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Drifting towards innovation: The co-evolution of patent networks, policy, and institutions in China's solar photovoltaics industry

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ABSTRACT

Since 2008, China has become the dominant force in solar cell production in the world. But what about technological development and innovation? This paper contributes to a better understanding of the accumulation process of indigenous innovation capabilities in emerging economies. It empirically analyses the case of photovoltaic (PV) technologies in China between 1988 and 2014 using patent indicators with a comprehensive definition of the entire system value chain. The contribution tracks the technological catching-up trajectory of the PV innovators in China and their collaboration networks against institutional milestones of industrial policy. Theoretically, the research draws on the concepts of innovation capabilities and technological systems. Methodologically, the paper uses patent indicators and network analysis to study patent co-application activities. The analysis shows a gap between China's share in the global PV market and its modest share of transnational patents. However, it gives evidence for a gradual technological catching-up in the 1G cell technologies, solar panels, and electronics. This catching-up is being driven by an increasing population of Chinese patent applicants clustered in isolated communities. The role of foreign actors in the co-patenting activities is surprisingly low and decreasing.

1. Introduction

This paper contributes to a better understanding of catching-up processes and economic development in emerging economies by studying the case of solar photovoltaics (PV) in China. Considering that China is a late-comer innovator in the PV industry, the paper applies patent and network analysis to shed light on the technological path underlying China's industrial development and the accumulation process of domestic innovation capabilities in the field.

There is strong evidence of the intensive research and development (R&D) efforts taking place in China in the last decades. China's technological development can be tracked empirically from both sides: input and output. On the one hand, Chinese spending in R&D has been growing rapidly since the beginning of the third millennium [1]. R&D as a share of GDP increased from 1.4% in 2007 to 2.05% in 2014, reaching almost the OECD level (2.38% in 2014) and well beyond the share reached in the European Union (1.9% in 2014). On the other hand, patent and trademark data suggest that China is gradually becoming an important player in the global landscape of innovation [2].

Science, technology and innovation studies have largely acknowledged that processes of technological change in countries are shaped by sector/technology specific institutions unfolding in particular cycles, trends and industry dynamics that cannot be explained exclusively by national forces [3–5]. From this perspective, our understanding of catching-up processes in China can very much benefit from the study of technological development in a specific field.

The development, production, and use of solar PV technology for generating electricity is growing rapidly all over the world [6]. Technology development and diffusion in terms of increasing production volumes, cells efficiencies, and installed capacities of PV power plants are taking place in developed and developing countries, where China has gradually become an important player [6,7]. In 2003, China's share in PV global production was less than 1%, however, it rapidly built up its capabilities to become the dominant force in solar cell manufacturing in the world in 2008 [8]. In 2013, China accounted for 60% of the global PV cell production [9] having more than 500 solar PV firms [8]. Together with the increasing activities in manufacturing crystalline silicon (c-Si) PV cells, there is evidence that China has gradually accumulated indigenous capabilities in advanced technologies in upstream segments of the industry [10–14].

Against this rapid growth of China's share in the global PV market, we examine whether a similar trend can be found in technological

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development and innovation. Using patent indicators, the paper analyses the Chinese innovation capabilities in PV technologies over the period 1988–2014. It further identifies the main actors in the field and the technological knowledge networks they are embedded in. More specifically the paper aims at answering the following research questions:

- To which extent is China accumulating innovation capabilities in PV technologies?
- Which technological catching-up trajectory has China followed in the PV sector?
- Which has been the role of local and foreign actors in this process?
- How have the underlying technological networks evolved over time?

The paper is structured in six sections. The next section summarises the state of the art in research studying the development of the Chinese PV industry. The conceptual framework guiding the empirical analysis of the paper is presented in Section 3. In Section 4, we introduce the data sources, methods, and indicators used. The empirical analysis of China's position in the global PV technology landscape, China's technological catching-up trajectory, and the underlying technological networks are presented in Section 5. We conclude in Section 6 by discussing the main results.

It is worth mentioning that the paper is highly descriptive. It uses patent and network analysis to delve into the Chinese PV innovation system with great technical detail. Patent and network indicators map the main actors driving technological catching-up along with their interactions.

2. Literature review

The rapid development of the PV industry in China makes the Chinese case especially interesting for studying processes of technological change in catching-up economies.

