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# Photovoltaic technology development: A perspective from patent growth analysis

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ABSTRACT

To catch up with the need for utilizing sunlight as an alternative energy source, photovoltaic technology has developed considerably fast in the last thirty-plus years. This article examines this technology's development from the perspective of patent growth analysis. Patent data are analyzed to find the photovoltaic technology growth trajectory. Mainly affected by environmental factors such as the price of crude oil, we observe two long-term waves of development trajectories. The current wave is found to be in the later growth stage of its life-cycle. After examining the correlation between technology development and crude oil price, a significant correlation is found between crude oil price's growth rate and photovoltaic patents' growth rate. As far as the market is concerned, it lags 10 years behind photovoltaic technology development.

With the assistance of keyword co-occurrence analysis, one can classify photovoltaic patents into five groups, with each carrying a characteristic of competing photovoltaic technologies: Emerging PV, CdTe, CIS/CIGS, Group III–V, and Silicon technologies. This research observes the patent growth trajectories for each technology. Among these competing technologies, Emerging PV, Group III–V, and Silicon are still growing strong, while CdTe and CIS/CIGS are in the mature stage. This result hints at a paradigm shift for photovoltaic technology development. Sustainability is added to the technical regime in addition to efficiency, cost, and reliability.

A policy other than the existing mechanism such as a feed-in tariff is suggested to stabilize photovoltaic technology development through the means of removing oil price fluctuations. Finally, several strategic issues are discussed from the technology development community's point of view.

## 1. Introduction

Photovoltaic technology has developed considerably fast in the last thirty-plus years. An abundant amount of literature has assessed the development trajectory or tried to predict the future of photovoltaic technology through various analytical perspectives—for example, efficiency trend and limitations [1,2], long-term material and environmental constraints [3,4], integrated view on cost, sustainability, and applicability [5], R&D strategy [6], and commercialization and market [7–10]. This article examines the development of photovoltaic technology from a different viewpoint: technology life-cycle. Growth trajectories for various photovoltaic technology types are investigated herein based on patent data.

Patent data have long been used in economical analysis [11] and have been applied to technology assessment and forecasting in recent years [12]. A patent is one possible output of science and technology development, revealing the intelligence of what organizations consider worth protecting. A collection of patents in a certain discipline may represent part of the accumulated knowledge within this science and technology discipline. The patent growth trajectory of a certain technology provides a good indication of its development status, including stages in the life-cycle, time to maturity, etc.

Crude oil prices went up and down like a roller-coaster ride in the late 2000s. In July 2008, oil peaked at a historical high of US$ 150 per barrel, but quickly plummeted to under US$ 40 in the second half of 2008. To a much lesser degree, the short-term development of photovoltaic technology is similar. Technology development is driven and certainly bounded by environmental factors in general. Naturally, crude oil prices seem to be the dominant driving force for photovoltaic technology. This article begins with a simple cross-correlation analysis to examine the

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direct impact of crude oil prices on short-term photovoltaic technology development.

Although there are short-term ripples in photovoltaic technology development, its long-term trend does not escape the natural law of growth. It is well known that human and animal population growth trajectories follow a logistic curve [13], also known as a S-shaped curve. Technology development, in general, does the same. When exponential growth encounters resource limitation, growth slows down and eventually reaches a level where the driving forces and resource constraints are at balance. Based on this assumption, the development trajectory of photovoltaic technology is estimated herein.

The market usually lags behind technology development for a certain period of time [14]. The length of the interval depends on various factors such as the technology itself, demand, usefulness, policy, etc. Some technologies may have a short interval, while others can be very long. It is an intriguing question for when the solar cell market is going flourish following its technology development. Comparing the growth trajectories of photovoltaic technology and the market could help answering this question.

One is certainly interested in knowing the development status of each major type of photovoltaic technology, which requires a classification of the collected photovoltaic patents. Keyword co-occurrence in the patent text provides rich information on the characteristics of a patent. The information is used to categorize keywords and patents. Grouping the patents enables a detailed examination of the growth trajectory of each type of photovoltaic technology.

The rest of the paper is organized as follows. Following this introduction, we delve into the correlation between crude oil prices and short-term photovoltaic technology development. The long-term trends of photovoltaic technology and the solar cell market are then cross-examined. After a brief introduction on patent co-occurrence analysis, we analyze the trends for each type of photovoltaic technology. The following section discusses some issues of the methodology. The paper concludes with implications of the findings from both the policy maker's and technology development community's point of view.

