Universität Bremen*

Exploring the Technological Innovation System of Solar Photovoltaics in China

FORGING AHEAD

Technology Development & Emerging Economies

with CD-ROM

Mahmood H. Shubbak

Forging Ahead

Against the pressing challenge of climate change, solar photovoltaics technology is widely considered as a clean and renewable alternative to fossil fuels. Landscaping the development of solar technology worldwide, the case of China is prominent, as the country experienced a successful catching-up and a dramatic growth in production, deployment, and development of solar modules over the past few years.

This dissertation takes you on a magic carpet ride through the technological innovation system of solar photovoltaics in China.

Through the pages of this book, you will be introduced to the technical components of the solar technology. You will track the development stages of the innovation system in China. You will meet the main actors in the system, get to know their capabilities, specialization profiles, and interactions. Additionally, you will see how their knowledge networks evolve over time. The dissertation further tells the story of political economy, solar wars, and the role of governmental policies in shaping the present status of the global technological system.

Throughout the dynamic development of the technological innovation system, its elements can be seen as interconnected gears, whose mechanism and final function is investigated here in order to understand their contribution in protecting the environment and achieving the welfare of humanity.

Quotations from paper reviews:

"I felt the paper is likely to be of significant interest to readers of Research Policy, given its relevance for renewable energy and climate policy, China's role in the global economy and in decarbonisation more broadly, and in meeting the Paris goals on climate. It is an insightful and useful paper that gets at some of the right questions, indeed centrally important questions… that would mean there is a great significance to the paper's contribution, as it will be a more definitive take than most, and an original angle, and it is also written more clearly… than most papers on this subject. Its contextual sections and literature reviews are robust."

"This paper provides a comprehensive appraisal of the evolution of the Chinese technological system of production and innovation in the field of PV technologies. This appraisal is based on a very thorough research and the authors are able to present also several interesting trends of evolution using also quantitative data, on installations, patents, market performance of major firms"

Anonymous reviewers of Research Policy

"The empirical part is very well executed and explained. The graphs and figures are of very high quality."

"The paper has an interesting empirical setting and analysis."

Anonymous reviewers of IJTLID

"The strength of this paper is that authors provide a lot of information about solar firms and Chinese solar PV industry, and provide a lot of interesting phenomena that directly come from their data analysis"

"the message of the paper is very clear with ample data"

"I particularly liked the part linking the policy to the result of analysis divided by the period. It gives another perspective of evidence on technological upgrading using patent data."

Anonymous reviewers of ERSS

For more info, visit the book webpage: www.shubbakom.wordpress.com/f_ahead

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Forging Ahead:

Technology Development and Emerging Economies

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LIST OF ABBREVIATIONS

1G	First generation technology
2G	Second generation technology
3G	Third generation technology
AC	Alternating Current
AD	anti-dumping duties
ANOVA	Analysis of Variance
a-Si	amorphous Silicon
BoS	Balance of System Components
BP	British Petroleum
BvD	Bureau van Dijk
CAFI	Chinese Applicants of Foreign Inventions
CAS	Chinese Academy of Sciences
CdS	Cadmium sulfide
CdTe	Cadmium telluride thin-film cells
CIGS	Copper Indium Gallium Selenide thin-film cells
c-Si	Crystalline Silicon
CVD	Anti-subsidy duties (Countervailing duties)
CVD	Chemical Vapour Deposition
DC	Direct Current
DGC	Duolun Golden Concord (mining company)
DOC	US Commerce Department
DSSC	Dye-Sensitized Solar Cells
DUI	Doing, Using and Interacting
ECLA	European Classification System
EPO	European Patent Office
EU	European Union
FACI	Foreign Applicats of Chinese Inventions
FDI	Foreign direct investment
FIT	Feed-in tariffs
FYP	Five-year plan
GaAs	Gallium Arsenide
GDP	Gross Domestic Product
HIT	Heterojunction with Intrinsic Thin layer
HVE	High Vacuum Evaporation
HWCVD	Hot-Wire CVD
IGI	IPC Green Inventory
INNO	Innovation-Capability Clusters
IPC	International Patent Classification
IPO	Initial Public Offering
IPR	Intellectual property rights
LEC	Liquid Encapsulated Czochralski growth process
M&A	Mergers and acquisition deals
MANOVA	Multivariate Analysis of Variance
MDI	Methylene diphenyl diisocyanate
MOCVD	Metalorganic CVD
MPPT	Maximum Power Point Tracking
NCIP	Net charges for using intellectual property
NET	Network-Embeddedness Clusters
NREL	National Renewable Energy Laboratory (US)
NSI	National System of Innovation
OECD	Organisation for Economic Co-operation and Development
PATSTAT	Worldwide Patent Statistical Database
PCT	Patent Cooperation Treaty
PECVD	Plasma Enhanced CVD
PV	Photovoltaics
R&D	Research and development
RTA	Revealed Technology Advantage
SGCC	State Grid Corp China
SiO_2	Silicon dioxide (quartz sand)
STI	Science, Technology and Innovation
TIS	Technological Innovation System
US	United States of America
USPC	United States Patent Classification System
VGF	Vertical Gradient Freeze
WIPO	World Intellectual Property Organization
η	Cell efficiency

Forging Ahead: Technology Development & Emerging Economies

Chapter 1

ABSTRACT

The present dissertation is motivated by the vital role that solar photovoltaics can play as a clean renewable energy source against the pressing challenges of climate change and depletion of fossil fuels. It introduces a comprehensive analysis of the technological innovation system of photovoltaics highlighting the prominent catching-up case of China in that sector. This introductory chapter presents the broader context, theoretical framework, analytical levels, and correlations between the cumulative papers of the thesis. Accordingly, the chapter comprises three main parts. First, the research background and motivation are introduced. Second, the conceptual framework of innovation systems and catching-up processes is presented along with some challenges to innovation studies that the thesis is attempting to meet. Finally, the third part of the chapter summarizes the cumulative research papers of the thesis against four analytical levels: techno, micro, meso, and macro levels. The introductory chapter closes by drawing overall conclusions and giving an outlook of the further development in the technological system of innovation under consideration.

KEYWORDS

Innovation System; Catching-up; Solar Photovoltaics Technology; Energy; Sustainable Development

AUTHORSHIP & PUBLICATION

This chapter is single authored by Mahmood H. Shubbak as the introductory paper of a cumulative thesis submitted to the Doctoral Commission of the University of Bremen in fulfilment of the requirements for a Dr. rer. pol. degree.

1. INTRODUCTION

The United Nations' millennium project has considered climate change as the first among other fifteen major challenges of the world (Glenn & Florescu, 2015). In fact, the global average temperature has increased by more than 0.9°C over the last century, for which, CO_2 emissions resulted from fossil fuel combustion are considered among the main causes (NRC, 2010; NASA, 2018a). The continuous trend of global warming is predicted to result in serious environmental and economic consequences on the precipitation rates, number of growing crops, drought periods, heat waves, ice melting, rivers flow rates, and even the size of burned areas by wildfire (Melillo, et al., 2014; Kraaijenbrink, et al., 2017; Figueres, et al., 2017).

Additionally, the scarcity of the conventional energy sources against a fast growing trend in the global demand constitutes another challenge. While fossil fuels currently account for more than 85% of the global primary energy, their depletion is predicted within the next few decades (Dorian, et al., 2006; British Petroleum, 2017). This can result in serious consequences not only on the economic growth rates of developed and developing countries, but also on international trade, consumption, transportation, and even the current socio-economic system of human civilization, unless a successful transition into efficient alternative sources of energy takes place.

To meet these challenges, renewable energy sources[1] are widely considered as clean and sustainable alternatives to carbon-based fossil fuels. Nonetheless, the differences in economic feasibility between both types (in terms of initial capital investment and cost per megawatt-hour) have long constituted a key obstacle for renewable sources to become major means of generating electricity at the global level (Holdren, 2006). On the other hand, three parallel paths could interactively lead to the grid parity: – first, product and process innovations in the field of renewables, second, mass production and vertical integration, and third, government subsidies for both supply and demand sides (Lund, 2007; Ellabban, et al., 2014). While the latter two paths concern with reducing the manufacturing and operational costs, the former is more associated with increasing power conversion efficiency.

Among the wide range of existing renewable energy sources, solar photovoltaics technology (PV) is considered the cleanest, safest, and most widely available (Hegedus & Luque, 2010). Although its physical principle, i.e. the photovoltaic effect, was discovered in the late nineteenth century, it is only recently, during the past decades, that the technology has experienced a dramatic growth in both development and deployment on a global scale (Brown, et al., 2015; Jäger-Waldau, 2013; NREL, 2017).

Reviewing the worldwide landscape of PV technology, the case of China is prominent, as the country has achieved a rapid growth in both production and installation capacities of PV modules over the past few years (de la Tour, et al., 2011; Brown, et al., 2015). Against this fact, and being inspired by the importance of innovative activities, subsidizing policies and mass-production processes in enhancing the stature of PV technologies in the global energy

[1] Renewable energy sources include hydropower, biomass, geothermal power, wind, and solar energy (both thermal and photovoltaic).

setting, this dissertation comprehensively studies the technological innovation system (TIS) of PV in China. It aims at understanding the trajectories and circumstances, under which China as an emerging economy was able to accumulate indigenous capabilities, catch-up, and forge ahead in this high-tech field. Furthermore, it attempts to look into the prospect of this technological system from both economic and technical perspectives.

Being in the form of a cumulative thesis, this dissertation comprises four scientific articles along with this introductory chapter. The contribution of this dissertation is fourfold: First, it provides a comprehensive technical definition of PV technologies enabling for the accurate and direct identification of their patents. Second, it investigates all the building blocks of the PV innovation system and their dynamic development in detail. Third, it uniquely identifies the patterns of innovative activities and network embeddedness within the system. Fourth, it expands the TIS concept by introducing two additional elements: the system firmodynamics, and the environment.

This chapter is organized in five sections. The next section introduces the research background and motivation of the dissertation. Section 3 presents the conceptual framework of innovation systems that forms the common theme guiding the empirical analysis of the thesis articles. It further reviews the literature on innovation, technology transfer, and catching-up processes. In section 4, the articles and the correlation between their research contexts are discussed. Finally, section 5 synthesises the main findings, draws conclusions, and gives a future outlook.

2. RESEARCH BACKGROUND & MOTIVATION

In this section, the broad backdrop, motivation, and research focus of the dissertation is considered in more detail. Accordingly, the section presents some empirical evidence on the global energy challenges and consequences; it introduces the solar PV technologies, highlights the potential vital role they can play in meeting these challenges, as well as the notable case of China in the PV sector.

2.1 Climate Change and Energy Challenges

Since the industrial revolution in the eighteenth century, the reliance on fossil fuel as the main energy source has grown dramatically. Coal formed the main fuel during the 19th century. It reached its historical peak in terms of production share in 1910 with more than 75% (National Research Council, 2006). Since then, a second wave within the energy industry has evolved with petroleum as the main source. Nowadays, fossil fuels such as coal, crude oil, and natural gas account for 85.5% of the global energy market (table 1).

Fossil fuels are chemically classified as hydrocarbons (organic compounds entirely consisting of Hydrogen and Carbon), which can react with oxygen molecules (O_2) under high temperature to release higher energy, water vapour (H_2O), and carbon dioxide (CO_2). Such exothermic process is mainly driven by the fact that the bond enthalpy summation of the oxygen and fuel reactants is less than that of the water and CO_2 products. Which yields more energy generated from forming the new bonds than the needed energy for breaking the old ones (Schmidt-Rohr, 2015).

One of the most important features of fossil fuels is their high energy density, where relatively large amount of energy can be stored per unit mass and volume (see table 1). Such characteristic makes them the optimal choice when considering transportation purposes. However, the main drawback of the conventional energy sources lies in the combustion output. CO_2 and H_2O vapour are radiatively active gases that can absorb radiant energy and re-emit it in all directions with thermal infrared wavelengths in a process called the greenhouse effect. While the greenhouse effect is vital for life on Earth through increasing the average temperature of its surface into 15 ºC (instead of -18 ºC) (Ma, 1998), high concentrations of the greenhouse gases in the atmosphere can result in abnormal global warming and climate change.

Table 1: Comparison between fossil fuels and solar PV technology

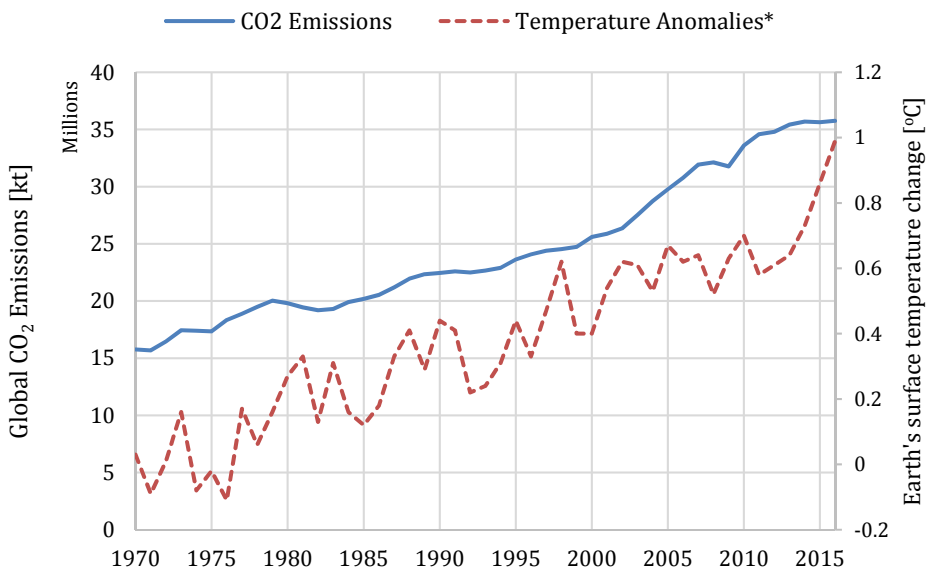
	COAL	OIL	GAS	PV
Share in Energy Consumption (in 2016) [a]	28.1%	33.3%	24.1%	0.6%
Proved Reserves (in 2016) [a]	1139 [Billion tons]	1706 [Billion barrels]	186.6 [Trillion m^3]	Renewable
Annual Extraction (in 2016) [a]	20.4 [Million tons/day]	92.2 [Million barrels/day]	9.7 [Billion m^3]	
Consumption Growth (per annum 2005-2015) [a]	1.9%	1.2%	2.3%	
Lasting for [years] [b]	71.4	38.9	33.9	~1 Billion [2]
Levelized Cost [$/MWh] in 2017 [c]	60-143	42-78	68-106	46-194 [g]
Price Growth (avg. per annum 2005-2015) [d]	4.7%	4.9%	7.8%	-17%
Energy Density [kWh] [e]	8.14 [per 1 kg]	11.63 [per 1 kg]	8.82 [per 1 m^3]	0.66 [daily per 1 m^2]
Lifecycle CO_2 Emissions [g/kWh] [f]	1000	778	443	40

[a]. Data source: (British Petroleum, 2017). [b]. estimated based on the proved reserves, annual extraction and consumption growth rates. [c]. Data source: (Lazard, 2017). [d]. Data compiled from (IRENA, 2018; British Petroleum, 2017), price growth $2016 (deflated using the Consumer Price Index for the US). [e]. Data source: (Mertens, 2014, p. 6), energy density for PV is calculated assuming annual irradiation of 2000kW/m^2.yr, and 12% overall efficiency of the PV system. [f]. Data compiled from (Alsema & de Wild-Scholten, 2006; Sovacool, 2008). [g]. The cost range is combined of utility-scale and commercial rooftop Crystalline-Silicon PV technologies. Author's own elaboration.

[2] Although the Sun still has 5 Billion years of age until it explodes, a runaway greenhouse state on planet Earth is expected within 1 Billion years (Leconte, et al., 2013).

To check this phenomenon, the trends of global CO_2 emissions are plotted against the changes in the average temperature of Earth's surface over the past 45 years (figure 1). While both indicators have experienced a continuous growth, the figure further shows a strong correlation between them. Furthermore, the data reveals a long-term global warming trend. In the last few years, the Earth's temperature went 0.9 ºC above the baseline average of 1951-1980. Although the amount of one degree Celsius might sound very tiny, the severity of the situation can be understood when imagining the huge amount of heat needed to warm up all the oceans, land, and atmosphere. Throughout the geological history of our planet, small changes in its temperature resulted in enormous changes in the global environment. For instance, it took only 5 ºC drop in Earth's temperature to enter the latest ice age 20,000 years ago (Carlowicz, 2010).

Figure 1: Global Warming and CO_2 Emissions



* Figures for temperature anomalies are given in secondary axis.
Data sources: **CO_2 emissions:** Emission Database for Global Atmospheric Research (EDGAR) release version 4.3.2. European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. **Earth temperature anomalies:** (NASA, 2018a; Hansen, et al., 2010).
Author's own elaboration

Currently, several vital signs of climate change are more observable (NASA, 2018b). Besides the increase in the global temperatures, a notable shrinkage in the Arctic sea ice with a rate of 13.2% per decade, as well as huge mass losses in the polar ice of about 127 and 286 Gigatonnes per year are registered in Antarctica and Greenland respectively. This obviously led to 17.8 cm rise of the global sea level over the past century. What makes the situation even worse is the fact that ice (covering 10% of Earth's surface) plays an important role in reflecting large portions of sunlight into space. Accordingly, ice melting can indirectly contribute in the global warming via a feedback effect. The continuous global warming is

predicted to result in further consequences on precipitation, environment, agriculture, biogeochemical cycles, and Earth's biosphere. This can seriously threaten the life on Earth (Vitousek, et al., 1997).

On the other hand, owing to the high consumption rates of the limited fossil fuel reserves, another serious challenge regarding global energy is leaning out. As shown in table 1, the proved reserves of coal can last 71 more years. The depletion of crude oil and natural gas is expected to take place even earlier (within 39 and 34 years respectively). Being the lifeblood of the current global economy, international trade, transportation, electricity, and petrochemical industry, the depletion of fossil fuel can drastically change the structure of the entire socio-economic system. It can lead into deep economic depression and reverse migration from cities to rural areas (Flinn, 2015). It nonetheless ushers in a mandatory standstill period of CO_2 emissions.

Eventually, both challenges, climate change and fossil fuel depletion, threaten the current human civilization in different ways. Despite being positively interrelated in causes, their consequences can be contradictory and even self-compensating. While climate change is an existential danger that might put an end to life on this planet, the depletion of fossil fuel, on the other hand, can put an end to global warming but also to the global economic system and its corresponding lifestyle. An efficient energy transition into clean and sustainable sources can maintain both the environmental and economic systems.

2.2 Solar Photovoltaic Technology

The fundamental problems with fossil fuel are caused by its high CO_2 emissions as well as its scarcity. Solar energy, on the other hand, is totally clean and renewable. The sun has been there billion years ago, and is expected to stay for at least one billion years more (Leconte, et al., 2013). Furthermore, the lifecycle greenhouse gas emissions of solar PV technology are around 40 grams of CO_2 per kWh compared to 443-1000 g/kWh for fossil fuels (Alsema & de Wild-Scholten, 2006; Sovacool, 2008).

Considering table 1, the advantages of PV technology over the conventional carbon-based energy sources are obvious in terms of availability, sustainability, and greenhouse emissions. Despite its slightly higher levelized cost per unit energy (especially for residential rooftop applications), the overall price of PV systems is declining with an average annual rate of 17% (table 1). On the other hand, the energy density of PV panels is far less than that of fossil fuel. As shown in table 1, the daily energy content of $1m^2$ crystalline-silicon PV system is around 0.66 kWh.[3] This highlights the need for more efficient cell technologies, large areas of panel covering, as well as efficient energy storage systems for PV to be competitive in the global energy market. (The information box below introduces the working principle of solar PV cells).

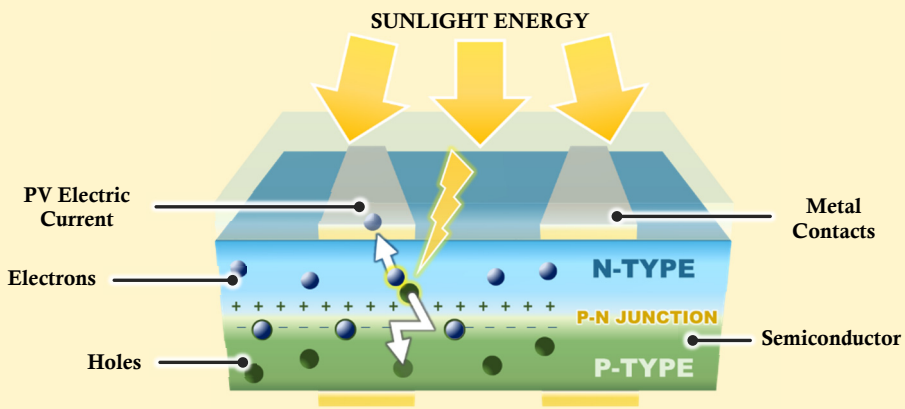
[3] To understand this value better, let us compare it with the case of car consumption of petrol. With fuel consumption of about 10 km/litre and average speed of 60 km/h, the energy of one-kilogram petrol (11.6 kWh) is enough to travel for ten minutes.

Information Box: How Photovoltaics work?

Solar PV cells are defined as electrical devices that are capable of directly converting the sunlight energy into electricity. This is achieved through a physical/chemical phenomenon called 'the photovoltaic effect'. A PV cell is generally built of semiconducting material such as Silicon. The electrical conductivity properties of semiconductors are intermediate between conductors (metals) and insulators. Based on quantum mechanics, the electrical conductivity of a material is directly related to its atomic number (number of protons or electrons in each atom) and the distribution of these electrons. Electrons can be found in discrete levels (or bands) of energy. While the electrons of a conducting material are shared by all atoms and thus free to move and form electric current, insulator electrons are tightly connected to their atoms. In semiconductors, electrons susceptible to enough external energy can leave their bands into higher energy levels gaining more freedom of movement across the material. Accordingly, two energy bands can be determined: the valence band (electrons tightly bonded to the atom), and the conduction band (electrons freely move). The material bandgap is defined as the energy difference between these two bands; it is equivalent to the external energy needed to free electrons out of their atoms.

Light consists of packets of energy called 'photons'. When photons with energy exceeding a material's bandgap hit its electrons, it can free them out of their atoms. However, without an external electric field, the photo-excited electrons will sink again into their valence bands. Here comes the role of PN-junctions. In a semiconducting silicon, atoms are ordered in a crystalline structure where each silicon atom (with 4 electrons in its outer shell) is bonded with four surrounding atoms. If the material is doped with impurity atoms with 3 electrons in their outer shells (e.g. Boron), positive charge carriers called 'holes' are formed. The resulting material is called positive type semiconductor (P-type). Similarly, a negative (N-type) semiconductor is obtained via doping silicon with impurities with 5 valence electrons (e.g. Phosphorus). As shown in figure 2, When P- and N-type semiconductors are put together, part of their respective holes and electrons can bond together creating an internal electric field within a free of charge-carrier region. The resulting structure is called 'PN-junction'.

Figure 2: The Physics of Photovoltaic Effect



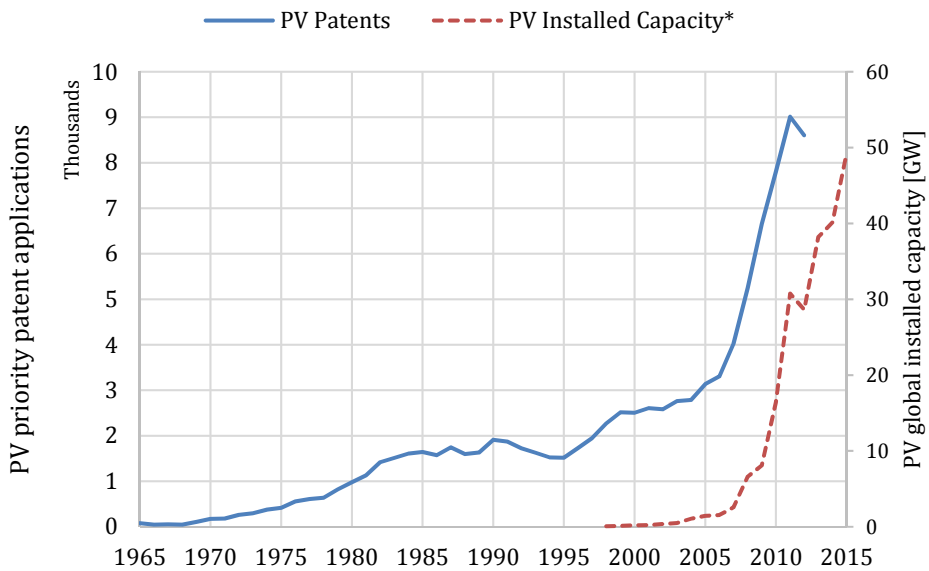
Author's own elaboration

Having the internal electric field of the PN-junction, the photo-excited electrons can now be forced to move into a specific direction forming electric current.

Therefore, when a sufficient light strikes the semiconductor material, it can free electrons and holes. Under the influence of the PN-junction electric field, electrons will be pumped towards the N-type, while holes towards the P-type (see figure 2). This forms an electric voltage difference and electric current that can be drawn out of the cell through its metal contacts as generated electricity.

Given the advantages of PV technology against the climate change and energy challenges, it has experienced dramatic growth in production, deployment, and development over the past decades. Figure 3 shows the trends of its patent applications and annual installed capacity since 1965. Two waves of growth in both indicators can be noted: first, during 1995-2005; and second, with sharp exponential growth since 2005. Solar PV systems are currently accounted for 0.6% of the global primary energy with more than 300 GWp cumulative installations worldwide. Throughout this thesis, the driving and facilitating factors behind this growth are discussed along with the technical, geographical, and organisational trends.

Figure 3: The Development Trends of PV Technology



Data sources: **Patents:** PATSTAT 2016b, priority filings defined using (de Rassenfosse, et al., 2013), PV related patents identified based on (Shubbak, 2017a). **PV installed capacity:** (British Petroleum, 2017; Brown, et al., 2015). Author's own elaboration

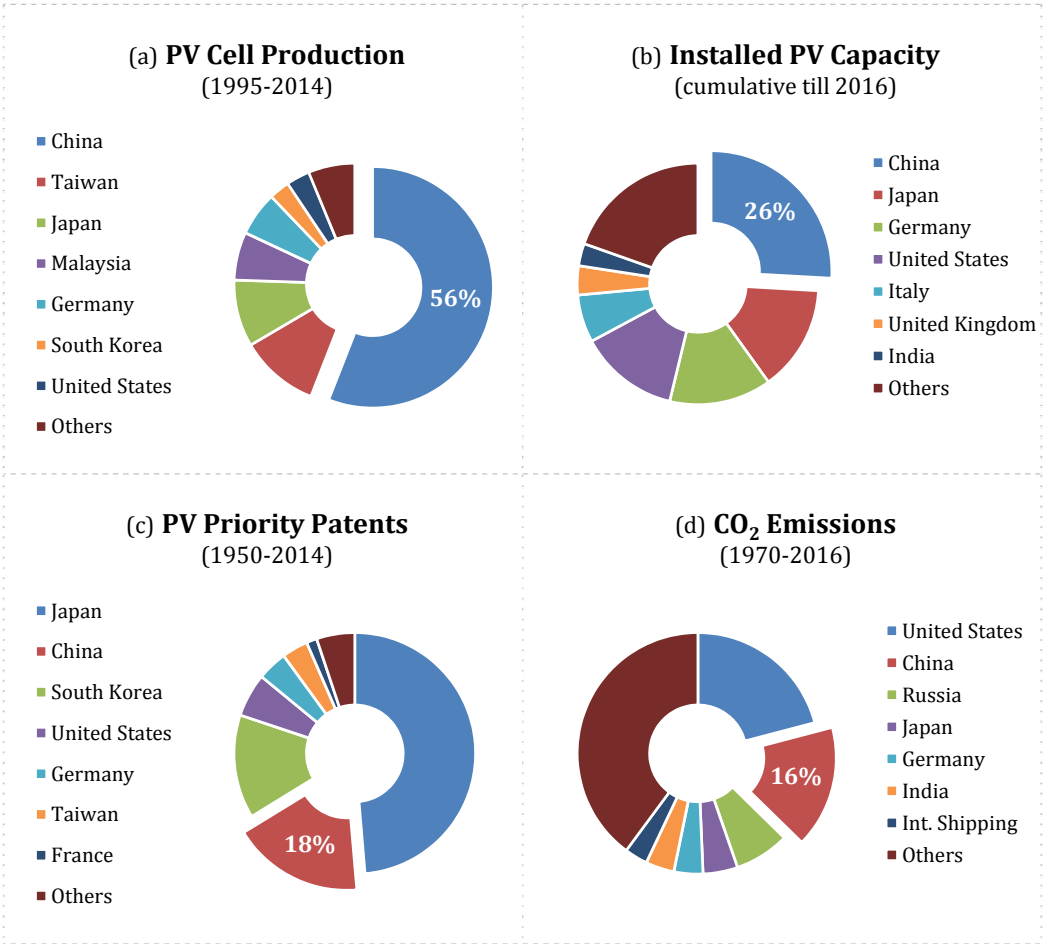
2.3 The Case of China

Considering the global landscape of PV, China has recently become an important player in both production and deployment of crystalline-silicon modules (UNEP, et al., 2010; Marigo, 2007). In 2008, it became the dominant force in PV production, controlling one-third of the

global market (Fu, 2015). Later, since 2011, its market share has stabilized at the level of 60% (Jäger-Waldau, 2013). Furthermore, the country has experienced an exponential growth in terms of cumulative installed PV power since 2011, becoming the world's leader since 2015 with more than 43 GW, and reaching the level of 130 GW in early 2018 (British Petroleum, 2017; China Energy Portal, 2018).

To better understand the prominent position of China in the global PV landscape, figure 4 shows the country's share in the accumulated production, installation, patenting, as well as CO_2 emissions over the past decades. China is the second producer of CO_2 in the world with a share of 16% of the accumulated emissions over 1970-2016 (figure 4d).

Figure 4: The Position of China in the Global PV Landscape



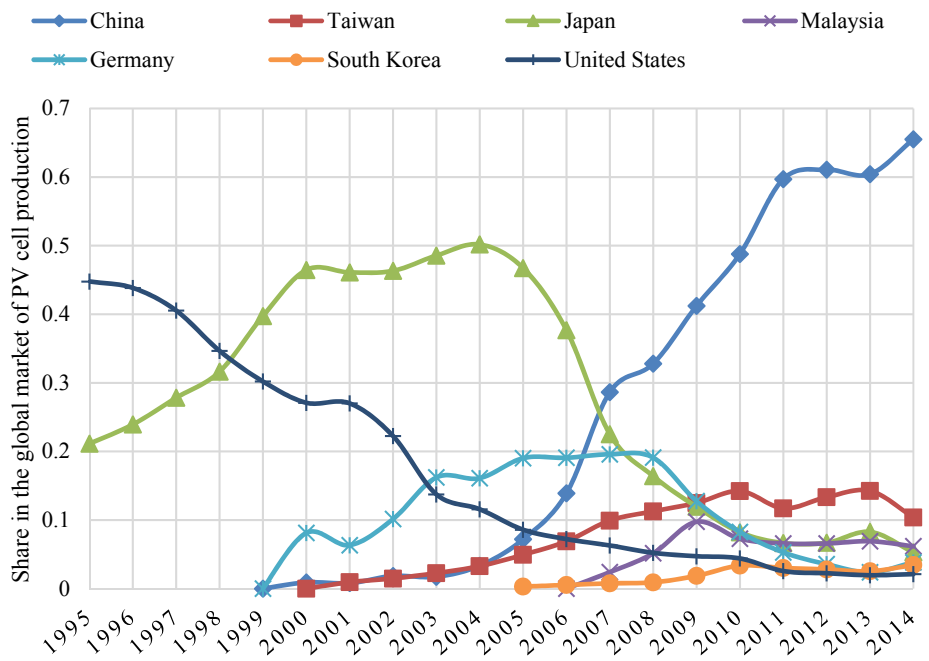
Data Sources: a: (Brown, et al., 2015; Mints, 2014), b: (British Petroleum, 2017), c: PATSTAT 2016b; (Shubbak, 2017a), d: EDGAR version 4.3.2. Author's own elaboration

Considering the market supply side during 1995-2014, Chinese companies accounted for 56% of the global production of PV cells and modules. This makes China the top producer

of the technology worldwide (figure 4a). Regarding the demand side of the global PV market, China is also the top country in terms of cumulative installed capacity with a share of 26% (figure 4b). The high shares in supply and demand were also accompanied by a growing stock of patent applications. Figure 4c shows that 18% of priority patent applications for PV inventions during 1950-2014 were filed by Chinese inventors.

The growing share of China in the global PV market came at the expense of the traditional leading countries in the field, i.e. Japan, Germany, and USA. Figure 5 shows the catching-up cycles for PV technology since 1995. While USA used to be the top producer of PV modules, it was overridden by Japan in 1999. The Japanese dominance of the market reached its peak in 2004, before gradually declining against the growth of the German and Asian manufacturers. However, China's catching-up in the field has followed a continuously growing trend since 2005, directly causing a sharp decline in the market shares of the Japanese and German manufacturers.

Figure 5: Catching-up Cycles for PV technology
market share trends of the top producing countries over 1995-2014



Data source: (Brown, et al., 2015). Author's own elaboration

Consequently, the prominent case of China in the PV sector has been the focus of attention by many researchers. Reviewing the literature on the development of PV industry in China, three types of studies can be found. The first group of research articles tracks the sector development over time (Yang, et al., 2003; Wang, et al., 2014; Honghang, et al., 2014; Fu, 2015; Zhang & Gallagher, 2016; Zhang & White, 2016). The second group takes a policy analysis nature (Zhao, et al., 2011; Zhang & He, 2013; Shen, 2017; Gruss & ten Brink, 2016).

On the other hand, the third group comprises comparative studies of the Chinese case with other emerging and developed countries in the field. (Huo, et al., 2011; Wu & Mathews, 2012; Gul, et al., 2016; Binz, et al., 2017).

Trade in goods, movement of skilled employees and inward foreigner direct investment were found as the main channels of technology transfer in the early stages of the PV sector development in China (Zhang & Gallagher, 2016; de la Tour, et al., 2011). Nonetheless, Zou, et al. (2017) diagnosed three main mechanisms blocking further development of the sector. These are poor connectivity in networks, unaligned competitive entities, and the absence of market supervision.

While considerable research on the Chinese PV development already existed, it nonetheless considers single aspects of the process at a time. This leaves a crucial part of the story untold. In other words, the dynamic interrelations between different dimensions, as well as the analysis of innovation, interaction networks, and environmental aspects had not been adequately addressed in the literature, neither is the comprehensive innovation system of the sector. Accordingly, this thesis adopts the innovation systems framework to incorporate the different elements and dimensions of the catching-up and development processes within the Chinese PV sector. More specifically, it attempts to understand the bidirectional interactions between government policy, collaboration networks, competences at firm level, and global market dynamics, along with their influence on innovation and environment.

3. CONCEPTUAL FRAMEWORK

Since the attention of the thesis is centred on the development of a specific technology, namely solar PV, this section lays down the definitions and theoretical foundations of technological change and innovation in economic thought. Technology has long been considered as an elementary production factor in economics (Romer, 1986; Lucas, 1988). Nonetheless, the word technology itself is usually used in different contexts for different meanings[4]. Drawing on the definition of Collins dictionary (1991), technology can be seen as the application of knowledge to industry. It is the methods and techniques used to solve problems and to employ knowledge into the production process. The extent to which technology relies on scientific knowledge varies across technological fields (Meyer-Krahmer & Schmoch, 1998; Pavitt, 1987).

In his theory of economic development, Schumpeter (1934) distinguished between three interrelated stages of technological change, which are (1) *invention* (creating new ideas), (2) *innovation* (developing the ideas into products or processes), and (3) *diffusion* (spreading of the products into markets) (Stoneman, 1995). Schumpeter argued that innovation is the main driving factor of economic growth. Innovation can appear in various forms, such as the introduction of new products or production methods, the opening of new markets, or the creating of new organizational positions (Schumpeter, 1934; Grupp, 1998; Pavitt, 1963).

[4] A comparison between different disciplinary definitions of 'Technology' can be found in (Fleck & Howells, 2001).

From this point onward, innovation studies took two parallel paths (Fagerberg, et al., 2012)[5]. The first path focuses on the innovation phases, organisation, and technology adoption at firm and individual levels (Rogers, 1962; Abernathy & Utterback, 1978; Nelson & Winter, 1982; Cohen & Levinthal, 1990). It is thus considered business- oriented. On the other hand, the second path concerns mainly about technology change, production, and public policy (Rosenberg, 1963; Freeman, 1974; Porter, 1990). Therefore, it is rather economics-oriented.

Being field-oriented, each path, despite having in-depth analysis, was nevertheless unable to capture the full view of innovation processes by its own. Moreover, the connections between both paths were not clear enough, neither were their links to other disciplines. Besides that, they used to represent innovation as a linear process. However, Kline & Rosenberg (1986, p. 275) argued that "*The process of innovation must -instead- be viewed as a series of changes in a complete system not only of hardware, but also of market environment, production facilities and knowledge, and the social contexts of the innovation organization*".

Additionally, innovation cannot be considered exclusively restricted inside firms, it is rather an outcome of interactive processes among networks of various firm- (such as producers, suppliers, and customers) and non-firm entities (such as universities, research centres, financial organisations, and governments) (Edquist, 2005; Günther, 2015). These issues have paved the way for a third theoretical path, which is the systematic perspective on innovation.

3.1. Innovation System Perspective

Freeman (1987) discussed the institutional arrangements that were taken in Japan for promoting innovation processes. He defined the national system of innovation (NSI) of a country as "*the network of institutions in the public and private sectors whose activities and interactions initiate, import, and diffuse new technologies*" (Freeman, 1987, p. 1). Additionally, he compared between Japanese and British systems of innovation in front of various institutional aspects such as political, financial, and industrial policies, as well as education and training. Along the same lines, Lundvall (1992) studied the role of interactive learning within user-producer interactions in the NSI frame. Another important contribution is (Nelson, 1993), where authors discussed the technical innovation and national systems of countries with different income levels.

Among the different definitions of the term 'system' in several disciplines, the biological systems definition seems to be the closest to the system of innovation, as it describes the complex network of related parts or entities interacting to achieve specific functions. Similarly, innovation systems consist of a group of interrelated actors (organisations) that interacts within a specific institutional framework in order to produce or utilize innovations. Accordingly, an innovation system has its own internal activities, such as research and development (R&D), competence building, new products and markets formation, interactive learning, institutions amending, as well as financing (Edquist, 2005).

[5] Fagerberg et al. (2012) present a thorough review about the knowledge base and development of innovation studies.

