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Comparing the Evolution of Crystalline Silicon Photovoltaic Cells: Technological Route and National Specialization

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Abstract

There are at least three types of photovoltaic cells derived from raw materials, which have not been differentiated in most of the previous literature. From a global perspective, we focus on a mainstream product in the photovoltaic energy market: crystalline silicon photovoltaic cells (CSiPVCs). This paper delineates the technological developing trend and global geographical distribution of CSiPVCs. Furthermore, the specific technological evolution route is emphasized on a national level. In terms of policy implication in China, and particularly in the context of China's recent predicament in the international PV market, the paper establishes a framework to disclose, in depth, the gap between China and technologically advantageous nations. Policy suggestions for China are proposed as well.

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Keywords: CSiPVCs; Solar Energy; Patent Analysis; Technology Evolution; National Specialization

1. Introduction

Solar energy has become one of the cleanest and highest regarded forms of green energy across the world as climate change is attracting more and more attention from scholars, enterprises and governments [1-2]. Crystalline silicon photovoltaic cells (CSiPVCs) have contributed over 80% in value to the solar energy market, and according to predictions by EPIA, this proportion will be maintained at 50% even up to year 2020 [3].

Since solar energy is highly technology intensive and related to R&D, the corresponding patent activities have very active in the last 50 years. Studies on the technology evolution and national comparisons are beneficial to developing countries, such as China, who seek to expand their competitive advantages and market opportunities in the field of solar energy. But literature on this issue is rare. A

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patent document provides abundant and useful information regarding time (via application/grant/priority date), technical origin, and destination (via priority nation or the applicant's location and grant nation), as well as technical quality and value (via citation or patent family) [4]. Patent documents have been widely applied in technical and innovation-related studies. In the IPC Green Inventory developed by the IPC Committee of Experts of WIPO, IPC classifications of 200 Environmentally Sound Technologies (ESTs) are assigned to help analyze patent information [5]. Photovoltaics are an important component of IPC Green Inventory which has inspired and facilitated quite a few of patent-based solar energy studies [6-7].

2. Data collection and methodology

2.1. Data collection

The paper chose the EPO worldwide patent database, Espacenet®, as the main data source. A proxy commercial software, *HIT*®, developed by a Chinese patent information exploitation company (Hamilton Innovation Technology Co., Ltd.), was applied to help retrieve, download, and sort data, as well as to further build up a local database. Data has been filtered to account for missing information, name duplication, and merged enterprises and acquisitions. Data with full-time span was collected on July 20, 2013 and a total of 5566 patents were included in the database.

2.2. Methodology

First, to combine the advice from solar energy experts and results of the literature review, we decomposed CSiPVCs technology into six sub-fields: ① solar-level silicon raw material and purification; ②solar-level crystal silicon preparation; ③ crystal silicon segment; ④ cells manufacturing; ⑤ cells module, and ⑥ control system, in accordance with production chains. Second, the patent retrieval strategy was formulated for each of the six sub-fields respectively based on IPC classification and keywords. Third, a four-dimensional "time-category-quantity-quality" framework was designed for cross-national comparison and national specialization identification (see Figure 1). The time dimension indicates the entry or the starting date of the CSiPVCs patent application; category refers to one of the six sub-fields; quantity stands for patent counts; quality is defined as the average citation and family size of the patent.

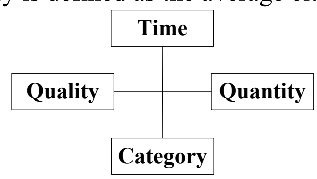

Fig.1. Framework for national specialization of CSiPVCs

3. Results

3.1. Data description

Within the 5566 patents, there are 35 countries, as origins, who have patented their invention in 30 filing destination countries (regional or international patent organizations). Ranked by quantity, China, Japan, South Korea, United States, and Germany are the top five nations both in terms of patent sources and application targets. 6% of CSiPVCs patents were filed at WIPO, while 2% was filed at EPO. There are 1751 patents in the fifth sub-field (⑤ cells module), which accounts for the most of the total counts, followed by sub-fields ③, ⑥, ①, ④ and ②.

3.2. Global technological route

Patent activities related to CSiPVCs date back to as early as the 1950s. We divide this history into three stages: 1952-1975, 1976-2004, and 2005-present (see Figure 2). Crystal silicon segment is the earliest sub-field in patent activities, followed by cells manufacturing. From 1952 to 1974, there were only few of patent applications; then, beginning in 1975, all of the six sub-fields witnessed fast and sometime fluctuating application growth. This trend did not change until 2005, when a rapid explosion occurred. The analysis of patent growth trends indicates that technological progress in the six sub-fields of CSiPVCs can be seen as a long story, in which each encouraged the other during their evolution as a whole.