## 2. Crude oil price and photovoltaic technology development

Technology development cannot escape the influence of the environment. The short-term development of photovoltaic technology is very much affected, among other things, by the crude oil price. When oil prices go up, the high cost of alternative energy sources such as solar cells becomes more acceptable, and the willingness to invest in R&D and to protect R&D output increase accordingly. Applying for a patent is a very important way of securing one's R&D output, though certainly there is a time lag for R&D effort to produce output. One hypothesizes that the development of solar cell patents is related to crude oil prices with a certain time lag. The hypothesis can be tested by simply collecting and then correlating the time series of crude oil prices and patent quantity data.

We take the annual average crude oil price data from a public domain source [22]. Prices are based on the historical free market prices of Illinois Crude as presented by Illinois Oil and Gas Association (IOGA). The patent data are taken from the "USPTO Patent Full-Text and Image Database" operated by the United States Patent and Trademark Office. With the designed query,[1] we collect photovoltaic and solar cell patents issued during the period 1976 through 2007, for a total of 3160 patents. All patent information including text is downloaded for later processing.

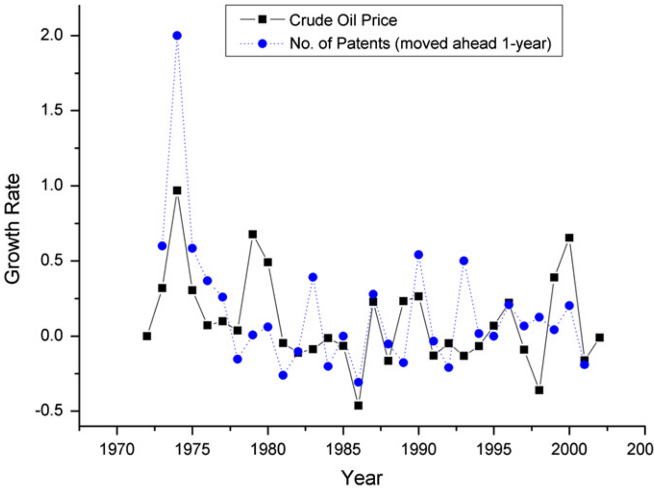

**Fig. 1.** Crude oil prices' growth rate and photovoltaic patents' growth rate. Note that the data on the number of patents are shifted ahead by one year in the graph. After the shift, the two time series show a close resemblance.

While there is some direct correlation between the yearly oil price and the number of patents,[2] a significant correlation is observed between the yearly growth rate of the crude oil price and the growth rate of photovoltaic patents. Fig. 1 shows the crude oil price's growth rate and photovoltaic patents' growth rate. The data on the number of patents are shifted ahead by one year in the figure. After the shift, the two time series coincide reasonably well. This implies that crude oil price variations are reflected in patent application around one year later.

Table 1 lists the cross-correlation between crude oil price's growth rate and photovoltaic patents' growth rate at various time lags. The peak of the cross-correlation occurs at an one-year lag. The peak value is 0.598 and it is statistically significant at the 0.01 confidence level. The hypothesis – that the development of solar cell patents is related to crude oil prices with a certain time lag – is supported and the time lag is one year. The implication of this hypothesis is immediate. Considering the relative high oil prices in 2008, one may project that solar cell patents will have a sharp increase in the year 2009.

## 3. Long-term development and the market

The population of human beings, bacteria, animals, and other beings in nature that grow to a limit follow an S-shaped growth trajectory. Technology development in many situations takes the same growth trajectory. The development of a category of technology usually begins with the birth of an innovative idea. The idea attracts researchers and technology developers who envision the economic potential of the technology. These early innovators work on the generic science and technologies and lay out the foundation of the discipline. The technology eventually grows exponentially when more and more innovators participate in the development. At a certain time, the growth of the development slows down as either a physical limit in the science or economical attractiveness in the market is encountered.

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[1] The exact query is "ABST/((photovoltaic or solar) and (cell$ or batter$ or device$ or method or process$ or power or energy or apparatus)) and ICL/H01L$ and ISD/19760101- > 20071231".

[2] The number of patent in a certain year is defined as the number of issued patents which have filed application in that certain year. This is because a patent usually has several years of delay between the application date and issue date. One should consider the application date to see the immediate effect.

**Table 1**
Cross-correlation between crude oil prices' growth rate and photovoltaic patents' growth rate.

| Cross-correlation | $t+0$ | $t+1$ | $t+2$ | $t+3$ | $t+4$ | $t+5$ |
|---|---|---|---|---|---|---|
| Growth rate (crude oil price vs. no. of patents by application date) | 0.140 | 0.598* | 0.177 | -0.103 | 0.162 | 0.084 |
| *p*-value | 0.468 | 0.001 | 0.359 | 0.595 | 0.401 | 0.664 |

*Notes*: in both cases, the peak of the cross-correlation appears at $t+1$. This implies that there is an one-year lag for the patent application to reflect the change in crude oil prices.

* Denotes that the correlation is significant at the 0.01 level.