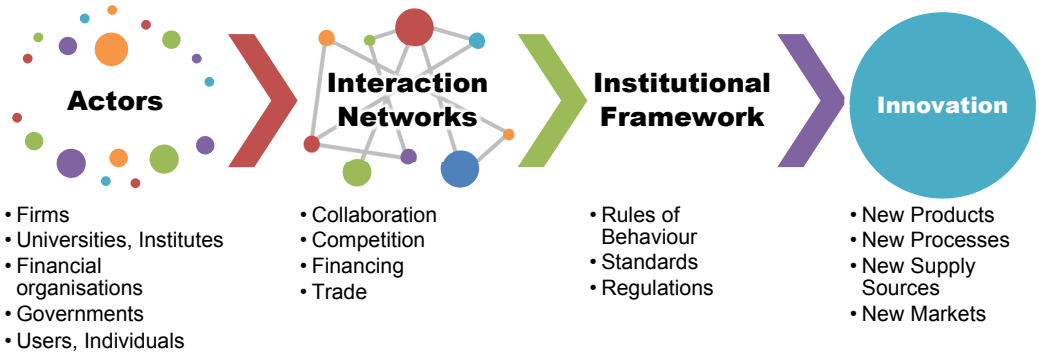
It is thus worth mentioning that the main function of innovation systems as an analytical tool is not to maximize the amount of innovation, but rather to "*understand both how innovation takes place and how it is transformed into macroeconomic performance*" (Lundvall, et al., 2009, pp. 5-6).

Similar to any other system definitions, innovation systems have boundaries that specify their analytical scope. The following main approaches to identify such boundaries of innovation systems can be recognised in literature:

1. Geographical approach, where spatial margins are considered either at the political borders of countries: ***national systems of innovations*** (Freeman, 1987; Lundvall, 1992; Nelson, 1993; Patel & Pavitt, 1994), or within country regions: ***regional systems of innovation*** (Cooke, et al., 1997; Braczyk, et al., 1998).
2. Sectorial approach, in which the system boundaries are drawn between different technologies: ***technological innovation systems*** (Carlsson & Stankiewitz, 1995), or are drawn between different industrial sectors: ***sectoral innovation systems*** (Breschi & Malerba, 1997; McKelvey & Orsenigo, 2001; Malerba & Nelson, 2011).

Whatever type of boundary it could have, an innovation system consists of three main building blocks: actors, interaction networks, and institutional framework (figure 6).

Figure 6: The Building Blocks of Innovation Systems



Author's own elaboration

For this thesis, the sectorial/technological innovation system of solar PV is investigated. The advantages of considering innovation systems as theoretical framework for the thesis relate to its inclusion of all the important factors influencing innovation process (Edquist, 1997), as well as the explicit consideration of learning, catching-up processes and interaction networks among actors. Carlsson & Stankiewicz (1991, p. 111) defined a technological innovation system as a "*network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology*".

3.1.1 Actors

Drawing on (Lundvall, 1992; Nelson, 1993; Edquist, 2005), actors and organisations within innovation systems form the main players that are involved, directly or indirectly, in learning, capability building, R&D, opportunity-making, inventive and innovative activities. Such actors can be firms, which do in-house R&D or outsource external knowledge through licensing and foreign direct investment (FDI) (Amsden & Chu, 2003; Jindra, et al., 2015). Firms are linked vertically with suppliers and users enabling for active upstream and downstream innovative relations (Malerba & Nelson, 2011). Another important group of actors includes universities and public research institutes. Besides their vital role in conducting basic and applied research, they are considered the main source for forming human capital. Financial and venture capital organisations, on the other hand, can provide significant support for entrepreneurship and innovation. Furthermore, government and public units can play an essential role in providing the regulatory platform and fostering innovation through integrated policies and subsidizing programs.

Each actor in an innovation system has its own attributes and characteristics. This includes the size, age, accumulated stock of knowledge, intellectual property, technological specialization, diversified profile, absorptive capacity, as well as economic performance. Such attributes are nevertheless functions of dynamic development, both over time and against interactions with other actors within the system. The understanding of single actors can highly contribute in a better understanding of the entire system that comprises them.

3.1.2 Interaction Networks

A key advantage of using the innovation system perspective as theoretical framework is the fact that innovation systems consider explicitly the interactions and collective processes inherent to technological change (Jacobsson & Johnson, 2000). Networks emerge in innovation systems through the interactions between organizations. The innovation systems perspective gives hence a conceptualization of technological change to study network structures in the technological development of emerging economies.

In economics, networks are considered coordination forms enabling the transfer and/or the share of resources, goods or services between actors (Elsner, et al., 2010). A large body of research focuses on how the organization and structure of networks influence the ability of firms to access external knowledge sources (Nooteboom, 2008).

Accordingly, interactions between several actors within an innovation system can take the form of collaboration, exchange, competition, financing, trade and distribution of products and equipment, licensing activities to use protected intellectual property, or vertical integration and linkages across global value chains.

Recently, an increasing unanimity in the literature has emerged on the significant effect of network embeddedness on innovation and economic performance at firm level (Hagedoorn, 1993; Rowley, et al., 2000; Gilsing, et al., 2008). Tsai (2001) finds that occupying central network positions provide organizations with access to new knowledge developed elsewhere,

which can lead to better innovative and economic performance, if these actors have the necessary absorptive capacity.

3.1.3 Institutional Framework

The third building block of an innovation system is its institutional framework. Institutions include formal sets of written laws, regulations and standards, as well as soft frames of the common habits, cultures, rules, practices, and values that regulate together the relations of an organisation with other actors in the system on the one hand, and the interactions among its internal departments and individuals on the other (Edquist & Johnson, 1997). The institutional setup is thus of central importance for innovation processes.

Institutions can be seen as "*the rules of the game in a society*" (North, 1990, p. 3) or as "*systems of established and prevalent social rules that structure social interactions*" (Hodgson, 2006, p. 2). Accordingly, the institutional framework of an innovation system can "*support, stimulate and regulate the process of innovation and diffusion of technology*" (Carlsson & Stankiewicz, 1991, p. 109).

As one of the core aspects of institutional infrastructure[6], public policy instruments are classified in three types: regulations, economic means, and information (Vedung, 1998). Economic instruments can influence both the supply and demand sides. Moreover, a growing discussion in literature (Borras & Edquist, 2013; Reichardt & Rogge, 2016) concludes that policy mixes are more appropriate to foster innovation than using individual instruments. Furthermore, Malerba & Nelson (2011) argue that government policies can affect economic sectors differently. In the area of renewable energy, public industrial policy has shown a significant influence on technology development in both developed and emerging economies (Johnstone, et al., 2010).

3.1.4 Other Building Blocks

Besides the previously discussed elements of innovation systems, Malerba (2002) identifies four more building blocks of a sectoral innovation system. These are the knowledge base and learning processes, the basic technologies relevant to the system, demand conditions, as well as variety generation and selection processes of technologies, products, firms, and strategies.

Knowledge base and learning processes play an important role in accumulating indigenous capabilities within actors of the innovation system. With different degrees of accessibility, knowledge can be created and transferred through the system interactions. On the other hand, different sets of basic technologies and demand conditions can be identified within each economic sector. They can thus form characteristic profiles for each sectoral system of innovation (Malerba, 2002).

Since the concept of innovation systems is "*associated with an evolutionary theory of economic change*" (Malerba & Nelson, 2011, p. 1649), variety creation, replication, and

[6] A comprehensive discussion and classification of rules and institutions can be found in (Scott, 1995; Geels, 2004).

selection of products, processes, technologies, strategies, organizations, and markets contribute fundamentally to the evolution of sectoral innovation systems.[7]

3.2 Technology Transfer and Catching-up Processes

Not long ago, it was believed that developing countries are able to catch-up by simply adopting a paradigm of 'liberalization, privatization and deregulation', however, this proved to be not enough to achieve the desired technological and economic development (Metcalfe & Ramlogan, 2008). In some cases, trade liberalisation led to totally counterproductive consequences, such as the case of Latin America, where some economies became restricted in exploiting their resource-based comparative advantages, or got trapped in performing low skill, non-engineering activities organized by foreign companies. In both cases, they were unable to build local innovation capacity (Lastres & Cassiolato, 2005; Metcalfe & Ramlogan, 2008).

Using the national innovation systems perspective, the difference in techno-economic performance between countries can be explained by their institutional structures, which determined their processes of knowledge accumulation (Malerba & Nelson, 2011; Metcalfe & Ramlogan, 2008). Therefore, to achieve successful catching-up and innovation processes in a developing country, from this perspective, comprehensive and interactive learning is essential, in which firms can master the design, production, and marketing of products that are new to them, but not necessarily new to the world. With time, firms will gain the ability to incrementally improve the quality of their products and introduce further innovations[8] (Mytelka, 2000).

Jensen, et al. (2007) distinguished between two modes of innovation:

1. **Science, Technology and Innovation (STI) mode**, which is based on the production and use of codified scientific and technical knowledge by the design departments of firms through R&D activities or collaborations with universities and research institutes.
2. **Doing, Using and Interacting (DUI) mode**, where tacit knowledge is gained through informal processes of learning and experience across the links between the design, production and sales departments.

However, increasing firm learning and innovation rates in developing countries, on the other hand, can increase polarisation in terms of incomes and employment. "*It may be more common in the South than in the north that interactive learning possibilities are blocked and existing competences destroyed for political reasons related to the distribution of power*" (Lundvall, et al., 2002, p. 226).

Consequently, Lundvall, et al. (2002) discussed the importance for developing countries, in order to achieve 'sustainable economic growth and well-being', to introduce new national

[7] Several ways of incorporating evolutionary concepts from biology and anthropology into economic thinking are reviewed in (Cordes, 2014).
[8] See the case of Korea in automobile industry and semiconductors, the case of India in software and pharmaceuticals, and the case of China in telecom equipment (Malerba & Nelson, 2011). Additionally, the PV case of China subject to this thesis provides another example along this line.

development strategies across integrated policies for education, labour market, taxations, industry, energy, environment, as well as science and technology. These polices are thus intended to build up social and technological capabilities at the national level.

The term social capability was originally used by Abramovitz (1986) to explain the differences between countries' ability to catch-up. He defined it as a combination of managerial and technical competence, government stability and capability of supporting economic growth, financial institutions and markets capabilities, and the trust level within the population (Fagerberg & Srholec, 2008).

Additionally, Kim (1997) introduced the term 'technological capability' as the country's ability to use technological knowledge in order to understand, use and improve technologies. Lall (1992) noted that such capability depend also on foreign technologies acquired via machinery imports or FDI besides the national technological efforts and potentials.

Fagerberg & Srholec (2008) identified four types of capabilities:

1. The development of the innovation system using indicators such as patents and publications intensity, education, information and communication technology infrastructure, and standards.
2. The quality of governance using indicators such as impartial courts, law and order, and property rights.
3. The character of the political system using indicators such as the index of democracy and autocracy, political constraint, political competitiveness, political rights, and civil liberties.
4. The degree of openness of the economy using indicators such as merchandise imports, and FDI.

In this thesis, learning and capability building processes are given significant consideration in studying the technological innovation system and identifying the main trajectories for developing countries to catch-up and forge-ahead in high-tech engineering fields.

Examining economic development of six industries, Malerba & Nelson (2011, p. 1663) identify two different catching-up trajectories. The first is through specialization in particular stages of the global value chain to access external knowledge and markets, building indigenous capabilities and then upgrading to a higher position in the value chain. The second is through subsidiaries and joint ventures with leading multinational corporations.

In a recent contribution, Lee & Malerba (2017) introduce the theoretical framework of catch-up cycles. They argue that in the evolution process of sectoral innovation systems, radical discontinuities open windows of opportunity, to which the responses by system actors can affect industrial leadership. Accordingly, four stages in industry catch-up cycle can be identified: entry, gradual catch-up, forging ahead, and falling behind.

Furthermore, Lee & Malerba (2017) distinguish between technological, demand, and institutional windows of opportunity. While technological windows of opportunity are usually opened upon the introduction of radical innovations, demand windows are rather

related to accessing and satisfying the requirements of new markets. On the other hand, institutional windows of opportunity are related to government interventions in industries and innovation systems through public policy and subsidizing instruments. Major changes in the institutional framework of an innovation system can also open an institutional window of opportunity.

3.3 Challenges to Innovation Studies

Reviewing a number of central contributions to the field, some of the challenges confronting innovation studies are listed in this subsection along with a brief consideration of how this thesis can contribute, albeit partially, towards overcoming them.

3.3.1 Interdisciplinary Approach

Lundvall (2013) highlights the need for engaging inter- and multidisciplinary knowledge[9] from natural science and engineering into innovation studies in order to gain deeper understanding of development and capability building processes in specific technological fields. He stated, *"To understand why innovation processes are diverse, there is a need for a minimum of insight in specific technologies. Therefore, innovation studies need to engage scholars with a background in natural science and engineering."* (Lundvall, 2013, p. 61).

Steinmueller (2013) further explained this challenge by emphasizing the fertility of intersecting areas between various disciplines, as well as the need for understanding the nature of technologies in order to grasp their innovation systems. "*A fundamental understanding of the nature of specific sciences and technologies is a vital, and often underappreciated, force for stabilizing and directing the development of our field of study*" (Steinmueller, 2013, p. 159).

Accordingly, the thesis attempts at contributing to the innovation knowledge base from this perspective by drawing on engineering and natural science knowledge to define and investigate the development of the solar PV system and its components.

3.3.2 Comparability and Replicability

Dolfsma & Leydesdorff (2011) stress the importance of consistent methods and frameworks for innovation studies to advance as a solid field of knowledge. Such consistency is essential for two reasons. First, it guarantees the comparability of different empirical analysis. Second, it makes research approaches replicable technologically (across different sectors), spatially (across different countries), and temporally (for more recent periods). *"There is a need for NIS studies to develop complementary and also quantitative methods in order to generate new insights that are comparable across national borders"* (Dolfsma & Leydesdorff, 2011, p. 312).

Having this challenge in mind, the thesis analyses quantitative measures for the concerned technological system of innovation, in terms of the competences of main actors, their

[9] While in interdisciplinary approaches, methods and knowledge from other disciplines are adopted and synthesized, multidisciplinary approaches, on the other hand, gather people from different disciplines and employ their knowledge and expertise within their boundaries (Choi & Pak, 2006).

interactions, and network measures, as well as economic and innovative performance. Moreover, the thesis provides a comprehensive definition of the PV technology components along with a replicable methodical approach for identifying its inventions.

3.3.3. Growth and Productivity vs. Environment and Sustainability

Innovation studies have long concerned with the role of innovation in stimulating competition, productivity, and economic growth. However, the increasing awareness of the global environmental and socio-economic challenges, such as climate change, energy, poverty, and inequality, requires switching the magnifying glass into such issues. This needs to be accompanied with the development of further tools and resources compatible with the new focus. "*The challenge for [innovation studies'] scholars is to respond to the pressing world need for more equitable development, and to ensure we have the conceptual, methodological, and analytical tools needed to facilitate this shift towards innovation for sustainable development…"* (Martin, 2013, p. 174)

The contribution of this thesis towards addressing this challenge is reflected in the motivation of the research and the selection of PV technology to be considered under the innovation system lens. Furthermore, through the analysis of the thesis, the environmental impact of the production and installation of solar modules is explicitly considered along with the innovative performance.

4. THIS DISSERTATION

This thesis comprises four research articles. Each article is presented as a whole chapter. They cover the various aspects of the technological system of innovation for solar PV technology and the prominent case of China's catching-up therein. Accordingly, this section is built upon two main parts. In the first part, the articles are discussed individually. It therefore provides a brief summary of the motivation, research questions, scope, main findings, and contribution of each article separately. On the other hand, the second part puts the four articles into a broader context highlighting their correlation and joint contribution to the body of knowledge in the field. It thus provides the cognitive guidance on how these articles can be read together through multi-level analysis of the innovation system.

4.1 An Overview of the Dissertation Papers

The encompassed papers in this dissertation are entitled as follows: Chapter 2: 'the technological system of photovoltaics: identification and analysis with patent classes'. Chapter 3 entitled 'drifting towards innovation: the co-evolution of patent networks, policy, and institutions in china's solar photovoltaics industry', chapter 4: 'innovation capability, network embeddedness and economic performance: profiling solar power innovators in china', and chapter 5: 'the technological system of production and innovation: the case of photovoltaics technology in china'.

While all of them concerns with the innovation issues in the solar PV sector, each paper has nonetheless its specific focus. The first article (chapter 2) concerns with the technical aspects of the system and its general trends. The second (chapter 3) focuses on networks. Whereas the third paper (chapter 4) profiles the performance of main actors within the system, the

fourth paper (chapter 5) provides a comprehensive overview of the technological system of production and innovation within the Chinese PV sector focusing on the institutional aspects along with other elements of TIS.

Additionally, some linkages and common elements exist between each pair of these papers. For instance, technological profiles are addressed at different levels in both chapter 2 and 4. Similarly, network embeddedness is considered in chapters 3 and 4. An elaborating on institutions can be found in chapters 5 and 3, and the environmental aspects are discussed in chapters 1 and 5. Figure 7 shows the different chapters of this dissertation along with their research focus and common elements.

Figure 7: An overview of the different chapters in the dissertation

- The numbers introduced in this figure are relevant to chapter numbers in the thesis.
- The titles of papers are shortened in this figure by highlighting the significant keywords of each paper.
- The research focus of each chapter and the common elements between chapters are represented in this figure using symbolic icons. Author's own elaboration

Furthermore, table 2 summarizes the main focus, temporal and spatial scope, as well as the technological innovation system elements that are addressed in each chapter within this thesis.

Table 2: Overview of the dissertation chapters

	Title	Main Focus	TIS Elements	Spatial Scope	Time Scope
2	The Technological System of Photovoltaics: Identification and Analysis with Patent Classes [a]	*- technical* *- methodical* *- patent analysis*	*- technologies* *- knowledge-base*	*Global*	*1950-2014*
3	Drifting Towards Innovation: The Co-Evolution of Patent Networks, Policy, and Institutions in China's Solar Photovoltaics Industry [b]	*- network analysis*	*- actors* *- interaction* *- institutions*	*China*	*1988-2014*
4	Innovation Capability, Network Embeddedness and Economic Performance: Profiling Solar Power Innovators in China [c]	*- pattern recognition* *- statistical analysis* *- economic performance*	*- actors* *- interactions*	*China*	*1995-2015*
5	The Technological System of Production and Innovation: The Case of Photovoltaics Technology in China [d]	*- innovation system analysis* *- policy oriented*	*- institutions* *- actors* *- interactions* *- environment** *- market firmo-dynamics**	*China*	*1995-2017*

a: (Shubbak, 2017a), b: (Dominguez-Lacasa & Shubbak, 2018), c: (see chapter 4), d: (Shubbak, 2017b)
* Additional elements to TIS as novel contribution of the thesis. Author's own elaboration.

4.1.1 The Technological System of PV[10]

This paper, (Shubbak, 2017a)[11], studies the development of PV technologies using patent indicators. It is motivated by the potential vital role of solar PV in addressing the major environmental challenges by providing a clean and sustainable energy. Accordingly, the understanding of the technology and the capturing of its development[12] are of a significant importance for research in both natural and social sciences. It can provide natural scientists with a clear insight into the current advances in the technology (the state of art) as well as into a rich stock of knowledge, engineering designs, materials, methods, and sufficient solutions to technical problems in the field. On the other hand, such understanding can support innovation studies and the evaluation of subsidizing policies conducted by scholars

[10] The article is single authored. It is envisaged for submission to a peer-reviewed scientific journal.
[11] This in-text citation is to an earlier version of the research article presented as a conference proceeding at the 29th Annual Conference of the European Association for Evolutionary Political Economy in Budapest, October 2017.
[12] Patent applications to protect intellectual property of novel inventions are considered along this paper as a proxy of the technological development.

in social sciences. Furthermore, by inspecting the patenting landscape, manufacturers can better identify the free technological spaces to operate in the field.

Having a technical nature, the scope of the paper is wide, both spatially and temporally. It covers the technology development across the international landscape since 1950. The research questions of this paper are related to the accurate definition of the technical system and components of solar PV, the identification of its relevant patent applications, and the analysis of their trends. Accordingly, the paper is mainly structured in three sections. The first section defines the PV system groups by thoroughly reviewing the various solar cell generations and the balance of system components. The second section introduces a methodical approach for identifying PV-relevant patents. After that, the geographical, technical, and organizational trends of the system over the past six decades are analysed in the third section.

The analysis within this paper reveals several interesting findings. It defines the technical system of PV into six groups: cells, panels, electronics, storage, testing, and portable devices. Each group comprises further levels of encompassed technologies. It provides a systematic methodology for identifying patent applications. Its results show that 95% of the global patent applications in the PV field belong to seven countries: Japan, South Korea, China, USA, Germany, Taiwan, and France. Most patents are filed by private companies and related to thin-film and crystalline silicon cell technologies as well as panels encapsulation and installation. Moreover, the results highlight the prominent case of China in terms of its high growth ratio in patent filings and its high revealed advantage in several technologies within the PV system.

Besides its comprehensive definition of the PV technical system for the purpose of innovation studies[13], the main contributions of the paper lay in the patent identification and classification. Not only can the resulting classification be further used to address wide range of research questions regarding the PV sector, but also the identification and classification methodology itself can be adopted for other technological sectors. It shows a relatively high accuracy, relevancy and replicability.

Finally, the paper confirmed and emphasized the prominent case of China in the field. Therefore, it motivated a further consideration of the country's technological innovation system, which is done in the following research papers in this thesis.

4.1.2 Drifting Towards Innovation: Co-patenting Networks[14]

Being motivated by the prominent catching-up case of China in the PV sector since 2008, the second paper (Dominguez-Lacasa & Shubbak, 2018) examines the technological knowledge

[13] The definition of PV technical system as provided by this paper reflects the complexity of the technology. It shows that solar PV is not one technology, but it rather comprises components, technologies, and manufacturing processes belonging to several fields of knowledge, such as physics, chemistry, electrical engineering, mechanics, optics, thermodynamics, as well as informatics and electronics.

[14] The article is co-authored with Iciar Dominguez Lacasa. It is published in the peer-reviewed journal: Energy Research & Social Science, Vol. 38, 2018, pp. 87–101. For my personal contribution to the article, see the declaration attached to the present thesis.

networks in the Chinese PV sector and the accumulation processes of indigenous innovation capabilities at the technological frontier. Furthermore, it briefly investigates the co-evolution of PV patent networks and its relevant public policies and plans in the country. Having the dramatic growth in China's share in the global market of PV production in the background, the paper is concerned with identifying whether a similar trend can be found in innovation.

The paper focuses on tracking the emergence and evolution of the Chinese co-patenting networks in the sector over 1988-2014. Accordingly, its scope is limited to transnational patent applications with inventors located in China. Patents are identified based on the comprehensive definition of the entire system value chain developed in the first paper (chapter 2; Shubbak, 2017a).

Theoretically, the paper draws on the concepts of innovation capabilities and technological systems. Its research questions revolve around inspecting the extent, to which China is accumulating innovation capabilities in PV technologies, identifying its technological catching-up trajectory and the role of local and foreign actors in this process, as well as tracking how the underlying technological networks have evolved over time against institutional milestones of industrial policy.

The paper follows the standard structure of empirical papers, with two theoretical sections: literature review and conceptual framework. They are followed by a methodology chapter stating the data sources, methods, tools, and indicators used throughout the paper. The results regarding patent and network analysis are presented over four periods, before discussions and conclusions are drawn in a final section.

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 technological catching-up processes in crystalline silicon cell technologies, solar panels, and electronics. The network analysis shows an increasing population of Chinese patent applicants clustered in isolated communities to drive technological catching-up. Nevertheless, it reveals that the role of foreign actors in the co-patenting activities is surprisingly low and decreasing.

The main contribution of this paper is that it puts forward the first network analysis of PV technological activities in China. Furthermore, the novelty of our contribution is twofold: First, it captures technological innovation along the complete PV technological system. Second, the paper identifies the network positions of the main innovators within the Chinese TIS and its dynamic development.

Finally, the paper motivated further research regarding the patterns of network interactions and their relations to catching-up processes and microeconomic performance on the one hand, and inspired further investigation of the puzzling difference between China's share in production and transnational patent applications on the other. Such aspects are thus addressed in the following chapters. It is worth mentioning that the network analysis conducted in this paper can be considered as a cornerstone of further consideration of network embeddedness indicators in the research on catching-up processes of emerging and developing economies.

4.1.3 Profiling Solar Power Innovators in China[15]

The paper explores the various patterns of innovation and network-embeddedness within the PV innovation system in China and examines the impact of these patterns on economic performance of the main actors within the system. It is motivated by the significant role of innovative activities (inventiveness and patenting) in achieving better economic performance (e.g. productivity) on the one hand, and promoting renewable energy sources as an economically feasible alternative to fossil fuels on the other. Additionally, it examines the facilitating role that network embeddedness (via collaborations within technological knowledge networks) can play in these processes.

Accordingly, the paper aims to address three research questions. The first question is related to the main actors in the Chinese PV innovation system and their characteristics. The second question deals with the patterns of innovative activities and knowledge network embeddedness within the system. Subsequently, the third question is concerned with the relationship between these patterns and characteristics of the actors, more precisely their size, age, and economic performance (i.e. turnover and productivity).

Throughout the paper, the leading PV innovators in China over 1995-2014 are identified using transnational patents and market share indicators. After that, the landscape of their activities is inspected through two hierarchical cluster analyses in parallel: First, based on the quantity, quality, impact and diversification of patenting activities, and second, based on the global integration, component size and position in technological knowledge networks.

The paper identifies six patterns of innovation capability: (1) the specialization in high-tech fields, (2) high technological diversity, (3) high impact, (4) high quantity, (5) weak innovation capability (low quantity and quality), and (6) no inventive activity. Similarly, it recognizes five patterns of network embeddedness: (a) high global integration, (b) high embeddedness (central positions in large network components), (c) small-world networks, (d) low network embeddedness, and (e) actors that are not engaged in technological collaborative networks.

The resulting patterns are cross-related to understand their interrelations with age, size and economic performance. Accordingly, the paper introduces and tests eight hypotheses. The conducted multivariate analysis of variance resulted in a significant relationship between innovation-network concurrency on the one hand, and the age, turnover and productivity of actors on the other. Global-integration in small-world networks is shown to be significantly related with economic performance. Additionally, the results suggest that innovation quality has higher importance than its quantity and diversity. While specialization in high-tech fields has positive impact on turnover, production-oriented firms with low-tech focus have interestingly a higher productivity.

The paper contributes to the body of knowledge in three ways. First, it provides a detailed profiling of the main actors within Chinese TIS in the field. Second, it uniquely defines two sets of patterns for both innovation-capability and network-embeddedness. Third, it

[15] The article is single authored. It is accepted for publication at the peer-reviewed journal: International Journal of Technological Learning, Innovation and Development.

introduces the novel analytical tool of 'concurrency matrix' to study the interaction between innovation and network patterns and its subsequent impact on microeconomic performance.

Accordingly, the paper pushes forward a new field by analysing the confluence of two different dimensions that have long been individually analysed in the literature. The replication of its methodology for other technological, geographical, or temporal contexts can contribute to further development in economic and business theories.

4.1.4 The PV Innovation System in China[16]

The research paper (Shubbak, 2017b)[17] comprehensively studies the technological production and innovation system of the Chinese PV sector over 1995-2017. It is motivated by the puzzle introduced in section 4.1.2 regarding the gap between the growth of China's market share and its modest share of transnational patent applications. Therefore, it aims at understanding the emergence and development of the innovation system by inspecting its actors against the dynamic development of their size and performance, the nature of their international involvement through FDI, joint ventures, and acquisition deals, as well as their technological specialization within the PV value chain through domestic and transnational patenting activities.

The paper utilises three analytical levels. The first level concerns with the institutional framework of the system from a political economy point of view. The second level focuses on the market dynamics of production and deployment of the technology. The third level is related to inventive and innovative activities. Furthermore, the paper illustrates the interactions between these levels and their impact on environment. Consequently, the analysis demonstrates the interrelated roles of various elements such as the transnational factors, subsidizing policies by the local government, external impacts and trade disputes, R&D activities and intellectual property protection, the mobility of researchers and skilled employees, as well as market dynamics of supply and demand.

The analysis of the paper recognises four periods of system development jointly influenced by market dynamics and government plans. It further shows that behind the continuous growth of the system, there were different driving and moderating factors in each period. The interactions and events occurring within the global PV system have long casted a shadow on the Chinese system dynamics. While they heavily stimulated production processes at the early stages, they formed external shocks and industry down-cycle at the latest stages. However, the successful intervention by the Chinese government through several policy instruments has so far led to continuous trend of capability building and innovation.

Based on that, the paper tracks the technological catching-up trajectory followed by China in the PV sector, and compares it with other cases from the literature. It further suggests several policy implications for China, other emerging and developing economies as well as for

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[16] This single authored article is revised and resubmitted for publication in the peer-reviewed journal: Research Policy.

[17] This in-text citation is to an earlier version of the research paper presented at the workshop 'Innovation in Emerging Economies' in Berlin, July 2017.

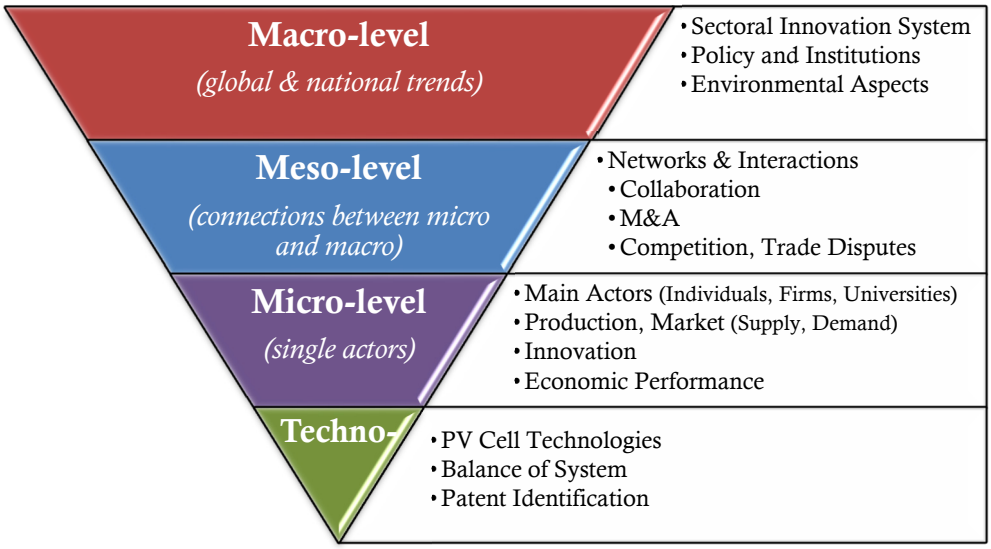
developed countries. The contribution of this paper can thus be seen through its detailed analysis of the system both vertically (through the entire value chain), and horizontally (by integrating all the building blocks of TIS and expanding it towards the firmodynamics and environmental elements).

4.2 How can these papers be read together?

To put the four papers together within an overall context, this section introduces a multilevel analytical approach. Accordingly, the building blocks of innovation systems can be distributed into four levels of analysis. The understanding of the entire system thus stems from capturing the dynamic processes horizontally within each level and vertically across the levels. The introduced levels are the techno- level, followed by the micro- level, then the meso- level, and finally the macro- level. Figure 8 illustrates the multilevel approach along with the various elements, processes, and indicators relevant to each analytical level.

While some of the dissertation papers are solely restricted within a specific analytical level, others comprise cross-level analyses. In the following subsections, a brief definition of each analytical level is given along with its corresponding elements and empirical indicators.

Figure 8: Multi-level analysis of the PV innovation system



Author's own elaboration

4.2.1 The Techno- level

As indicated by its name, the analytical techno-level is concerned with the technical aspects of the system. Therefore, it can be seen as the lowest level of analysis within the technological

innovation system as it is the closest to the technology itself[18]. The main contribution of the thesis at the techno-level is represented by the comprehensive definition of the solar PV technical system in chapter 2. The definition is then used within the other chapters to understand the various forms of technology and to capture their corresponding inventions through patent indicators.

While chapter 2 introduces the technology components along with the methodological approach to identify their patents, chapter 3 applies the methodology to collect PV transnational patent applications in China for conducting the network analysis. Similarly, chapter 4 builds upon the identified patents to recognise the innovation capability patterns of the main applicants as well as their technological profiles. Therein, the technical aspects play a significant role for calculating the clustering indicators: high-tech index and technological diversity. Furthermore, the techno-level is utilized in chapter 5 through discussing the results and understanding the intertwined relations between various actors in the light of system's technical complexities.

For example, the techno-level provides us with the fact that coal acts as an important reactant within the reduction process of SiO_2 in electric-arc furnace to produce metallurgical grade silicon[19]. Without having that in mind, the acquisition of Duolun Golden Concord (owner of coalmine in Inner Mongolia) by GCL-Poly (the largest silicon-feedstock producer in China) in 2008[20] would have not been understood. Similarly, the relation between the joint ventures of foreigner firms in China and its technological specialization in the early stages of system development are better understood in the light of techno-level aspects.

Furthermore, China's catching-up trajectory can be seen at the techno-level as successive learning processes of technologies with varying complexity. Such development track started with building indigenous capabilities to produce portable devices (powered by PV cells imported from Japan, Europe, and USA). This stage was followed by mastering solar panel production (by connecting and encapsulating imported PV cells). After that, a growing number of Chinese cell manufacturers were established; however, they used to implement the final production stages of c-Si cells. Up to this point, Chinese manufacturers were still dependent on the global markets for purified silicon-feedstock supply. The next stage within the technological catching-up trajectory was characterized with the emergence of domestic poly-silicon feedstock industry. Later on, the Chinese technological system expanded vertically to include capabilities in PV electronics.

The final remark to be mentioned under the techno-level is the interesting differences between the global trend of PV technologies (Ch. 2, fig. 8) and the Chinese technological catching-up

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[18] The terminology of 'low' and 'high' used for describing the analytical levels here is based on how close the underlying investigations are to the technology. It follows the same logic used in computer science for describing programming languages. i.e. high levels are far from the technology/machine and closer to the observer/user, while low levels are the opposite. It is worth mentioning that such terminology has nothing to do with the complexity nor the significance of the analytical levels.

[19] See section 2.1.1 in chapter 2, for technical details of this process.

[20] See section 4.2.3 and table C in chapter 5, for more details about the international involvement through merger and acquisition deals.

(Ch. 3, sec. 6; Ch. 5, sec. 5.2). While the global development took the track of feedstock – cells – testing – panels, China's catching-up on the other hand followed a reverse-engineering track: devices – panels – cells – feedstock.

Given the technological specificity of the PV innovation system, it is obvious that the detailed consideration of the techno-level has a vital role in understanding the individual aspects of each chapter, as well as to comprehend the broader context of the overall picture.

4.2.2 The Micro- level

Microeconomics can be defined as a bottom-up approach to understand the decisions and behaviour of individuals, firms and groups regarding the allocation of scarce resources. Accordingly, it deals with their characteristics and the issues affecting them, such as supply, demand, and production. Following the same logic, the analytical micro-level introduced in this section deals with the characteristics of the main actors within the TIS (individuals, firms, universities, etc.) along with production indicators, market dynamics of supply and demand, and innovative/economic performance. Although it is a higher level than techno, it is still concerns with indigenous attributes of single actors within the innovation system.

In this dissertation, the micro-level consideration can be seen in the profiling of PV innovators in China (Ch. 4, sec. 4.1 and sec. 4.2.1) as well as in the market- and firmo-dynamic analysis (Ch. 5, sec. 4.2). Throughout the micro-level analysis, the focus is on the bidirectional effects between the system dynamics and the characteristics/behaviour of its actors. For instance, the down-cycle of PV industry due to the imbalance between demand and supply in 2011 (see Ch. 5, sec. 4.2.3) is an essential aspect of the micro-level. Another example is the significant impact of innovation capability on economic performance of the main actors (as shown in chapter 4).

The catching-up trajectory at the micro-level can be perceived through the dramatic growth of PV cell manufacturers (both in innovative and economic performance) during 2002-2011, which was driven by a rapidly growing demand in the global market. This was followed by a down-cycle and stagnation stage in 2011 due to a sudden shrinkage in the demand side of the market. However, the interim stagnation of the Chinese cell manufacturers was accompanied with a continuous growth for actors along the previous and subsequent chains of the system value-chain, namely the feedstock and electronic technologies respectively[21]. In the following stage within the catching-up trajectory, the micro-level analysis shows a gradual growth of a Chinese domestic market for PV technologies.

Finally, the micro-level analysis reveals distinct roles for various organizational types. Therefore, they affect and can be affected by the system dynamics differently.

4.2.3 The Meso- level

This analytical level aims at revealing the vertical connections between micro- and macro-levels. In other words, it addresses the links between several micro-level elements that can

[21] While the micro-level alone cannot explain this process, it nonetheless clearly captures it and highlights it for further consideration.

affect the macro structure of the system. Therefore, within this level the focus is not on the actors themselves but rather on the interfaces between them, i.e. their interactive networks. As discussed in section 3.1.2, the interactions between actors within an innovation system can take several forms, such as collaboration, trade of goods and equipment, merger and acquisition (M&A), competition and trade disputes, as well as employees' mobility, knowledge transfer, and licencing activities of protected intellectual property.

The meso-level analysis in this thesis is distributed among chapters 3, 4, and 5. While chapter 3 focuses on the dynamic development of collaboration processes through technological knowledge networks over time, chapter 4 identifies the embeddedness patterns of the main actors in these networks in order to inspect their effects on economic performance. The other types of interaction are addressed in chapter 5.

The overall results at the meso- analytical level in this thesis reveal a vital role of networks and interactions in forming the system dynamics and influencing both the magnitude and direction of its development. By considering the interactions between several actors within the PV technological system of production and innovation in China, many of the ambiguous observations at the lower levels (micro- and techno-) can be sufficiently clarified. For example, the reasons behind the sharp downturn in the international PV demand that occurred in 2011 can be better understood when considering the conflicts and trade disputes in the sector globally (see Ch. 5, sec. 4.1.2). Another example is related to the role of network embeddedness in shaping and facilitating the relationship between innovation capability and economic performance (as addressed in Ch. 4, sec. 5.2).

The Chinese catching-up process in the PV field can be observed under the meso- lens through the development of technological networks and the transnational factors therein. It started with few network components with high share of foreign actors. Then it developed into a more fragmented structure through an increasing number of Chinese actors clustered in isolated network components with high modularity. Such components had either a complete-graph structure or a flower structure (several complete graphs connected via a central node). In the stages that follow, some of these network components were linked to form an extended network structure. Such catching-up trajectory is also confirmed with the foreign direct investment (FDI) and M&A indicators. As shown in chapter 5, a switch in the FDI direction within the Chinese PV sector can be noted since 2007, when China transformed from a recipient into an active acquirer in the international landscape.

Finally, it is worth noting that the identified patterns of network interactions can further be used to capture the main catching-up mechanisms throughout the system development stages. This can consequently inspire further in-depth analysis regarding technology transfer on the higher level.

