,polymer,plastic
Dye-sensitized	dye,titanium oxide,tio2

Figure 2: Trends of patent applications by type of solar cells

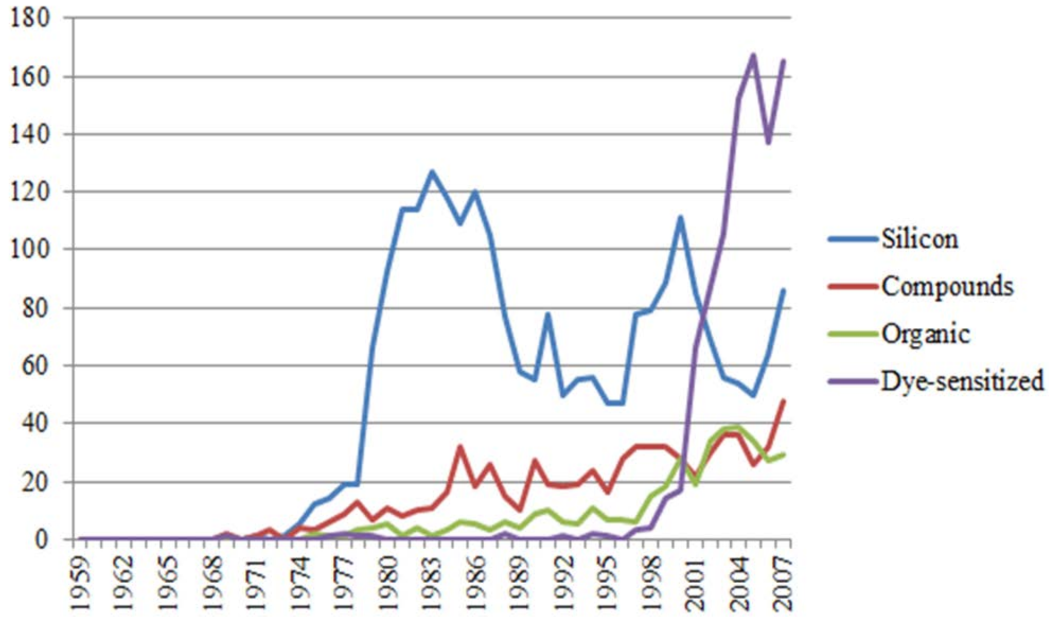


Table 2: Sample size for empirical analysis by technology and applicant type

	Silicon	Dye	Total
University Industry	29	39	68
University Only	16	79	95
Industry Only	504	631	1,135
Total	549	749	1298

Table 3: Descriptive statistics of independent variable

	Silicon		Dye−sensitized	
	Mean	Std. Err.	Mean	Std. Err.
UI_exp	0.03	0.01	0.14	0.01
NPL	0.25	0.02	0.49	0.02
NPL*UI_exp	0.01	0.01	0.08	0.00
International	0.01	0.00	0.00	0.00
Inventor	0.82	0.02	0.80	0.03
Past_patent	4.97	0.04	4.83	0.06
Past_cited	0.93	0.02	1.06	0.02

Table 4: Regression results 1 (dependent variable= normalized forward citation, TOBIT model)

	(1)	(2)	(3)	(4)	(5)	(6)
UI_dummy	−2.429 (1.09)	−6.214 (1.63)				
Silicon*UI_dummy		6.472 (1.36)				
U_dummy	1.116 (0.59)	2.526 (1.22)				
Silicon*U_dummy		−8.272 (1.59)				
NPL	−1.192 (1.15)	−1.934 (1.40)	−0.692 (1.26)	−1.626 (2.15)*	−0.872 (1.51)	−1.622 (2.03)*
Silicon*NPL		1.853 (0.89)		2.039 (1.86)+		1.541 (1.37)
UI_exp			0.426 (0.44)	0.506 (0.46)	−0.658 (0.46)	0.507 (0.32)
Silicon*UI_exp				0.039 (0.02)		−5.811 (1.61)
NPL*UI_exp					2.072 (1.07)	0.014 (0.01)
Silicon*NPL*UI_exp						15.138 (2.91)**
International	−7.101 (0.87)	−6.543 (0.80)	−3.455 (0.82)		−3.505 (0.83)	−3.372 (0.81)
Inventor	1.585 (1.80)+	1.478 (1.66)+	0.382 (0.81)	0.404 (0.86)	0.378 (0.80)	0.479 (1.03)
Past_patent	0.029 (0.08)	0.044 (0.12)	0.000 0.00	0.007 (0.04)	−0.007 (0.03)	−0.003 (0.01)
Past_cited	2.970 (2.75)**	3.005 (2.77)**	1.608 (2.78)**	1.577 (2.73)**	1.666 (2.86)**	1.515 (2.64)**
Silicon	5.631 (5.39)**	5.049 (3.93)**	3.031 (5.46)**	2.313 (3.47)**	3.030 (5.45)**	2.398 (3.59)**
Constant	−16.907 (6.79)**	−16.602 (6.59)**	−7.841 (5.90)**	−7.431 (5.55)**	−7.802 (5.87)**	−7.264 (5.49)**
Observations	1298	1298	1135	1135	1135	1135

Absolute value of t statistics in parentheses
+ significant at 10%; * significant at 5%; ** significant at 1%

Table 5: Regression results 2 (dependent variable= dummy variable of examiner citation, LOGIT model)

	(1)	(2)	(3)	(4)	(5)	(6)
UI_dummy	−1.326 (3.00)**	−1.010 (1.83)+				
Silicon*UI_dummy		−0.753 (0.82)				
U_dummy	−0.651 (2.03)*	−0.836 (2.15)*				
Silicon*U_dummy		0.721 (1.02)				
NPL	−0.042 (0.29)	−0.023 (0.12)	0.035 (0.23)	0.104 (0.52)	0.004 (0.02)	0.069 (0.33)
Silicon*NPL		−0.055 (0.19)		−0.180 (0.59)		−0.167 (0.53)
UI_exp			−0.335 (1.21)	−0.481 (1.50)	−0.558 (1.30)	−0.743 (1.33)
Silicon*UI_exp				0.594 (0.92)		0.562 (0.64)
NPL*UI_exp					0.400 (0.71)	0.420 (0.61)
Silicon*NPL*UI_exp						0.640 (0.45)
International	1.953 (2.15)*	1.884 (2.10)*	1.377 (1.49)		1.367 (1.48)	1.363 (1.48)
Inventor	0.060 (0.48)	0.070 (0.55)	0.124 (0.94)	0.133 (1.01)	0.123 (0.93)	0.123 (0.93)
Past_patent	0.098 (1.75)+	0.098 (1.74)+	0.141 (2.37)*	0.139 (2.33)*	0.140 (2.34)*	0.139 (2.31)*
Past_cited	0.273 (1.79)+	0.272 (1.79)+	0.304 (1.86)+	0.299 (1.83)+	0.317 (1.92)+	0.312 (1.88)+
Silicon	0.453 (3.17)**	0.463 (2.60)**	0.426 (2.86)**	0.468 (2.51)*	0.427 (2.87)**	0.449 (2.38)*
Constant	−2.158 (6.42)**	−2.170 (6.35)**	−2.449 (6.81)**	−2.456 (6.70)**	−2.442 (6.78)**	−2.444 (6.64)**
Observations	1298	1298	1135	1135	1135	1135

Absolute value of t statistics in parentheses
+ significant at 10%; * significant at 5%; ** significant at 1%