Gradually, the development virtually stops and reaches the end of the technology's life-cycle. During the later development stage, production and process techniques rather than basic science become the main theme of development.

A standard S-shaped curve can be represented mathematically in the form [13]:

$$S(t)=\frac{\kappa}{1+\exp[-(\ln(81)/\Delta t)(t-t_m)]}, \tag{1}$$

where $\kappa$ is the growth limit, $t_m$ is the midpoint of the growth trajectory, and $\Delta t$, the "characteristic duration", is the time it takes to grow from 10% to 90% in the growth limit. The curve is also called the logistic curve or the Pearl curve.

There are situations where growth comes in multiple phases. A growth trajectory that contains multiple phases can be seen as the sum of multiple S-shaped curves. For the case of two growth phases, the growth trajectory is simply the sum of two logistic trajectories. It is commonly represented by bi-logistic function $S_b(t)$.

$$S_b(t)=S_1(t)+S_2(t), \tag{2}$$

where

$$S_1(t)=\frac{\kappa_1}{1+\exp[-(\ln(81)/\Delta t_1)(t-t_{m1})]},$$

$$S_2(t)=\frac{\kappa_2}{1+\exp[-(\ln(81)/\Delta t_2)(t-t_{m2})]}, \tag{3}$$

and $\kappa_1$, $\kappa_2$ are the growth limits, $t_{m1}$, $t_{m2}$ are the midpoints, $\Delta t_1$, $\Delta t_2$ are the characteristic durations for the two sub-trajectories, respectively.

When a growth curve is two phases in nature, the bi-logistic function (2) will fit better than the single logistic model (1). Loglet Lab software [15] has a built-in algorithm to decompose a growth trajectory into two sub-trajectories. Under these situations, the overall growth trajectory $S_b(t)$ may not look S-shaped, as the summation of two logistic curves with different characteristics can be deviated from their original form.

Applying the concept above to the accumulated count of issued patents, one obtains the growth trajectory of photovoltaic technology. The two-phase growth model fits much better than the single phase growth model. Fig. 2a shows the resulting growth trajectory $S_b(t)$. In the figure, two separate growth trends can be clearly visualized. Each is identified with the mark (1) or (2) at their midpoint. Fig. 2b displays the two decomposed sub-trajectories of this growth curve along with the market growth curve, which will be explained in the following paragraphs.

The growth of the first trajectory came to an end during the period 1988–1989. It was most likely discouraged by the low crude oil price, because the period was a time when crude oil was at an extremely low price.[3] The second trajectory began its growth stage around the year 1991–1992 when oil prices stabilized after the end of the Second Gulf War.[4]

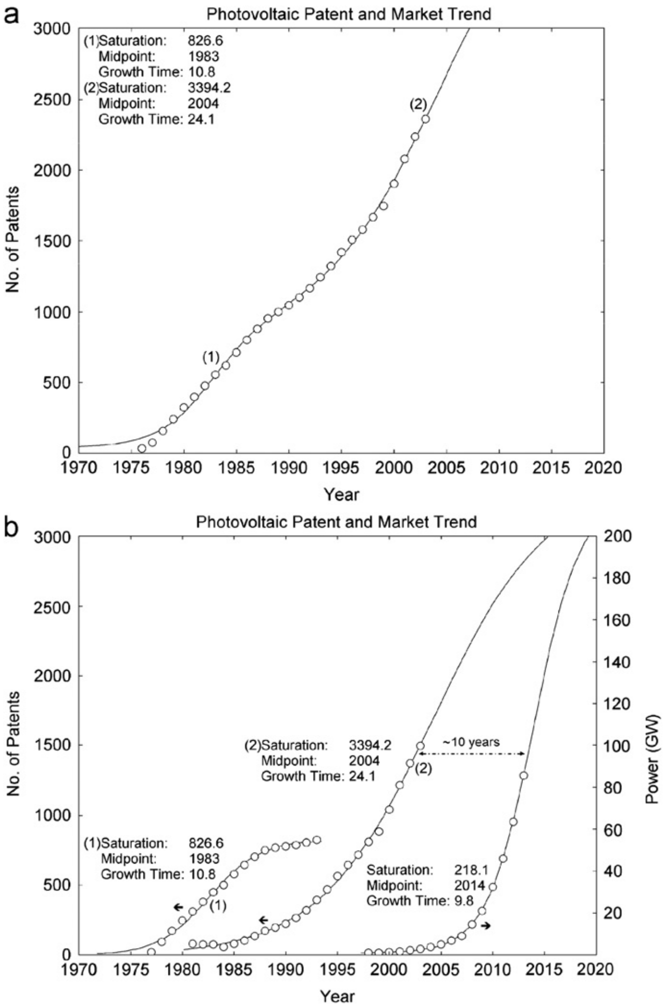

Fig. 2. (a) Growth trajectories of overall photovoltaic patents. (b) Growth trajectories of photovoltaic patents and the market. The two curves on the left are the patent growth trajectories; the one on the right is the market trend. The market growth trajectory lags behind the patent growth trajectory by around 10 years. The unit of the market data is GW.