4.2.4 The Macro- level

Macroeconomics can be defined as top-down approach to study an economy as a whole by considering its structure and performance. It thus addresses large-scale issues such as growth, inflation, unemployment, as well as the effects of public policies on the national or regional economy. Similarly, the macro- analytical level introduced in this thesis deals with the high-

level aspects of the technological innovation system. Such aspects include the overall development of the system, its institutional framework, as well as the environmental aspects.

Accordingly, the analytical focus at the macro-level is neither on the technology, nor on the actors (competences and interactions). It is rather on the overall behaviour of the technological innovation system. Accordingly, it looks at the aggregation and integration of the techno-, meso-, and micro- effects, as well as at the externalities that can affect these levels.

In this thesis, the macro-level analysis is distributed among chapters 2, 3, and 5. While chapter 2 tracks the geographical trends of system development. Chapters 3 and 5 address the governmental plans, public policy, and institutional infrastructure of the system. Additionally, an explicit consideration is given for the environmental impacts of both production and innovation activities in chapter 5.

The catching-up trajectory can be seen under the macro-lens through the dynamic development of government plans and subsidizing policies. It started with the focus on scientific and technological research by supporting education through cooperative projects. Then it switched into supporting the import of manufacturing equipment through tax reductions. This was followed by creating an atmosphere conductive to export-oriented industry through supportive regulations and subsidies. Finally, a major switch towards stimulating a domestic demand was noted. Such dynamics had a varying impact on environment. While it increases CO_2 emissions posing additional burdens on the air pollution problems in China during the early stages, the domestic deployment of the overcapacity in the later stages yields a positive CO_2 net savings.

The significance of considering the macro-level analysis in this thesis is the fact that it offers interesting insights on the interrelations between the Chinese and the global technological systems of production and innovation in the PV field. It highlights how the interactions and events occurring within the global system have casted a shadow on the Chinese system dynamics.

5. CONCLUSION AND OUTLOOK

The present thesis explores the technological innovation system of solar photovoltaics in China. It captures the learning, catching-up, and forging-ahead processes taken by the emerging country over the past decades. The statistics regarding production, installation, and development of PV technologies highlight the prominent case of China. Therefore, the thesis attempts at comprehensively studying this case. Throughout its cumulative papers, the dissertation studies the PV innovation system in China from multiple perspectives and at several analytical levels.

First, the PV technology is considered with technical detail against its categories, generations, and components. In this regard, a methodical approach to capture patent applications that are relevant to each PV component is introduced in chapter 2. It is further used to track the geographical, organizational, and technical development trends of the global PV system. Consequently, the significance of such contribution can be seen from two perspectives. First,

its results provide an accurate replicable tool for PV patent identification, which can be used by other researchers for conducting empirical research in the field. Second, the methodology itself can be used in a broader sense to identify inventive activities in other technological fields beyond solar PV.

The second perspective addressed in the thesis is concerned with the main actors within the innovation system. It identifies them, profiles their competences, and disentangles the interrelated influences of their innovative activities, network-embeddedness patterns, and economic performance. Such contribution pushes forward the confluence analysis of two different dimensions whose impact on economic performance have long been analysed in a single basis.

Since innovation is more likely to emerge within the interfaces between actors rather than their internalities, the third perspective of this thesis on the innovation system considers the interactions between its actors. This is achieved through studying the collaborations within knowledge networks (Ch. 3), the patterns of network embeddedness (Ch. 4) as well as M&A deals, licensing, and trade disputes (Ch. 5).

The fourth perspective considers the institutional framework of the system and its connections with the global market dynamics. On the one hand, the thesis studies the macro- and micro- level effects of the Chinese government interventions in the system throughout its various development stages, and on the other hand, it put them in the broader context of the global market situation and external shocks. This sets the groundwork for the introduction of the system firmodynamics element at its micro-level.

It is worth noting that despite the successful catching-up of China in the PV sector, the specialization of the country is still restricted in the 1G solar cell technologies (crystalline silicon) and solar panels as the current dominant design. The country's contribution in the development of other PV technologies and generations is still modest. Additionally, the analysis shows that most of the Chinese inventions in the field are of incremental nature revolving around the dominant design. However, a dominant design forms an interim stability point that can be changed with the appearance of radical innovations. This can expose China's PV industry to the threat of declining susceptible to the emergence of radical innovations[22]. The fact that needs to be taken by the Chinese PV manufacturers as a motivation to keep developing and forging ahead.

Even so, the dissertation does not stop at analysing the various elements of the PV innovation system in China. It rather studies the impact of its dynamics on the environment. Accordingly, the dissertation links the TIS empirical analysis back with its main motivation regarding climate change and sustainable development.

Overall, the case study presented in this thesis reveals the complementary roles of all these elements in shaping the successful catching-up of China. Knowledge networks, indigenous capability building, and the successful governmental policies in response to external shocks

[22] See for instance how the inventing of the transistor in 1948 caused a drastic decline in the vacuum tube industry (Tushman & Anderson, 1986).

have all shown significant impacts. Such success story can further be seen as a beacon illuminating the way forward for other emerging and developing countries to get inspired by, and benefit from its lessons.

The results further highlight the significant role that innovation in solar energy can play in addressing the global challenges and providing the world economy with clean sustainable energy supply[23]. While climate change threatens our environment on the one hand, and fossil fuel depletion threatens our economic system on the other, solar energy holds out the promise of protecting both of them.

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[23] It is worth mentioning that the sunlight striking earth in one hour contains more energy than that consumed by human beings in a whole year (Pettersson, et al., 2012).

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The Technological System of Photovoltaics: Identification and Analysis with Patent Classes

Chapter 2

ABSTRACT

Against the pressing challenges of climate change and depletion of fossil fuel reserves, renewable energy sources such as solar photovoltaics (PV) are widely considered as a clean and sustainable alternative. PV technologies have grown into a substantial field of research and development through a growing stock of scientific publications and patents. Currently there are three main generations of PV cell technologies: crystalline silicon; thin-film; and emerging technologies. Besides, the balance of system (BoS) technologies such as panels, electronics, and energy storage form an important research area. The present article studies the development of the PV technological system using patent indicators. It is composed of three main sections. First, it defines the system groups by thoroughly reviewing the various cell and BoS technologies. Second, it introduces a methodical approach for identifying its relevant patent applications. Finally, the geographical, technical, and organizational trends of the system over the past six decades are analysed. The analysis shows that 95% of patent applications in the PV field are filed by inventors located in seven countries. Most patents are filed by private companies and related to thin-film, crystalline silicon cell technologies, panel encapsulation and supporting structures. The patent analysis provides an overview of the technological landscape and the freedom spaces available for manufacturers.

KEYWORDS

Solar Energy; Photovoltaics Technology; Cells; Balance of System: Patent Profiles; IPC Classes

JEL CLASSIFICATION

C80; Q40; O31; O34

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Information Box: Broader Context

Climate change is the major challenge of the world according to the United Nation's millennium project. In fact, the global average temperature has increased by one degree Celsius over the last century, with CO_2 emissions resulted from fossil fuel combustion considered among the main causes. Scientists predict the continuous global warming to result in serious environmental and economic consequences on precipitation rates, droughts, growing crops, rivers' flow rates, ice melting, and sea-level rising. To meet these challenges, renewable energy sources such as solar photovoltaics are widely seen as clean alternatives. Recently, they have grown in both development and deployment. However, the economic feasibility -in terms of initial capital and energy costs- has long constituted a key obstacle. Even so, innovation, mass-production, and government subsidies can interactively lead to the grid parity. Inventions with high technological and economic values are usually protected through patent filings. Since patents act as a bridge between successful innovative activities and markets, the study of their indicators is vital to understand the technical situation and to evaluate the subsidizing policies. Introducing an exclusive definition of the technological system of photovoltaics, this article aims to accurately identify the relevant patent applications and to analyse their trends geographically, technically, and organizationally.

1. INTRODUCTION

Among the wide range of existing renewable energy sources, solar photovoltaics (PV) is considered as "the cleanest and safest technology with which to generate electricity even at the GW production scale" (Hegedus & Luque, 2011, p. 24). Since the discovery of PV effect in the nineteenth century, the technology has experienced dramatic development vertically – in terms of solar cell types, technological generations and efficiencies (NREL, 2017; Mertens, 2014), horizontally – in terms of its associated technical fields in chemistry, physics, electronics, and mechanics (Whitaker, et al., 2010; Hegedus & Luque, 2011), as well as on the market dynamics level of production and deployment (Byrne & Kurdgelashvili, 2010; Brown, et al., 2015).

Today, development of material components, manufacturing methods, and applications for both PV cell and balance of system (BoS) technologies is a substantial research field. Thousands of corresponding scientific articles as well as patent applications are being published yearly. Patents are widely considered as a bridge between successful research and development activities on the one hand, and commercial markets on the other. They are usually filed by companies, universities, and research institutes to protect intellectual properties of high technological and economic values. Accordingly, the study of patent indicators has been of central importance for researchers in both natural- and social sciences. While patents can offer chemists, physicists, and engineers a comprehensive picture of the current technological situation, the state of the art, and development prospects, they provide policy makers and economists with a rich data source to evaluate the effectiveness of innovation and subsidizing policies.

Patent databases contain information of millions of patent applications in almost all technological fields. Consequently, the accurate identification of patent filings relevant to a specific technology is not a simple matter. Such accurate identification is nonetheless crucial for ensuring the quality of patent indicators and the validity of conclusions drawn out of them. Even utilizing the technological classification systems developed by patent offices, the identification process is still confronted with numerous difficulties and challenges. First, the complexity of high-tech systems makes it challenging to distinguish between similar technologies without detailed technical verification. The second difficulty is related to the diversity of large technological systems, whose components usually belong to a wide range of different technologies. Third, it is difficult to address market-oriented research questions depending solely on technological classification. Pavitt (1985, p. 95) highlighted the importance of effective matching between the established patent classification scheme, the industrial classifications, and technically coherent fields of development. Fourth, the subjectivity of the technological classification of patent filings due to patent examiner judgements is considered another hurdle for the identification and assignment process (Venugopalan & Rai, 2015).

The purpose of this article is to provide a comprehensive definition of the technological system of photovoltaics in terms of its structure and components, to systematically identify its relevant patent applications, and to analyse their technical, organizational, and geographical trends over time. The article is organized in five sections. Section 2 outlines the structure, work principle, and various components of the PV technological system. Section 3 compares different identification methods of patent applications and introduces the research methodology, data sources, and indicators. In section 4, the results concerning the global development trends of the PV technological system are analysed. Finally, section 5 synthesises the main findings and draws conclusions.

2. THE TECHNOLOGICAL SYSTEM OF SOLAR PHOTOVOLTAICS

The PV technological system is a power system comprises a sequence of interconnected components that work together to convert sunlight energy into electricity, utilize the generated energy, store it, or invert it (figure 1). Accordingly, a PV system, whether centralized utility-scale or distributed, consists of two main groups of elements: solar cells, and balance of system technologies (BoS).

While cells are responsible for generating electric energy out of the solar irradiation, BoS components are important for connecting, chemically protecting, and mechanically mounting the cells into panels, as well as electronically regulating their output levels to be used, stored in batteries, or fed into the utility grid. Additionally, the system includes testing and monitoring processes and portable devices powered by PV electricity. (See figure 1 for an overview of the PV system components).

Figure 1: The Technological System of Solar Photovoltaics

Author's own elaboration

2.1 Solar Cell Technologies

Solar cells represent the building block and main component of PV systems. A solar cell is defined as an electrical device that directly converts the energy of photons into direct current (DC) electricity through a chemical/physical phenomenon called the photovoltaic effect. Photons with energy exceeding the cell material band-gap are absorbed causing excitation of charge-carriers and thus electric current and voltage. The conversion efficiency (η) is calculated as the percentage of the incident light power on the cell surface that is converted into electrical energy under standard conditions.

Solar cells are classified into three generations of technology. While the first generation (1G) encompasses crystalline silicon wafer-based cells, the second generation (2G) comprises thin-film technologies such as Cadmium telluride (CdTe), Copper indium gallium di-selenide (CIGS), amorphous Silicon (a-Si), and single-junction Gallium Arsenide (GaAs) cells. On the other hand, the third generation (3G) includes the emerging cell technologies of organic materials as well as the multi-junction cells.

Only c-Si and thin-film technologies are available in mass production for civil applications. In terms of market share, c-Si cells are dominant in the market with 93% of the total produced capacity in 2015 (69% multi-crystalline cells and 24% mono-crystalline), while thin-film technologies form only 7% of the total production (3% a-Si, 2.5% CdTe, and <2% CIGS) (Beiter & Tian, 2016). On the other hand, the expensive high-efficient technologies of GaAs and multi-junction cells are mostly used for space power applications (Hubbard, et al., 2009).

2.1.1 Crystalline Silicon Technologies (c-Si)

Single-junction c-Si is currently the dominant cell technology in the global PV market. The wafer-based conventional cells are classified according to their crystalline structure into four main types: Mono-crystalline, Poly-crystalline, Heterojunction with Intrinsic Thin layer (HIT), and Microcrystalline. Regardless of the final crystalline structure, the initial stage of c-Si cell manufacturing aims at the production of high-grade purified silicon. Raw materials of quartz sand (SiO_2) and coal (C) are processed inside electric arc oven to generate metallurgical-grade silicon (98% pure), which undergoes further hi-tech processes in several reactors to produce solar-grade polysilicon (with at least 5 nines purity 99.999%) (Mertens, 2014; Ceccaroli & Lohne, 2011; Chigondo, 2017).

The second stage of manufacturing processes comprises crystal growth methods, where mono and multi-crystalline ingots are produced. While mono c-Si consists of a continuous single crystal, poly c-Si contains multiple small crystals. Consequently, they differ in their production processes. Mono-crystalline ingots can be obtained using the Czochralski process, float-zone, or Bridgman–Stockbarger techniques. On the other hand, poly c-Si follows simpler manufacturing processes such as Bridgman columnar growth and block-casting techniques, where melted polysilicon undergoes gradual directed cooling process (Rodriguez, et al., 2011).

In the following manufacturing stages, both mono- and poly- ingots are sliced into wafers (with a typical thickness ~ 300 μm) to be doped with p-n impurities and soldered with conducting surfaces, which together compose the solar cell. Efficiency records for such PN homojunction-barrier type cells are 25.3% and 21.3% for mono- and poly- cells respectively (NREL, 2017).

As indicated by its name, an HIT cell is obtained by subsequently depositing p- and n-type hydrogenated amorphous silicon (a-Si:H) thin layers (~ 20 nm each) on the top and bottom sides of an intrinsic c-Si wafer (~ 200 μm) (Battaglia, et al., 2016). Such hybrid structure of conventional and thin-film technologies was originally developed and patented by the Japanese company Sanyo in 1990 (Tanaka, et al., 1992). With the advantages of high conversion efficiency (research cell record at 26.6%), improved temperature coefficient, higher open-circuit voltage, and less needed energy during manufacturing, HIT cells are considered as a promising technology.

The fourth type of c-Si technologies is microcrystalline. Being a form of porous silicon, microcrystalline silicon (sometimes referred to as Nano-crystalline) has tiny grains of c-Si within its amorphous phase. It is considered as thin-film c-Si technology with efficiency record of 21.2%. Unlike the other c-Si technologies (which are based on self-supporting wafers), the active microcrystalline thin layer (~ 1 μm) is deposited from a gas-phase (SiH_4 and H_2) through plasma enhanced chemical vapour deposition (PECVD) or hot-wire chemical vapour deposition (HWCVD) processes (Klein, et al., 2004; Gordijn, 2005) on a glass substrate before treated into PIN structure.

2.1.2 Thin-film Technologies

To avoid the high economic and environmental cost of c-Si cells (in terms of material and energy), a second generation of technology has been introduced since 1970s. Thin-film PV cells are manufactured by depositing thin layers of photovoltaic materials (thickness < 2 μm) to form a heterojunction barrier. Due to the direct and wide bandgap of most thin-film semiconductor materials (1.5-1.8 eV), 2G cells have better temperature coefficients as well as a good performance in indirect light. Furthermore, the main advantage of thin-film cells stems from their very small thickness. Accordingly, they can be deposited on flexible substrate materials, they can be connected into modules during the manufacturing process of the cells through laser cutting, and they can be vertically stacked to form the 3G tandem (multi-junction) cells.

The categorization of thin-film cells is based on the deposited materials. This includes II-VI compound semiconductors such as Cadmium telluride (CdTe) and Cadmium sulfide (CdS); I-III-VI semiconductors such as CIGS; and amorphous silicon (a-Si). CdTe films can be produced using various techniques such as sputtering, high vacuum evaporation (HVE), and metalorganic chemical vapour deposition (MOCVD) (Kumar & Rao, 2014). Its cell efficiency record is 22.1%. On the other hand, CIGS cell technology of cell record around 22.6% can be manufactured using screen-printing, spray coating, spin coating, MOCVD, or electron beam deposition (Ramanujam & Singh, 2017).

a-Si thin-films with PIN structure are usually obtained using PECVD manufacturing process similar to microcrystalline silicon. However, the main difference between a-Si and c-Si technologies is the order of Si atoms. In a-Si material, atoms have extremely irregular structure with many dangling bonds, which are passivated with hydrogen atoms during deposition to mitigate electron-hole recombination. a-Si thin-film cells (~ 0.5 μm thickness) have an efficiency record of 14% and are widely used to power small electronic devices such as calculators.

The disadvantages of the discussed 2G thin-film technologies include their slightly lower efficiencies compared to c-Si, GaAs and multi-junction cells; the scarcity of raw Tellurium; the toxicity of Cadmium; and the degradation of a-Si power efficiency under light influence due to Staebler-Wronski effect.

2.1.3 Single-junction Gallium Arsenide (GaAs)

Despite being a type of thin-film technologies, the III-V direct bandgap semiconductor GaAs has superior electronic properties. Therefore, it is classified as a separate group in our definition of the PV system. This is also consistent with the NREL classification of PV cell technologies (NREL, 2017). With its bandgap level of 1.424 eV (at 300 K), GaAs is considered the optimum material to match the distribution of photons in the solar spectrum. Accordingly, it holds the highest efficiency record for a single-junction solar cell of 28.8%. This wide bandgap also yields a good performance under low light conditions. Besides its high saturated-carrier-velocity, GaAs has a low temperature coefficient, making it suitable for hot regions, as its conversion efficiency is less sensitive to temperature. Additionally,

GaAs films are lightweight, impervious to radiation and ultra-violet light, and thus convenient for aerospace applications. The main disadvantage of GaAs cells are their very expensive prices comparing to silicon based cells.

Several processes can be used to manufacture GaAs cells. Single crystals of GaAs are usually grown using the vertical gradient freeze (VGF) method (Gault, et al., 1986), the Bridgman-Stockbarger technique, or the liquid encapsulated Czochralski (LEC) growth process (Weiner, et al., 1971; Elliot, et al., 1984). Alternatively, GaAs layers can be deposited using MOCVD process (Fukui, et al., 1991).

2.1.4 Multi-junction Cells

To circumvent the Shockley-Queisser limit for single-bandgap devices (efficiency ≤ 31% or 41% depending on concentration ratio (Shockley & Queisser, 1961)), a third generation of solar cells has been developed since 1979 (Conibeer, 2007; Cotal, et al., 2009). The principle of this technology is to stack multiple thin-film layers of photovoltaic materials with different bandgaps to absorb the larger possible portion of the solar spectrum (sunlight wavelengths). Such semiconducting p-n layers include Ge, GaInAs, GaInP, GaAs, InAlAs, a-SiGe, μSi, and a-Si:H. Consequently, the resulted multi-junction cells can achieve very high conversion efficiencies (current record is 46% under concentrator system). Because of their complex manufacturing processes and high price, multi-junction cells are not used in civil applications but rather for powering spacecraft and satellites such as the International Space Station, Mars Global Surveyor, Juno Spacecraft, and Hubble Space Telescope.

2.1.5 Emerging and Organic Technologies

The fifth family of solar cells is the emerging technologies. It includes two main groups that are still non-commercial under research and development phase: the organic, and dye-sensitized solar cells (DSSC).

Being developed since the late 1980s, Organic solar cells use conductive organic polymers (such as copper-phthalocyanine and perylene tetracarboxylic derivative) to absorb light energy and generate electricity (Kippelen & Bredas, 2009). Organic light absorber layers are very thin (100-200 nm) consisting mostly of carbon. Consequently, lightweight flexible organic modules can be fabricated using roll-to-roll manufacturing techniques (Huang, et al., 2008). The cell efficiency record of organic technologies is 11.5%. Despite their low efficiency, organic materials are of relatively low cost and can offer the advantage of transparent solar cells (Traverse, et al., 2017; Zhao, et al., 2014). Unlike inorganic semiconductor cells that generated electrons and holes, organic cells are considered excitonic solar cells, where incident photons generate tightly bound Frenkel excitons first, before being separated with the use of a bulk heterojunction of mixed donor and acceptor layers that transfers and receives electrons respectively (Leo, 2016).

On the other hand, DSSC were originally developed by Brian O'Regan and Michael Grätzel in 1991 as a promising low-cost PV technology (O'Regan & Grätzel, 1991). DSSC consist of nanostructured metal-oxide electrodes (such as nanocrystalline/ nanoporous TiO_2) covered with sensitizing dyes (e.g. Ruthenium-polypyridine) and liquid iodide/triiodide electrolytes

(Fakharuddin, et al., 2014). When photons hit the dye, they can release electrons from their conjugated bonds to form electric current out from the anode through the outer circuit and back to the platinum cathode to be internally carried back to the dye through the electrolyte. The photo-electrochemical system of DSSC is fabricated using roll-printing techniques. With a conversion efficiency record of 11.9%, DSSC offers cheap, flexible and semi-transparent cells. However, the major disadvantages of this technology are related to the use of liquid electrolytes, which are vulnerable to leakage, expanding, or freezing under extraordinary temperature conditions. Accordingly, solid-state DSSC can form a promising upgrading of the technology.

2.1.6 Common Elements

Regardless of the semiconductor materials used in fabricating PV cells, there are several common elements, components, and techniques relevant for almost all cell technologies. These are (1) the materials and deposition processes of cell electrodes, (2) the texturing (roughening) methods of cell surfaces using acid etchants to reduce optical losses due to internal reflections, (3) wiring and inter-cell connection techniques within solar modules, and finally (4) doping materials and methods for producing the p- and n- semiconductors of cell junctions.

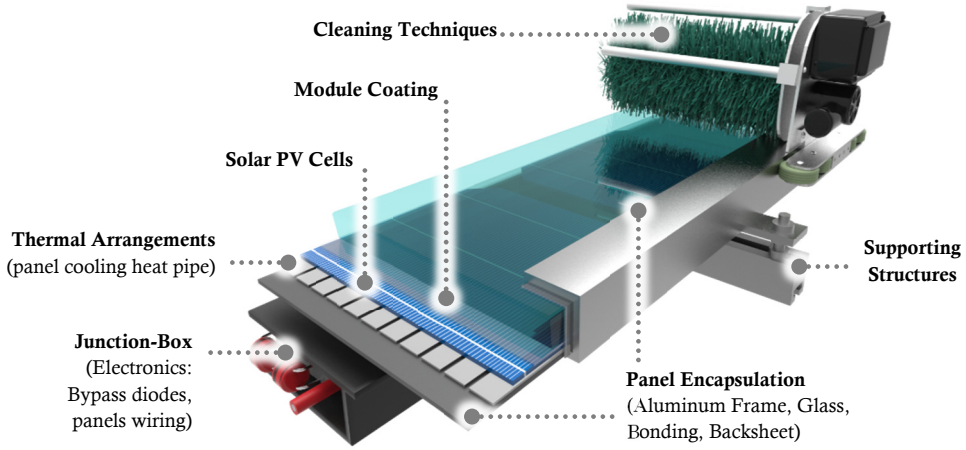
2.2 Balance of System Technologies

While cell technologies focus on the physical and chemical principles of converting light energy into electricity at a single-cell level, the balance of system technologies are related with delivering the generated energy in a sufficient manner to be used in the consumption side (Venugopalan & Rai, 2015). This includes the production and installation of solar panels, electronic charge controllers, battery storage units, testing and monitoring methods, and solar-powered portable devices.

2.2.1 Solar Panels

Solar panels are produced by coating, wiring, and encapsulating arrays of PV cells together. PV cells can be connected in series to increase output voltage, or in parallel to increase current. With the growing demand for solar energy powering both residential and utility-scale plants, the development of panel mounting and racking systems has gained a growing importance. The technological group of solar panels (figure 2) concerns mainly with mechanical engineering techniques. It consists of seven subgroups: (1) coating and protection processes of solar cell surface, (2) design of panel containers and encapsulation techniques, (3) roof covering methods and the mechanical design of mounting and supporting structures, (4) optical elements and arrangements such as mirrors and lenses used in concentrated PV systems, (5) thermal elements and arrangements mainly designed for cooling solar cells in order to avoid efficiency degrading due to high temperatures, (6) cleaning methods of PV panels including sand, dust, and snow removing robots and techniques, and finally (7) any technological aspects related to designing, building, and controlling utility-scale PV power plants.

Figure 2: Solar Panel Technologies



Author's own elaboration

2.2.2 Electronics

The electronic circuits relevant to PV technology include three main groups: junction boxes, charge controllers, and inverters.

Junction boxes are installed on the backside of each solar panel (figure 2). They contain diodes and cables wiring panels together and with inverters or batteries. Two types Schottky-barrier diodes are used to protect panels from being overheated or damaged by reverse current: bypass-diodes and blocking-diodes. During daytime, if a panel get shaded, its current output falls drastically, so is the current through the string of the series panels to which it belongs as well as the output power. Additionally, the unshaded panels produce higher voltages that can reverse-bias the shaded cells causing hot-spot heating. Bypass diodes wired in parallel with each panel are used to circumvent this effect. On the other hand, blocking diodes connected in series between PV panels and batteries guarantee that electric current flows only in the direction from panels to batteries. Consequently, they protect the panels from current flow from the batteries at night.

Charge controllers are used to regulate the power transfer from PV panels to batteries in off-grid systems. They protect batteries from overcharging, and guarantee the operation of the solar panels at their peak power using maximum power point tracking algorithms (MPPT) that adjust the impedance connected to the panels depending on the operational conditions of illumination and temperature. MPPT can yield 20% power gain.

To match the generated PV power with the utility grid for feeding-in purposes, the DC output of PV panels needs to be inverted into alternating current (AC). PV inverters are used for this purpose. They are also useful in the local off-grid network to provide electrical appliances with their rating AC input levels.

2.2.3 Energy Storage

PV power generation is mainly dependent on sunlight intensity, which variates during the day as well as throughout the year. Accordingly, it is essential to PV systems to have means and components that guarantee the availability of energy whenever it is needed at the consumption side. The balance between energy supply and consumption is achieved using energy storage systems. This technological group contains the means and techniques for storing the PV generated energy, either internally (in-cell storage) using capacitors, or externally using batteries. Energy storage is an important feature especially for off-grid PV systems.

2.2.4 Testing and Monitoring

This group includes the inspecting and testing processes of the performance of solar cells and panels, both during- and after- manufacturing.

2.2.5 Portable Devices

The last group in our definition of the PV technological system comprises the portable devices powered by solar modules. This includes lighting devices, as well as thermal devices for heating or cooling purposes.

3. DATA AND METHODOLOGY

For the empirical analysis introduced in this article, patent data from the Worldwide Patent Statistical Database (PATSTAT) version 2016b were mainly used. PATSTAT contains more than 68 million patent applications filed worldwide, over around two hundred years, and covering all patentable subjects, fields, and technologies. In this section, we discuss the use of patents as an indicator of technological change that can lead to economic growth. We further introduce patent families, priority filings, and patent classification systems. After that, we review the available approaches used for identifying patent applications relevant to a specific industry. Finally, we introduce our identification approach for PV patents.

3.1 Patents as indicator of technological change

With more than one million new inventions being filed yearly in patent documents, patents are considered one of the richest sources of technological information. They reflect the accumulation of inventiveness knowledge as well as innovative activities conducted by research and development laboratories. Patents were originally created as a legal protection instrument that gives inventors exclusive time-limited rights to commercially produce, use, and sell their inventions while preventing others from making any commercial use of them without a prior permission or licence. Therefore, they are widely considered as a form of intellectual property with high technological and economic value (Pavitt, 1963). Patents comprise an interesting detailed insight on the accumulated knowledge of human beings for a relatively long period of time, along with the state of art in various cognitive fields. Additionally, being disclosed to the public containing detailed technical information and metadata about citations (knowledge sources) and affiliations (geographical locations) of

applicants and inventors, patent indicators are increasingly used by researchers in innovation studies.

However, the use of patent data as a sole measure of innovation encounters some limitations. Besides the wide variation in patenting propensity across countries, sectors, and organizations (Johnstone, et al., 2010), intellectual property laws and administrative procedures vary widely across patent authorities of different countries, and are subject to continuous adjustments. This fact needs to be taken into consideration when comparing absolute counts of patent filings across countries. Moreover, the cognitive values of patents are not alike; some patents contain radical innovations of high value, while many others have modest incremental improvements. In general, patents are directly related to solving technical problems, developing new processes, or discovering new materials, ideas, or inventions. However, they have nothing yet to do with products and markets. Therefore, they cover the inventiveness stage of technological change, rather than the entire innovative performance.

3.1.1 Patent Families and Priority Filings

Patent family is defined as a group of patent applications filed in several countries (patent authorities) to protect the same invention (OECD, 2009). Families are usually used in patent statistics to avoid double counting of same innovations when considering cross-country analysis of patent belonging to an industrial sector or a specific technology. Among different procedural definitions of patent families, we are using priority-filings for our analysis. As an extended family definition, a priority filing (de Rassenfosse, et al., 2013) uses the earliest patent application of each invention to indicate its family regardless of patent authority. It gives an accurate indication of the time and place where inventions first took place. Therefore, it can be used to capture and compare the complete landscape of patenting activities of several inventor countries.

3.1.2 Patent Classification

During examining processes, patent applications are classified into groups based on their technological content in order to facilitate novelty establishment, testing, and comparison with the state of the art. This process implements pre-defined classification systems agreed among patent offices and examiners. The International Patent Classification (IPC) is considered the most common system. It is used by more than hundred patent offices worldwide. Developed by the World Intellectual Property Organization (WIPO) under the Strasbourg Agreement 1971 and being updated on a regular basis, IPC provides a hierarchical system of symbols for the classification of patents according to the different areas of technology to which they pertain. In its 2016.01 version, the IPC divided the universe of patentable technologies into 8 main areas (named sections). Under which, detailed levels of 130 classes, 639 subclasses, 7,434 groups, and 65,152 subgroups were introduced to provide the full classification at its fifth level (Figure 3). This detailed allocation allows for the subject matter of a patent to be thoroughly classified.

Figure 3: International Patent Classification System

SECTION H: Electricity

CLASS H01: Basic electric elements

SUBCLASS H01L: Semiconductor devices…

GROUP H01L 31: sensitive to infra-red radiation, light, electromagnetic radiation…

SUBGROUP H01L 31/052: Cooling means directly associated with the PV cell…

H 01 L 31/052

Data source: WIPO IPC version 2016.01. Author's own elaboration

3.1.3 Approaches for identifying patents related to a specific technology

The main available approaches are: patent classification systems, keyword search, topic modelling and machine learning methods, sectoral identification, and expert selection. Using any of these approaches for research purposes is a trade-off between data completeness, data relevancy, as well as method simplicity and replicability. This section introduces a brief review of these approaches, their strengths, weaknesses, and applications.

1. Patent Classification Search

Following this approach, patent filings relevant to a specific technology are retrieved using the technological classes assigned by patent offices during examining process or their overlaps (Johnstone, et al., 2010; Benson & Magee, 2013; FRINNOV, 2009). Such classification systems are IPC (international), USPC (American), ECLA (European), and CPC (Cooperative- jointly developed by the European and American patent offices). The most famous example of this approach for environmental innovation research is the WIPO IPC Green Inventory (IGI).

Besides their replicability, direct availability, and technological basis, a key advantage of using patent classes is their language-independent nature. Searching and extracting patent documents written in different languages can be simply obtained through filtering IPC codes. This advantage is more pronounced in compared with other approaches such as keywords, topic-modelling, or expert-selection, where translations from different languages is essential for data completeness.

On the other hand, the IPC searching approach is not directly applicable if the designated sectors mismatch its classes. Hence, it is possible to obtain noisy inaccurate results when considering market-oriented research questions. Additionally, patent classification can be subjective due to examiners' judgement. It is also dynamic and regularly updated by adding new classes and removing others.

2. Keyword Search

In this approach a predefined set of keywords (technical terminology) is used along with Boolean rules (AND, OR, NOT, etc.) to search the important segments of patent applications (titles, abstracts, claims, etc.) and select the relevant patents (Costantini, et al., 2015; Liu, et al., 2011). Keywords can be either proposed by industrial experts and engineers, or extracted from representative patent filings.

Although keywords are among the most popular and convenient methods for technology-based patent analysis (Wu & Mathews, 2012; Johnstone, et al., 2010), it has some drawbacks when applied alone. Besides being time consuming, some relevant patents can be falsely excluded because of the various ways a technology can be described in the patent text which sometimes do not include the exact keywords. On the other hand, the keywords can be mentioned in the context of a non-relevant patent for explanation or comparison purposes. Accordingly, mere keyword searching might end up with many false positives. Furthermore, the outcome of this approach can largely differ when using different keywords or even when changing the combinational logic rules.

3. Topic Modelling

Topic modelling and machine learning methods are mainly based on the use of computer for recognizing patterns in patent texts that can be used for identifying specific technologies automatically after being trained with a sufficient amount of data (Venugopalan & Rai, 2015; Lopez & Romary, 2010). Although these methods sound very promising, the large effort, time and computational power they need in the machine teaching stages as well as the difficulty to find the exact point when the machine can be considered well-trained, and thus can be further used for automatic classification, are all among the major drawbacks. Additionally, being very specific to its design circumstances and algorithm variables, the replicability of such methods is still questionable.

4. Sectoral Identification

This approach starts with listing the active companies within the industrial sector under consideration. The next step is to search for patents filed by these companies. Applying such a firm-oriented approach can give precise results in terms of relevancy. However, some important data will be completely lost: especially for inventions by non-firm actors such as universities, research institutes, and individuals, or relevant innovations by firms from other industrial sectors. The second disadvantage is the need for additional data sources for firm activities and industrial sectors. Furthermore, some companies have a wide range of technological activities that can lead to false positives when including all their patent portfolios through this approach.

5. Expert selection of patents

In this approach, the relevant patents out of a pre-filtered stack of files are manually identified and classified into industrial sectors by a team of experts in different technological fields

(Scherer, 1984). Although it is theoretically the most precise identification method, it is impractical and inapplicable when considering several thousands of patent applications.

Combinations of these approaches are increasingly being used in research to optimize the completeness, relevance, and replicability of patent identification. Such strategies can be found, for example, in (Wu & Mathews, 2012; de la Tour, et al., 2011; Wang, 2011) as well as this contribution.

3.2 Methodological Approach:

In order to identify the patent applications related to the technological system of photovoltaics, this paper introduces an integrated methodology that combines all the previously mentioned approaches. The main aim is to compensate the weaknesses of each approach with the strengths of the others, so that the final results can offer high levels of data completeness, relevancy, and replicability. The proposed methodology (figure 4) consists of four successive processes: (1) building an inventory of IPC codes for PV system, (2) codes verification, (3) validation, and finally (4) assigning these codes into the PV system groups and subgroups defined in section 2.

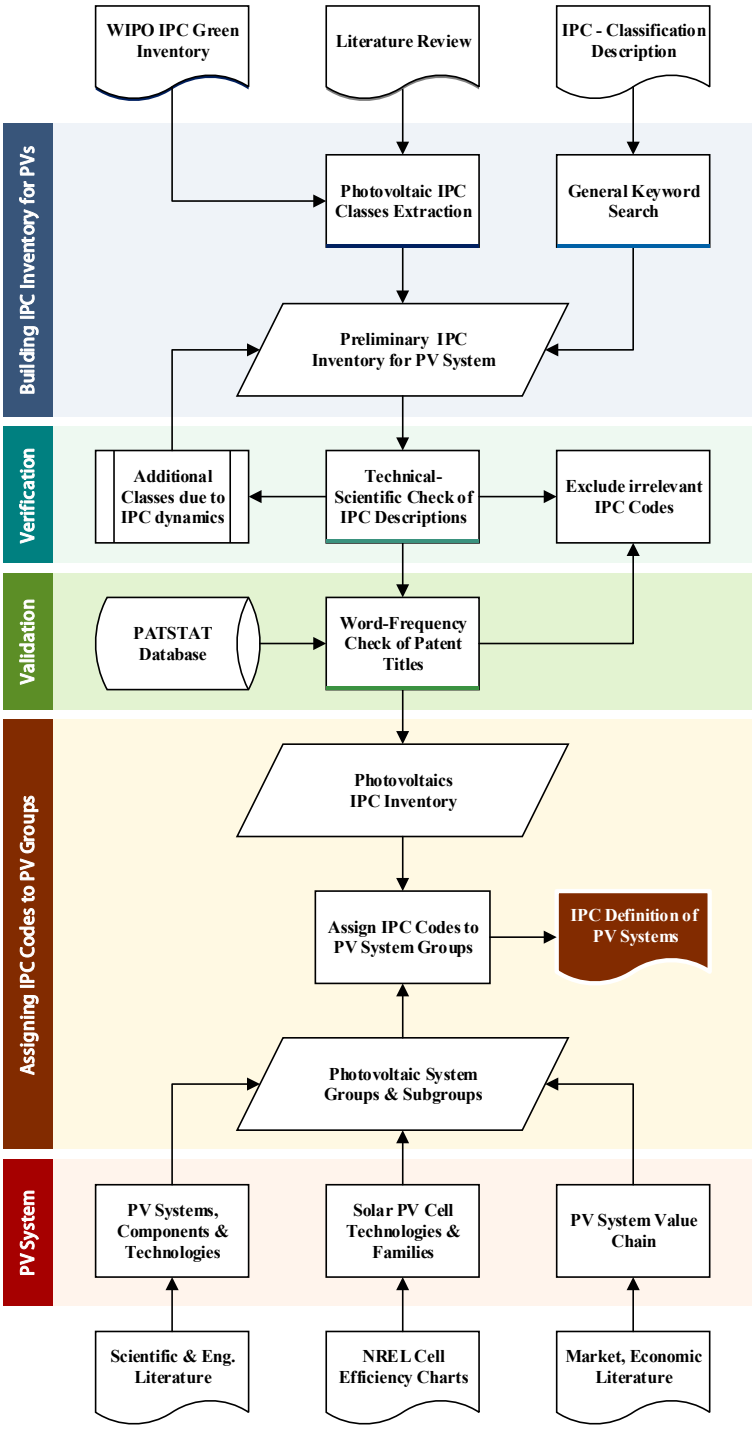
3.2.1 Building IPC inventory for PV system

PV-related IPC codes were extracted from four main types of sources: (1) the IGI, (2) reports by international organizations such as WIPO and OECD, (3) scientific publications, and (4) a general keyword search for IPC subgroups that refers to solar PV in its documentation. This process ended up with a total number of 284 IPC subgroups being collected in a preliminary IPC inventory for the PV technological system.