Huang et al. [15] apply history event analysis to describe the Chinese success. They identify four phases of PV industrial development between 1985 and 2012. First, modest industrial activities in the manufacturing and use of PV systems in China occurred in the context of the socialist economy during 1985–1996. At this stage, PV products were not been used for civil applications [14]. With the encouragement of private entrepreneurial activities in the PV field, industrial activities scaled up. Foreign turnkey production lines as well as manufacturing equipment for solar cells were acquired by a few Chinese firms. In the period 1997–2003 this foreign technological acquisition triggered a learning process supported by continuous interaction between foreign PV producers and Chinese actors [15, p. 782]. The entrance of China in the World Trade Organization in 2001 opened the Chinese economy with strong stimulating effects for PV manufacturing. Interactions with the global PV value chain favoured the acquisition and use of foreign technologies with important learning effects for Chinese actors. Because of China's late entrance, well-working turnkey production lines were available that enabled learning effects from technology adoption [15,13]. At the same time, policy targeted the development of PV technology from 2001 onwards, including it in national plans and in specific research programs. Foreign projects and domestic capital triggered the development of the industry as the influence of global forces continued to shape the Chinese PV industry. Between 2004 and 2008 the industry benefited from the increasing European demand as well as from the strong support of the Chinese government. The increasing global demand for PV originated a shortage in key raw materials for cell manufacturing (high purity polycrystalline silicon) increasing the prices considerably in 2004. Demand and price developments triggered further entrepreneurial activities. Most importantly, the global market brought up additional incentives for Chinese PV cell manufactures to improve their technologies in polycrystalline silicon-manufacturing [16,15,13]. At this stage, "it seems that the development of the competence in PV machinery design and manufacturing did not come from technology import, but from the R&D development of the Chinese machinery manufacturers" [15, p. 783]. Although Chinese PV machinery was still lagging behind the advanced level of international machinery and the value chain was still dependent on imported technology, Chinese actors were able to develop technological competencies becoming strong competitors in the global market [13, p. 201, 15, p. 785]. The industrial and technological dynamic observed in the supply of PV cell manufacturing, (especially in c-Si cell machinery), was not accompanied by increases in the domestic demand which developed very slowly making the Chinese PV industry fully export oriented. The last period discussed in the literature (2009–2012) has been characterized by the overcapacity of the domestic supply, the strong domestic competition (obstructing research and development activities and experimentation) and the slowdown of the global demand for PV. This situation forced the Chinese government to implement several measures to promote the domestic market including a feed-in tariff (FIT) for PV generation established in 2011 [16]. Scholars view the weak domestic market for PV and the lack of market supervision as important obstacles for the further development of the Chinese PV industry [13,15].

Researchers have studied this development to identify the main factors influencing the rapid industrialization of the PV sector in China. The role of policy has been an important research focus. Even though the industry starts developing before the explicit engagement of the Chinese government in the sector, the government has modified the legal framework, introduced market incentives and implemented industrial and research policy instruments explicitly targeting the development of the PV industry [17–20].

Interestingly, research suggests that policy regimes in developed economies have largely influenced the Chinese experience as well [21,11]. Quitzow [21] studies the interactions between the Chinese and the German technological innovation systems at the national level and the reciprocal influences via transnational linkages. Iizuka [11] stresses how the industrial and technological paths in leading economies can influence the industrialization of the PV sector in a latecomer economy. In the case of Chinese PV industry, the influence occurred on the one hand through international trade and, on the other hand, through the impact of the policy implemented in Europe (large subsidies such as FITs). Policy instruments for technology deployment in developed countries opened up market opportunities for Chinese manufacturers promoting exports and the formation of the Chinese PV industry.

In what concerns technological catching-up and innovation, a number of contributions have studied the technological path underlying the Chinese PV industrial development using different empirical approaches such as export data, field interviews, and company case studies [22,12–14] Only de la Tour et al. [22] use patent indicators for the period 1997–2007.[1] All these contributions take a supply chain perspective to explore technological activities in the process of developing, assembling, installing and running a PV system for power generation. Upstream, midstream and downstream segments of the supply chain are considered.[2] However, the exact definition of the supply chain and the level of detail varies largely across the contributions. In general terms, the main limitation of these studies is the narrow definition of PV systems solely considering c-Si cells and modules.[3]

[1] de la Tour et al. [22] count patent families where patents have been granted in the US and in China.

[2] Two core technologies are considered: "polysilicon technology" to prepare the key raw material for cell manufacturing (upstream segment), and "solar cell technology", which includes the production and assembly of PV cells into modules (midstream). Modules are then used in PV systems (downstream).

[3] A broader definition, including other technological families of PV cells as well as Balance of Systems (BoS) components for system integration is not considered in the literature.