We conduct the same growth analysis on global photovoltaic market data [23]. The market growth trajectory is shown as the right-most curve in Fig. 2. The global photovoltaic market is growing fast, but has yet to reach the high growth part of its trajectory. The growth seems to be in the infant stage of the life-cycle.

The market usually lags behind technology development for a certain time, depending on the complexity of the technology, its

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[3] Amidst the Iran–Iraq War, average crude oil prices fell by over 50% in 1986. In July 1986, crude oil price dipped under US$9 per barrel. See article "Chronology of world oil market events (1970–2005)", Wikipedia.

[4] The First Gulf War ended on February 27, 1991 when the Iraqi government announced acceptance of the UN resolution and moved its troops out of Kuwait.

applications, and needs. A common method to detect the lag is through a cross-correlation calculation between the time series of the two trajectories. Between two S-shaped curves, the lag can be easily estimated by comparing the two midpoints. As shown in Fig. 2b, the lag between photovoltaic technology and the market is around 10 years—that is, it takes around 10 years for developed photovoltaic technology to reach the market. The implication of this long lag is discussed in the last section of this paper.

## 4. Classification through keyword CO-occurrence in patents

To observe the growth trajectory for different photovoltaic technologies, one needs to classify patents. [11] suggests that one of the major problems in using patents for economic analysis is classification. To obtain patents with the correct classification, one simple approach is to search from the patent database using International Patent Classification (IPC) or United States Patent Classification (USPC) codes,[5] but usually a new technology may be classified to many codes and a code usually does not include just one technology. One cannot use the IPC or USPC code alone to do the search. Another approach is to search directly from the patent database with major categorical keywords. For example, one can query the patent database using categorical keywords such as a-Si, organic, dye-sensitized, cadmium telluride (CdTe), copper–indium–selenium (CIS), copper–indium–gallium–selenium (CIGS), or a combination of them.

The above approach suffers two problems. First, a patent that uses the terminology other than the one given may be neglected. For example, amorphous silicon can possibly be otherwise expressed as “a-Si”, “amorphous Si”, “amorphous semiconductor”, etc. The solution, exhausting all the possibilities, can be tedious. Second, the patent text (including abstract, claims, and description) containing a keyword does not necessarily guarantee that it belongs to the category to which the keyword belongs. For example, a patent on CIGS technology may reference CdTe for comparison purposes.

This study applies a keyword analysis methodology to classify patents—that is, classifying patents by observing their keyword co-occurrence pattern. Patents with similar keyword pairs in the text are grouped together. Callon et al. [16] introduced the basic concept of co-word analysis. The method used herein is a variation of what Callon et al. [16] proposed. Two major characteristics of the new method signify the difference. First, the method treats the system as a bipartite network with keywords and patents as two distinct types of nodes. Both the patents and keywords are classified at the same time. In other words, patents along with their significantly associated keywords are classified as a unit. In the end, both the keywords and patents are grouped. Second, the method allows overlaps among groups. Some keywords or patents may belong to more than one group after the classification. This is an important characteristic of the method, considering that some keywords and patents belong to more than two classes by nature. For example, indium is a material used both in CIGS and Group III–V solar cells, and so the method allows the keyword indium to belong to both the CIGS and Group III–V groups.

The classification procedure is as follows:

(1) Extract keywords from the patent text. A text mining tool is used to extract terminologies from the abstracts, claims, and description text of all patents. Terminologies up to three words are allowed. Around 6,000 terminologies are extracted at this stage. Experts specialized in photovoltaic technology then examine the list manually. After removing the irrelevant terms, the size of the keywords is reduced down to around 1000. Two guidelines are followed in selecting the keywords. First, select only nouns, including nouns of multiple words. Second, focus on materials, such as indium, cadmium, SiGe, etc., as well as symbolizing terms such as CIGS, CdTe, organic film, plastic material, polycrystalline Si, etc.
Many of the terminologies in this raw list carry similar meanings—for example, “DSSC”, “dye-sensitized photovoltaic cell”, “dye-sensitized solar cell”, “organic dye-sensitized metal” and “sensitizing dye” all refer to the same technology. One then uses “dye_sensitized” to be the alias word for these five terminologies. The final keyword list consists of 76 alias words. We will refer to ‘alias word’ as keyword hereafter.
(2) Count the occurrence frequency for each keyword in a patent. One counts the occurrence frequency of each terminology within a patent and then aggregates the count of terminologies with the same alias words. This results in a keyword frequency list for each patent.
(3) Find the co-occurrence frequency for all keyword pairs. Before counting the co-occurrence frequency, possible noises are filtered out by applying a threshold. The threshold requires that the keywords appear at least three times and more than 4% in total keyword counts within that certain patent. Patents that do not have any keywords complying with the above requirements are excluded. A total of 2394 patents remain and are admitted for later processing.
(4) Establish the co-word network. The network has keywords as nodes and co-occurrence frequency as the link weight between a pair of nodes. The higher the link weight is, the more frequent the pair of keywords is mentioned in all the patent document.
(5) Classify the keywords and patents. Patents are grouped together based on their similarity in using keywords. Patents and keywords are classified at the same time. Five is assigned as the number of classes to begin the computation.