3.2.2 Verification

The second process of the proposed approach is to verify the IPC codes collected in the preliminary inventory. Verification is defined as the internal checks that guarantee the system compliance with regulations, specifications, or imposed conditions (PMI, 2008). Accordingly, the verification of IPC codes checks whether they are originally designed for PV purpose or not. A thorough investigation of the technical terms and notes available in the IPC documentation were done for each subgroup individually. Consequently, additional 38 IPC subgroups were added to the preliminary inventory, mostly belonging to a subclass that was introduced since 2014, and hence not included in the IGI and the reviewed literature. On the other hand, 99 IPC codes were excluded from the inventory in this stage, based on expert investigation, as they are irrelevant to PV. For example, many of the codes belonging to the IPC group (H01L 21) were excluded, as they refer to the manufacturing of other electronic devices such as diodes, transistors, computer memories and integrated circuits. Such electronic devices undergo very similar manufacturing processes to those of c-Si cells. However, as the IPC clearly distinguish between the different final products, they were excluded from the inventory.

Figure 4: Research Methodology Flowchart



Author's own elaboration

3.2.3 Validation

Validation is defined in engineering project management standards as an external checking process guarantees that the system meets the needs of the stakeholders (PMI, 2008). Accordingly, the validation process here refers to the formal checks done to assure that the collected IPC codes in the inventory are actually used by examiners in patent offices around the world for classifying PV patents. This was done using text statistical analysis (keyword frequency check) across the titles of all patents classified under each IPC subgroup. PATSTAT database was used for this purpose. It resulted in excluding further 67 IPC codes that were figured out been used in practice for classifying patent applications related to CMOS camera sensors, transistors, and LCD technologies, and not related to PV cells or any other components within the PV technological system.

Up to this point, a final IPC inventory of 156 codes for PV technological system has been generated, undertaken multilevel examination checks, and thus ready to be used.

3.2.4 Assigning IPC codes to PV system groups

The final step in the proposed approach is the assignment of IPC codes into the PV system groups and components defined in section 2. However, two special cases were found: global- and combined subgroups. Combined subgroups contain patents related to several PV technologies at the same time. On the other hand, global subgroups are those not only designed for PV technologies. They include patents for processes, manufacturing methods, or apparatus that represent an input for many technologies including but not limited to PV (e.g. the process of purifying silicon to produce single crystalline wafers is a global input process in the engineering world of Nano- and Micro- technology. Such wafers can be used for manufacturing transistors, integrated circuits, CMOS camera image-sensors, or mono c-Si PV cells). The significance of having the global IPC classes flagged in this definition is to indicate components in the PV system supply-chain that are not solely focusing on PV, but also supply other industries with elementary materials.

The final results of our approach are shown in table 1, where the IPC codes (identified in this section) are assigned to the PV technologies (defined in section 2). To sum up, the significance of the introduced approach lies in its detailed utilisation of the IPC system to identify PV technologies at the largest possible resolution, i.e. the 5th level of classification comparing to the three levels used in previous works. Furthermore, it bridges the gap between the scientific and market sides of the technology, and thus supports innovation studies in this field. While some of the already available identification methods are very difficult to be re-applied with other data sets or time periods, the introduced definition is fully replicable because it based on IPC subgroups that are used by almost all patent offices worldwide.

With this definition, specialization research questions can be addressed easily and more effectively. National trends of inventive activities along with domestic technological advantage can be investigated at various levels of the PV field. In other words, alternative to the aggregated data for the whole system, PV patenting activities and trends can be captured and compared at more detailed levels.

Table 1: IPC Codes of the PV Technological System Components

GROUPS	SUBGROUPS	IPC CODES	
Cells	**1. Crystalline Silicon Cells**	H01L 31/028 H01L 31/0352**	H01L 31/068 H01L 31/18**
	1.1 Monocrystalline (Single Crystal)	C01B 33/02* C30B 29/06* C30B 15/00-36*	H01L 31/061 H01L 31/077
	1.2 Polycrystalline	C30B 28/00-14*	H01L 31/0368
	1.3 Silicon Hetero-structures (HIT)	H01L 31/0747	
	1.4 Thin-film Silicon Microcrystalline	H01L 31/06**	H01L 31/072**
	2. Thin-film Technologies	H01L 27/142 H01L 31/0445 H01L 31/046 H01L 31/0256**	H01L 31/0475 H01L 31/065 H01L 31/0248**
	2.1 CIGS, CZTSSe	H01L 31/032	H01L 31/0749
	2.2 CdTe	H01L 31/0296 H01L 31/0264**	H01L 31/073
	Both 4.1 and 4.2	H01L 31/0272	H01L 31/0336
	2.3 Amorphous Si:H	C23C 14/14* C23C 16/24* H01L 31/0376 H01L 31/04**	H01L 31/0392 H01L 31/075 H01L 31/20 H01L 31/07**
	3. GaAs Cells	H01L 31/0304 H01L 31/0693	H01L 31/0735
	4. Multi-junction Cells	H01L 31/0312 H01L 31/0328 H01L 31/043 H01L 31/047 H01L 31/0687	H01L 31/0725 H01L 31/074-0745 H01L 31/076 H01L 31/078
	5. Emerging Photovoltaics	H01L 51/44-48	
	5.1 Dye-sensitized cells	H01G 9/20	
	5.2 Organic Cells	H01L 27/30 H01L 31/0384	H01L 51/42 H01L 31/0468**
	6. Common Elements	H01L 31/036	
	6.1 Electrodes	H01L 31/0224	
	6.2 Surface Textures	H01L 31/0236	
	6.3 Cells Connection	H01L31/0463-0465	H01L 31/05
	6.4 Doping Materials	H01L 31/0288	
Panels	**1. Coating/Protection**	H01L 31/0216	H01L 31/041
	2. Containers/Encapsulation	H01L 25/00 H01L 25/16-18* H01L 31/02	H01L 31/0203 H01L 31/048-049
	3. Roof Covering and Supporting Structures	E04D 1/30 E04D 13/18 H01L 31/042	H02S 20/00-32 H02S 30/00-20
	4. Optical Elements/Arrangements	H01L 31/0232 H01L 31/054-56	H02S 40/20-22
	5. Thermal Elements/Arrangements	H01L 31/024	H01L 31/052-0525
	6. Cleaning	H02S 40/10-12	
	7. Power Plants	H02S 10/00-40	

Electronics	**1. Junction Box (Bypass Diodes)**	H01L 31/044-0443	H02S 40/34-36
	2. MPPT	G05F 1/67	
	3. Inverters, Feeding Circuit	H02J 3/38	H02S 40/32
	4. General Electronic Elements	H02S 40/30	
Energy Storage	**1. In-cell Storage (Capacitors)**	H01L 31/053	
	2. Battery Charging Arrangements	H02J 7/35	
	3. Batteries	H02S 40/38	
Monitoring / Testing	**1.Testing during manufacturing**	H01L 21/66	
	2.Testing after manufacturing	H02S 50/00-15	
Devices	**1. Lighting Devices**	F21L 4/00	F21S 9/03
	2. Thermal Devices (heating, cooling)	H02S 40/40-44	
Combined	Combinations of the groups above	H01L 31/00 H02S 40/00	H02N 6/00 H02S 99/00

*global subgroups (not only for PV), **mainly for the designated subgroup but might contain other cell technologies

4. ANALYSIS AND RESULTS

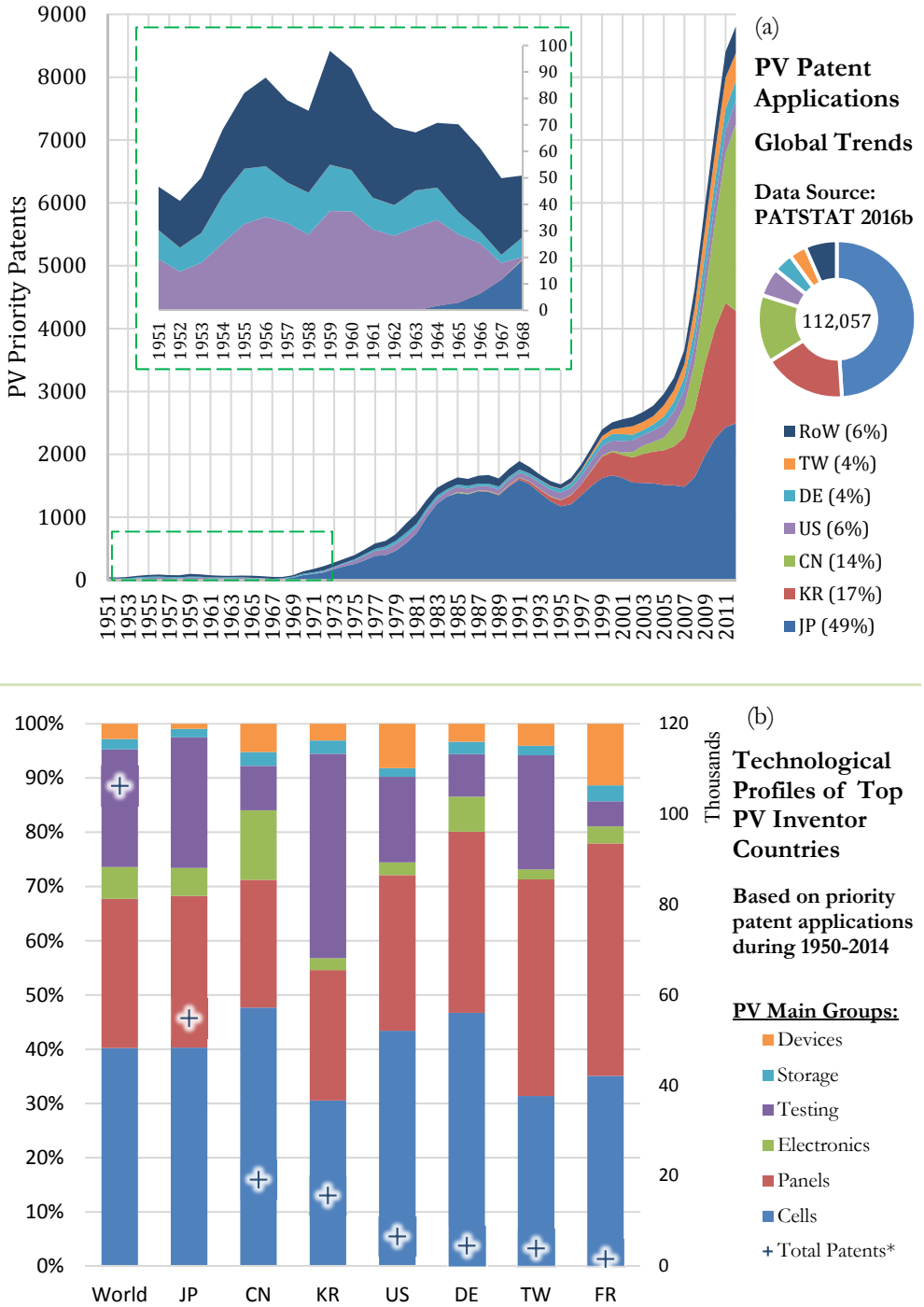
In this section, the general trends of PV patent applications are investigated, followed by a detailed consideration of the technological system development from three main perspectives: geographical, technical, and organizational, as in (Pettersson, et al., 2012).

4.1 General Trends

Landscaping the universal patenting activities in PV sector since 1950, we found more than 112,000 priority patent applications. They were filed in 73 different patent offices by around 50,000 applicants and 200,000 inventors from 110 countries. Figure 5a shows the trends for annual counts of priority patent applications during the period 1951-2011. Patent stocks are counted based on the country of inventor as a better proxy of the location, where inventions took place. The trends show a continuous growth of patenting activities within the PV sector. Starting from low patenting levels below 100 filings per annum during 1950's and 1960's with inventors mainly from USA and Europe (esp. Germany, UK and France), a dramatic growth during 1970-1985 can be noted. Annual patents reached the level of 1,600 in 1984 then stabilised below the level of 2,000 until early 1990's. This growth was mainly driven by Japanese inventions. Despite the notable decrease in filings occurred in 1991-1994 (which can be related to the general decline in patenting activities in Japan in all fields during early 1990's (WIPO, 2008)), a second wave of growth within the PV system occurred during 1995-2000. It was rather driven by the entry of South Korea to the PV sector. Global PV patents exceeded the level of 2,500 in 2000. Since 2006, a third and even steeper growth jointly driven by China, Korea, and Japan has raised patent applications to the level of 9,000 filings per annum in 2011. In recent years, the case of China seems prominent, as it has experienced the highest growth (average annual rate above 40% since 1997).

In what concerns the technological distribution, figure 5b shows that 39% of the global patents belongs to solar cell technologies. The solar panels group forms the second largest group with the share of 27%, followed by testing techniques (21%), and electronics (6%).

Figure 5: General Trends of PV Priority Patents

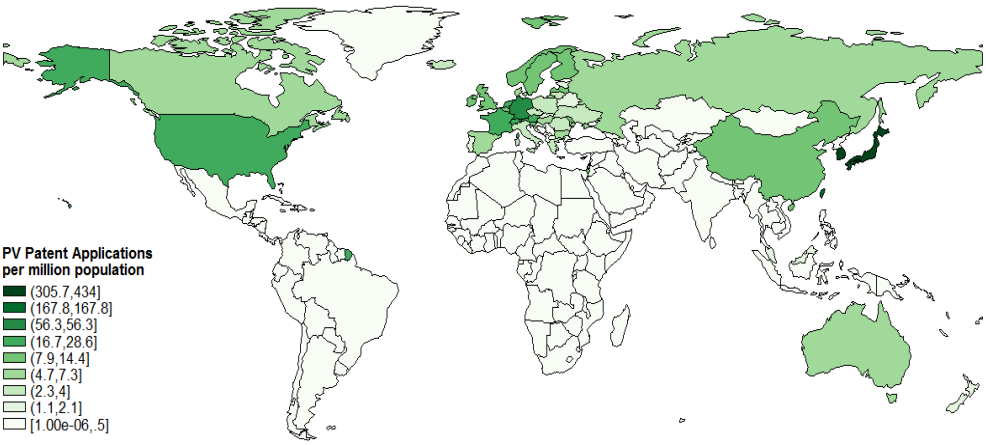


*Figures for total patents are given in secondary axis. Author's own elaboration

4.2 Geographical Perspective

In terms of accumulated patent applications in the field during the full period, only seven countries were accountable for 95% of the total filings. These countries are Japan (49%), Korea (17%), China (14%), USA (6%), Germany and Taiwan (4% for each), and France (1%) (Figure 5a). Figure 6 shows a world Choropleth map of accumulated PV patent applications per population of countries. Japan, Korea, and Taiwan holds the top per-capita PV patents of 434, 305.7, 167.8 respectively, followed by Germany (56.3), Switzerland, France, and USA (around 25 each). On the other hand, China comes at the tenth place with 14.4 PV patents per capita.

Figure 6: World Map of PV Patent Applications per Population of Countries



Author's own elaboration

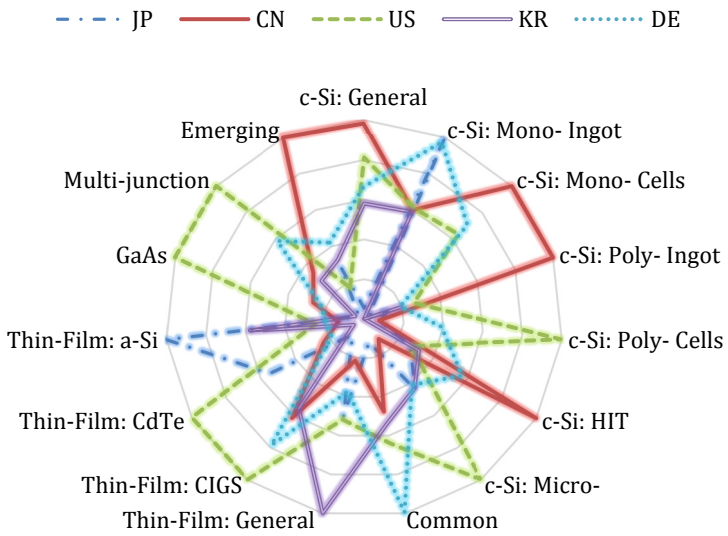
To investigate the technological profiles of the top countries, we first considered the general technological groups within the PV system definition. Figure 5b shows that the cells group holds >40% of filings in China, Germany, USA and Japan, while panels form the main specialization of France and Japan. On the other hand, 37% of the Korean PV patents belong to the testing & monitoring group.

Going one level deeper with the technological specialization analysis of the top PV inventor countries, we calculated their Revealed Technology Advantage (RTA) index (Balassa, 1965; Soete & Wyatt, 1983) for each technological group (figure 7). The RTA values in the figure were normalized to the range of [0-1] with relevance to the maximum value in each group. For what concerns cell technologies (figure 7a), China has shown a relative advantage in c-Si cells (esp. mono-Si cells and poly-Si ingots) as well as in the emerging cell technologies. Japan and Germany have a relative advantage in mono-Si ingots. While Korea has advantage in general thin-film technologies, USA is highly specialized in the CdTe, CIGS, GaAs, and multi-junction technologies. In the a-Si thin film technology, Japan holds the highest RTA.

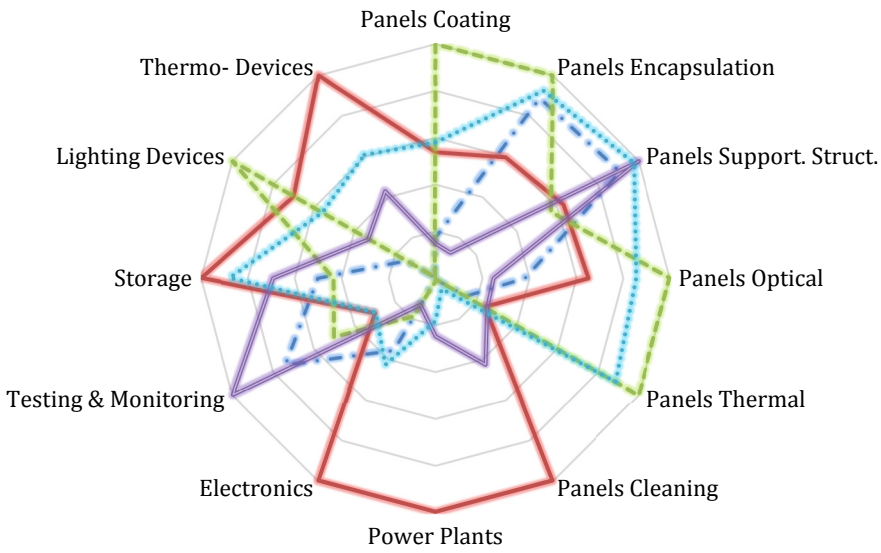
On a related front, figure 7b shows the RTA levels within the BoS technologies. While USA has a relative advantage in the coating, encapsulation, optical, and thermal groups of PV

panels, China is more specialized in PV power plants, panel cleaning, electronics, energy storage and thermal devices. On the other hand, Korea, Germany and Japan have the lead in panel supporting structures.

Figure 7: RTA Specialization Profiles of Top 5 Countries



(a) PV Cell Technologies



(b) PV Balance of System Technologies

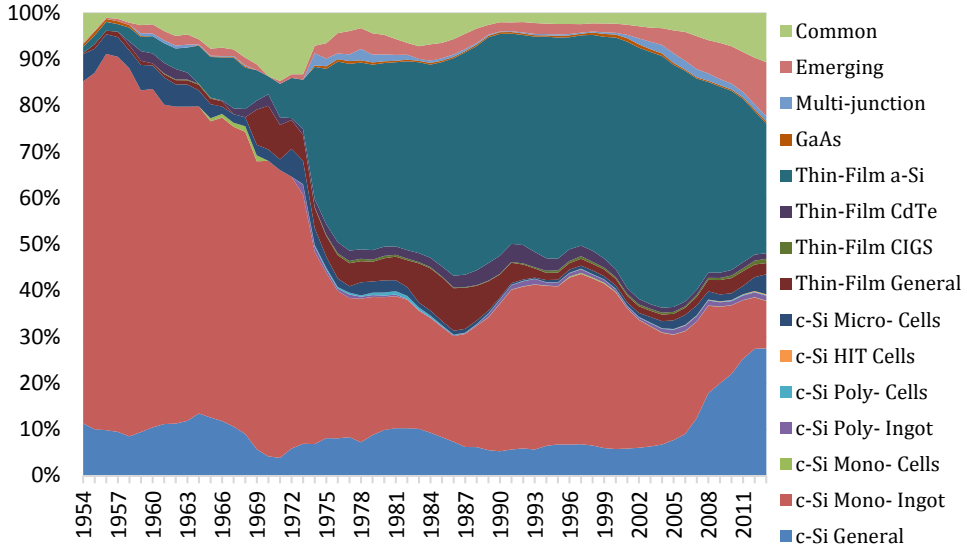
Author's own elaboration

4.3 Technical Perspective

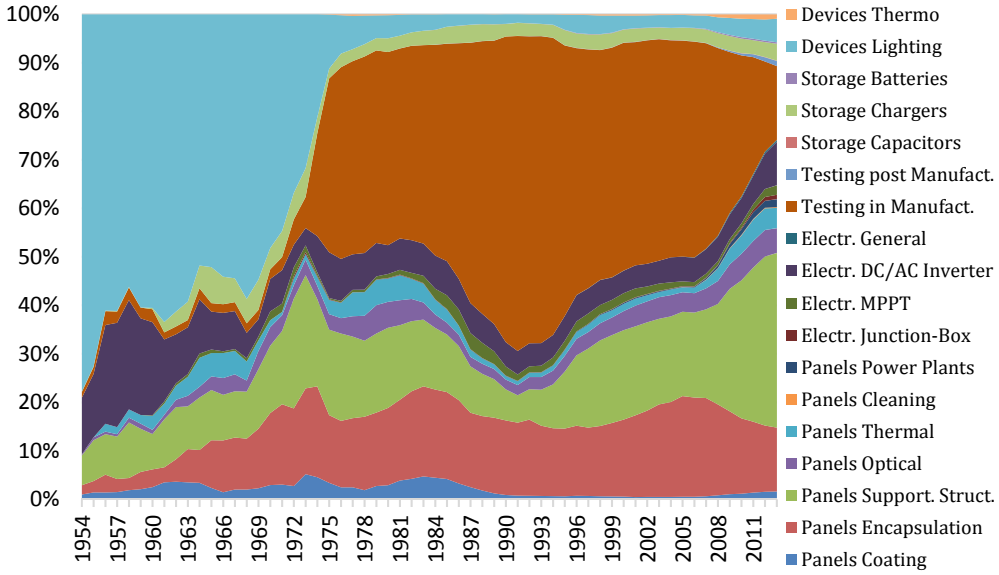
To understand the dynamic development of the PV system from a technical perspective, the annual-share trends of each technology are shown in figure 8. It highlights the relative importance of PV technical groups over time.

Figure 8: Temporal Distribution of PV Technologies

(a) PV Cell Technologies



(b) PV Balance of System Technologies



Author's own elaboration

In respect of cell technologies (figure 8a), mono-Si ingots form the dominant technology over 1954-1974. However, since 1974, the thin-film technology of amorphous silicon has become the most patented cell technology. A growth of emerging technologies since 2001 can be noticed. Moreover, the fabrication of c-Si cells is gaining an increasing importance since 2005.

On the other hand, the landscape of BoS technologies (figure 8b) shows two major shifts in technical focus of patents. During 1954-1974, lighting portable devices held around 60% of patentable inventions. However, testing techniques (during-manufacturing) became the dominant technology over 1975-2005. Finally, a growing stream of panels' encapsulation and supporting structures can be noted since 2005.

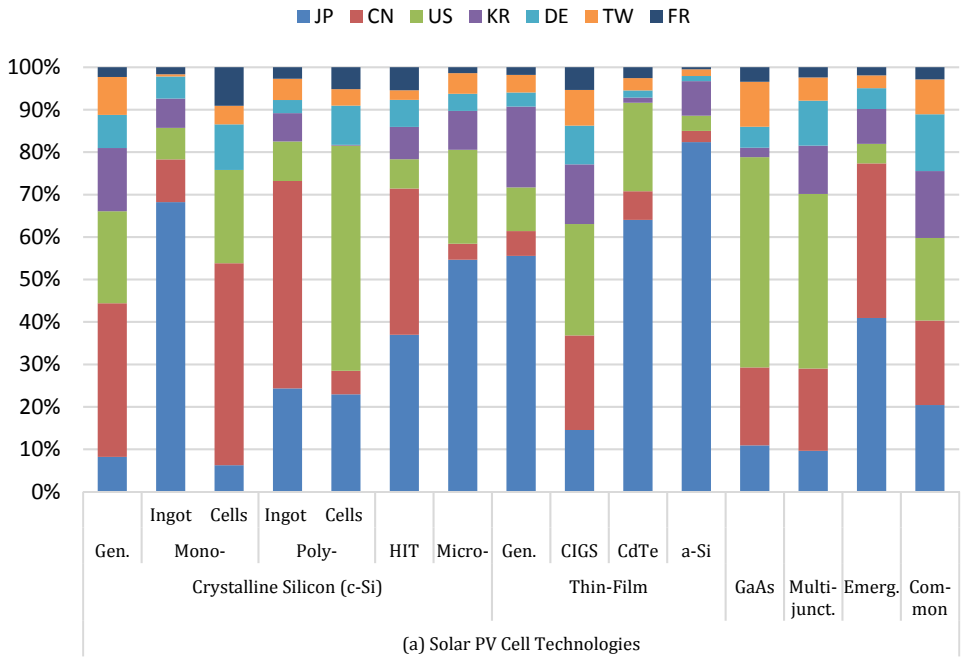
Considering the spatial distribution of PV technologies over the top patenting countries (figure 9), diversified patterns can be noted. Concerning c-Si cell technologies (figure 9a), around 70% of patents in mono c-Si ingots are developed in Japan. While China holds large portion of the patents in mono c-Si cells and multi c-Si ingots, USA is accountable of half the global patents in poly c-Si cells.

Similar trends are noted for HIT and the emerging cell technologies, where 70% of the patents are held equally by Japan and China. In microcrystalline and general thin-film technologies, Japan holds around 55% of the priority filings. Though half of the patents of CIGS technologies are filed by USA and China, CdTe and a-Si cells are mostly developed in Japan. On the other hand, the expensive high efficient technologies of GaAs and multi-junction cells are dominated by USA. The analysis further shows an equally distributed pattern across the top countries in what concerns the common elements group within cell technologies.

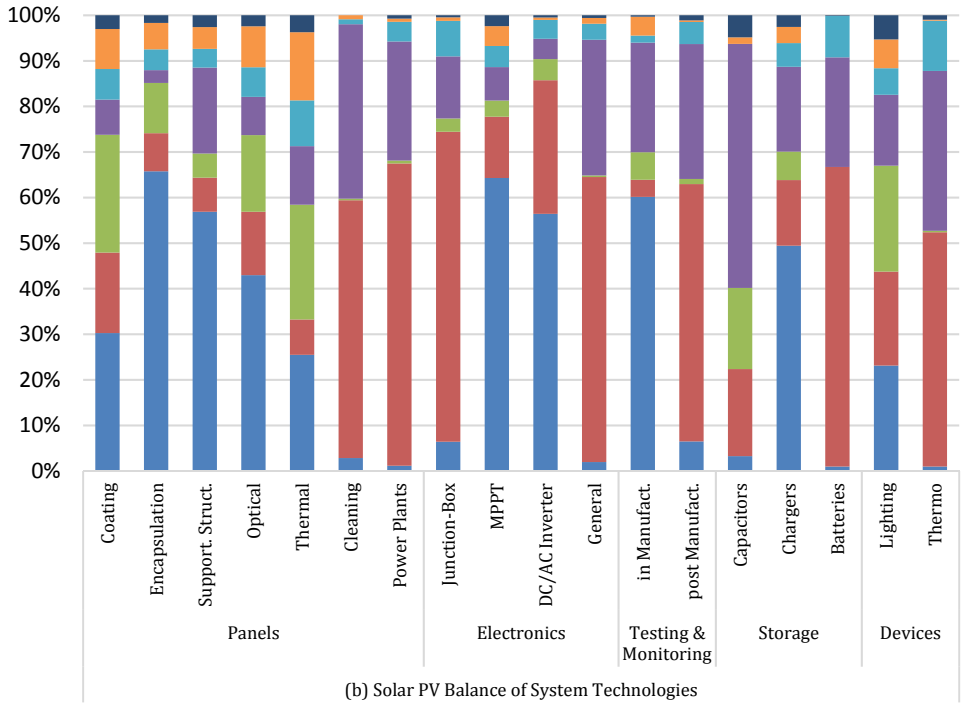
Regarding the BoS technologies (figure 9b), the analysis shows a diversified distribution patterns too. In panel technologies, most encapsulation and supporting structure patents are filed by Japan. While China is specialized in utility-scale power plants, USA has around 25% of the coating and thermal arrangements. Panel cleaning technologies are dominated by China and Korea.

As far as the electronics group is concerned, PV junction-box patents are mostly filed by China, while 60% of the patents for MPPT and inverter technologies are held by Japan. Testing during manufacturing is dominated by Japan, whereas post-manufacturing testing techniques are mostly patented in China. In both cases, Korea comes in the second place with a share around 25% of the patents. Internal energy storage techniques are mostly patented in Korea. The same holds for battery technologies in China and charging arrangements in Japan. Whereas a homogeneous distribution of lighting device patents is found across Japan, China, USA and Korea. Thermal devices are dominated by China, Korea and Germany.

Figure 9: Spatial Distribution of PV Technologies



(a) Solar PV Cell Technologies



(b) Solar PV Balance of System Technologies

Author's own elaboration

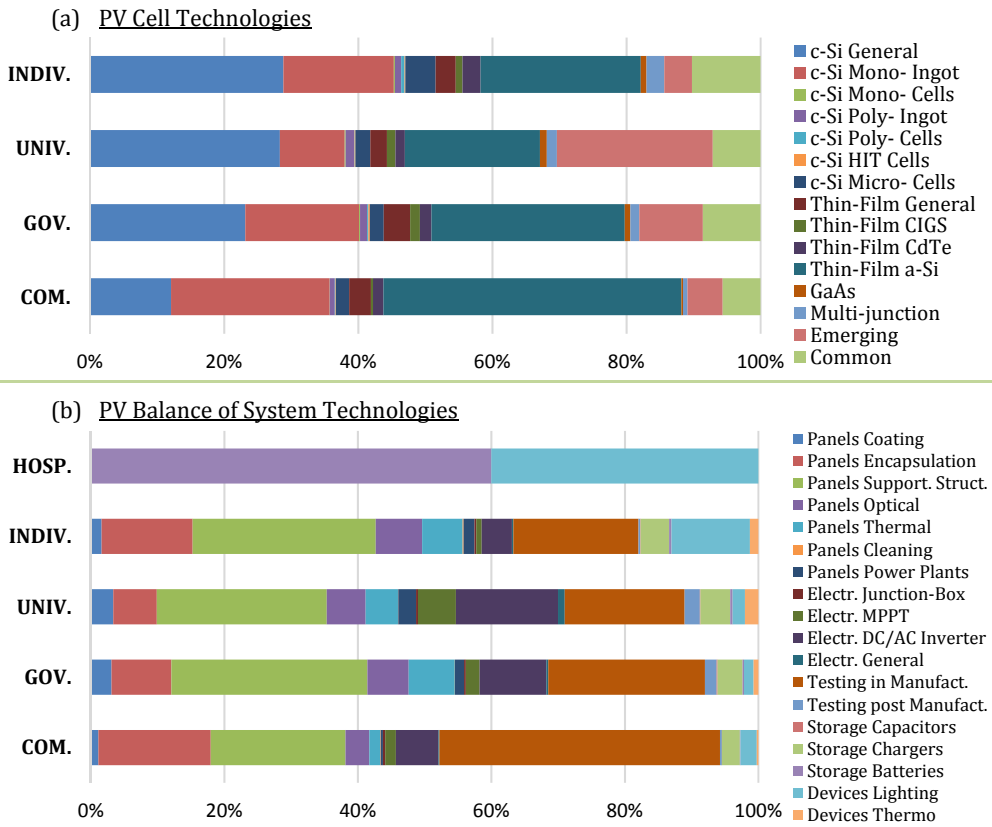
4.4 Organizational Perspective

Five organizational types were found as applicants for PV patents: private companies, public organizations (such as government owned companies and research centres), universities, hospitals, and individuals. Most priority patents are filed by private companies (78%), individuals (12%), and universities (5%).

Figure 10 shows the distribution of PV technologies over the organizational types of applicants. 45% of companies filed patents in a-Si thin-film cells compared with 39% in c-Si technologies. State-owned organizations have a similar portfolio, however a less share of thin-film technologies is compensated with patents in c-Si and organic cells. For universities, the share of emerging and organic cell technologies seems prominent. The portfolio of individuals is more homogenous.

With regard to BoS technologies (figure 10b), companies have relative advantage in testing (during manufacturing) and panel technologies. Prominent share for the electronics group (MPPT and DC/AC inverters) is noted in universities. Furthermore, the portfolio of hospitals comprises patents in off-grid energy storage (batteries) and lighting devices.

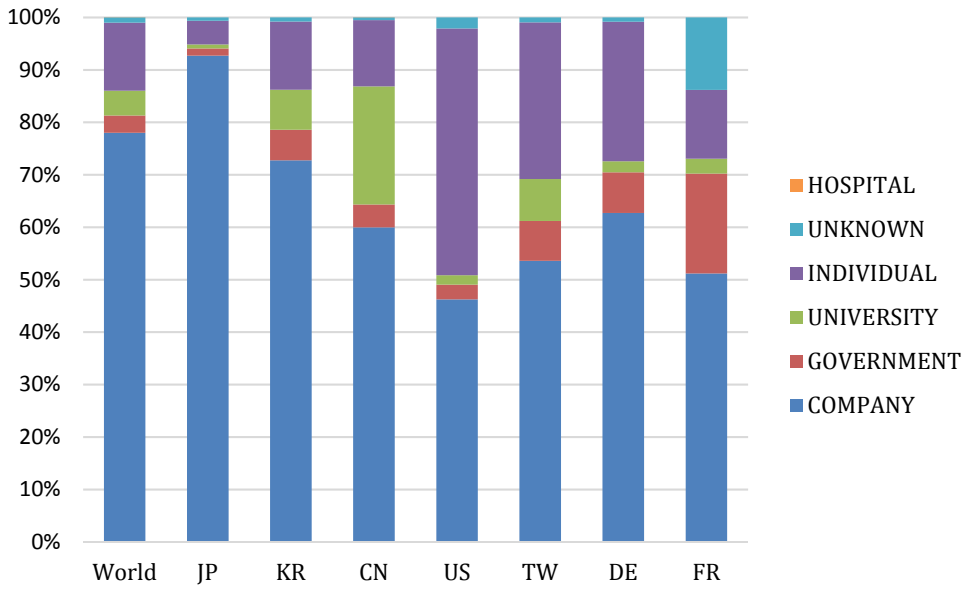
Figure 10: Technical Distribution of Organization Types of Patent Applicants



Author's own elaboration

Regarding the geographical distribution of organization types, figure 11 shows different patterns for the top countries. While the vast majority of PV patent applicants in Japan are private companies, around 50% of the American applicants are individuals. On the other hand, universities have a prominent share in the Chinese patents (22%). In France, government owned organizations are accounted for 19% of the country's patents in the PV sector.

Figure 11: Geographical Distribution of Organization Types of Patent Applicants



Author's own elaboration

5. CONCLUSIONS

The methodical approach introduced in this article distinguishes between different solar cell technologies making them directly capturable with patent classes. Furthermore, it offers a wider and more comprehensive definition of the PV technological system including the BoS components: electronic circuits, mechanical supporting structures, and portable devices, in conjunction with the cell and module technologies. This allows for a clear differentiation within the system between electrical-, mechanical-, as well as chemical micro-technology based knowledge.

Using the technological system of photovoltaics defined in section 2, we identified its relevant priority patent applications through a sequential procedure of IPC identification, verification, validation, and technical assignment processes as explained in section 3. Accordingly, the geographical, technical, and organizational trends of PV global patenting over the last sixty years were discussed in section 4. The proposed approach shows a high

level of data completeness; high relevancy; relative simplicity and replicability for future implementation.

The results revealed interesting findings regarding the three perspectives. The geographical analysis shows that 95% of PV patents are filed by inventors in seven countries, which are Japan, Korea, China, USA, Germany, Taiwan, and France. In terms of technological specialization, China is mostly focused on the 1G c-Si cells, while Korea, Japan, and USA have relative advantage in the 2G thin-film technologies. Regarding the efficient technologies of GaAs and multi-junction cells (3G), USA is the main innovator so far. The technical analysis further shows two main shifts in the patenting focus, first in 1974 from the purification of monocrystalline silicon to the thin-film technology of amorphous silicon, and second to the fabrication of c-Si cells since 2005. This has been accompanied by a shift from lighting devices towards testing and monitoring, and later to solar panels during the same years. Finally, the organizational analysis shows a significant importance of private companies in filing patent applications in the PV field. However, other types of organizations play important roles in some countries, such as individuals in the USA and Germany, universities in China, and public research institutes in France.

Overall, the paper attempts at profiling the global trends and advances in the field of solar photovoltaics. Despite patents can reduce the freedom-to-operate in front of several manufacturers, they, nonetheless, strongly indicate the technological development within the sector in the broader context. Even with the several milestones yet to be achieved, solar technology is widely considered as a promising energy source for a sustainable future. Besides its vital role in the earth's ecosystem, photosynthesis, climate, warmth, and light, sun does still have much more to offer.

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Drifting Towards Innovation:
The Co-evolution of Patent Networks, Policy, and Institutions in China's Solar Photovoltaics Industry

Chapter 3

ABSTRACT

Since 2008, China has become the dominant force in solar cell production in the world. 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. An increasing population of Chinese patent applicants clustered in isolated communities has driven technological catching-up in solar photovoltaics. The role of foreign actors in the co-patenting activities is surprisingly low and decreasing.

KEYWORDS

Photovoltaics; China; Network Analysis; Transnational Patents

JEL CLASSIFICATION

D85; O31; O34; Q42; Q55

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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 (OECD, 2016). 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 (Godinho & Ferreira, 2012).

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 (Malerba, 2002; Carlsson & Stankiewicz, 1991; Malerba & Nelson, 2011). 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 (UNEP, et al., 2010). 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 (UNEP, et al., 2010; Marigo, 2007). 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 (Fu, 2015). In 2013, China accounted for 60% of the global PV cell production (Jäger-Waldau, 2013) having more than 500 solar PV firms (Fu, 2015). 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 (Lema & Lema, 2012; Iizuka, 2015; Zhang & Gallagher, 2016; Zou, et al., 2017; Sun, et al., 2014).