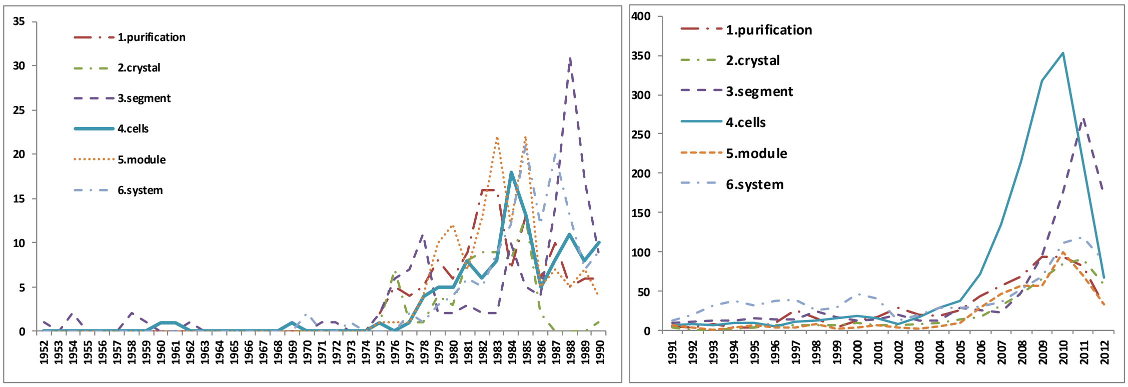

Fig. 2. Technological evolution of CSiPVCs (1952~2012)

3.3. National specialization

On a national level, we find that the United Kingdom and United States applied the earliest patents in CSiPVCs and ranked as the top two countries in 1952 and 1954 respectively. Twenty years later, Germany and Japan began to apply patents in this field and another 10 years later, China and Korea joined the global competition. The year of 2006 was a watershed because China became the largest country in the patent application of CSiPVCs. Further analysis indicates that each country has its own key core sub-fields: China focuses on crystal silicon segment and cells module; Japan is rich in control system; for Korea, over 84% of patent are in sub-field cells module, while the United States focuses on cells module.

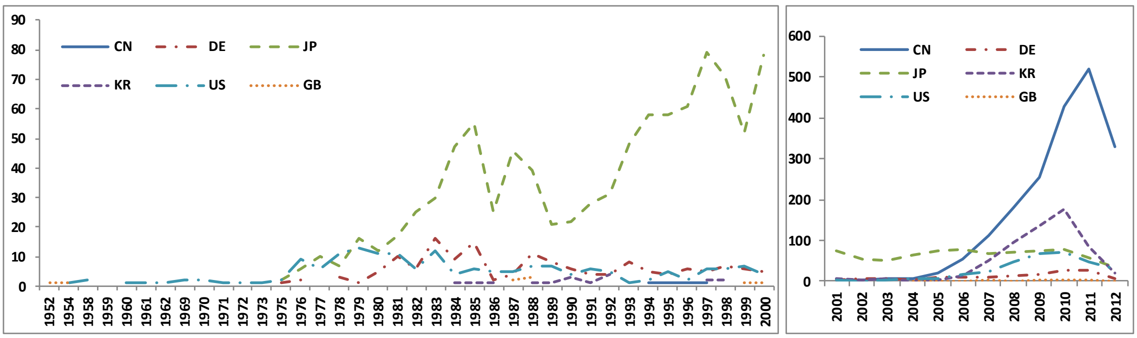

Fig.3. Comparison of major nations in patent application trend of CSiPVCs (1952~2012)

3.4. Gaps between China and developed countries

Table 1 lists the direct gaps between China and developed countries with five indicators of which core patent was defined by top 100 most cited patents. Even though China ranks top one in patent application counts, the quality of these patents is not optimistic. The average citation of China is 0.05, whereas the rate for the United States is 12.67. Even Korea, a country in nearly the same developing phase as China, the value is 0.45. China is also weak from the perspective of average family size, which is only 29.2% of Germany and 16.9% of the United States. The majority of Chinese patents are filed domestically and only 2.1% are applied outside of country border, which leaves China far behind Germany and the United States. Additionally, China does not possess any core patents in CSiPVCs; 53.9% of the core patents are from the United States and 32.4% are from Japan.

Table 1. Comparison of major nations in CSiPVCs patent

Nation	Patent application	Average citation	Average family size	% of international patent	% of core patent
China	1928	0.05	1.23	2.1	0
Japan	1726	2.98	2.24	24.0	32.4
Korea	614	0.45	2.63	17.8	1.0
United States	493	12.67	7.28	49.7	53.9
Germany	294	4.68	4.21	63.6	9.8

4. Discussion and conclusion

This paper carries out a comparative analysis of the technological routes and national specialization of CSiPVCs, which enables us to gain an understanding of the integrated pattern of the evolution in CSiPVCs. Based on the study, we find that six sub-fields of CSiPVCs are developing helically and are mutually promoted from a global perspective. The United Kingdom and United States are technology pioneers whose technological evolution traces back to the 1950s, whereas China and Korea are rapid followers whose patent counts have been escalating fast in recent years. Apart from the advantage of the absolute number of patent applications, China's current situation is not favorable. The low quality of patents and a desperate shortage of core patents trap China into an embarrassing situation where its enterprises import costly technology, high-technology equipment, and production lines, and then sell their low value-added products back into developed countries.

The market and technological development of China's CSiPVCs have been isolated. China has been world's largest country in solar cell production and export, with over 90% of its market in western countries since 2007. In 2012, however, China's solar cell producers faced broad and extensive anti-dumping and anti-subsidy probes from the United States, Europe and even India. From another aspect, almost 98% of Chinese patents are filed domestically and China holds none of the core patents in CSiPVCs (Table 1). To some extent, the motivations of Chinese innovators to apply for patents are different from the motivations of innovators from developed nations. This complicated situation is broadly believed to be related to regional governments' innovation policies, and particularly their patent subsidies.

The gap between China and developed countries are large not only in entry time, but also in innovation competence. Other than intensive efforts to expand domestic markets and to adjust the nation's industrial structure, the Chinese government should begin to re-emphasize long-term basic research input. Market forces should be respected and it is the enterprises outside of the government that should be the leading actors of solar cells innovation.

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Biographic

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