The classification results in five classes of technologies: the Emerging PV, CdTe, CIS/CIGS, Group III–V, and Silicon. They are named based on the keywords assigned to the class. The Emerging PV class includes mainly polymer and dye-sensitized technologies. The Silicon class includes all types of Silicon-based bulk and thin-film technologies. The CdTe, CIS/CIGS, and Group III–V classes are self explanatory. Table 2 shows keywords for each subcategory. These keywords exemplify the materials used in each type of technology.

Among the patents, 270 (out of 2394) are classified to more than one class. The overlapping-class characteristic of the method relieves the quandary of forcing an ambivalent patent to one category. One example is U.S. patent 4,366,337. The invention concerns growing a CdS compound on a Silicon-based substrate. The method classifies it as belonging to both the CdTe and Silicon categories. The keywords ‘G_II’, ‘G_II_II_VI’, ‘fluorine’, ‘germanium’, ‘indium’, and ‘thallium’ are classified in two categories. Not surprisingly, ‘indium’ is successfully categorized to both the CIGS and Group III–V classes.

## 5. Growth stages of various photovoltaic technologies

After classifying photovoltaic patents into five groups, one performs a growth analysis to observe the growth trajectories of all five classes of technologies. Figs. 3–7 present these growth

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[5] For example, one may tempt to search for an organic type of photovoltaic using IPC code H01L/51. IPC code H01L/51 represents “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.”

**Table 2**
Keywords for each category of photovoltaic technology.

| Category | No. of patents | Keywords |
|---|---|---|
| Emerging PV | 494 | Dye_sensitized(1.00) fluorescent_dye(1.00) fullerene(1.00) nanoparticle(1.00) organic_PV(1.00) pigment(1.00) porphyrin(1.00) acrylic(0.99) dye(0.99) polyethylene(0.99) aromatic_group(0.98) organic_material(0.98) phenyl(0.98) ruthenium(0.97) polystyrene(0.96) plastic_material(0.95) polymer(0.95) porous_layer(0.95) polypropylene(0.94) organic_film(0.92) TiO(0.90) plastic_film(0.89) nanocrystalline_Si(0.87) fluorine(0.48) |
| CdTe | 215 | CdTe(0.98) cadmium_compound(0.95) CuS(0.89) G_II_VI(0.75) cadmium(0.67) tellurium(0.62) G_II(0.48) G_II_II_VI(0.36) |
| CIS/CIGS | 107 | G_I_III_VI(1.00) chalcopyrite(1.00) CIGS(0.98) selenium(0.96) CIS(0.95) molybdenum(0.82) G_II_II_VI(0.64) indium(0.58) G_II(0.52) |
| Group III–V | 761 | G_III_III_V(1.00) G_III_III_V_V(1.00) GaAs(0.97) multijunction(0.97) quantum_well(0.93) G_III_V(0.89) G_III_V_V(0.85) beryllium(0.84) gallium(0.74) thallium(0.66) p–n(0.58) singlecrystalline_Si(0.50) germanium(0.42) indium(0.31) |
| Silicon | 1087 | Microcrystalline_film(1.00) microcrystalline_layer(1.00) n–i–p(1.00) SiC(0.99) SiGe(0.99) amorphous_layer(0.99) crystalline_Si(0.98) i_type(0.98) microcrystalline_Si(0.98) p–i–n(0.98) silicon_film(0.97) amorphous_Si(0.95) amorphous_film(0.95) silicon_layer(0.95) polycrystalline_layer(0.94) multicrystalline_Si(0.94) nonsinglecrystalline_Si(0.90) polycrystalline_film(0.89) InO(0.88) tandem(0.86) neodymium(0.85) potassium(0.83) polycrystalline_Si(0.76) InSnO(0.67) germanium(0.57) fluorine(0.52) thallium(0.31) |

*Notes*: keywords selected are mostly materials. Numbers in parentheses denote the likeliness of the keywords belonging to the category. This table lists only the keywords with a likeliness greater than 0.3. Keywords led by 'G_' represent compounds that contain elements belonging to the specified group in the period table.