Against this rapid growth of China's share in the global PV market, we examine whether a similar trend can be found in technological 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. (2016) 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 (Sun, et al., 2014). 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 (Huang, et al., 2016, 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 (Huang, et al., 2016; Zou, et al., 2017). 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 2004-2008, 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 (Song, et al., 2015; Huang, et al., 2016; Zou, et al., 2017). 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" (Huang, et al., 2016, 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 (Zou, et al., 2017, p. 201; Huang, et al., 2016, 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 (Song, et al., 2015). 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 (Zou, et al., 2017; Huang, et al., 2016).

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 (Huo & Zhang, 2012; Zhao, et al., 2013; Shen, 2017; Zhang & He, 2013).

Interestingly, research suggests that policy regimes in developed economies have largely influenced the Chinese experience as well (Quitzow, 2015; Iizuka, 2015). Quitzow (2015) studies the interactions between the Chinese and the German technological innovation systems at the national level and the reciprocal influences via transnational linkages. Iizuka (2015) 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 (de la Tour, et al., 2011; Zhang & Gallagher, 2016; Zou, et al., 2017; Sun, et al., 2014) Only (de la Tour, et al., 2011) use patent indicators for the period 1997-2007.[24] 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.[25] 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.[26]

Existing results point out that in the industry emergence phase, China did not have competences in PV technologies. The recruitment of skilled Chinese entrepreneurs and the acquisition of foreign turnkey production lines were the main channels for technology adoption. The production process using manufacturing equipment did not require complex technologies and skills. At first, this strategy of foreign technology acquisition did not bring domestic innovation capabilities (de la Tour, et al., 2011). However, learning process have been taking place. (Zhang & Gallagher, 2016) describe a vertical integration process observed in Chinese leading PV manufacturing firms. Cell manufacturing companies entered the upstream segments to produce purified silicon, investing in research to develop their own technology. The vertical integration strategy ensured stable material supply and accelerated knowledge sharing across segments (Zhang & Gallagher, 2016, p. 196).

The research results available do not give a clear view of the role of foreign actors for Chinese technological innovation. (de la Tour, et al., 2011) point out that foreign direct investment (FDI) and joint-ventures have not played a significant role for technology development and innovation. According to case study analyses of technology transfer in low carbon sectors in China, foreign firms facilitate knowledge flows and learning for transferring existing technology for production processes. There is no evidence of knowledge transfer and technological collaboration in innovation activities (Watson, et al., 2015). Interestingly, in the study of patterns of technological collaboration in the solar cell industry using patents put forward by (Lei, et al., 2013), China shows a stronger tendency to collaborate internationally than other countries (even though it has a small total number of patents in the field).

The reviewed studies suggest that the innovation capabilities to develop PV technologies in China have been accumulated through domestic research and development activities. The trade of intellectual property rights such as licensing has played no role. The role of FDI, collaborative research, and joint ventures has not been sufficiently discussed in the literature. Furthermore, there are is no deep quantitative analysis so far studying the process of

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[24] (de la Tour, et al., 2011) count patent families where patents have been granted in the US and in China.

[25] 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).

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

accumulation of capabilities in PV in China at the industry level considering in detail the different technologies and industrial segments involved. The interactions of innovators as well as the roles of non-firm actors such as universities, research institutes, state-owned companies, and individuals in the innovation system are still uncovered in the literature. There is still open room for quantitative research to explore (i) whether China is transcending from producer to innovator in PV technology, (ii) the technological path followed in the catching-up process and (iii) the role of foreign actors in this process. Taking an evolutionary perspective, the paper attempts to fill in these gaps in the literature.

3. CONCEPTUAL FRAMEWORK

Our conceptual framework to study the accumulation of innovation capabilities for the development of PV in China and the technological networks shaping this process draws first on theoretical contributions to innovation in catching-up economies. Moreover, our research takes an innovation systems perspective to include networks and, at least to some extent, institutions in the process of accumulating innovation capabilities.

The role of innovation for economic development has been a matter of intensive research (Fagerberg, et al., 2010). The literature on technological catching up stresses that the development and diffusion of technologies in latecomer economies go hand in hand with learning and knowledge accumulation (Fu, et al., 2011; Lall, 1992; 1993; Ernst & Kim, 2002; Kim, 2001). Lall (1992) and Kim (1999; 2001) conceptualize what they call 'technological capability' as a key factor driving economic development. At the national level, technological capability is a country's ability to use knowledge in order to understand, use and improve technologies. The concept of technological capability seems at first very fuzzy. Empirical research faces the challenge of explaining clearly what this concept stands for, especially if it attempts to capture it empirically.

Bell (Bell, 2009, p. 10) distinguish two types of technological capabilities triggering economic development in catching up economies: production capabilities and innovation capabilities. To him, "production capabilities" are technological capabilities embodied in physical and human capital needed to operate existing forms of technology. This capability requires good operational efficiency as well as skilled technical and blue-collar workforce. Considering the state of the art in research on the development of the PV industry in China described in the previous section, Chinese actors accumulated production capabilities to adopt and use the foreign technology becoming world leaders in PV cell manufacturing. "Innovation capability" on the other hand, enables the creation of new configurations of product and process technology as well as the introduction of modifications and improvements to technologies already in use (Bell, 2009, p. 10). The accumulation of innovation capabilities is about moving from copying and adopting existing technology towards improving existing technologies or creating new ones.

The importance of networks for our research becomes clear if we consider the context in which capabilities are accumulated. According to Lall (Lall, 1992; Lall, 1993), technological capability is accumulated through technological learning. He acknowledges that learning by

catching-up economies can occur through access to international technology flows via FDI or through any other means of technology transfer mechanisms. However, he emphasizes that the assimilation and further development of technologies requires building new capabilities locally. This capability building occurs in collaboration. Usually firms interact with other organizations (suppliers, research institutes, training centres, universities and other supporting organizations) undertaking, supporting or complementing technological activities. Both, in-house accumulation of knowledge and linkages between organizations are hence essential to building the necessary capabilities for technological learning in developing countries (Lall, 1993, p. 100). From this perspective, the accumulation of technological capabilities in PV in China takes place in a broad institutional context orchestrating the access to global technology flows in the PV sector and to national knowledge resources. The concept of technological system brings in this broader perspective, placing the accumulation of innovation capabilities in an institutional context (Bell, 2009, pp. 37-38).

Carlsson and Stankiewicz (1991, p. 111) define a Technological System as "*a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of a technology*". Jacobsson and Johnson (2000) identify three main building blocks in the technological systems of renewable energy technologies: (i) actors and their competences, (ii) the institutions shaping actors' technological decisions and (iii) the interactions between actors.

The main advantage of considering this systemic framework for our purposes of capturing innovation capabilities is the explicit consideration of interactions (networks) (Bell, 2009, pp. 37-38). The interest on networks in the field of innovation research and technology studies is not new and goes beyond the conceptualization of capabilities in the context of economic development (Freeman, 1991). Scholars point out that especially uncertainty and complexity inherent to the development of technologies foster interaction among organizations and network formation for the transfer of knowledge and information (Powell, et al., 1996). The contribution of networks to technological change draws also on the access they offer to the network members to additional resources (including information and knowledge). Moreover, in processes of technology adoption and development, networks influence the institutional setup shaping the spread of a technology as well as the definition of desirable characteristics of a technology (Jacobsson & Bergek, 2004). Finally, in the context of catching-up, networks appear as the coordination mechanism enabling the access to external resources as well as the learning interactions for accumulating innovation capabilities (Bell, 2009).

The operationalization of these theoretical concepts should help us to answer our research questions. The empirical challenge lies first in developing indicators that capture the accumulation of innovation capabilities in China in PV. These are the capabilities triggering the move from producers to innovators in catching up economies. The accumulation of innovation capability is difficult to measure, but it can be assessed in terms of increasing levels of innovative capability (Lall, 1992). We will derive appropriate patent indicators for this purpose (see section 4). Next, our empirical analysis will mainly focus on the network dimension of the PV technological system in China. To a certain extent, we will consider key

technological attributes of the main actors involved in technological development as well as the key milestones of research and industrial policy in China. Nonetheless, actors and institutions are not the focus of this paper.

4. DATA AND METHODS

The empirical analysis introduced in this paper focuses on the inventive interactions side of technological systems, mainly technological knowledge networks of patenting activities. As an analytical framework, the technological systems framework stresses that the locus of innovation, and thus technological change, can be found within the interactions between types of actors and organizations. From this perspective, the patent and network analysis developed in this paper differentiate the types of organisations involved in technological activities, their interactions (Carlsson & Stankiewicz, 1991) measured in terms of co-patenting activities, as well as the role of transnational actors (Gosens, et al., 2015). However, it is worth noting that from the perspective of technological systems, the interactions between actors include other relationships besides co-patenting activities. Our research is limited to technological activities involving patent applications and to those technological collaborations that can be traced through patent co-applications. These activities and interactions are at the far end of developing inventive outcomes susceptible of industrial application. The next sections discuss in detail the patent and network indicators used.

4.1 Patent Analysis and Indicators

Despite the well-known limitations for using patents as an indicator of technological innovation (Archibugi, 1992; Pavitt, 1985), patent filings act as a key link between successful inventive activities and markets. Patent data covers large temporal and spatial scope, and it contains detail technical information about the inventions along with their legal and intellectual owners (or so called patent applicants and inventors respectively). Therefore, it provides a rich insight into the accumulated knowledge stocks, knowledge flows, as well as the cooperation activities in the sake of knowledge creation. Pavitt (Pavitt, 1985, p. 82) argued that since patent applications are filed over "*the whole cycle of development and commercialisation of an innovation, it* [can] *be assumed that patent statistics reflect innovative – and not just inventive – activities*". Furthermore, patent indicators (such as co-applications, co-inventions or citations) can be used to captured process of technology transfer and learning processes. Recent contributions have adopted these type of patent indicators to study technological collaboration and knowledge flows in China in the PV sector (Lei, et al., 2013; Wu & Mathews, 2012).

In this paper, the study of innovation capabilities accumulated in the PV field in China is mainly grounded on the analysis of patent data. Drawing on (Frietsch & Schmoch, 2010) and using the EPO Worldwide Patent Statistical Database (PATSTAT) version 2015b, patent indicators are derived in terms of counts of transnational patents.

Transnational patent applications are defined as patent applications filed at the European Patent Office (EPO), and international patents filed under the Patent Cooperation Treaty (PCT), avoiding double counting of applications that belong to the same family, as described

in equation 1.

$$TN = \{x \mid x \in EPO \cup PCT\} \qquad \text{(Equation 1)}$$

Transnational patent applications are expected to have high economic and technological value, for which applicants seek protection in several markets cross the national borders. The indicators analysed in this paper hence capture accumulated PV innovation capabilities with a business potential from an international perspective. We refer to these as capabilities at the technological frontier[27]. Furthermore, to capture local innovation capabilities, patent applications are assigned geographically to the countries where inventors are located (using the inventors' addresses). The focus of the empirical analysis is on the transnational patent applications that have at least one inventor located in China.

Nonetheless, the sole consideration of patent counts does not tell the full story. For this reason, we use **forward citation index (*Fwd_Citn*)** as a proxy for the quality of transnational patent applications. The index reflects the technological impact of inventive activities. It is calculated for each actor as the average number of citations received *(C_i)* over patent life time [28] *(age)* for all transnational patent applications *(N)* filed by the actor (equation 2).

$$Fwd_{Citn} = \frac{1}{N}\sum_{i=1}^{N}\frac{C_i}{age_i} \qquad \text{(Equation 2)}$$

Furthermore, for a first assessment of **the role of foreign actors** in triggering the accumulation of innovation capabilities in PV technologies in China, we use two patent indicators put forward by Guellec & de la Potterie, (2001). The indicators consider the geographical location of patent applicants (*App*) and inventors (*Inv*) to assess cross border interactions in technological activities. Accordingly, the first indicator we use is concerned with the offshoring activities of foreign firms in China. It is thus calculated as the ratio of patent applications assigned to Foreign Applicants and invented by Chinese Inventors[29] (FACI), to the total volume of Chinese Inventions (CI) based on fractional counting (equation 3).

$$\text{FACI Rate} = \frac{\text{FACI}}{\text{CI}};\ FACI = \sum\frac{App_{Frgn}\,.\,Inv_{CN}}{App\,.\,Inv}, CI = \sum\frac{Inv_{CN}}{Inv} \qquad \text{(Equation 3)}$$

This indicator captures the extent to which actors outside China are seeking to protect inventions developed in laboratories or R&D subsidiaries located in China. The larger the indicator, the stronger the role of foreign actors in driving the technological accumulation of innovation capabilities in China.

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[27] Incremental innovations relevant for local markets only can be captured with domestic patent applications to national patent offices, or with the priority filings of patent families. Such activities are out of the scope of this paper.

[28] To make the forward citation index comparable across patent applications with different priority dates, the number of applications citing a patent under consideration (x) is divided by the number of years elapsed since x has been filed.

[29] Considering a simple example of one patent application that has two applicants (one of them is Chinese and the other is foreigner) and three inventors (one is Chinese and the others are foreigners), FACI in this case equals $^1/_6$, while CI equals $^1/_3$, yields offshoring indicator of ½.

At the same time, we consider a second indicator for the Chinese activities sourcing knowledge from abroad. This indicator captures the extent to which actors (applicants) located in China are seeking for protection of technological inventions developed abroad (by inventors located outside China) (CAFI). The indicator is calculated as the ratio of CAFI to the total volume of patents owned by Chinese Applicants (CA) based on fractional counting[30] (equation 4). Accordingly, it reflects the ability of Chinese actors to exploit technological inventions developed abroad.

$$\text{CAFI Rate} = \frac{\text{CAFI}}{\text{CA}};\ CAFI = \sum \frac{App_{CN}\ .\ Inv_{Frgn}}{App\ .\ Inv}, CA = \sum \frac{App_{CN}}{App} \quad \text{(Equation 4)}$$

4.2 PV Technical System

To identify PV relevant inventions, we use the patent identification scheme developed by (Shubbak, 2017). The classification goes beyond the narrow value chain definitions applied in previous studies. It offers a comprehensive and very detailed definition of different technologies and components along the production value chain of the PV large technical system, therefore, it is especially useful for analysing catching-up trajectories. Using a classification scheme mainly based on IPC classes, Shubbak (2017) defines six PV fields: (i) *solar cells*, (ii) *solar panels*, (iii) *electronics*, (iv) *monitoring and testing*, (v) *energy storage*, and (vi) *portable devices* for lighting, heating and cooling purposes.

These main groups involve at the same time different technologies and subcategories. For instance, the first group, solar cells, represents an active research field in physics, photo- and electro-chemistry, including high-tech developments in micro technology (and in recent applications nanotechnology). It comprises three generations of technology with five different technological families based on the semiconductor materials and manufacturing processes. These are: the matured first generation 1G technologies of ***crystalline silicon cells (c-Si)***; the second generation 2G technologies of ***thin-film technologies*** and ***single-junction Gallium Arsenide (GaAs) cells***; as well as the third generation 3G technologies of ***multi-junction*** and ***emerging/organic PV cells*** (NREL, 2016; Hegedus & Luque, 2010; Mertens, 2014). These families differ widely in both manufacturing complexity and power conversion efficiency, and thus in the required development capabilities, costs, and practical applications.

For example, c-Si cells (with cell efficiency records $\eta \approx 21\text{-}27\%$) and thin-film cells ($\eta \approx 14\text{-}23\%$) are used for the civil applications such as residential and utility solar panels, or in some electronic devices such as calculators and lighting systems. The expensive high efficient technologies of GaAs ($\eta \approx 27\text{-}29\%$) and Multi-junction cells ($\eta \approx 31\text{-}46\%$) are widely used for space power applications (Hubbard, et al., 2009; Hegedus & Luque, 2010). Organic technologies on the other hand ($\eta \approx 11\text{-}12\%$) are still under development phase in research laboratories. (Cell efficiencies source: (NREL, 2016))

[30] Considering the same example used in footnote 3, CAFI in that case is equal to $^2/_6$, while CA equals ½, which yields outsourcing indicator of $^2/_3$.

The second PV group, solar panels, involves mainly mechanical engineering components and processes that are used for (1) *solar modules manufacturing and* ***protection***, (2*) panel* ***encapsulation***, (3) ***supporting structures*** *for solar panels on building roofs*, (4) ***optical*** and (5) ***thermal*** *elements* and arrangements associated with PV panels, and finally (6) *PV* ***power plants***.

The third group covers the electronic elements and electrical circuits that are directly associated with the PV power systems, such as modules' electrical connections, bypass diodes junction box, solar electric charge controllers and maximum power point trackers, as well as feeding circuit DC/AC inverters. Those components represent an active research field in electrical and power electronics engineering.

4.3 Social Network Analysis and Indicators

The network analysis in this paper is based on co-applications of transnational patents with at least one inventor located in China. Each patent applicant is plotted as a network node whose size represents the number of patent applications made by the applicant in the period under consideration. An edge between nodes represents a co-application: two applicants are linked because they are applying together for a patent. Edges/co-applications are used as a proxy for technological collaboration in innovation processes. An edge captures hence interactions between two actors involved in the process of accumulating capabilities in PV technologies. These interactions may take place either because the technological invention occurred in collaboration or because the industrial exploitation of the technological invention involves both actors. The edges are weighted by the frequency of the co-applications in the period and is represented by the thickness.

The use of patent co-applications to capture these types of interaction has been extensively discussed in the patent indicators literature (OECD, 2008). The main weakness of using co-applications as a proxy for collaborative activity lies on the fact that the proxy cannot capture all types of collaboration. For instance, actors involved in joint technology development may opt to form a joint venture for the collaborative R&D project and apply for the corresponding patents with a single applicant. The indicator is hence underestimating collaborative activities (OECD, 2008, p. 62). On the other hand, the use of co-applications allows to consider the different organizational forms of patent applicants in collaborative activities (Universities, research centres, private and state companies or individuals) if the affiliations are identified and classified accordingly[31]. Even though co-applications are not perfect measures of technology collaboration, the increasing number of joint-fillings involving national and international partners speaks for its value as a collaboration proxy (OECD, 2008).

[31] Co-inventions do not allow for this type of organizational analysis without a considerable effort in data gathering and actor and affiliation identification.

Throughout the network analysis introduced in this paper, we calculate several indicators both at whole-network and single-node levels[32]. At node level, two embeddedness indicators are used:

The betweenness centrality (*Btwn*) of an actor reflects the importance of its position in connecting several components of the network, and thus, for our purposes, in transferring knowledge. The indicator is measured as the number of shortest paths between other nodes in the network that pass through the designated node ($\sigma_{st}(n_i)$), over the total number of such paths (σ_{st}) (Freeman, 1977) (equation 5).

$$Btwn = \sum_{s \neq n_i \neq t} \frac{\sigma_{st}(n_i)}{\sigma_{st}} \qquad \text{(Equation 5)}$$

The weighted degree (*Deg*) of an actor represents the total number of ties that directly link the actor with its patent co-applicants. If two actors have more than one joint patent, the additional collaborations are added to their degrees. Consequently, this indicator reflects the total number of collaborations for each actor.

The degree indicator is further aggregated at the network level by calculating the average degree of the whole network. It thus reflects the average number of technological collaborations per patent applicant during the time period under consideration.

Additionally, four indicators at the network level are considered for the sake of understanding the topology and overall characteristics of the co-patenting activities within the system:

Components represents disconnected subgraphs of the network, i.e. all nodes within a component are directly or indirectly connected, while no ties can be found between nodes that belong to different components. The number of components gives an indicator of the level of fragmentation of the network.

Network diameter is the longest of all calculated shortest paths $|\sigma_{st}|$ in the network (equation 6). It reflects the linear size of the network and thus the largest distance between actors in the components.

$$Dia = \max(|\sigma_{st}|) \qquad \text{(Equation 6)}$$

The graph density is the ratio between the actual number of edges (E) in the network to the maximum number of possible edges based on the given number of nodes (N) (equation 7). It reflects to which extent is the network close to a complete graph (where all nodes are directly connected). The higher the graph density, the stronger structure it has, and thus the easier knowledge could be transferred therein.

$$Density = \frac{2E}{N(N-1)} \qquad \text{(Equation 7)}$$

The Modularity (Q) of the network is defined as the fraction of edges falling within clusters (e_{ii}) minus the expected of such fraction in randomly distributed edges (E_r) (equation 8)

[32] Social network analysis in this paper was conducted using Gephi 0.9.1 software (Bastian, et al., 2009). For detailed explanation of network indicators, see (Jackson, 2008).

(Newman & Girvan, 2004). It is a measure of the strength of division of the network into clusters. Networks with high modularity have densely connected nodes within each cluster but sparse connections between different clusters (Blondel, et al., 2008).

$$Q = \sum_i e_{ii} - E_r \qquad \text{(Equation 8)}$$

5. RESULTS

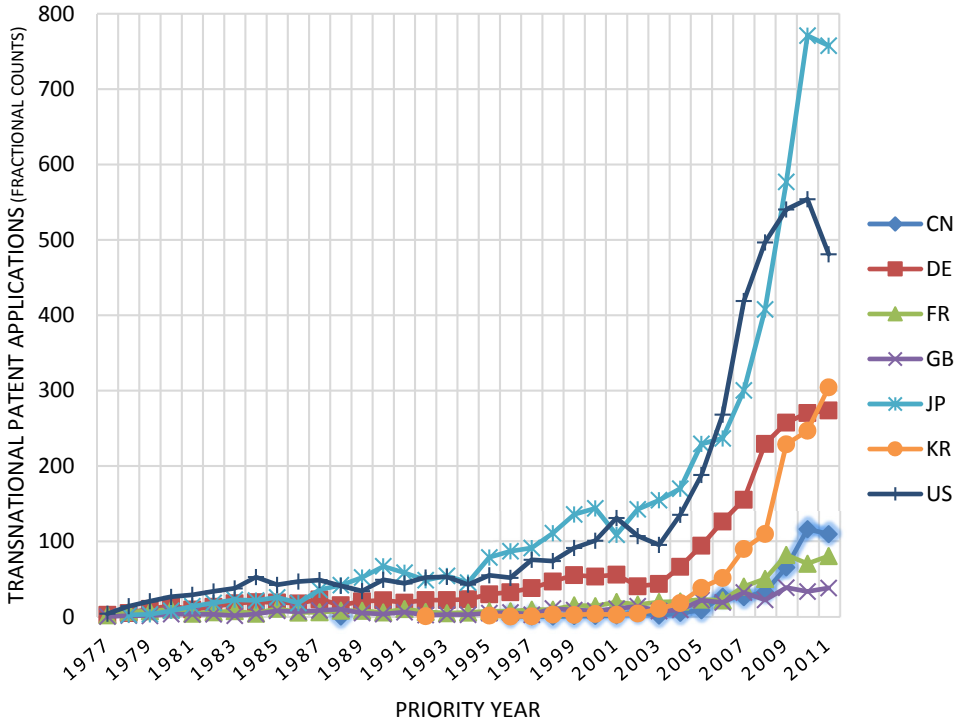
This section presents the empirical results of our patent and network analysis. It focuses on the accumulation of innovation capabilities within the Chinese PV sector, and on the position of the country in the global PV scene. Furthermore, it identifies the main actors driving the PV inventive activities at the technology frontier. First, the internal attributes of the main actors, represented by their specialization, quantity and quality of inventive activities are discussed. Second, the interactions between them, represented by co-patenting networks, are examined. The network analysis considers the dynamic interactions between Chinese and foreign actors on the one hand, and between different types of organisations (firms, public sector research organisations, individuals, and the state) on the other.

5.1 China's position on the global PV technological landscape

Reviewing the worldwide transnational patent activities in PV technologies during the period 1977-2014, the trends in Figure 1 show that China occupies the sixth place in accumulated patent applications. It comes directly after Japan, the United States of America, Germany, South Korea, and France respectively. Chinese inventors were involved in about 3% of the total number of transnational patent applications in the PV field.

Moreover, the trends show that China has even exceeded France in terms of annual transnational patent application counts during the past five years. Starting from a very low level of transnational patent applications in the PV field in the late nineties, patent activities by Chinese inventors started to increase dramatically in 2008, to reach the level of 110 transnational patent applications in a fractional counting basis in 2011, out of the total number of 2366 applications in the same year. The country experienced the highest growth rate in transnational patent applications in the field during last five years, with an average annual growth rate of 50% during 2007-2011.

Figure 1: Patent trends of leading inventor countries in PV[33]



Source: PATSTAT 2015b. Author's own elaboration

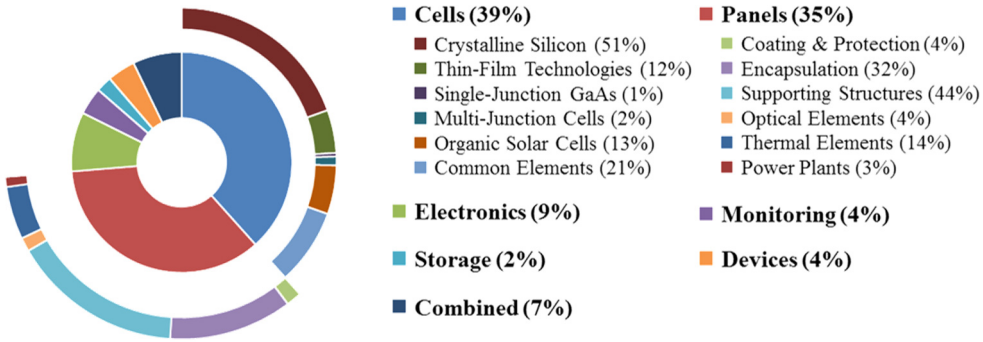
5.2 Chinese transnational patent applications in PV technologies

From this section on, we consider the Chinese trend line of transnational patent applications shown in figure 1 for further analysis. We identified 1201 patent applications with at least one inventor located in China during the period 1988-2014. We will refer to these patent applications as Chinese PV transnational patents. The further investigation of these patents shows that the earliest patent was filed in 1988 by the Chinese Academy Physics Institute, to protect a general purpose manufacturing process of an alloy material that can be used in solar cell production. However, during the following eight years, no technological inventions in PV technologies were filed until 1996 when a continuously increasing number of foreigner and national applicants started to apply for PV patents. Table 1 shows the general statistics for applicants, inventors, and overall technological specialization within the Chinese patents portfolio.

[33] According to the patenting administrative procedures, patent applications are made publically available eighteen months after the priority date, therefore to avoid data misinterpretation, the last years were not shown in the trends.

Table 1: General statistics for Chinese PV transnational patents in 1988-2014

Total PV Transnational Patents:	1201	
Priority Years:	1988-2014	



	Applicants	Inventors
Number of Actors:	2227	2631
Avg. Num. of Actors per Patent:	1.85	2.19
Min. Number of Actors:	1	1
Max. Number of Actors:	18	17
Number of Countries:	27	21
Top Countries (%Share):	China (82%) United States (8%) Taiwan (2.3%) Germany (1.8%)	China (83%) United States (6.4%) Germany (1.8%) Japan (1.3%)
Num. (Ratio) of Collaborations:	727 (60.5%)	825 (68.7%)

Data Source: PATSTAT 2015b. Author's own elaboration.

Looking at the technological specialization in the Chinese PV portfolio for the period 1988-2014, solar cell technologies and solar panels seem to be the dominant fields with the shares of 39% and 35% respectively. Although the PV electronics group has been experiencing a rapid growth in patenting activities since 2010, it is still lagging behind the first two groups with a share in the total patent fractional counts of about 9%. On the other hand, monitoring and energy storage technologies have the lowest patent shares of 4% and 2% respectively. Inventions with combined nature make 7% of the total patents (table 1).

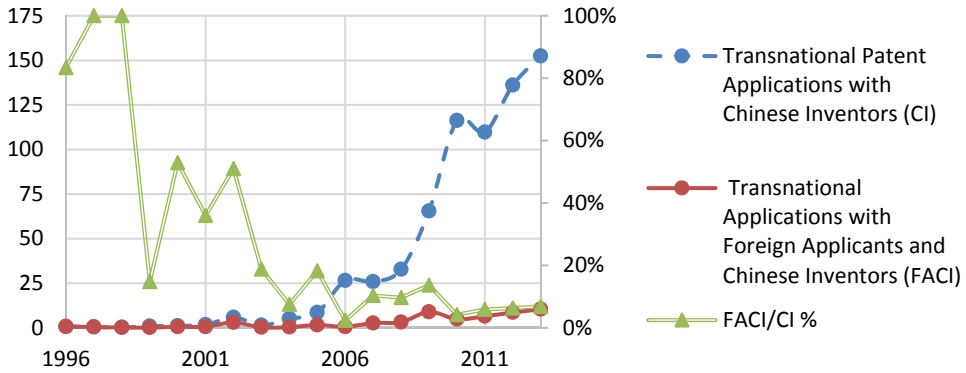
Furthermore, going one level deeper, the specialization analysis shows that the Chinese innovation capabilities mostly focus on the first generation 1G (c-Si) technology with a share of 51% of all cell patent applications. A smaller share of patents (12%) goes for the second generation 2G (thin-film) technologies. Interestingly, the organic cell types within third generation 3G technologies hold a share of 13%. Nonetheless, China's capabilities in the high efficient types within 3G (GaAs and multi-junction cells) seem to be very small, with shares of only 1% and 2% respectively. In what concerns solar panel technologies, encapsulation

and mechanical supporting structures hold the highest share in the Chinese portfolio with 32% and 44% of solar panel patents respectively.

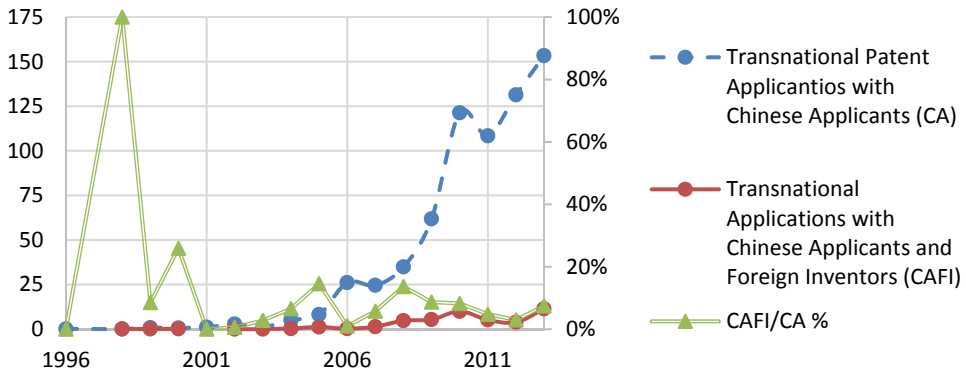
Considering the internationalisation indicators of Chinese patenting activities in the PV sector, annual trends are presented in Figure 2. Regarding offshoring activities of foreigners in China, the share of transnational applications of Chinese PV inventions with applicants located abroad (FACI/CI) decreases remarkably after 2003 to a level below 10%. On the other hand, for the Chinese technological activities sourcing knowledge from abroad, the share of transnational applications with Chinese applicants and foreign inventors (CAFI/CA) is moderate and quite stable throughout the period 2000-2013. The share remains below 10% except in 2005 (18%) and 2009 (14%). These indicators speak for a moderate and relatively weak role of foreign actors in the recent developments of accumulation of innovation capabilities in China in PV technologies.

Figure 2: Indicators for internationalisation of PV patenting activities in China

a) Foreign patent applicants and Chinese inventors



b) Chinese patent applicants and foreign inventors



Data Source: PATSTAT 2015b, own elaboration.

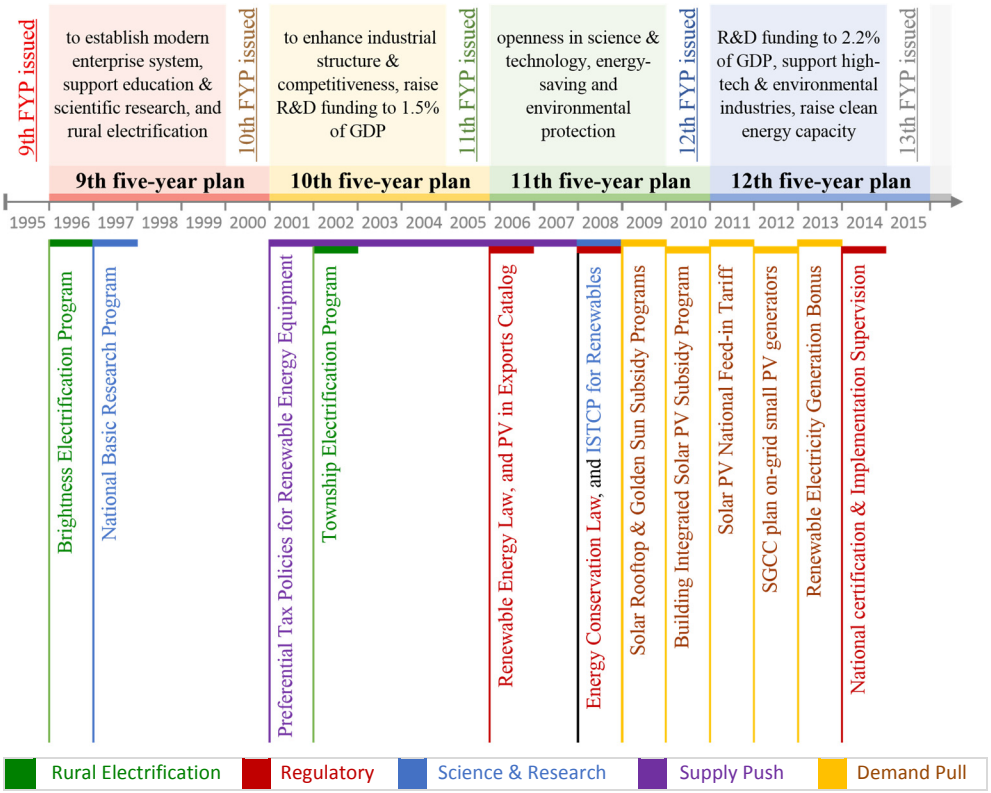
Despite this low and decreasing role of foreign actors in terms of the quantity of patenting activities within the Chinese PV system, the analysis of patent quality shows a relatively

advantage of their filings over applications assigned to local actors. The forward citation index for transnational patents applications of foreign applicants is at the level of 0.92 on average, comparing to 0.5 for patents of Chinese applicants, which means that the small share of patents assigned to foreign actors have nonetheless a higher technological impact.

5.3 Co-patenting Networks and Institutions within the PV Technological System

The network analysis introduced in this section focuses on how the population and the interactions of actors accumulating capabilities in PV technologies have evolved over time, and on the characteristics of the most important actors driving technological development within the institutional infrastructure. The analysis considers four periods: 1995-1999, 2000-2004, 2005-2009, and 2010-2014. The periods are consistent with the general institutional situation in China as represented by the five-year plans (FYP) adopted by the Central Committee of the Communist Party of China (the highest political body in the people republic). Each period in our analysis starts with the year of issuing the FYP as shown in figure 3. The figure additionally shows a timeline of the main government policies relevant to renewable energy and PV technology.

Figure 3: Timeline of institutional milestones in the PV sector in China



Data Source: compiled from Climate Policy Database by NewClimate Institute; China Internet Information Center (both accessed in October 2017); (Zhang & He, 2013); (Iizuka, 2015). Author's own elaboration.

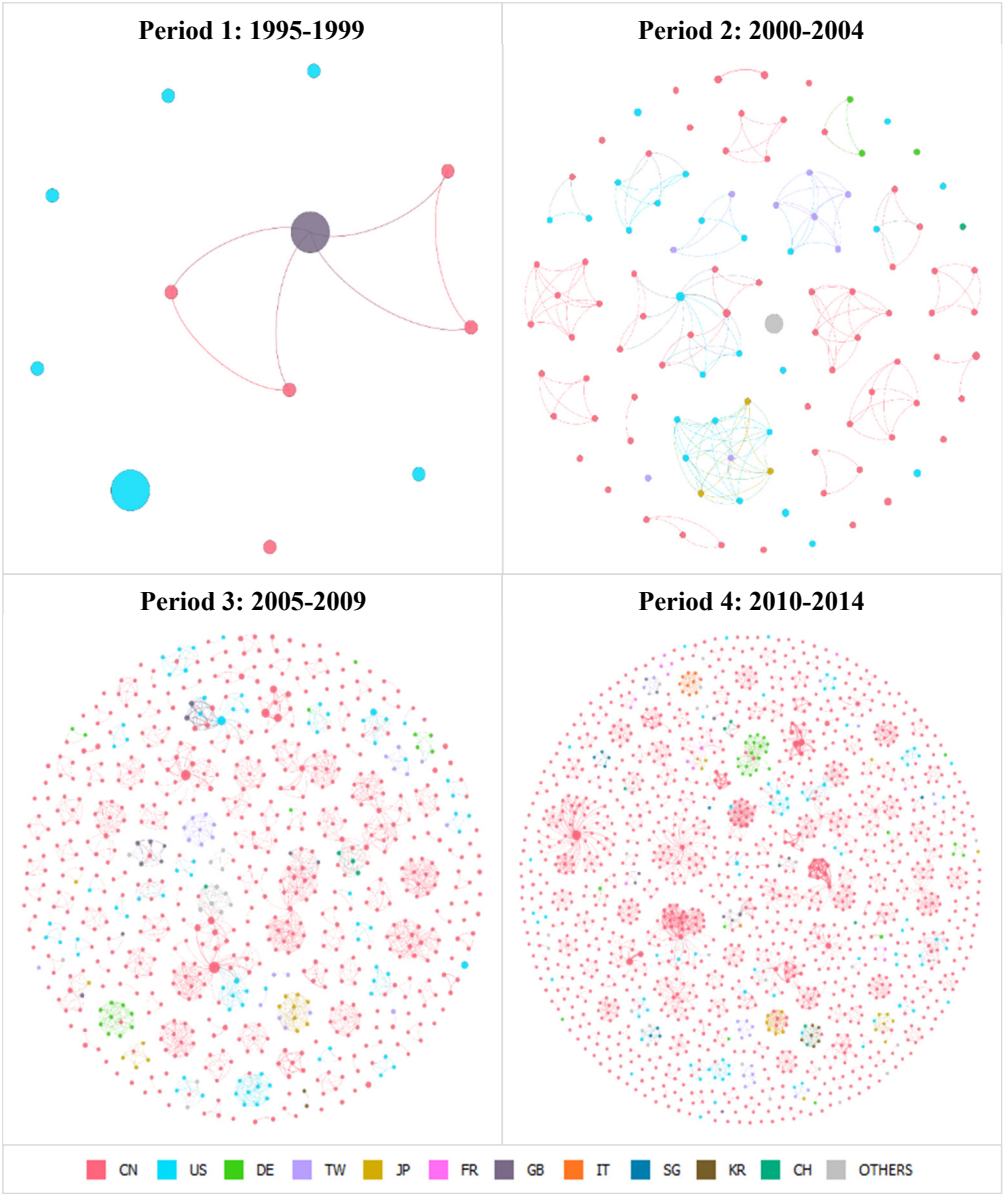
Five types of policies are identified: rural electrification programs, regulatory policy instruments, science and research programs, supply push, and demand pull policies. Further detailed consideration of the instruments is presented later in the period-level analysis subsections.

Considering the technological interactions, figure 4 shows the network in each period of analysis. The colour of the nodes represents the geographical location of the applicants. Between 1995 and 2014 the number of nodes has grown considerably, especially after 2004, with mainly Chinese applicants entering the population. Foreign applicants were located mainly in the United States (blue), Germany (green) and Taiwan (purple). Co-applications by actors located in different countries are relatively low and decreasing. The presence of foreign applicants has been decreasing continuously.

Table 2 presents a set of indicators related to patenting and co-application networks in the different periods. The number of transnational patent applications of Chinese inventions, the number of nodes (patent applicants) and the number edges (co-applications) have increased considerably between 1995 and 2014. The share of foreign applicants amounted more than 50% in the period 1995-1999 and has dropped to 15% in the most recent period. The analysis identifies different types of actors as patent applicants: individuals, companies and public research organisations. Individuals hold the largest share (76.9% in the full period 1995-2014) followed by companies with a share of 18.5%.

In what concerns the technology fields within the PV system, we can observe clear changes in the relative importance of different fields in the total output of transnational patent applications. In the first period, patent applications concentrated on the field “devices” (low-tech) which amounted more than 50% of the applications. However, in the most recent period this field holds only 3% while solar cells and electronics (high-tech) have reached considerable shares compare to the first period. Solar cells and panels amount for 70% of the patent applications between 2010 and 2014.

Figure 4: Network dynamics of applicants and their respective geographical location. 4 periods: 1995-1999, 2000-2004, 2005-2009, and 2010-2014.



Nodes represent patent applicants; node size depends on the number of patents. Edge thickness represents the number of co-applications. Data extracted from PATSTAT 2015b. Author's own elaboration.

Table 2: Network statistics for the periods of Analysis

		Period I: 1995-1999	Period II: 2000-2004	Period III: 2005-2009	Period IV: 2010-2014	Full Period: 1988-2014
Statistics	TN Patent Apps.	10	60	284	846	1201
	Nodes	12	109	733	1488	2226
	Edges	6	173	1844	3911	5789
	Foreign Applicants	58.33%	38.53%	21.83%	15.05%	18.28%
Actor Type	Individuals	41.67%	69.72%	80.9%	74.6%	76.86%
	Companies	41.67%	25.69%	14.87%	20.3%	18.5%
	Universities	16.67%	2.75%	3%	3.09%	2.96%
	Research Institutes	0%	0.92%	0.68%	1.48%	1.12%
	Government	0%	0.92%	0.55%	0.54%	0.54%
Technology Sec.	Solar Cells	5.88%	23.45%	44.43%	38.31%	39%
	Solar Panels	23.53%	23.45%	31.11%	33.19%	35%
	Electronics	0%	0%	3.14%	13.18%	9%
	Monitoring & Testing	17.65%	17.24%	3.52%	3.93%	4%
	Energy Storage	0%	6.21%	2.57%	1.96%	2%
	Devices	52.94%	20%	2.95%	3.58%	4%
Net. Measures	Average Degree	1	3.174	5.031	5.257	5.201
	Network Diameter	2	2	4	6	8
	Graph Density	0.091	0.029	0.007	0.004	0.002
	Modularity	0.111	0.898	0.963	0.966	0.974
	Components	8	41	177	349	512

Data extracted from PATSTAT 2015b. Author's own elaboration.

Regarding the network structure, Table 2 gives five network indicators capturing its characteristics and changes along the four periods. Even though the average degree has increased between the first and the fourth period, the network diameter, the density and the large modularity suggest that the population of patent applicants has grown to build a wide network of decreasing density clustered in isolated communities (components).

The main actors within the Chinese system are listed in (table 3) along with their activity periods (*p*), their types, countries, quantity (*TN*) and quality (*fwd*) of transnational patents, specialization, and network embeddedness (*deg* and *btwn*).

Table 3: Main actors in the PV Technological System in China

P	Actor*	Type	Ctry	TN	fwd	deg	btwn	Specialization
1	Speedfam Corp.	COM	US	2	0.86	0	0	Monitoring, Testing
1	Sol-Lite Manufacturing Co.	COM	CN	1	0.13	2	0	Panels, Devices
1	Solar Wide Industrial Ltd	COM	CN	1	0.00	2	0	Devices
1	Coleman Co.	COM	US	1	0.36	0	0	Devices
1	California Institute of Tech.	EDU	US	1	0.22	0	0	Panels
1	University Leland Stanford	EDU	US	1	2.10	0	0	Cells
2	Omnivision Internat Holding	COM	KY	11	0.30	0	0	Panels
2	Freescale Semiconductor Inc.	COM	US	3	0.00	11	25	Panels, Monitoring
2-4	Du Pont	COM	US	19	1.80	37	186	Cells, Panels
2	Applied Materials Inc.	COM	US	2	0.46	15	53	Monitoring, Testing
2	Infineon Technologies Corp	COM	US	2	0.15	0	0	Monitoring, Testing
3	Silicon China HK	COM	CN	8	0.21	13	3	Cells, Panels
3-4	Wuxi Suntech Power Co Ltd	COM	CN	27	0.61	77	2181	Cells, Panels
3-4	BYD Co Ltd	COM	CN	39	0.37	51	301	Cells, Panels
3-4	Honeywell Int Inc	COM	US	9	0.25	12	96	Cells
3-4	Gen Electric	COM	US	14	0.92	20	369	Electronics, Cells
3-4	State Grid Corp China	GOV	CN	16	1.00	56	1996	Electronics
3-4	Canadian Solar CSI Cells	COM	CA	13	0.71	31	6	Cells, Panels
3-4	University Tsinghua	EDU	CN	12	0.57	44	6717	Cells, Panels, Testing
4	AU Optronics Corp**	COM	CN	49	0.63	92	1515	Cells, Panels, Elect.
4	Oceans King Lighting	COM	CN	29	0.66	49	37	Organic Cells
4	Trina Solar Energy	COM	CN	23	0.40	26	179	Cells, Panels
4	BOE Technology Group	COM	CN	17	0.50	5	6	Cells, Monitoring
4	Xiamen Sanan Opto Tech.	COM	CN	14	0.67	31	14	Cells, Panels
4	Shenzhen China Star Opt	COM	CN	14	0.50	12	33	Cells, Panels, Testing
4	Inst. Microelectronics CAS	EDU	CN	13	0.25	32	496	Cells, Panels, Testing
4	Yingli Energy Ltd	COM	CN	11	1.00	33	580	Cells, Panels
4	Rongxin Power Electronics	COM	GB	9	0.42	70	799	Electronics

*. Actors in this table are sorted according to their appearance in the periods of analysis (p).
**. Although the company has its headquarters located in Hsinchu Taiwan, AU Optronics is considered Chinese in PATSTAT 2015b, because the patent applicant with this name is a subsidiary located in China.

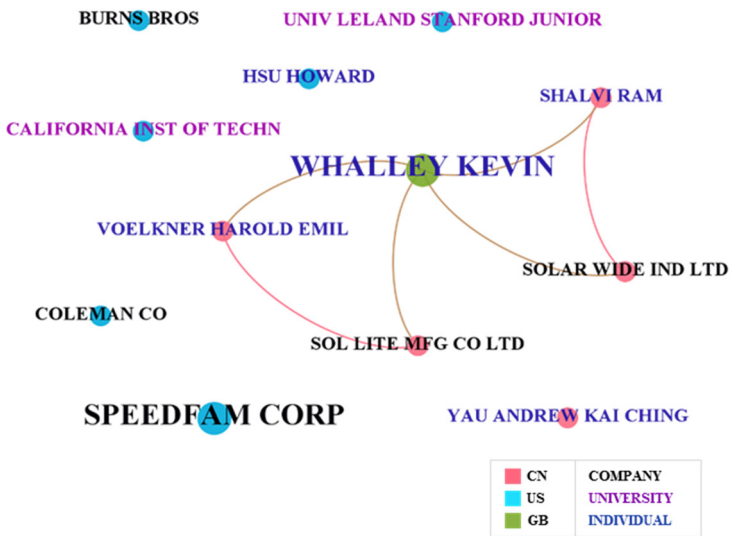
More detailed consideration of network structure, institutional infrastructure, and main actors in each period are given in the following subsections:

1. The first period (1995-1999)

This period started with the adoption of the 9th FYP in 1995, which focused on the establishment of modern enterprise system, supporting of scientific research, and launching of national projects for rural electrification such as 'Brightness Electrification Program' in

1996. Accordingly, portable devices powered by off-grid renewable sources were of high interest. This was also reflected in the technological specialization within the Chinese PV technological system in this period, where the patent applicant population was relatively small (12 actors applying for 10 transnational patents) and patents were mainly within the portable devices field. Figure 5 gives the network with information on the geographical location of the actors (node colours) and the type of actors (label colours).

Figure 5: Network of applicants in the first period (1995-1999)



Data extracted from PATSTAT 2015b. Author's own elaboration.

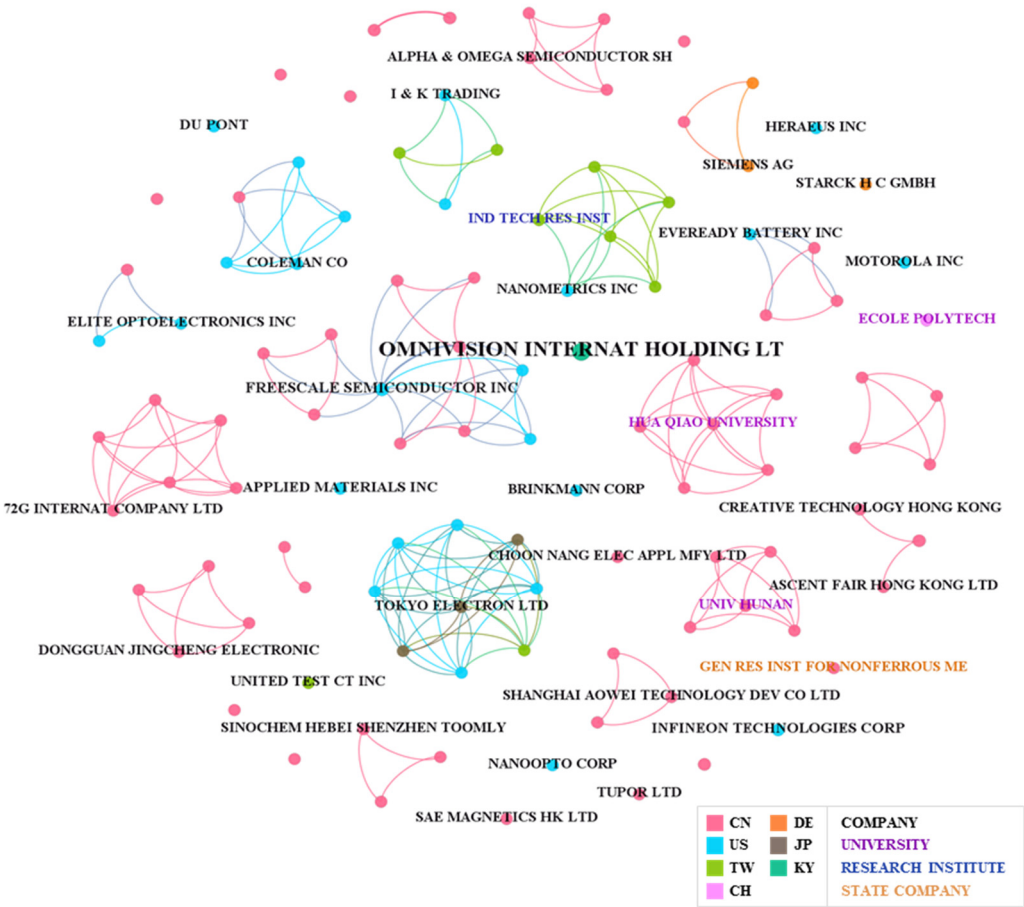
Foreign actors were located mainly in the USA. The main actor was an individual from Great Britain interacting with Chinese applicants. Interestingly, interaction among actors was very low. Actors from the USA were mainly universities that did not interact with Chinese applicants. The patent filed by Leland Stanford Junior University had the highest quality in terms of forward citation index (*fwd*=2.1). The Chinese actors were two companies and two individuals interacting with the main actor in the period.

2. The second period (2000-2004)

In this period (figure 6), the network expands in terms of nodes and diameter. The main actors located in China or in the USA focused largely on the PV technology field of panels (which requires no high knowledge and innovation capabilities, however, is closer to the core of the PV technological system). In this period, public research organisations were no longer among the main actors. This coincided with an intensive policy focus on supporting the PV industry through preferential tax policies for renewable energy equipment during 2001-2007 (figure 3).

Interestingly, the main applicants located in China were individuals while the applicants located in the USA were only companies. This may be related to institutional aspects of patenting activities in each country. Already in this period, Chinese actors ranked among the top performers in terms of number of patent applications. The network was already quite divided in communities. Chinese actors interacted especially with other Chinese actors and, to a lesser extent, with companies located in the USA. The American company Du Pont appeared in the technological system in this period and stayed active through the next stages with patents of relatively high impact (*fwd*=1.8) in cells and panels.

Figure 6: Network of applicants in the second period (2000-2004)



Data extracted from PATSTAT 2015b. Author's own elaboration.

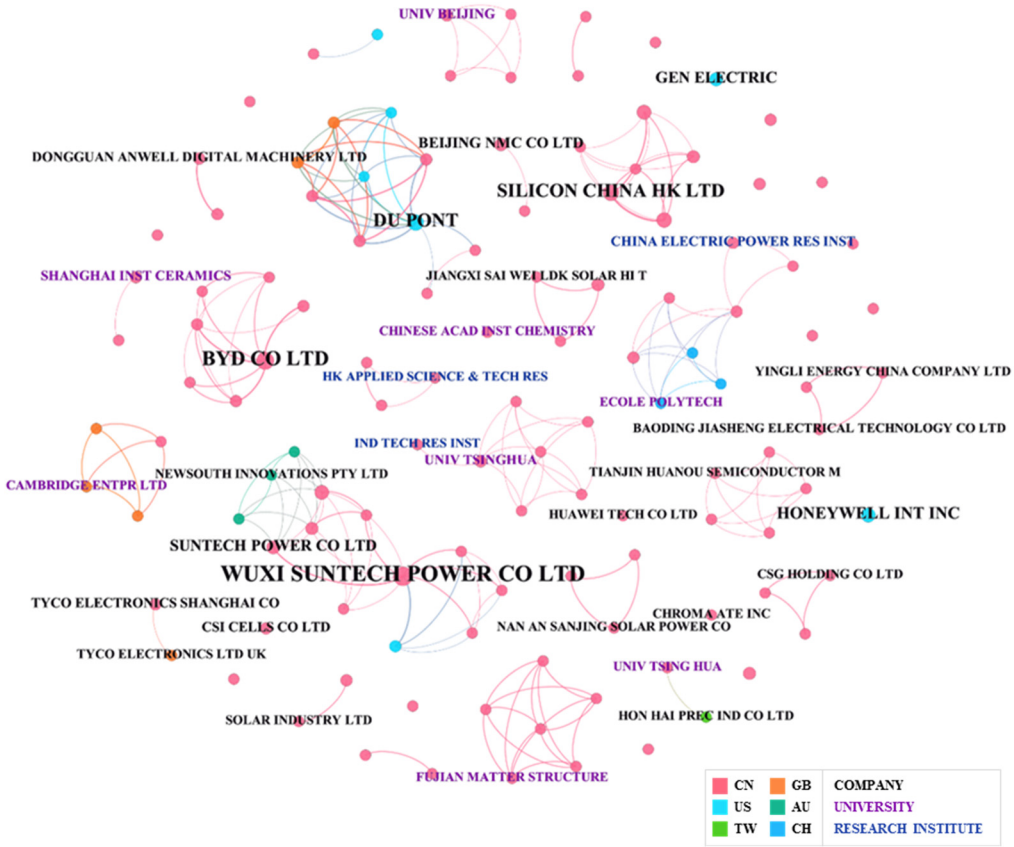
3. The third period (2005-2009)

In this period, the network continues to expand in terms of nodes and communities established. Figure 7 shows the period network exclusively including nodes with at least two patents. This filter was applied for visualization purposes showing 16% of the total nodes in the period. Interestingly, the number of public research organisations (research institutes and

universities) increased dramatically. The main actors in terms of patent applications were mostly located in China and focusing largely on cells and panels. The network reaches a higher degree of modularity with Chinese applicants co-applying largely with other Chinese applicants. This dramatic growth took place in the light of government policies being geared towards openness in science & technology, supporting PV as export-oriented industry (was included in the 'Catalog of Chinese High-Tech Products for Export' in 2006) (figure 3).

Chinese companies took the lead among the top patent applicants. Wuxi Suntech ranked first in terms of number of patents as well as centrality measures. It was embedded in a cluster with American and Taiwanese co-applicants. The second and third ranked actors (BYD and Silicon China HK) were also located in China but not involved in cooperation with foreign applicants. The main foreign actors were companies located in the USA: Du Pont, Honeywell, and General Electric. Only Du Pont had relatively high degree and betweenness centrality suggesting intensive interactions with other actors located in USA, China, and UK. Interestingly, most of the main actors appearing in this period continue to file patents in the following period.

Figure 7: Network of applicants in the third period (2005-2009)

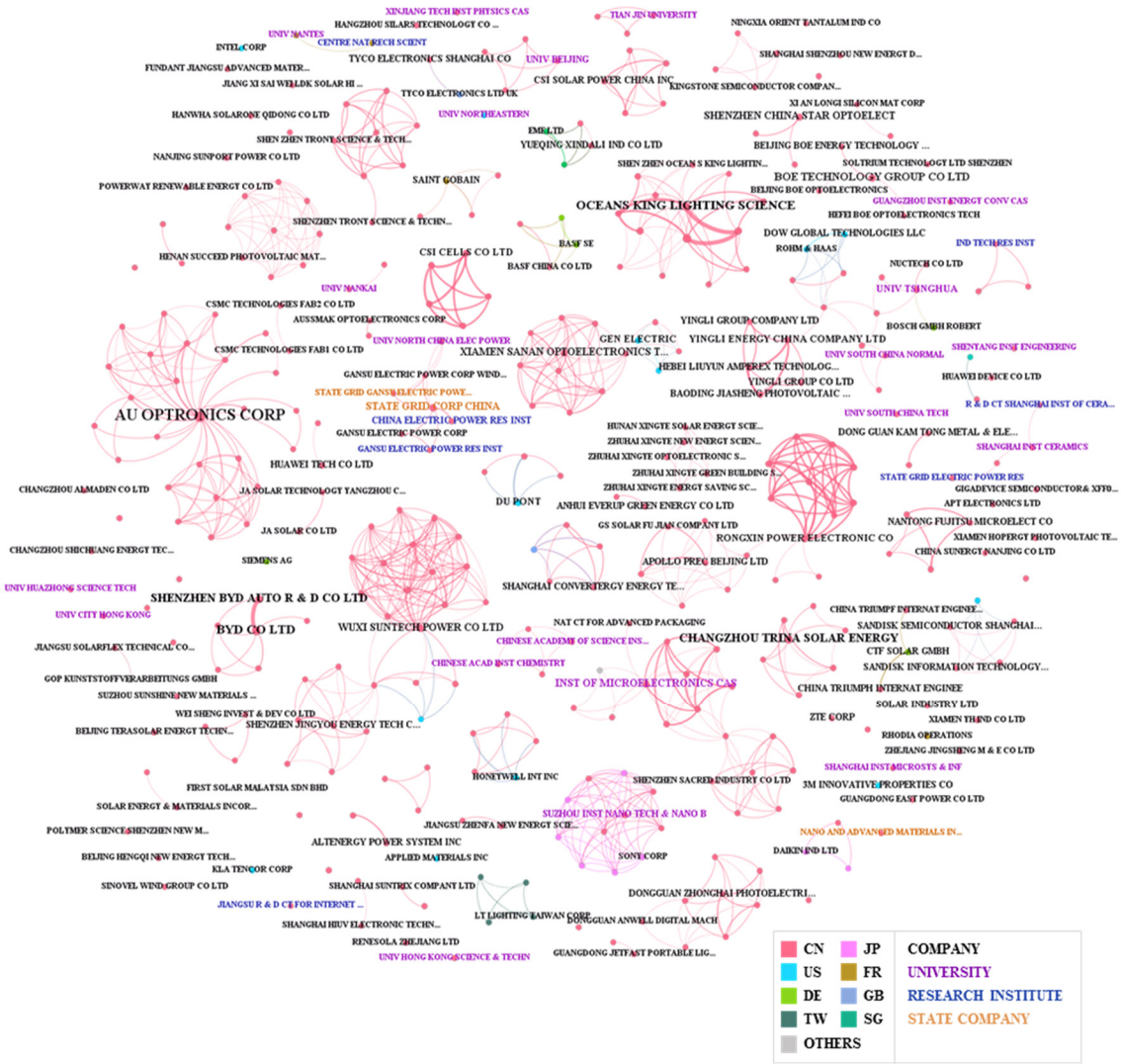


Nodes are co-applicants with at least 2 patent applications (17% of total nodes in the period are visible). Data extracted from PATSTAT 2015b. Author's own elaboration.

4. The fourth period (2010-2014)

Since 2009, an institutional shift in the governmental policy-mix towards demand pull can be noticed (figure 3). With the 13th FYP stressing the goal of raising clean energy capacity nationwide, the number of applicants keeps increasing in this period and the network remains in a highly clustered structure (figure 8).

Figure 8: Network of applicants in the fourth period (2010-2014)



Nodes are co-applicants with at least 2 patent applications (26% of total nodes in the period are visible). Data extracted from PATSTAT 2015b. Author's own elaboration.

Considering network indicators, selected co-applicants seem interesting. The leader in terms of patent applications was the company embedded in a small cluster within the network. AU Optronics ranked highest in terms of patents and centrality measures. The company,

nevertheless, was not interacting with any foreign actors. Next main actor showed a relatively isolated position in the network: BYD reached low levels of centrality.

The companies Wuxi Suntech and State Grid Corp China (SGCC) had a different position in the network. These actors show very high degree and betweenness centrality in the considered period. They have hence prominent positions in the network in terms of number of interactions and with the role they play in connecting actors within the overall network. Interestingly, since 2014, Trina Solar Energy holds the global record of best research cell efficiency in poly c-Si cells (NREL, 2016). Furthermore, a leading Chinese company focused in 3G organic cells appeared in this period, namely Oceans King Lighting.

Two universities appear among the top patent applicants in this period: Institute of Microelectronics at Chinese Academy of Sciences (CAS), and the University of Tsinghua, both held a relatively high number of patents (13 and 12 respectively) but most importantly they reached high levels of centrality comparing to other top ranked actors. These results speak for their importance in the network.

6. DISCUSSION AND CONCLUSION

The results suggest a continuous process of accumulation of innovation capabilities in PV technologies in terms of transnational patent applications. Patent activities of inventions including at least one Chinese inventor started to increase dramatically after 2008. Since 2010, China is occupying the fifth place in terms of annual transnational patent filings in PV technologies, following Japan, USA, Germany and South Korea. Short-term policy instruments applied by the Chinese government in line with its successive five-year plans supported this development

In what concerns **the role of foreign actors in this process**: interestingly, foreign patent applicants of Chinese inventions were very relevant at the earliest stages of development. However, in the most recent period Chinese actors seem to have accumulated the innovative capabilities to trigger both inventing as well as patenting activities (which require a certain level of managerial skills), whereas the presence of foreign co-applicants diminishes drastically. The process of accumulation of innovation capabilities does not depend on foreign companies in the most recent period.

In general, the specialisation of Chinese innovation capabilities within PV system is mainly focused on c-Si cells and panel technologies, while the electronics field is gaining an increasing importance. The dynamic analysis shows an interesting **catching-up trajectory**. Chinese inventors established their innovation capabilities within the PV technological system in the late nineties by developing portable devices powered by solar cells. Acquiring the high-tech inputs (solar cells) from international markets, China protected inventions that implement these cells to power devices for daily life applications such as lighting, heating and cooling. The main institutional motivation was the rural electrification plans by the government.

The next step started in the first decade of the 21st century by developing manufacturing capabilities in solar panels. Although most of the PV cells were still imported, increasing activities in fabricating solar cells were reflected in the growth of patent applications in the 1G c-Si cell technologies. Chinese producers used to import solar grade silicon feedstock from large firms located in the USA, Japan and Europe (Fischer, 2012). Moreover, the Chinese manufacturers introduced and protected inventions in solar modules and panels that were mainly exported to international markets. During this stage, Chinese technological capabilities expanded towards activities with higher technological complexity. Nonetheless, China was still way behind the PV technological frontier of purified silicon feedstock for the 1G cells let alone the second and third generations.

Recently, more innovation capabilities have been accumulated in the field of 1G cells as exemplified by the growing share of patent applications in this field, in the increasing number of patents for silicon purification, as well as in the high cell efficiency records achieved by Chinese firms such as Trina Solar in 2014. Interestingly, the emerging 3G technology of organic solar cells holds a relatively high share in the recent patenting activities. The data thus suggest that the accumulation of innovation capabilities in China is occurring to a certain extent at the technological frontier of solar cell technologies.

Considering the Chinese state policy incentives and green power plants establishment in the last decade (Fischer, 2012; Iizuka, 2015), an increasing demand for the associated electrical components has emerged. This demand drives development activities in the PV electronics field, which is mainly dominated by the SGCC and some large international firms. The accumulation of innovation capabilities is taking place in the development of feeding and inverting circuits as well as in power controllers.

The network analysis using patent data gives interesting insights in **the interactions taking place over time**. The population of actors involved in patenting activities in China has been continuously growing within a quite decentralised landscape of applicants, especially individuals. The network density has been decreasing with the increasing number of nodes. In general, the network displays a very high degree of modularity with Chinese patent applicants co-applying largely with other Chinese applicants. The patterns of interaction differ quite clearly across the main actors. For example, in the last two periods, Wuxi Suntech held a relative large number of patents within the matured 1G technologies of c-Si cells and was embedded in a dense cluster with foreign co-applicants. A slightly different pattern can be observed in AU Optronics, whose innovation capabilities were diversified along the full PV system value chain with a larger share of panels and c-Si cells. Nonetheless, the company was not interacting with any foreign actors. Other leading actors had low interactions but held important positions in terms of patent counts. For instance, BYD was embedded in a small isolated cluster but accounted for a considerable level of innovation capabilities in the most recent period. Following the same network pattern, the company Oceans King Lightening has accumulated capabilities in the emerging field of organic cells in the most recent period and was embedded in a relatively isolated cluster of Chinese actors.

In conclusion, the results suggest an increasing innovation capability building in China measured by transnational patent applications. Such patents are considered to capture capabilities at the technological frontier with high economic value. Although there is a gap between China and the leading economies at the frontier in PV technologies, the gap is decreasing. China is transcending from producer to innovator in PV technology. We tracked the Chinese technological trajectory and found an important role of institutional framework and learning activities in the process. The landscape of patents has been growing to create a decentralised network of interactions clustered in communities. Within these communities the level of innovation capabilities of the main actors and their patterns of interaction are quite heterogeneous. The role of foreign actors has decreased clearly. However, the results further suggest a gap between the strong position of China in the global market of PV modules and its modest share in transnational patent applications.

Throughout this research, several results were found that could raise questions to be investigated in further analysis. First, the gap between the Chinese market share and transnational patents suggest a puzzle that could be addressed through considering the industry dynamics and detailed catching-up processes over time. A second interesting insight into the Chinese PV system can be achieved by mapping patent data with production data through a worldwide comparative analysis. Furthermore, a third perspective could be to investigate the behind-frontier innovation capabilities in the field using priority filings, domestic patent applications, or patent families. Finally, the reasons behind the switch of Chinese policy orientation from supply push to demand pull in 2010 as shown in figure 3, can be deeper investigated in future research.

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Chapter 4

Innovation Capability, Network Embeddedness and Economic Performance:
Profiling Solar Power Innovators in China

ABSTRACT

This paper explores the patterns of innovation-capability and network-embeddedness within the innovation system of solar photovoltaic (PV) technologies in China. It further examines the impact of these patterns on economic performance. Identifying the leading PV innovators in China between 1995-2014 using transnational patents and market share indicators, the landscape of their activities is inspected through two hierarchical cluster analyses in parallel: First, based on the quantity, quality, impact and diversification of patenting activities, and second, based on the global integration, component size and position in technological knowledge networks. Finally, the resulting clusters are cross-related to understand their interrelations with age, size and economic performance. The multivariate analysis of variance (MANOVA) shows a significant relationship between innovation-network concurrency and the age, turnover and productivity of actors. Global-integration in small-world networks is significantly related with economic performance. Quality of innovation shows higher importance than quantity and diversity. While specialization in high-tech fields has positive impact on turnover, firms with low-tech production-oriented focus have interestingly a higher productivity.

KEYWORDS

Innovation System; Photovoltaics Technology; China; Patent Profiles; Network Embeddedness Patterns; Cluster Analysis; Economic Performance

JEL CLASSIFICATION

D24; D85; O31; O34; Q42; Q55

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1. INTRODUCTION

Innovation has long been considered as a main driver of economic development at the macro-level (Schumpeter, 1934). Theoretically, it has been shown that within an industry, there is a significant correlation between innovative activities undertaken in companies and the financial performance measured by growth in assets, turnover, and productivity (Pavitt, 1963, p. 207). However, empirical findings about the relationship between innovation capability and firm performance on the micro-level have been mixed. While many studies validated a positive impact (Geroski & Machin, 1992; Crepon, et al., 1998; Cainelli, et al., 2006; Andries & Faems, 2013), others found no or even negative relationships (MacDonald, 2004; Artz, et al., 2010).

This suggests a puzzle, which we attempt to answer by inspecting the role of network embeddedness in shaping and facilitating the relationship between innovation and economic performance. An increasing consensus in the academic literature has recently emerged on the significant effect of embeddedness in interfirm networks on the innovative and economic performance of firms (Powell, et al., 1996; Gilsing, et al., 2008). In this paper, we will suggest that the impact of innovation capability on economic performance is highly heterogeneous across different network-embeddedness patterns.

Accordingly, the paper aims to disentangle the combined effects of innovation-capability and network-embeddedness patterns on age, size, and financial performance of organisations. Considering the technological upgrading within the solar photovoltaics (PV) industry in China, we address the following research questions:

- Which are the main actors in the Chinese PV innovation system? Which characteristics do they have?
- Which patterns of innovative activities and knowledge network embeddedness could be found in the system?
- What is the relationship between these patterns and economic performance?

To answer these questions, the paper is organized in six sections. The next section reviews the relevant literature. Section 3 introduces the research methodology, data sources and indicators used in the empirical analysis. In section 4, the results concerning main actors, innovation and network patterns are presented. In section 5, the resulting patterns are cross related to understand their confluence on economic performance. Finally, section 6 synthesises the main empirical findings, draws some conclusions, and highlights the limitations of the research and areas for future study.

Information Box: Broader Context and Conceptual Framework

To meet the challenges posed by climate change, renewable energy sources are widely considered as a clean and sustainable alternative to the conventional sources (fossil fuels). However, the differences in economic feasibility between both types (in terms of initial capital and megawatt-hour costs) have long constituted a key obstacle for renewable sources to become a major means of generating electricity at the global level. On the other hand, three parallel paths could interactively lead to the grid parity: – first, product and process

innovations, second, mass production and vertical integration, and third, government subsidies for both supply and demand sides of renewable sources. While the latter two paths concern with reducing the manufacturing and operational costs, innovation is more related to increasing power conversion efficiency. To understand the interrelated roles of the three parallel paths, the use of the conceptual framework of innovation systems sounds reasonable.

Technological Systems of Innovation:
Innovation is not exclusively restricted inside firms, it is rather an outcome of active interrelations between various firm and non-firm entities within complex systems (Günther, 2015). The systemic approach of studying innovation was developed in the late 1980s at a national level (Freeman, 1988; Lundvall, 1992) and later, at sectoral and technological levels (Carlsson & Stankiewicz, 1991; Breschi & Malerba, 1997). The significance of this framework lies in its comprehensiveness and inclusion of all the important factors influencing innovation (Edquist, 1997). Carlsson & Stankiewicz (1991, p. 111) defined technological innovation systems (TIS) as "network of agents interacting in a specific economic area under a particular institutional infrastructure... and involved in the generation, diffusion, and utilization of technology". From that perspective, TIS aims at understanding innovation by considering three analytical blocks – (1) the innovative actors, (2) the network structure of their interactions, (3) the institutional framework.

Nonetheless, given the instability and politics-dependent nature of government subsidizing programs[34], innovation and mass production are considered more important for renewables to become competitive per se in the global energy market. Accordingly, the focus of this paper is on the characteristics of innovators (actors), their technological knowledge networks (interactions), and associated economic performance (productivity). The institutional framework of the TIS is out of the scope of this paper.

2. THEORY AND HYPOTHESES

2.1 The Influence of Innovation Capability on Economic Performance

The impact of innovative activities on economic performance has long been at the centre of the attention of many studies (Franko, 1989; Geroski & Machin, 1992; Schmidt, 1995; Lester, 1998; Crepon, et al., 1998; Evangelista & Vezzani, 2010; Hashi & Stojčić, 2013; Adeyeye, et al., 2013). Cainelli, et al. (2006) found a significant positive impact of innovation on economic growth and productivity of firms. Andries & Faems (2013) highlighted the positive contribution of innovation performance and patenting activities to the profit margins of both SMEs and large firms. In this sense, we expect a positive impact of innovation capability of firms on their economic performance.

Hypothesis 1a: *The innovation capability of an organization is positively related to its economic performance.*

[34] See for instance, the decision of US president Donald Trump in June 2017 to withdraw the United States from the 2015 Paris climate agreement and its impact on the federal government plans and policies (Victor, et al., 2017).

Malerba & Orsenigo (1997) studied the sectoral patterns of innovative activities, showing that although turbulent innovative activities are fundamental for industrial evolution (creative destruction), persistent innovative activities by large established firms are also important for deepening technological capabilities (creative accumulation). They found that effective patterns of innovation depend mainly on the structural characteristics of the technology and its related learning processes. As innovative companies get bigger, they usually accumulate more technological knowledge, financial assets, and market experience becoming better able to invest in substantial research and development projects as well as to introduce more innovations. Therefore, we expect a positive relationship between companies' age and size on the one hand, and their innovation capability on the other. Stated more formally:

> ***Hypothesis 1b:*** *The age of an organization is positively related to its innovation capability.*
>
> ***Hypothesis 1c:*** *The size of an organization is positively related to its innovation capability.*

However, the sole consideration of the quantity of innovative activity throughput can be misleading. Further characteristics of innovation can be of a higher importance, such as its quality and diversity. Innovations of high quality can have a significant impact on the value and adoption rates of final products, and thus on the market share and revenue of their developers. Sampson (2007) studied the impact of technological diversity and alliance organizational form on firm innovative performance highlighting the importance of alliances along with moderate technological diversity for innovation. Furthermore, Leten, et al. (2007) found an inverted U-shaped relationship between the technological diversification of a firm and its performance, where technological coherence plays a moderating role. While Hitt, et al. (1997) emphasized the importance of product diversification in moderating the negative effect of international diversification on firm performance at the first stage of internationalization, Lu & Beamish (2004) showed positive net gains from internationalization up to a certain point at the second phase of multinationalism. This leads to the following hypothesis:

> ***Hypothesis 1d:*** *The quality of innovation is more effective than its quantity and diversity in improving economic performance of organizations.*

2.2 The Influence of Network Embeddedness on Economic Performance

An increasing unanimity in the literature has recently emerged on the significant effect of network embeddedness on innovation and economic performance of organizations (Hagedoorn, 1993; Rowley, et al., 2000; Gilsing, et al., 2008). Ahuja (2000) showed that both direct and indirect ties between firms in collaboration networks within chemicals industry have positive impact on innovation. A similar significant relationship between embeddedness and innovation could be found in semiconductors industry (Stuart, 1998), steel industry (Rowley, et al., 2000), biotechnology (Powell, et al., 1996), and food manufacturing (Tsai, 2001).

Koka & Prescott (2008, p. 658) argued that types of network positions are likely to impact firm performance differently under different contexts. Tsai (2001) found that occupying central network positions can provide organizational units with access to new knowledge developed elsewhere, which can yield more innovations and better economic performance, provided that these units have the necessary absorptive capacity. Gilsing, et al. (2008, p. 1729) argued that "position alone does not tell the full story", a successful outcome also depends on technological distance and network density. The results of (Uzzi, 1996) suggested that, up to a threshold point, network embeddedness could enhance economic effectiveness and competitiveness. Rowley (2000, p. 384) found that the strength of network ties influenced returns on assets contingent upon industry factors. Powell, et al. (1996) found positive impact of network diversity on firms' rate of growth. Goerzen & Beamish (2005) stressed that firm strategies of either being focused in homogeneous networks, or having very diverse alliances, resulted in superior performance compared to the majority firms with moderate network diversity. Furthermore, as organizations get bigger, additional ties to their established networks are expected to be added, enhancing its embeddedness and network position. In sum, this leads to the following hypotheses:

Hypothesis 2a: *The network embeddedness of an organization is positively related to its economic performance.*

Hypothesis 2b: *Older organizations are more embedded in networks.*

Hypothesis 2c: *Larger organizations are more embedded in networks.*

2.3 The Combined Influence

Although the effect of innovation and network embeddedness on economic performance is well established in academic literature, it is nonetheless only discussed on an individual basis. This leaves an important part of the image unclear. In other words, the combined effect of both dimensions is still to be addressed[35]. Considering the research gap introduced in section 1, we examine the following thesis: the different effects of innovation capability on economic outcome are attributed to different network structures or embeddedness levels. So that, we expect a positive effect of the interaction between innovation capability and network embeddedness on economic performance. Stated more formally:

Hypothesis 3: *The innovation capability of an organization is more positively related to economic performance when the organization has a high network embeddedness level.*

To test the hypotheses of this paper, a micro-level analysis is conducted within a specific technological field in a specific country, namely solar photovoltaics (PV) in China.

[35] From that perspective, the present paper can be considered as an attempt to push this area of research forward by studying the cross interaction between innovation capability and network embeddedness and its impact on economic performance.

The contributions of this paper are threefold: First, it provides a detailed profiling of the main actors within the innovation system of PV technologies in China. Second, it uniquely defines two sets of patterns for both innovation-capability and network-embeddedness. Third, it introduces the novel analytical tool of 'concurrency matrix' to study the interaction between innovation and network patterns and its resulting impact on economic performance of firms.

3. DATA AND METHODS

Among the wide range of existing renewables, PV is considered as "the cleanest and safest technology with which to generate electricity even at the GW production scale" (Hegedus & Luque, 2010, p. 24). China has recently become the main global player in both production and deployment of PV crystalline-silicon (c-Si) modules (UNEP, et al., 2010; Marigo, 2007). In 2008, it became the dominant force in PV production, controlling one-third of the global market (Fu, 2015). Later, since 2011, its market share has stabilized at the level of 60% (Jäger-Waldau, 2013). Furthermore, the country has experienced an exponential growth rate in terms of cumulative installed PV power since 2011, becoming the world's leader since 2015 with more than 43 GW, and reaching the level of 78 GW in 2016 (British Petroleum, 2017).