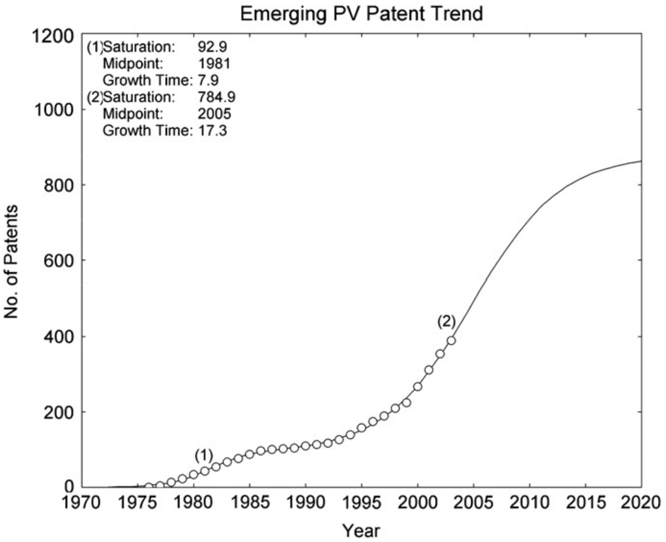

**Fig. 3.** Growth trajectories of Emerging PV patents. The midpoint of the main growth trajectory is in 2005.

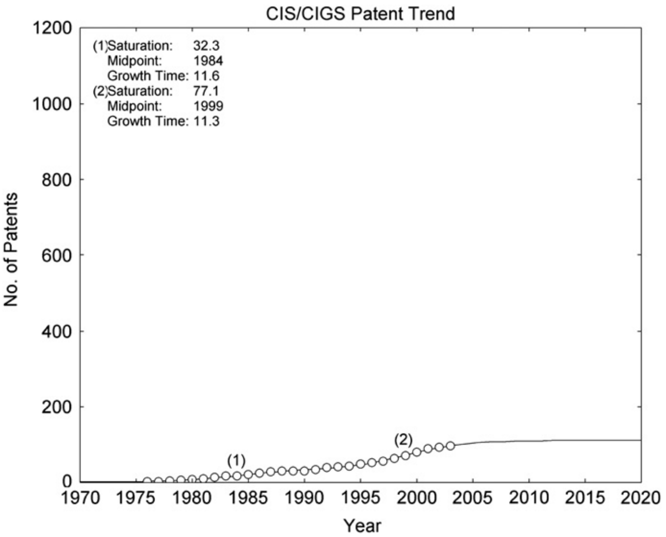

**Fig. 5.** Growth trajectories of CIS/CIGS patents. The midpoint of the main growth trajectory is in 1999.

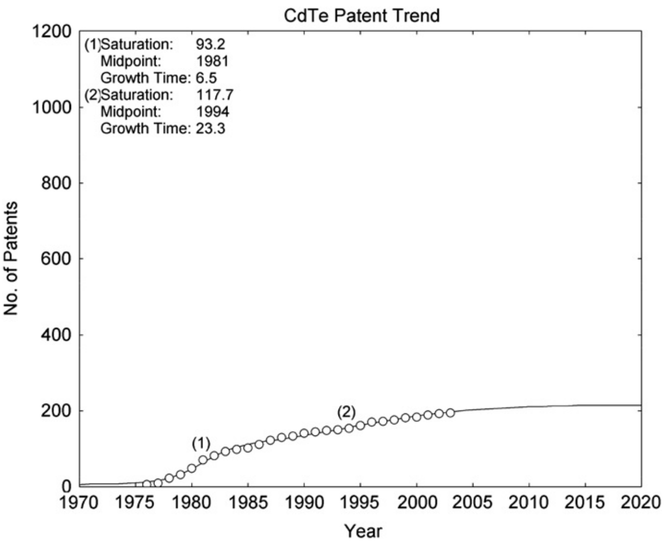

**Fig. 4.** Growth trajectories of CdTe patents. The midpoint of the main growth trajectory is in 1994.

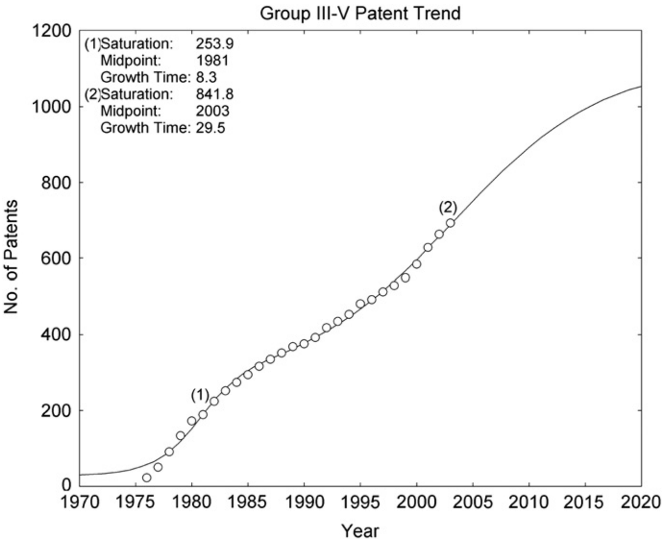

**Fig. 6.** Growth trajectories of Group III–V patents. The midpoint of the main growth trajectory is in 2003.

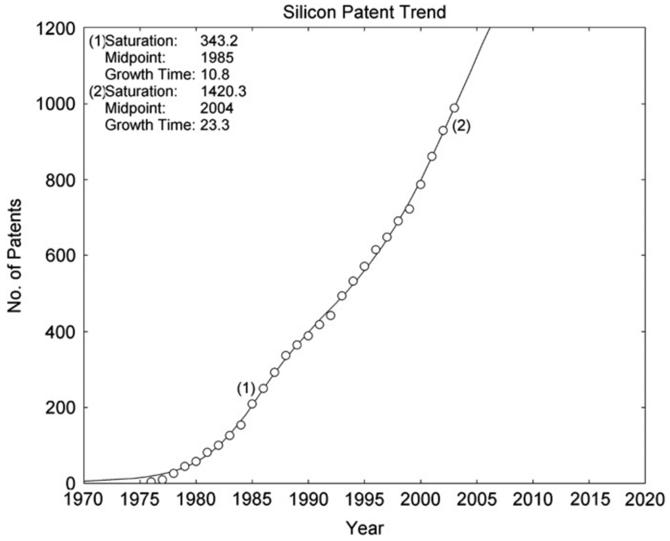

**Fig. 7.** Growth trajectories of Silicon patents. The midpoint of the main growth trajectory is in 2004.

**Table 3**
Expected technology life-cycle for various photovoltaic technologies.

| Technologies | Midpoint (year) | Characteristic duration (years) | Mature year |
|---|---|---|---|
| Overall | 2004 | 24.1 | ~2016 |
| Emerging PV | 2005 | 17.3 | ~2014 |
| CdTe | 1994 | 23.3 | ~2006 |
| CIS/CIGS | 1999 | 11.3 | ~2005 |
| Group III–V | 2003 | 29.5 | ~2018 |
| Silicon | 2004 | 23.3 | ~2016 |

*Note*: the CdTe and CIS/CIGS technologies are at the mature stage of their life-cycle as of 2006. Others are at the second phase of the growing stage. In particular, the Group III–V technology is still growing strong. Mature year is the time when 90% of the growth limit is reached.

trajectories. Table 3 summarizes the characteristics of each growth trajectory.

All five technologies grow in two distinct phases. In Figs. 3–7, each phase is marked (1) or (2) at the midpoint to denote their phase. The first phase generally halts in the period 1985–1990. As mentioned earlier, this coincides with the period when crude oil hit extremely low prices. The growth stage of the current phase begins at the end of the first phase.