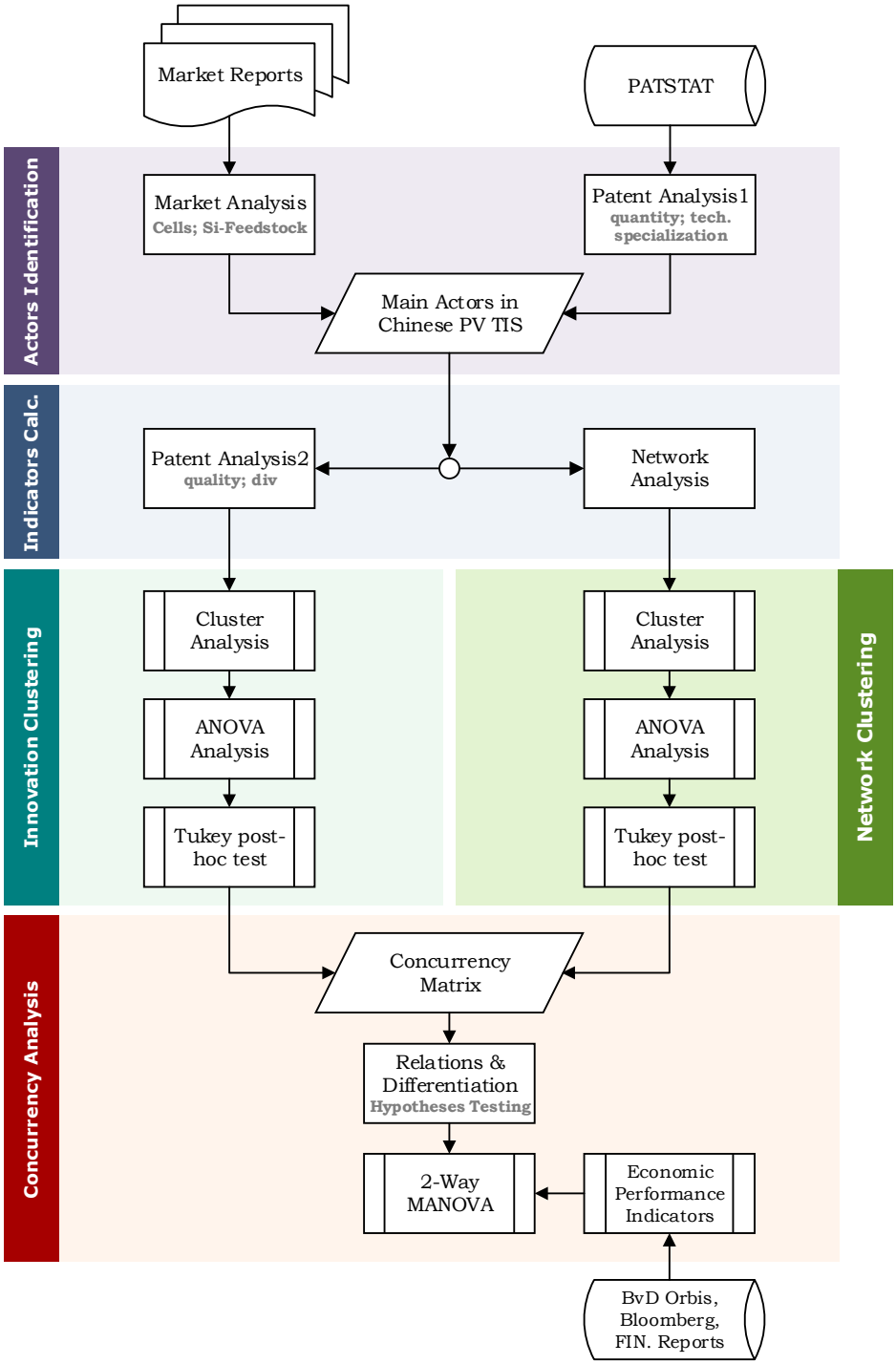
Against this rapid growth of China's share in both supply and demand sides of PV, and being inspired by the importance of innovation, networking, and mass production processes in enhancing the stature of PV technologies in the global energy landscape, this paper studies the characteristics of the leading actors within the technological innovation system of PV in China using a combination of patent-, network-, and cluster analysis.

For the empirical analysis, patent data from PATSTAT (the Worldwide Patent Statistical Database) are mainly used. Pavitt (1985, p. 82) argued that patent statistics can be used as a proxy of innovative and not only inventive activities, considering the fact that they are usually filed "over the whole cycle of development and commercialisation of an innovation". Zahra & George (2002) considered patent filings to evaluate the exploitation element of absorptive capacity at firm level. Despite the well-known limitation for using patents as a proxy for innovation (Archibugi, 1992; Kleinknecht, et al., 2002), patent statistics are, nonetheless, widely considered as the "best available output indicator" for innovation capability (Sawang, et al., 2017, p. 157; Freeman, 2004).

To extract PV relevant patent applications, we use the identification scheme developed by Shubbak (2017a). It offers a comprehensive definition of different technologies along the PV value chain. Using a classification scheme mainly based on IPC classes, Shubbak (2017a) defines six PV groups – solar cells, panels, electronics, monitoring, energy storage, and solar-powered portable devices. The scheme provides further detailed subgroups of the embodied technologies (see the technological subgroups in figure 4).

The quantitative analysis of this paper is carried out based upon four stages (figure 1):

Figure1: Research Methodology Flowchart



Author's own elaboration

1. Identification of main actors

In this stage, the main actors in the Chinese PV system of innovation are identified using patent and production data. The resulting list of innovators and active actors is thus compiled from the following sources:

- The largest purified-silicon feedstock producers in China with more than 1% share in the global market. [*Data source:* (Yu, et al., 2016; Roselund, 2016; Shubbak, 2017b)].
- The largest Chinese manufacturers of c-Si cells with more than 1% share in the global market. [*Renewable Energy World (Mints, 2014); dataset of (Brown, et al., 2015), and* (Shubbak, 2017b)].
- The top 5% transnational patent applicants, within the entire PV system, for inventions taken place in China. [*PATSTAT 2015b,* (Dominguez Lacasa & Shubbak, 2018; Shubbak, 2017a)].
- The top ten patent assignees for inventions within the main technological groups of the system: cell technologies, panels, and electronics. [*PATSTAT 2015b,* (Shubbak, 2017a)].

2. Calculation of indicators

In this stage, quantitative measures of innovative performance and collaboration network embeddedness are calculated for each actor in the innovators list. This is done, first, through patent analysis of the quantity, quality, and diversification of inventive activities, and second, through social network analysis of actor positions and global integration in patent co-applicant networks. A full list of indicators and data sources used throughout this paper is contained in table 1.

Table 1: Variable Definitions and Data Sources

Variable	Description	Data Source
Innovation Performance (Inventive Activities)		
Pat	Quantity: number of transnational patent applications filed by an actor during 1995-2014	PATSTAT 2015b, PV patents identified and classified using (Shubbak, 2017a)
Fwd_Citn	Quality1: Average of forward citations to the patents of an actor over patent age. Proxy for techno-economic impact	
High_tech	Quality2: Percentage of high-tech patents of the total patent applications filed by an actor	
Div	Technological Diversification of patent applications of an actor	
Network Embeddedness		
Deg	Weighted degree of actor node in the PV co-patenting network in China over 1995-2014. Proxy for inventive collaboration	PATSTAT 2015b, (Dominguez Lacasa & Shubbak, 2018)
Btwn_cn	Betweenness centrality of actor node in the PV co-patenting network in China over 1995-2014. Proxy of actor's importance for knowledge transfer over technological network	

Clust_coef	Clustering coefficient of actor node in the PV co-patenting network in China over 1995-2014. Proxy for embeddedness in small-world network	
Com_Size	Network component size: number of nodes in the component (community) to which an actor belongs	
Frgn_coll	Collaboration with foreigner actors: percentage of non-Chinese actors in network component to which an actor belongs	
Characteristics and Economic Performance		
Age	Age of an actor: number of years since the establishment of an actor till 2015	BvD Orbis database, Bloomberg LP data; Forbes lists; Firm websites and financial reports
Turnover	Economic performance: operating revenue (turnover) of an actor in 2015 (values in million US dollars)	
Employees	Size: number of employees of an actor in 2015 (in thousands)	
Productivity	Operating revenue over the number of employees. Proxy for the efficiency of economic activities done by an actor	

With regard to the innovation dimension, the following variables were calculated:

The number of transnational patent applications (*Pat*) is used as a proxy for the quantity of innovation. It is calculated based on (Frietsch & Schmoch, 2010) as the number of patent applications filed at the European Patent Office (EPO), and international patent applications filed under the Patent Cooperation Treaty (PCT), avoiding double counting of EPO applications at the international phase (equation 1).

$$Pat = |TN| \,; TN = \{x \mid x \in EPO \cup PCT\} \qquad \text{(Equation 9)}$$

The two types, EPO and PCT, are the only cross-border enforceable patents, and are thus expected to have high economic and technological value.

Forward citation index (*Fwd_Citn*) is used as a proxy for exogenous quality of innovation (technological impact of inventive activities). It is calculated for each actor as the average number of citations received *(C_i)* over patent life time[36] *(age)* for all transnational patent applications *(N)* filed by the actor (equation 2).

$$Fwd_{Citn} = \frac{1}{N}\sum_{i=1}^{N}\frac{C_i}{age_i} \qquad \text{(Equation 10)}$$

The share of high-tech patents in the actor's portfolio (*High-tech*) is used as a proxy for endogenous quality of innovation. The indicator is based on (Shubbak, 2017a).

The technological diversification index (*Div*) reflects the extent to which an actor is engaged in inventive activities within several technological groups across the PV value chain (Leten, et al., 2007; Suominen, et al., 2017). It considers the diversity of patent portfolio of

[36] To make the forward citation index comparable across patent applications with different priority dates, the number of applications citing a patent is divided by the number of years elapsed since the patent has been filed.

an actor calculated as the complement of normalized Herfindahl-Hirschman index (Hirschman, 1964) for patent shares *(s_i)* of PV main groups *(N)*. (equation 3)

$$Div = \frac{1}{N-1}(1 - N\sum_{i=1}^{N} s_i^2) \qquad \text{(Equation 11)}$$

<u>As for the network embeddedness dimension, the following indicators are considered[37]:</u>

The weighted degree (*Deg*) of an actor in network analysis represents the total number of ties that directly link the actor with its patent co-applicants. If two actors have more than one joint patent, the additional collaborations are added to their degrees. Consequently, this indicator reflects the total number of collaborations for each actor.

The betweenness centrality (*Btwn_cn*) of an actor reflects the importance of its position in connecting several components of the network, and thus in transferring knowledge. The indicator is measured as the fraction of shortest paths between other nodes in the network that pass through the designated node (Freeman, 1977). (equation 4)

$$Btwn\_cn = \sum_{s \neq n_i \neq t} \frac{\sigma_{st}(n_i)}{\sigma_{st}} \qquad \text{(Equation 12)}$$

Where: s, t: represents any other nodes in the network; σ_{st}: is the total number of shortest paths between s and t; $\sigma_{st}(n_i)$: is the number of shortest paths between s and t that pass through the designated node n_i.

The size of network component (*Com_size*) is calculated as the number of nodes in the connected subgraph to which an actor belongs. It reflects the overall number of co-patenting partners that are reachable by the actor either directly or indirectly.

The clustering coefficient (Clust_coef) of a node reflects the tendency of its neighbourhood to link together. It is measured as the ratio of existing links *(e_i)* between a node's neighbours *(k_i)* to the maximum possible links they could have (equation 5). High clustering coefficient is considered as an indicator for small-world networks.

$$Clust\_coef = \frac{2e_i}{k_i(k_i-1)} \qquad \text{(Equation 13)}$$

Finally, the global integration indicator (Frgn_coll) reflects the ratio of collaborations between the designated actor and foreigner (non-Chinese) actors. It is calculated as the ratio of foreigners in the network component of the concerned actor.

For industrial actors which have no patent applications and thus not appearing in co-patenting network, the diversity, centrality and clustering coefficients are set to -1.

[37] Network indicators are based on (Dominguez Lacasa & Shubbak, 2018), where social network analysis was conducted using Gephi 0.9.1 software (Bastian, et al., 2009). For detailed explanation of network analysis and indicators, see (Jackson, 2008).

3. Cluster Analysis

In this stage, the calculated indicators are used to assign actors into specific groups through two cluster analysis processes in parallel. The use of cluster analysis as a tool of discovery spans several disciplines in both natural and social sciences. Besides its use for pattern recognition, classification, and taxonomy construction, cluster analysis is widely used to reduce large complex datasets into meaningful homogeneous groups. The resulting groups can further serve as a basis for classifying new observations or developing inductive generalizations (Anderberg, 1973). Consequently, the purpose of cluster analyses in this paper is to explore the patterns of innovative activities (INNO) as well as the patterns of network embeddedness (NET) within the technological system of PV, and to classify its main actors accordingly.

To do so, the four innovation-performance indicators are used in the first cluster analysis, while the five network-embeddedness variables are used in the second. Both cluster analysis are of hierarchical type, utilizing Ward's method, considering Euclidean distance as similarity measure, and normalizing variables to the 0-1 interval (Anderberg, 1973; Mooi & Sarstedt, 2010).

The two cluster analyses are followed by robustness check of variance ratio criterion through one-way ANOVA. The purpose of this step is to insure significant differences among group mean values. Furthermore, a Tukey HSD (honest significant difference) post-hoc test is performed for better understanding of the resulting clusters and thus labelling them. All the statistical and cluster analysis operations throughout this paper are conducted using IBM SPSS Statistics, version 24.0. (IBM Corp., 2016).

4. Co-evolution analysis (concurrency matrix and economic performance)

In this stage both cluster sets are integrated into one concurrency matrix to study their interaction and confluence on economic performance of actors. Multivariate analysis of variance (MANOVA) is performed for this purpose, having actors' age, turnover, number of employees, and productivity as dependent variables.

The statistical general linear model of MANOVA is shown in equation 6. Where Y_{ij} represents the vector of observations for INNO treatments in NET blocks, ν is the overall mean vector, α_i is the effect of INNO on the dependent variables, β_j is the effect of NET on the dependent variables, γ_{ij} is the non-additive effect of INNO*NET interaction on the dependent variables, and ε_{ij} is the experimental error vector.

$$Y_{ij} = \nu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ij} \qquad \text{(Equation 14)}$$

To insure a temporal order between the independent and dependent variables, the data for clustering variables spans from 1995 to 2014, while the general characteristic and economic performance indicators are considered for 2015. Nevertheless, it is worth stressing that causality is yet "a logical and theoretical task that extends beyond the bounds of statistical analysis" (Grice & Iwasaki, 2007, p. 201).

Finally, the complete image compiling the three analytical dimensions is illustrated in circular genome visualization using (Krzywinski, et al., 2009).

4. RESULTS

4.1 The Main Actors within the Chinese PV System

Throughout the patent and market analysis conducted in this section, 37 organisations were identified as the main actors in the innovation system (table 2). Despite the relatively small size of this sample, the identified actors have however a prominent place within the system. They were accountable for 31% of global Si-feedstock production and 34% of global c-Si cell manufacturing during 2010-2015.

They held significant shares of the Chinese PV production in the same period, 60% of c-Si cells and 90% of feedstock. Furthermore, they were involved in co-patenting network components accountable for 41% of the overall Chinese transnational patent applications over 1995-2014. The detailed results are explained in the following subsections.

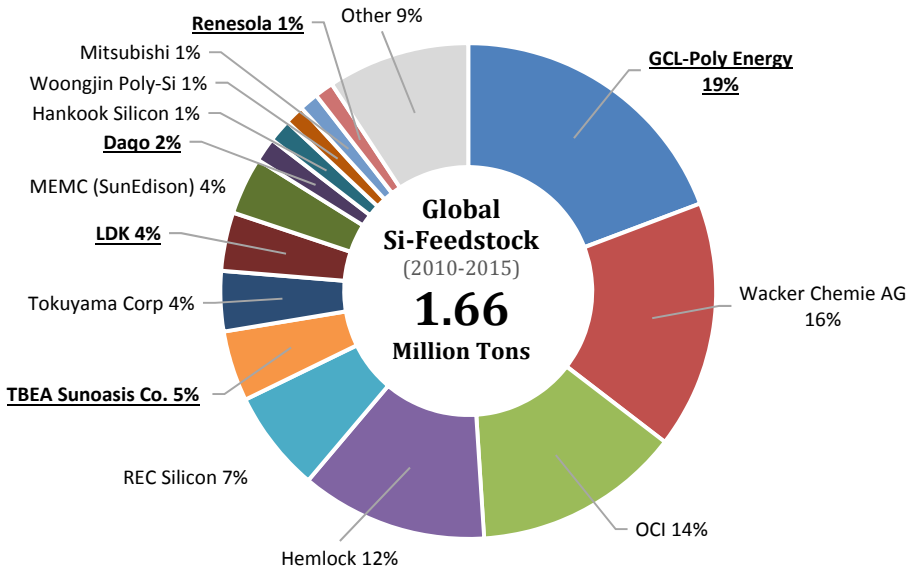
4.1.1 Production and Market Share

To identify the most active actors in the technological system of PV in China, the global markets of solar cells and purified silicon feedstock are first considered. c-Si is the dominant technology in the global market of solar PV. In 2015, it had 93% share of the total produced capacity of PV cells. It also formed the main focus of Chinese production. However, among the manufacturing process of c-Si cells, the purification of polysilicon into solar-grade of 99.999% and its subsequent processes of ingot production are considered the core technology (Si-feedstock) (Mertens, 2014, pp. 99-102).

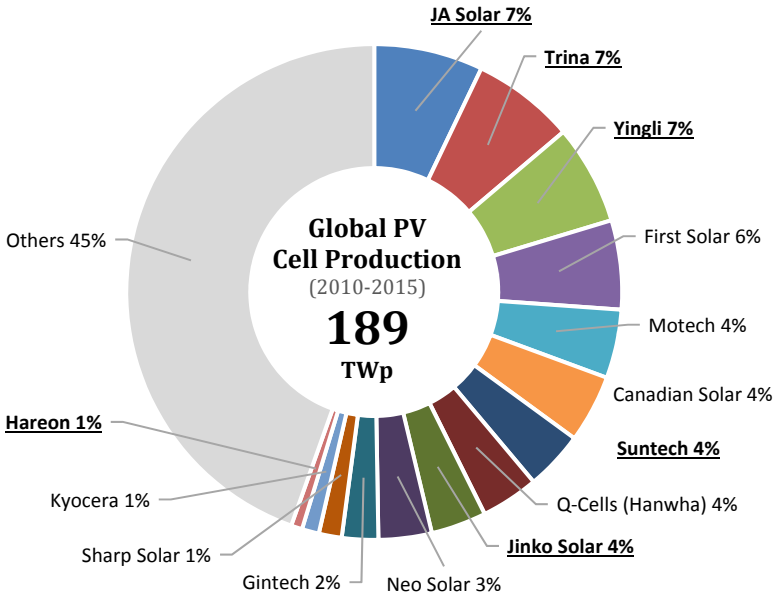
Figure 2 shows the market shares of global PV producers during 2010-2015. As illustrated in figure 2a, the Si-feedstock global market is dominated by 14 firms sharing 91% of the 1.66 million metric ton market. Among those, 5 Chinese producers accountable for 31% share of the global market can be identified (underlined and shown in bold in figure 2a). On the other hand, the c-Si silicon cell market is more fragmented with the top 14 firms holding 55% share of the 189 TWp market (figure 2b). 6 Chinese manufacturers of solar cells with total market share of more than 30% are identified (underlined and in bold).

Figure 2: Market Share of Global PV Producers 2010-2015

a. Global Si-Feedstock Production



b. Global PV Cell Production

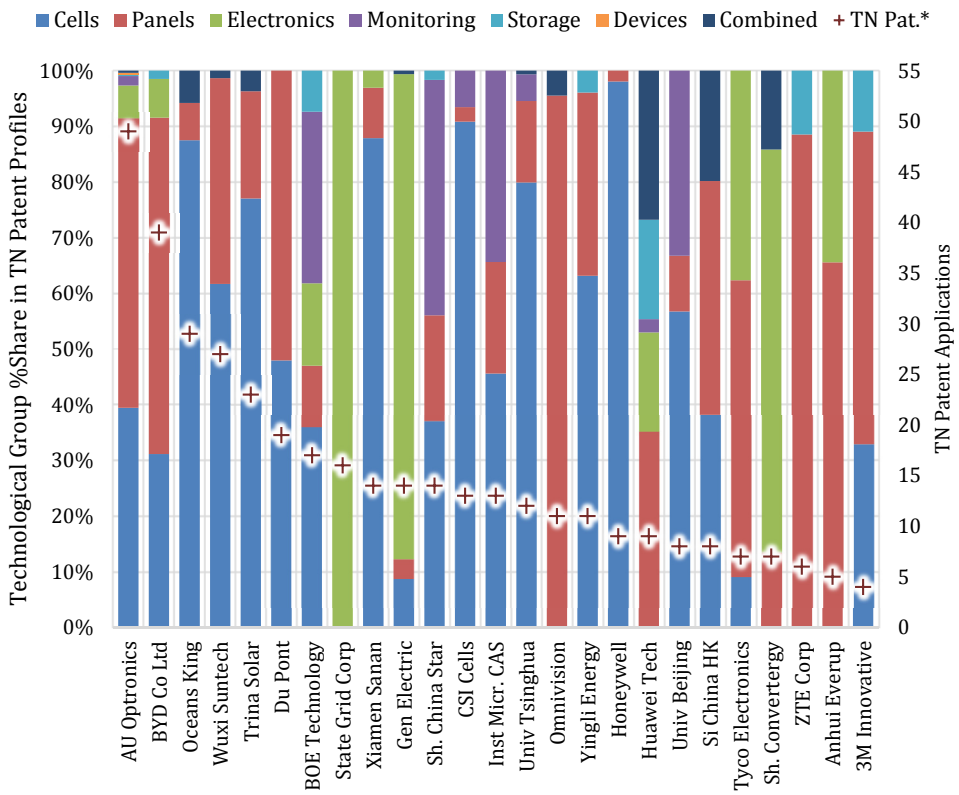


Author's own elaboration. Data compiled from the following sources: (Yu, et al., 2016; Roselund, 2016; Mints, 2014; Brown, et al., 2015; Shubbak, 2017b)

4.1.2 Inventive Activities (Technological Profiles)

To have a deeper insight into the actors driving the development of technological capabilities in the TIS of China, the patent analysis focuses next on the specialization profiles of the top 5% transnational patent applicants during 1995-2014 (figure 3). The resulting 25 organisations directly accumulate 32% of the total Chinese transnational patents in PV technologies. Interestingly, 3 Chinese universities and 8 foreigner companies are found among these organisations. Figure 3 shows the patenting stocks of those top 25 applicants along with their technological profiles in the main PV groups. Similar to the overall trend within the Chinese transnational patent landscape in PV, the leading organisations are mostly specialized in cells and panels with only three exceptions. These are the State Grid Corp China, the American multinational enterprise General Electric, and the Chinese company Shanghai Convertergy, where high specialization in electronics is noticed.

Figure 3: PV Technological Specialization of the Top 5% TN Patent Applicants in China



Actors in this figure are accountable for 32% of the total Chinese transnational patents in PV sector.
* figures are shown in secondary axis. Data source: PATSTAT 2015b. Authors' own elaboration.

Going deeper to the next level of analysis, the technological profiles of the leading actors within the main three PV groups are considered. Within each field of solar cells, panels, and electronics, the top 10 patent assignees are listed against their patent shares in technological

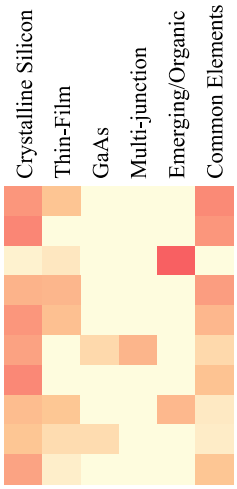
subgroups (figure 4). As shown in figure 4a, the specialization of solar cell innovators is highly focused in c-Si cells and elements. On the other hand, encapsulation and supporting structures form the specialization fields for solar panel innovators, while feeding converter circuits are on focus of electronics innovators. All applicants that appear in the top-10 innovator lists (figure 4) are considered for the research sample.

Figure 4: Tech. profiles of the top 10 PV patent assignees in China 1995-2014

Heatmap representation of transnational patent applications in PV Cells, Panels and Electronics

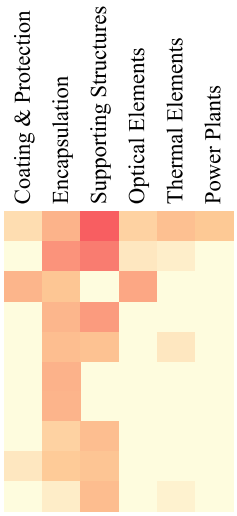
Patent Applications
Heatmap Colour

(a) Solar Cell Technologies



	% in Cells
AU Optronics Corp	39%
Changzhou Trina Solar Energy	79%
Oceans King Lighting Science	87%
BYD Co Ltd	40%
Wuxi Suntech Power Co Ltd	55%
Xiamen Sanan Optoelectronics Technology Co Ltd	84%
CSI Cells Co Ltd	91%
Honeywell Int Inc	94%
University Tsinghua	80%
Yingli Energy China Company Ltd	82%

(b) Solar Panel Technologies



	% in Panels
AU Optronics Corp	51%
Byd Co Ltd	54%
Omnivision International Holding Ltd	95%
Wuxi Suntech Power Co Ltd	44%
Du Pont	53%
Tyco Electronics Shanghai Co	65%
Sandisk Information Technology Shanghai Co Ltd	99%
ZTE Corp	81%
Changzhou Trina Solar Energy	16%
Anhui Everup Green Energy Co Ltd	71%

(c) Electronic Technologies

	% in Electronics
State Grid Corp China	100%
Gen Electric	77%
China Electric Power Res Inst	83%
Rongxin Power Electronic Co	100%
Shanghai Convertergy Energy Technology Co Ltd	75%
AU Optronics Corp	7%
Boe Technology Group Co Ltd	21%
State Grid Electric Power Res	100%
Siemens AG	83%
Huawei Tech Co Ltd	18%

Data Source: PATSTAT 2015b. Author's own elaboration

Table 2: The Main Actors in PV Technological Innovation System in China

	Actor	Typ	Ctry	Est. Yr.	Trnover [mill. $]	Empl [th.]	TN Pat	Specialization
1	Siemens AG	COM	DE	1847	89,059	351.0	4	electronics
2	Yingli Energy Ltd [a,c]	COM	CN	2006	1,535	14.5	11	c-Si cells
3	Shanghai Convertergy Ltd [c]	COM	CN	2010	3	0.05	7	electronics
4	Uni Tsinghua	EDU	CN	1911	1,850	7.2	12	education
5	Du Pont	COM	US	1915	25,268	52.0	19	c-Si, TF, 3G cells
6	Wuxi Suntech Power Ltd [a,c]	COM	CN	2001	621	2.0	27	c-Si cells
7	Sandisk Information Tech.	COM	US	1988	5,570	8.8	5	electronics
8	Gen Electric	COM	US	1892	117,184	305.0	14	electronics
9	Xiamen Sanan Opto Tech.	COM	CN	1993	741	7.1	14	LED, 3G cells
10	Honeywell Int Inc	COM	US	1885	30,000	125.0	9	chemicals, cells
11	State Grid Corp China	GOV	CN	2003	38,286	927.8	16	electricity trans.
12	China Elect. Power Res Inst	INST	CN	1951	n.a.	1.8	8	research
13	BYD Co Ltd	COM	CN	1995	12,252	200.0	39	automobile, cells
14	Rongxin Power Electronics	COM	GB	2012	1,000	2.6	9	energy, elect.
15	Tyco Electronics Co	COM	CH	1941	12,200	75.0	7	elect., panels
16	Inst. Microelec. CAS	EDU	CN	1928	65	0.8	13	research
17	ZTE Corp	COM	CN	1985	12,220	69.1	6	panels, elect.
18	Trina Solar Energy [a,c]	COM	CN	2006	3,036	13.6	23	c-Si cells
19	Oceans King Lighting [c]	COM	CN	1995	136	2.7	29	organic cells
20	Canadian Solar CSI Cells [a,c]	COM	CA	2001	3,468	9.0	13	c-Si cells
21	BOE Technology Group	COM	CN	1993	7,448	42.8	17	display, elect.
22	AU Optronics Corp	COM	TW	2001	11,018	62.8	49	c-Si cells, panels
23	Shenzhen China Star Opt	COM	CN	2009	2,520	7.5	14	electronics
24	Omnivision Tech.	COM	US	1995	1,379	2.2	11	panels
25	Silicon China HK	COM	CN	1992	15	0.1	8	c-Si cells, panels
26	Huawei Tech Co Ltd	COM	CN	1987	59,466	140.0	9	electronics
27	Uni Beijing	EDU	CN	1898	1,290	8.6	8	education
28	Anhui Everup Green Energy [c]	COM	CN	2001	27	0.2	5	panels, elect.
29	3M Innovative Prop. Co	COM	US	1902	30,274	89.8	4	elect., storage
30	Jinkosolar Co Ltd [a,c]	COM	CN	2006	2,477	14.0	1	c-Si cells
31	Ja Solar Co Ltd [a,c]	COM	CN	2005	2,084	12.6	2	c-Si cells
32	Renesola Ltd [b,c]	COM	CN	2006	1,299	5.4	1	Si-feed., cells
33	Tbea Xinjiang Sunoasis [b,c]	COM	CN	2000	1,046	5.0	1	Si-feedstock
34	LDK Solar Hi-Tech Ltd [b,c]	COM	CN	2005	3,490	13.3	2	Si-feedstock
35	GCL-Poly Energy [b,c]	COM	CN	2006	4,546	17.7	0	Si-feedstock
36	Daqo Group Co Ltd [b,c]	COM	CN	1965	2,638	10.0	0	Si-feedstock
37	Hareon Solar Technology [a,c]	COM	CN	2000	933	6.1	0	Poly-Si cells

Actors in this table are sorted according to their appearance in PATSTAT 2015b database.

Actors 1-34 were involved in co-patenting network components accountable for 41% of the Chinese TN patent applications in PV technologies. [a]. Those seven firms were accountable for 34% of the global c-Si PV cell production during 2010-2015 (60% of the Chinese production). [b]. Those five firms were accountable for 31% of the global Si-feedstock production during 2010-2015 (more than 90% of the Chinese production). [c]. The business of those fifteen firms are solely focused on PV energy sector.

4.2 Cluster Analysis

Table 3 contains the descriptive statistics and the correlations between variables for all observations in the sample.

Table 3: Descriptive Statistics and Correlation Matrix

	Variable*	Mean	Std.	Min	Max	1	2	3	4
1	Pat	11.27	10.80	0	49	1.000			
2	Fwd_Citn	0.45	0.40	0	1.83	0.378	1.000		
3	High_tech	0.35	0.35	0	1	0.019	0.173	1.000	
4	Div	0.29	0.47	-1	0.86	0.405	0.412	0.064	1.000
5	Deg	21.65	24.06	-1	92	0.792	0.398	0.225	0.221
6	Btwn_cn	462.62	1210.72	-1	6717	0.248	0.181	0.137	0.072
7	Clust_coef	0.27	0.51	-1	1	0.022	0.104	0.273	0.579
8	Com_size	33.49	39.59	0	134	0.280	0.180	0.292	0.207
9	Frgn_coll	0.11	0.19	0	1	-0.013	0.258	-0.088	0.052
10	Turnover**	13.50	25.80	0.003	117	0.009	0.349	0.457	0.099
11	Employees	70,629	166,380	50	927,839	0.130	0.329	0.473	-0.019
12	Age	41.05	44.71	3	168	-0.100	0.313	0.230	0.128

		5	6	7	8	9	10	11	12
5	Deg	1.000							
6	Btwn_cn	0.500	1.000						
7	Clust_coef	0.041	-0.064	1.000					
8	Com_size	0.522	0.628	0.240	1.000				
9	Frgn_coll	-0.049	0.050	0.112	0.084	1.000			
10	Turnover**	0.002	-0.030	-0.002	-0.007	0.146	1.000		
11	Employees	0.232	0.160	-0.051	0.192	-0.023	0.586	1.000	
12	Age	-0.126	0.143	0.132	0.043	0.246	0.600	0.207	1.000

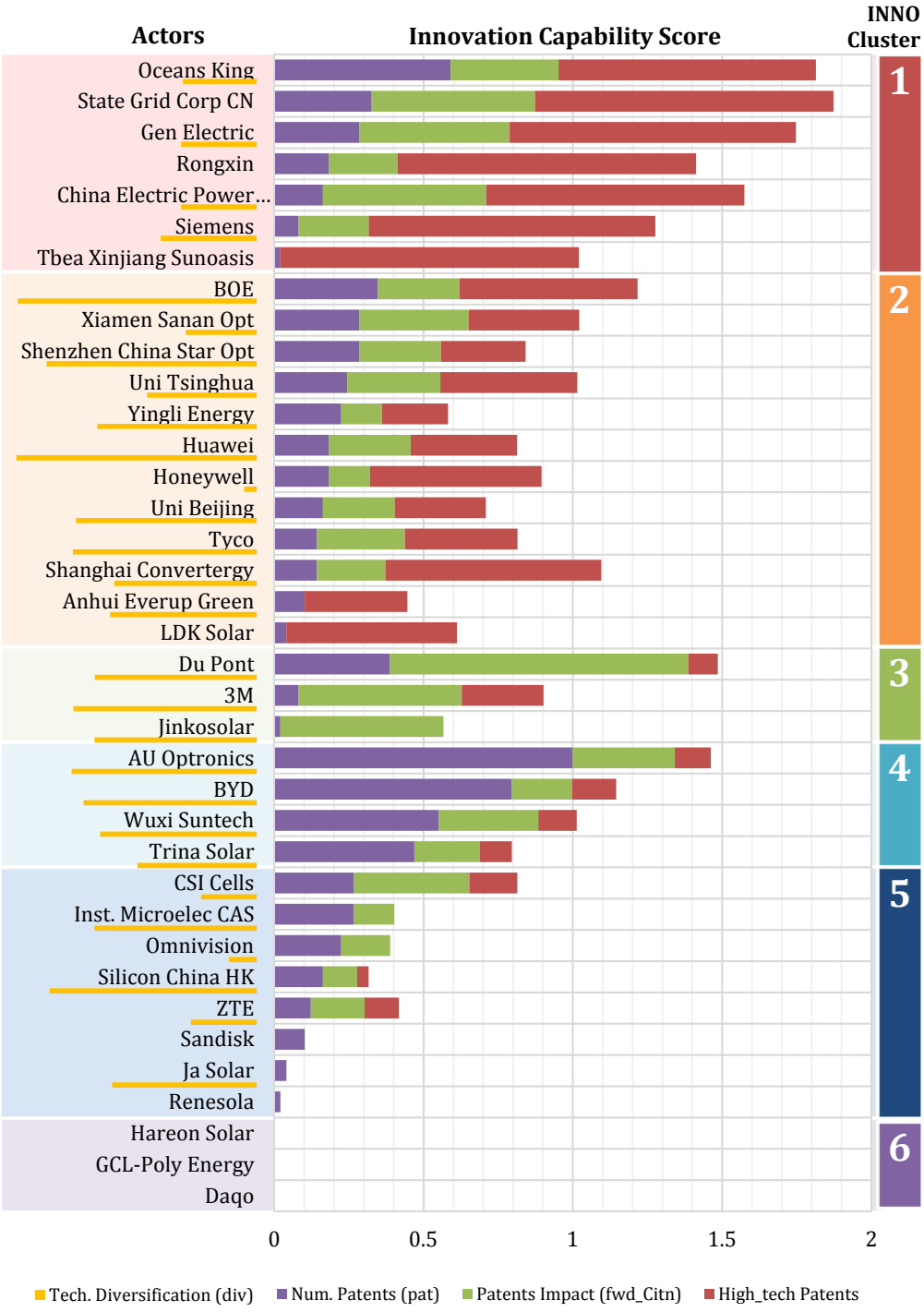
*. Number of observations N=37.
**. Turnover values are given in billion US dollars, its N=36.
Note: Variables are defined in table 1.

4.2.1 Patterns of Innovation Capability

Considering the quantity, quality and diversity of patenting activities as clustering variables for innovation capability, six clusters were identified. Figure 5 shows the normalized variables for each actor along with the distribution of actors into the resulting clusters. The left side of figure 7 shows the dendrogram of the cluster analysis.

To check the effectiveness of the analysis in classifying actors according to their innovative performance, Analysis of variance (ANOVA) is used. Furthermore, Tukey HSD post hoc test is subsequently conducted to understand the characteristics of each cluster. Table 4 contains the statistical results of ANOVA analysis and Tukey test for innovation capability clusters (INNO).

Figure 5: Inventive Activity Profiles of the Top PV Innovators in China



Authors' own elaboration, Data Source: PATSTAT 2015

Table 4: ANOVA and Tukey HSD Analysis for Innovation Capability Clusters

ANOVA Analysis for Innovation Capability Clusters						
		Sum of Squares	df	Mean Square	F	Sig.
pat	Between Groups	2727.791	5	545.558	11.478	0.000**
	Within Groups	1473.506	31	47.532		
	Total	4201.297	36			
fwd_citn	Between Groups	3.355	5	0.671	9.146	0.000**
	Within Groups	2.274	31	0.073		
	Total	5.630	36			
div	Between Groups	6.289	5	1.258	23.612	0.000**
	Within Groups	1.651	31	0.053		
	Total	7.940	36			
high_tech	Between Groups	4.089	5	0.818	73.321	0.000**
	Within Groups	0.346	31	0.011		
	Total	4.435	36			

Post Hoc Test: Multiple Comparisons (Tukey HSD)							
Dependent Variable	**INNO (I)**	**INNO (J)**	**MeanDiff. (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
high_tech	**1**	**2**	.518**	0.050	0.000	0.365	0.670
		3	.825**	0.073	0.000	0.604	1.047
		4	.823**	0.066	0.000	0.622	1.024
		5	.910**	0.055	0.000	0.744	1.076
		6	.949**	0.073	0.000	0.728	1.171
	2	**3**	.308**	0.068	0.001	0.101	0.515
		4	.306**	0.061	0.000	0.121	0.491
		5	.393**	0.048	0.000	0.246	0.539
		6	.432**	0.068	0.000	0.225	0.639
fwd_citn	**3**	**1**	.644*	0.187	0.019	0.076	1.211
		2	.890**	0.175	0.000	0.359	1.421
		4	.775**	0.207	0.009	0.148	1.403
		5	1.052**	0.183	0.000	0.495	1.608
		6	1.277**	0.221	0.000	0.605	1.948
pat	**4**	**1**	22.929**	4.321	0.000	9.810	36.040
		2	24.917**	3.980	0.000	12.840	37.000
		3	26.500**	5.266	0.000	10.520	42.480
		5	27.125**	4.222	0.000	14.310	39.940
		6	34.500**	5.266	0.000	18.520	50.480
div	**1**	**6**	1.165**	0.159	0.000	0.681	1.648
	2	**1**	.343*	0.110	0.041	0.010	0.676
		6	1.508**	0.149	0.000	1.056	1.960
	3	**6**	1.608**	0.188	0.000	1.036	2.180
	4	**6**	1.570**	0.176	0.000	1.035	2.105
	5	**6**	1.298**	0.156	0.000	0.824	1.772

Only positive significant mean differences are shown in this table. Definitions of variables are stated in table 1.
*. The mean difference is significant at the 0.05 level.
**. The mean difference is significant at the 0.01 level.