Observing the growth trajectories, it is apparent that CdTe and CIS/CIGS technologies have attained the mature stage of their life-cycle. Silicon-based technology has not yet reached the end of its life-cycle. Furthermore, it is believed that most of the current development of Silicon type technology is related to production and process improvement. Other technologies are at the growing stage of their life-cycle. Among all technologies, the Group III–V technology has the longest life-cycle.

The slowdown in the development of CdTe and CIS/CIGS technologies hints at a sign of a technological paradigm shift. Dosi [17] defined technological paradigm as: "…'model' and a 'pattern' of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies." From the inception of photovoltaic technology, sunlight-to-electricity conversion efficiencies, module and system cost, and outdoor reliability have been the three major focuses of the technology developing community. Regularly published 'Solar Efficiency Tables' [18] raise such awareness, especially for efficiency improvement. Significant advancements have been achieved in these areas [19]. Nevertheless, environmental awareness gradually becomes another factor in technology development. Andersson and Jacobsson [3] suggested that in the long run the deployment of CdTe, CIS/CIGS, and dye-sensitized cells may be limited due to the use of scarce metals such as tellurium, indium, selenium, and ruthenium. It seems that sustainability is now added to the technological patterns in addition to efficiency, cost, and reliability.

## 6. Discussion

Some methodological issues are worth a discussion. This study uses patents as the proxy for technology development, which is based on the assumption that a patent represents a good sample for technical knowledge developed by the photovoltaic community. However, not all developers apply for patents for their new technologies, nor do all patents issued proffer technical significance. Despite these limitations, a patent analysis should still be able to highlight major trends in technology development.

Abundant information is obtained through extracting keywords from all patent texts, including abstracts, claims, and descriptions. Obtaining all this information has a negative side, as noise comes with it. Although a threshold mechanism is used to filter out the noise, wordy references to technologies other than the focus of a patent may still cause occasional misclassifications. One other way to reduce the noise is to extract keywords from only the abstracts and claims. This may run the risk of losing much useful information. One way or another, exact classification is difficult to achieve. For the purpose of examining the growth trajectory, we have chosen to have more information.

The classification results in five classes of technologies. Questions may arise why these five specific classes have been chosen? A number of methods for classifying photovoltaic technologies are seen in the photovoltaic literature. Shalav [20] provided the most elaborate classification, where more than ten classes were identified. Too many classes will reduce the number of patents in each class and make the growth analysis less reliable. Too few classes, on the other hand, suffer the problem of grouping several important technologies into one. After several attempts, five is found to provide the best balance between analysis requirement and a commonly agreed category in the current market. In addition, the classification does not avoid excluding fairly new technologies such as bio-photovoltaic, etc.[6] Patents on these technologies are too few to be classified alone. Even if they are identified as a group, the size of the data will not be enough to conduct growth analysis.

Growth curve analysis is based on mathematical extrapolation. The confidence level of the estimation is low when the amount of data given is few and the trajectory is in its early growth stage. All the growth trajectories are estimated based on a large pool of data and are themselves quite mature with the exception of market data, which include merely 16 years of data and are in the very early stage of growth. One should note that the future market growth may deviate greatly from the projected trajectory.

## 7. Conclusions and policy implications

Through patent analyses, this study provides four pieces of evidence that should interest photovoltaic policy makers and the technology development community. First, the short-term

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[6] As of July 2009, there have been no bio-photovoltaic related patents granted by USPTO. One bio-photovoltaic patent application (2007015796) filed by Massachusetts Institute of Technology is seen in the USPTO application database.

growth rate of photovoltaic technology development is very much affected by crude oil prices. Second, the solar cell market lags behind its technology development by around 10 years. Third, overall photovoltaic technology development is still in the growth stage of its life-cycle. Fourth and finally, among the various competing technologies, the patenting activities for Emerging PV, Silicon, and Group III–V are still rather active.

Based on this paper's evidence, some implications are immediate. From the policy maker's point of view, the short-term fluctuation of technology development is not desirable, because it can slow down or even halt R&D investment. Various incentive policies from the market side have been proposed and implemented to stimulate and maintain solar cell deployment. For example, a feed-in tariff (FiT) program has successfully been put into practice in Germany, Spain, and other countries.[7] A recent large-scale incentive program is China's 'Golden Sun' program, which sets to deploy 500 MW of solar cells in two or three years. Starting from July 2009, China's government will subsidize 50% to 70% of investment for solar projects that connect to grid networks. Grid companies are required to buy all surplus electricity output from solar power projects at similar rates to the benchmark on-grid tariffs set for coal-fired power generators.

An interesting 'floor price' idea [21] can be seen as a direct application of this study's first finding. It suggests maintaining a guaranteed lower bound for the price of oil within a country. This sends a stable oil price signal to domestic technology developers and investors. As such, the returns from developing alternative energy sources can be assured. Oil price fluctuations and their disturbance to technology development will then be minimized.

Several strategic issues arise from the technology development community's point of view. First, the solar cell market is in the early growth stage. Market opportunities are wide open, but the fundamentals of photovoltaic technology, in particular for the silicon-based type, are basically established. Other than working on the fundamentals, material modification, device structure optimization, and manufacturing process improvement are important subjects which can make technological contributions to the photovoltaic industry. Innovation in fabrication technology in terms of process and equipment for higher throughput and better yield is constantly exercised by the industrial sector research. Typically, towards the end of the life-cycle, the technology development is geared more to process improvement. Second, the photovoltaic market lags behind technology development for quite a long time. The R&D effort and investment will take many years to harvest gains, especially for brand new concepts. Long-term financial planning for investment is needed if a brand new concept is selected as the R&D target. For example, developers of bio-photovoltaic technology should not expect to see a market for such technology in a short time. To keep the development active, financial support from various stages of development – such as prototyping, efficiency improvement, and production process design – should be carefully planned ahead. Third, after dominating the solar cell market for several years, silicon-based technology is facing market competition from technologies such as CdTe, CIS/CIGS, and Group III–V, etc. The technology to survive the longest and to make the most profit is as of yet an unknown. Selecting the right technology to develop is crucial. Considering the gradual shift in the technical pattern towards sustainability, the 'rightness' may be judged by a balance between the cost-performance ratio and sustainability.

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[7] A FiT program works as follows. The state is committed to buy renewable electricity at an above-market price set by the government over a long period of time, for example, from 20 to 25 years. The extra cost is spread over all other electricity users who do not have facilities to generate renewable electricity.