The results show that for all clustering variables, there was a statistically significant difference between INNO clusters as determined by one-way ANOVA at the $p<0.001$ level. The post hoc comparisons, using Tukey HSD test, revealed that high-tech innovations were significantly higher in the first cluster INNO1 compared to all other clusters. INNO2 had also significantly greater high-tech innovations than those of INNO3, 4, 5, and 6. On the other hand, the cluster INNO3 showed statistically significant advantage over all other clusters in forward-citation score. The quantity of innovative activities (number of patent filings) was significantly higher in INNO4 compared to the others. Finally, in terms of technological diversification, INNO6 was significantly lower than all other clusters. INNO1 also had significantly lower diversification than INNO2.

Taken together, these results give better insight into the differences between clusters:

1. **INNO1:** comprises the actors with high-tech speciality.
2. **INNO2:** actors have higher diversity within medium technological sophistication.

Although the remaining clusters are specialized in low-tech, each one of them has its defining characteristic:

3. **INNO3:** actors have patents with high impact (i.e. receiving more forward citations).
4. **INNO4:** actors have high quantity and technological diversity of patent filings.
5. **INNO5:** innovations are low in quantity and quality.
6. **INNO6:** firms did not file any transnational patents in the period of consideration.

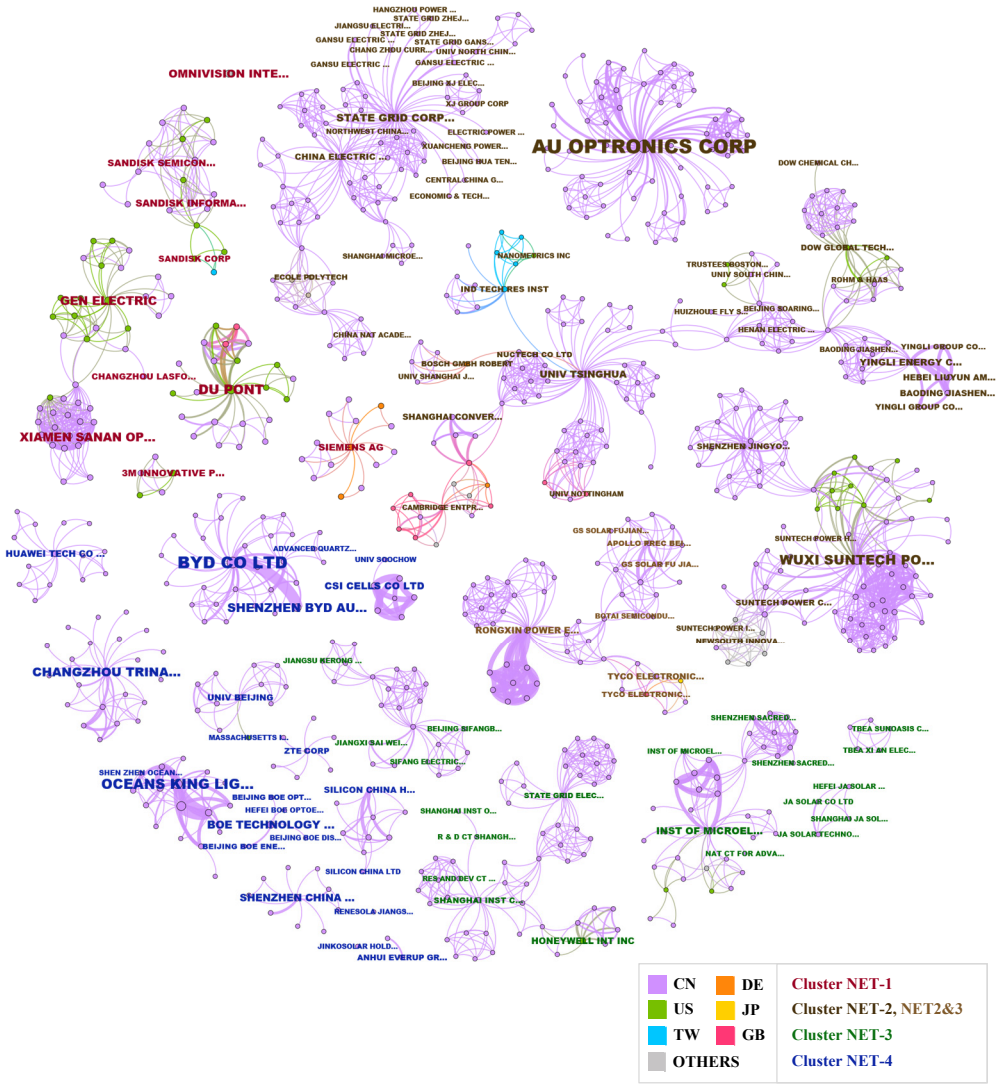
4.2.2 Patterns of Network Embeddedness

The second analytical dimension is built upon network analysis of collaboration in patents. Figure 6 shows a subgraph of co-patenting network of PV in China. It contains the components to which the identified actors of the sample belong. This subgraph represents 35% of the complete network in terms of nodes and 51% in terms of edges. The colour of nodes represents the country where applicants are located.

In this stage a second cluster analysis is conducted, but this time based on network embeddedness variables. The resulting clusters are labelled with NET throughout this paper. The right side of figure 7 shows the dendrogram of this cluster analysis. Furthermore, node labels in figure 6 are coloured based on their NET clusters. As illustrated in both figures 6 and 7, five NET clusters were identified.

Similar to the procedure done for INNO clusters (section 4.2.1), one-way ANOVA and Tukey HSD test is conducted for NET clusters (table 5). Again, the results show that for all clustering variables, there was a statistically significant difference between NET clusters at the $p<0.001$ level. Tukey HSD test revealed significant advantage for the first cluster NET1 in collaboration with foreigners. On the other hand, actors within NET2 had significantly higher component size, degree, and betweenness centrality than other clusters. Network clustering coefficients for actors in NET3 were significantly larger than those of other NET clusters.

Figure 6: Co-Patenting Network of the Top PV Innovators in China



Subgraph of the co-patenting network of Chinese patents over 1995-2014. 35% of nodes and 51% of edges are visible. Data source: PATSTAT 2015b; (Dominguez Lacasa & Shubbak, 2018). Authors' own elaboration.

Taken together, these results show:

1. **NET1:** contains actors with high global integration.
2. **NET2:** actors have high embeddedness in the collaboration network as shown by their central positions in relatively large components.
3. **NET3:** fulfils the requirements of small-world networks, given the relatively low degree and high clustering coefficients of its actors.
4. **NET4:** contains actors with low network embeddedness.
5. **NET5:** contains firms that did not file any transnational patents.

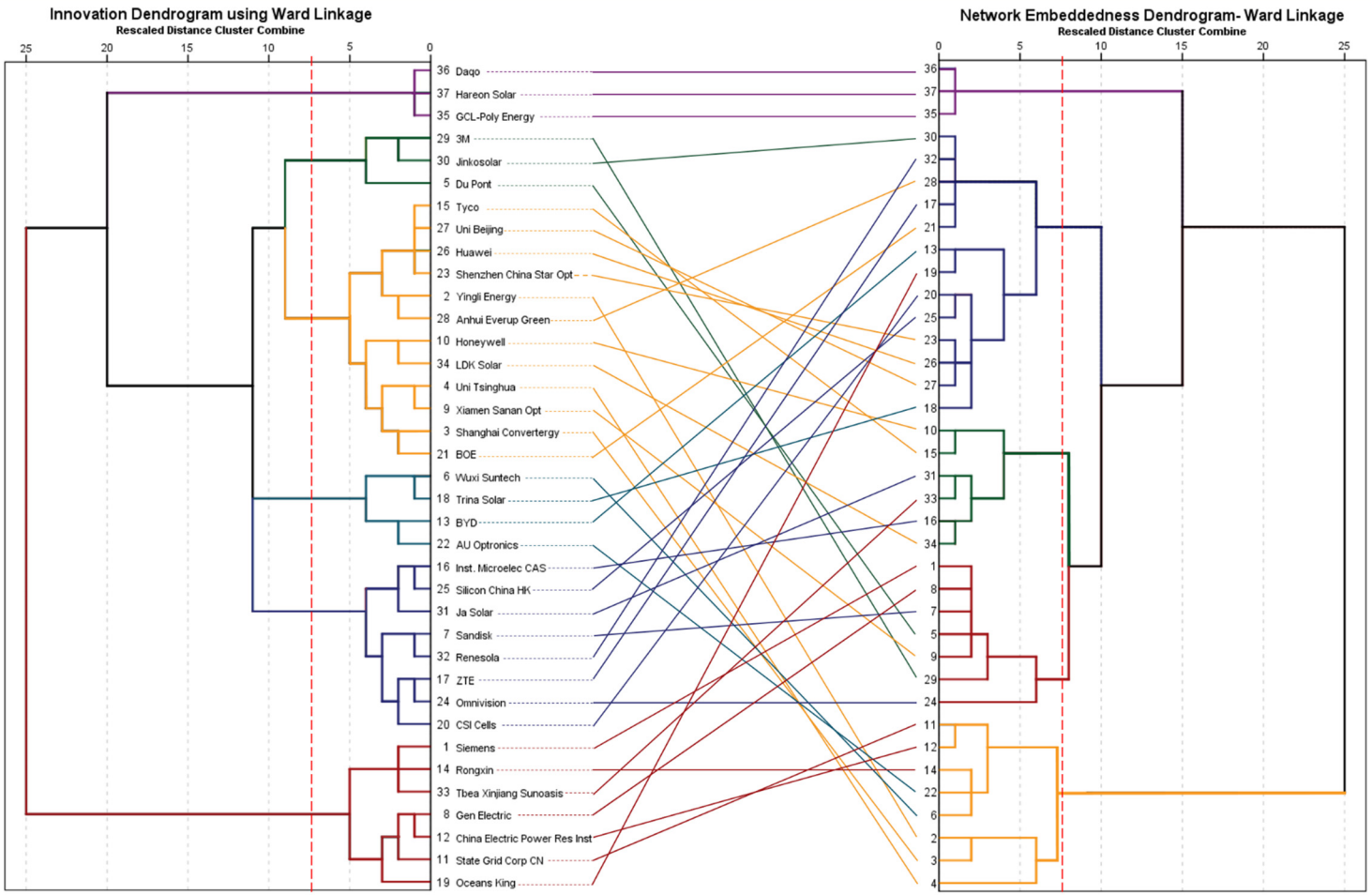
Table 5: ANOVA and Tukey HSD Analysis for Network Embeddedness Clusters

ANOVA Analysis for Network Embeddedness Clusters						
		Sum of Squares	df	Mean Square	F	Sig.
deg	Between Groups	11440.301	4	2860.075	9.740	0.000*
	Within Groups	9396.131	32	293.629		
	Total	20836.432	36			
btwn_centr	Between Groups	22669354.315	4	5667338.579	6.025	0.001*
	Within Groups	30100986.107	32	940655.816		
	Total	52770340.422	36			
clust_coef	Between Groups	7.228	4	1.807	26.729	0.000*
	Within Groups	2.163	32	0.068		
	Total	9.392	36			
com_Size	Between Groups	43785.029	4	10946.257	27.703	0.000*
	Within Groups	12644.214	32	395.132		
	Total	56429.243	36			
frgn_coll	Between Groups	0.863	4	0.216	13.921	0.000*
	Within Groups	0.496	32	0.016		
	Total	1.360	36			

Post Hoc Test: Multiple Comparisons (Tukey HSD)							
Dependent Variable	**NET (I)**	**NET (J)**	**Mean Diff. (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
						Lower Bound	**Upper Bound**
frgn_coll	**1**	**2**	.307**	0.064	0.000	0.120	0.493
		3	.390**	0.069	0.000	0.189	0.590
		4	.407**	0.058	0.000	0.238	0.575
		5	.413**	0.086	0.000	0.165	0.661
com_Size	**2**	**1**	76.411**	10.288	0.000	46.685	106.136
		3	67.292**	10.735	0.000	36.273	98.310
		4	86.510**	8.932	0.000	60.701	112.319
		5	97.125**	13.457	0.000	58.241	136.009
deg	**2**	**1**	36.375**	8.869	0.002	10.750	62.000
		3	47.042**	9.254	0.000	20.302	73.781
		4	36.452**	7.700	0.000	14.203	58.700
		5	54.375**	11.601	0.000	20.856	87.894
btwn_centr	**2**	**1**	1857.759**	501.958	0.007	407.405	3308.112
		3	1924.116**	523.792	0.007	410.674	3437.557
		4	1900.222**	435.821	0.001	640.963	3159.482
		5	1953.116*	656.608	0.041	55.917	3850.315
clust_coef	**1**	**5**	1.426**	0.179	0.000	0.908	1.945
	2	**5**	1.296**	0.176	0.000	0.787	1.805
	3	**1**	.439*	0.145	0.036	0.021	0.857
		2	.569**	0.140	0.003	0.163	0.975
		4	.678**	0.128	0.000	0.307	1.049
		5	1.865**	0.184	0.000	1.334	2.396
	4	**5**	1.187**	0.167	0.000	0.706	1.668

Only positive significant mean differences are shown in this table. Definitions of variables are stated in table 1.
*. The mean difference is significant at the 0.05 level.
**. The mean difference is significant at the 0.01 level.

Figure 7: Dendrograms and Cross-relations for Innovative-Performance and Network-Embeddedness Clusters



Authors' own elaboration.

5. CONCURRENCY ANALYSIS AND HYPOTHESES TESTING

5.1 Concurrency-Matrix

The analysis explained in section 4 resulted in clearly discernible clusters for both innovation capability and network embeddedness. However, towards achieving the aim of this research of understanding the confluence of both dimensions on the economic performance, a concurrency matrix of their cross relations is created (table 6). The cross relating is also shown in figure 7 linking both dendrograms.

Having the NET clusters as rows and the INNO clusters as columns[38], the concurrency matrix provides the exact positioning of actors in this two-dimensional space. As shown in table 6, actors can be found in 16 out of the 30 possible combinations in the matrix.

Table 6: Concurrency Matrix - Mapping of PV Innovators in China

			INNO-6	INNO-5	INNO-4	INNO-3	INNO-2	INNO-1	
Many-frgn	Medium	Medium-clustering		Sandisk Omnivision		Du-Pont 3M	X.Sanan-Opt	Siemens Gen Elect	**NET1**
Med-frgn	**Large-size**	Medium-clustering			Wuxi-Suntech AU-Optronics		Yingli S.Convertergy Uni-Tsinghua	State Grid CC CEPR Rongxin	**NET-2**
Few-foreigners	Med-size	**S-World**		Inst.Micr-CAS Ja-Solar			Honeywell Tyco LDK-Solar	TX-Sunoasis	**NET-3**
Few-foreigners	Small-size	Low-clust.		ZTE CSI-Cells Si-China-HK Renesola	BYD Trina-Solar	Jinkosolar	BOE S.China-Star Huawei Uni-Beijing Anhui-Everup	Oceans-King	**NET-4**
No-patents			GCL-Poly Daqo Hareon						**NET-5**
			No-patents	Few-patents	**Many-patents**	Few-patents	Medium-patents		
				Low-impact	Med-impact	**High-impact**	Medium-impact		
				Low-tech			**Med-tech**	**High-tech**	

[38] The characteristics of network and innovation clusters are shown in the left and bottom sides respectively. The significant feature of each cluster is stated in bold.

Besides its important use as illustrative tool per se for understanding the nature of actors' technological engagement, the introduced concurrency matrix provides a promising basis for classifying new actors within the system or even for inductively generalizing the classification into other technological fields and systems. Another important application of the matrix is to use it for testing the research hypotheses.

5.2 Hypotheses Testing

To investigate whether a significant relationship can be found between the identified patterns, concurrency interactions, and economic performance of actors, a two-way multivariate analysis of variance (MANOVA) is utilized having age, size, turnover, and productivity as dependent variables. Table 7 shows the results of Pillai's trace, Wilks' Lambda, Hotelling's trace, and Roy's largest root multivariate tests of the full factorial model of INNO and NET clusters. The results show significant relationships between INNO*NET interaction on the economic performance at the level of $p<0.01$. This result confidently rejects the null hypothesis that the multivariate means of all groups are equal.

Table 7: Results of multivariate tests for INNO*NET full factorial model

Multivariate Tests[a]						
Effect		**Value**	**F**	**Hypothesis df**	**Error df**	**Sig.**
Intercept	Pillai's Trace	0.936	61.766[b]	4.000	17.000	0.000**
	Wilks' Lambda	0.064	61.766[b]	4.000	17.000	0.000**
	Hotelling's Trace	14.533	61.766[b]	4.000	17.000	0.000**
	Roy's Largest Root	14.533	61.766[b]	4.000	17.000	0.000**
INNO	Pillai's Trace	0.946	1.549	16.000	80.000	0.103
	Wilks' Lambda	0.260	1.824	16.000	52.573	0.052*
	Hotelling's Trace	2.090	2.025	16.000	62.000	0.025**
	Roy's Largest Root	1.656	8.282[c]	4.000	20.000	0.000**
NET	Pillai's Trace	1.151	2.955	12.000	57.000	0.003**
	Wilks' Lambda	0.190	3.290	12.000	45.269	0.002**
	Hotelling's Trace	2.558	3.340	12.000	47.000	0.001**
	Roy's Largest Root	1.585	7.528[c]	4.000	19.000	0.001**
INNO * NET	Pillai's Trace	1.768	2.263	28.000	80.000	0.002**
	Wilks' Lambda	0.046	3.006	28.000	62.717	0.000**
	Hotelling's Trace	6.709	3.714	28.000	62.000	0.000**
	Roy's Largest Root	4.640	13.257[c]	7.000	20.000	0.000**

a. Design: Intercept + INNO + NET + INNO * NET.
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.
*. Significant at the 0.1 level.
**. Significant at the 0.05 level.

Inspecting the model for between-subject effects on each dependent variable, table 8 shows a significant effect of innovation-capability on actors' turnover, as well as significant relationships between network-embeddedness, age, turnover and productivity. Similar significant relationships were found between INNO*NET interaction with the dependent

variables of age and economic performance. However, no significant effects were found for any of the model elements on firms' size (number of employees).

To clearly illustrate the results and test the research hypotheses, the identified patterns are combined based on their commonalities. This results in three innovation levels:

1. **High-quality innovation level:** combines the high-tech and high-impact innovation clusters, INNO1 and INNO3 respectively.
2. **High-diversity innovation level:** combines the diverse med-tech and high-quantity clusters, INNO2 and INNO4 respectively.
3. **Low innovation level:** combines the innovation clusters INNO5 and INNO6.

On a related front, three network patterns are defined as:

A. **High centrality pattern:** contains the highly embedded actors of the cluster NET2.
B. **Small-world pattern:** combines the globally integrated and highly clustered actors of NET1 and NET3 respectively.
C. **Low embeddedness pattern:** combines the network clusters NET4 and NET5.

Figure 8 illustrates the detailed comparisons of dependent variables (estimated marginal means) across the innovation groups and network patterns.

Table 8: 2-Way MANOVA Analysis for INNO*NET Concurrency

2-Way MANOVA: INNO*NET (Tests of Between-Subjects Effects)						
Source	**Dependent Variable**	**Type III Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig.**
Corrected Model	**age***	4.43E+04[a]	15	2.95E+03	2.179	0.052*
	turnover**	1.90E+10[b]	15	1.27E+09	5.935	0.000**
	employees	5.19E+05[c]	15	3.46E+04	1.466	0.209
	productivity**	5.14E+05[d]	15	3.43E+04	2.942	0.013**
Intercept	**age****	3.72E+04	1	3.72E+04	27.462	0.000**
	turnover**	3.32E+09	1	3.32E+09	15.519	0.001**
	employees**	1.17E+05	1	1.17E+05	4.939	0.038**
	productivity**	1.50E+06	1	1.50E+06	128.515	0.000**
INNO	age	2.53E+03	4	6.32E+02	0.466	0.760
	turnover**	2.96E+09	4	7.40E+08	3.465	0.026**
	employees	1.12E+05	4	2.80E+04	1.186	0.347
	productivity	9.46E+04	4	2.37E+04	2.030	0.129
NET	**age***	1.13E+04	3	3.77E+03	2.778	0.068*
	turnover**	3.57E+09	3	1.19E+09	5.575	0.006**
	employees	6.48E+04	3	2.16E+04	0.914	0.452
	productivity**	1.36E+05	3	4.52E+04	3.877	0.025**
INNO * NET	**age***	1.99E+04	7	2.84E+03	2.097	0.092*
	turnover**	8.42E+09	7	1.20E+09	5.628	0.001**
	employees	2.20E+05	7	3.14E+04	1.331	0.287
	productivity**	2.32E+05	7	3.32E+04	2.847	0.031**
Error	age	2.71E+04	20	1.36E+03		
	turnover	4.27E+09	20	2.14E+08		
	employees	4.72E+05	20	2.36E+04		
	productivity	2.33E+05	20	1.17E+04		

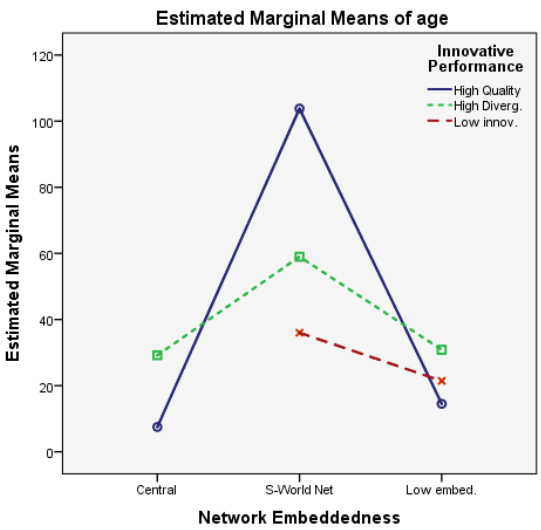
Total	age	1.30E+05	36
	turnover	2.99E+10	36
	employees	1.18E+06	36
	productivity	2.84E+06	36
Corrected Total	age	7.14E+04	35
	turnover	2.33E+10	35
	employees	9.92E+05	35
	productivity	7.48E+05	35

a. R Squared = .620 (Adjusted R Squared = .336)
b. R Squared = .817 (Adjusted R Squared = .679)
c. R Squared = .524 (Adjusted R Squared = .166)
d. R Squared = .688 (Adjusted R Squared = .454)
*. Significant at the 0.1 level.
**. Significant at the 0.05 level.

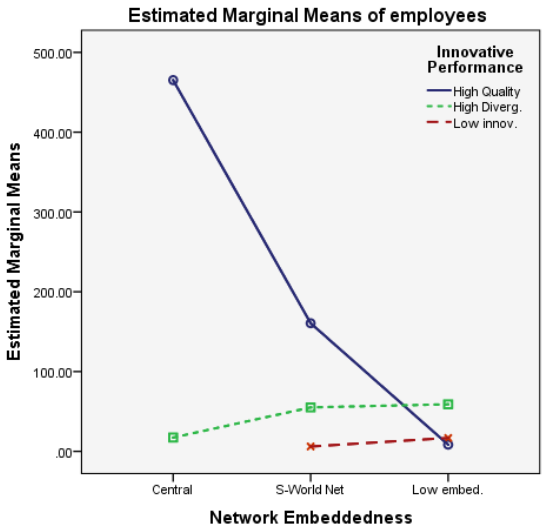
According to figure 8c, actors with high-quality innovations or high-diversity have significantly higher turnover than those with low-innovation. This result supports **Hypothesis 1a**, which states that organizations with high innovation-capability are likely to achieve higher economic performance. Although the hypothesis is strongly supported for turnover, a non-significant negative effect can be found for the second indicator of economic performance: productivity (figure 8d), where low innovative actors score higher productivity levels. This result can be explained by the fact that such firms are usually of smaller size and are usually focusing on matured technologies, where mass production is more important than R&D for a successful business.

Figure 8: Age, Size, and Economic Performance across Concurrency-Matrix Clusters

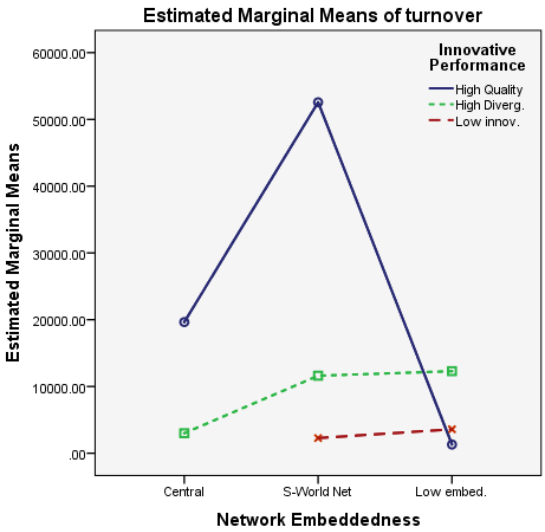
(a) Age of Actors



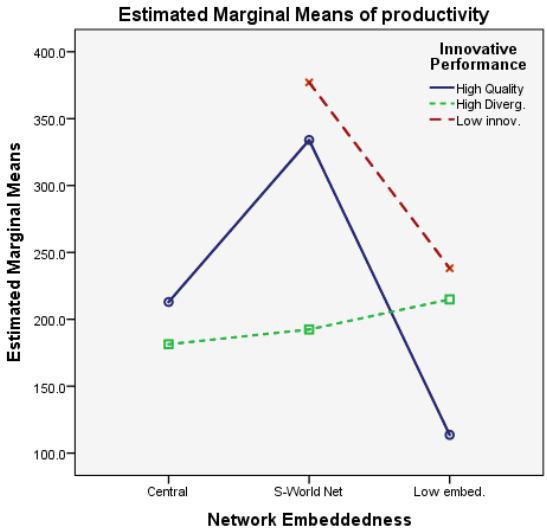
(b) Size of Actors (Number of Employees)



(c) Turnover of Actors (operating revenue)



(d) Productivity of Actors



Authors' own elaboration.

Hypothesis 1b suggested a positive relationship between firm's age and innovation capability. The results shown in figure 8a support this hypothesis, as firms with high-quality innovations or high-diversity are relatively older than low-innovation firms.

Figure 8b shows positive relationships between firm size, on the one hand, and innovation capability and network embeddedness, on the other. However, due to the non-significant MANOVA, we cannot confidently accept **Hypotheses 1c and 2c**, nor reject them.

Hypothesis 1d suggested a higher importance of innovation quality than quantity in influencing economic performance. The results shown in figure 8 support this hypothesis (only in highly embedded networks), where actors with high-quality innovations achieved higher turnover and productivity levels than those with high-diversity and quantity.

Regarding network embeddedness, figures 8c and 8d show higher economic outcomes for small-world and high-centrality patterns only when innovation quality is high. However, network embeddedness is negatively related with economic performance in the other innovation levels. This yields a partial support of **Hypothesis 2a**. Additionally, since actors in small-world networks are relatively older than low-embedded firms (figure 8a), **Hypothesis 2b** is supported.

Finally, **Hypothesis 3** suggested a higher positive impact of innovation on economic performance when network embeddedness is high. Figure 8c shows a significant higher turnover for actors with high-quality innovations when they are embedded in small-world networks or when they have central network positions. Therefore, we can confidently accept hypothesis 3.

The analysis revealed another interesting remark regarding the innovative organizations, whose activities are technologically diversified. Such firms tend to achieve higher economic performance when operating in small networks with low embeddedness. Sourcing external knowledge in technological fields beyond the specialization of a company is widely considered among the main motivations of interfirm collaboration. Accordingly, this tendency can be explained by the fact that having a diversified portfolio of technological activities internally, such firms need less external collaborations.

5.3 The complete image

Putting everything together, figure 9 shows the full overview of the main actors within the Chinese innovation system of PV technology. The circular visualization shows actor profiles, clustering variables, resulting clusters, concurrency, and productivity (as an indicator of economic performance).

Figure 9: The Complete Image of PV Innovators in China

Circular Visualization of Clustering, Concurrency, and Economic Performance

Author's own elaboration.

The upper half of the circle represents INNO clusters, with heatmaps of their clustering variables, as well as a bar chart of economic productivity. The lower half of the visualization represents the NET clusters along with their clustering variables heatmap.

Actors are numbered as in table 2. The central area within the circular graph shows the concurrency relations between the two cluster sets. Finally, co-patenting links are shown in the lower left quarter of the figure. The figure helps better understanding of the results and viewing all the discussed aspects simultaneously.

6. DISCUSSION AND CONCLUSION

The present research analysed the patterns of innovative activities and network embeddedness and their impact on economic performance of leading actors within the Chinese technological system of innovation in the field of solar photovoltaics. Based on several market and patent indicators, the paper identified 37 organisations as the main actors in the system. These few actors, however, have a prominent position in the system as they are accountable of more than 60% of PV production and 41% of patenting activities in China.

Moreover, six different patterns of innovative activity were recognized along with five network embeddedness patterns. Introducing the analytical tool of concurrency matrix, the co-evolution of both dimensions was captured. The results showed a significant effect of the interaction between innovation-capability and network-embeddedness dimensions on the economic performance of organisations. Confirming the literature on single-basis effects, the paper came up with additional insights on the confluence of both dimensions.

Furthermore, the results revealed interesting findings regarding the most significant factors in each dimension. The analysis went further than confirming the positive impact of innovation on economic performance. It shows that the quality of innovation outcomes is even more important than their quantity or diversity.

Similarly, within the network-embeddedness dimension, another interesting finding is that organizations belonging to small-world network patterns achieved even a higher economic performance than those of high centrality. This highlights the greater importance of the structure of network components than the positions of individual nodes. Although organizations in small-world networks had, on average, less direct ties to other actors, the structure of their network components provides them with high proximity to more actors, albeit indirectly.

Taken together, the results show that the combination of high-quality innovation and small-world networks yields in a significantly higher turnover. On the other hand, organizations with high technological diversity tend to operate with low embeddedness in small network components. Interestingly, firms with low-tech and production-oriented focus scored higher levels of productivity.

Some limitations regarding the lack of involvement of two more elements can be considered as an area for further research. Those are the institutional side of innovation system and the dynamic dimension of network analysis over time.

Overall, the paper attempted to push forward a new field by analysing the confluence of two different dimensions that have long been analysed in single basis. The replication of the research methodology for other technological, national, or regional contexts to test whether similar relationships could be found, would likely contribute to economic and business theories development. Whereas, taking the concurrency aspect into consideration in both management strategies and policy making, clean energy technologies such as PV would reach their ultimate goal of being both competitive and politics independent.

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The Technological System of Production and Innovation: The Case of Photovoltaics Technology in China

Chapter 5

ABSTRACT

This research paper studies the Chinese technological system of production and innovation in the field of Photovoltaics (PV). It contributes to a better understanding of the emergence and development of the system by utilising three levels of analysis - the institutional framework of the system, the market dynamics of production and deployment, and the composition of innovation related activities. The analysis demonstrates the interrelated roles of transnational factors, local government policies, and research and development (R&D) activities undertaken by the main actors, in shaping the system dynamics. Tracking the relative position of China in the global PV manufacturing, installation, and technological development, the analysis shows a gap between the growth of China's market share and its modest share of transnational patent applications. This suggests a puzzle, which the paper attempts to answer by inspecting the individual companies in the system against four aspects. First, the dynamic development of their size and performance. Second, the nature of their international involvement through foreign direct investment (FDI) and mergers and acquisition deals (M&A). Third, their technological specialization within the PV value chain over time. Fourth, the spatial scope of their patenting protection endeavours. The analysis recognises four periods of system development jointly driven by market dynamics and government plans. Behind the continuous growth of the system, there were different driving and moderating factors in each period.

KEYWORDS

Sectoral Innovation System; Solar Photovoltaics; Institutions; Crystalline-Silicon Market; Patent Analysis; Environment

JEL CLASSIFICATION

L11; O31; O38; Q42; Q48; Q55

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1. INTRODUCTION

Renewable energy sources, as wind, solar, and geothermal power, are widely seen as potential solutions to environmental problems. Therefore, they form an essential part of strategies for sustainable development (Jaramillo-Nieves, Del Río, 2010; Lund, 2007; Valente, 2005). China has prominent role in the literature on PV technologies in developing countries, as it experienced dramatic production growth during a very short period. In 2003, China's share in PV global production was less than 1%. However, the country has rapidly built up indigenous capabilities to become the dominant force in solar cell manufacturing in the world since 2008 (Fu, 2015). In 2013, China accounted for 60% of the global PV production (Jäger-Waldau, 2013). The dramatic growth in China's market share occurred despite a relatively modest growth in its transnational patent applications until 2008. Even with a faster growth rate in the following years, China's transnational patent application share is still far behind the traditional leading countries in the field (Dominguez Lacasa & Shubbak, 2016; 2018).

This suggests a puzzle, which we attempt to answer by inspecting the individual companies in the system against four aspects. First, the dynamic development of their size and performance. Second, the nature of their international involvement through foreign direct investment (FDI) and mergers and acquisition deals (M&A). Third, their technological specialization within the PV value chain over time. Fourth, the spatial scope of their patenting protection endeavours. Consequently, the paper utilizes three analytical levels: institutions, production, and innovation.

In the next section, the conceptual framework and literature review are presented. Section 3 introduces the materials and methods used through the paper. Section 4 shows the detailed empirical results concerning the three analytical levels. A discussion of the results is represented in section 5 in a chronological order over four periods. We finally conclude by stressing the main outcomes and implications in section 6.

2. LITERATURE REVIEW

The conceptual framework of this research is built upon the commonly used analytical tool of 'innovation systems', which is a systemic approach originally developed in the end of the twentieth century to analyse innovation processes at national level (Freeman, 1988; Lundvall (ed.), 1992; Nelson (ed.), 1993). Alongside with national innovation systems, regional- (Cooke et al., 1997) and technological/sectoral level (Carlsson & Stankiewicz, 1991; Malerba, 2002; Malerba & Nelson, 2011) concepts were introduced. An advantage of the systemic approach is that it includes all the important factors influencing innovation process (Edquist, 1997).

Technological innovation systems (TIS) can be defined as "network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" (Carlsson, Stankiewicz, 1991, p. 111). Accordingly, the system consists of three main elements: (i) **actors** and their competences, (ii) their **interactions**, (iii) **institutional framework** (Jacobsson. Johnson, 2000). Additionally, Malerba (2002, p. 251) identifies four more building blocks of a sectoral

innovation system as: the **knowledge base** and learning processes, the basic **technologies** relevant to the system, **demand** conditions, as well as **variety generation and selection** processes of technologies, products, firms, and strategies.

Institutions and institutional set up "are of crucial importance for innovation processes" (Edquist, 1997, p. 25). Institutions can be understood as "the rules of the game in a society" (North, 1990, p. 3) or as "systems of established and prevalent social rules that structure social interactions" (Hodgson, 2006, p. 2). Carlsson and Stankiewicz (1991, p. 109) characterise the institutional infrastructure of a TIS as "a set of institutional arrangements (both regimes and organizations) which, directly or indirectly, support, stimulate and regulate the process of innovation and diffusion of technology." Public policy instruments, as one of aspects of institutional infrastructure, are classified in three types: regulations, economic means, and information (Vedung, 1998/2010, p. 30-33). Economic instruments can influence both the demand and supply sides (Borras, Edquist, 2013). Moreover, recent discussion in literature (e.g. Reichardt, 2016; Kivimaa, Kern, 2016; Borras, Edquist, 2013; Veugelers, 2012; Flanagan *et al.*, 2011) leads to the conclusion that policy mixes are more appropriate to facilitate innovations than using individual instruments. Malerba & Nelson (2011) argue that government policies can affect economic sectors differently. In the area of renewable energy, public and industrial policy has shown a significant influence on technology development (Johnstone, et al. 2010; Baker & Sovacool, 2017).

On the other hand, actor interactions and transnational aspects are particularly important for the evolution of TIS. The influence of transnational factors on innovation processes traditionally takes the form of technology transfer through FDI (Blalock, Gertler, 2008; Barell, Pain, 1997). Other channels are: trade in goods, licencing, and movement of people (Hoekman et al., 2005). In the TIS approach, transnational factors are more broadly understood, and include among others: (i) international scientific cooperation, (ii) global mobility of skilled personnel, (iii) transnational corporations, (iv) global production networks, (v) global equipment markets and market competition, (vi) global technology markets (Gosens et al., 2015, pp. 381-383). Examining economic development of six industries, Malerba & Nelson (2011, p. 1663) identify two different catching-up trajectories. The first is through specialization in particular stages of the global value chain to access external knowledge and markets, building indigenous capabilities and upgrading to higher positions in the value chain. The second is through subsidiaries and joint-ventures with leading multinational corporations.

In a recent contribution, Lee & Malerba (2017) introduce the theoretical framework of 'catch-up cycles'. They argue that in the evolution process of sectoral systems, radical discontinuities open 'windows of opportunity', to which the responses by system actors can affect industrial leadership. Accordingly, four stages in industry catch-up cycle can be identified: entry, gradual catch-up, forging ahead, and falling behind. Furthermore, Lee & Malerba (2017) distinguish between technological, demand, and institutional windows of opportunity.

To answer the research puzzle introduced in section 1, and to understand the driving factors of the successful forging ahead of China in the PV industry, we will use the

technological/sectoral innovation system framework considering both the dynamics of political economy and windows of opportunity within catch-up cycles.

Reviewing the literature on the Chinese PV sector, international trade in goods, movement of skilled employees, and FDI were found main channels of the technology transfer (de la Tour et al., 2011). Similarly, Zhang and Gallagher (2016) pointed out that migration of skilled human resources allowed gaining expertise and information in the early stage of China's TIS development[39]. Recent studies about the PV technology in China can be divided into four groups: investigations of PV sector development, policy analysis, comparative studies, and network analysis (Table 2.1).

Table 2.1 Research on the PV sector in China

Main area of interest	Authors
PV Sector Development	Huang et al. (2016); Zhang, Gallagher (2016); Zhang, White (2016); Binz, Anadon (2016); Iizuka (2015); Fu (2015); Honghang et al. (2014); Wang et al. (2014); de la Tour et al. (2011); Wu, Hou (2011); Yang et al (2003); Si-Cheng (1987) Wei et al. (1981)
Policy Analysis	Shen (2017); Gruss, ten Brink (2016); Qiang et al. (2014); Zhang et al. (2014); Liu, Goldstein (2013); Zhang, He (2013); Fischer (2012); Fu et al. (2012); Huo, Zhang (2012); Li et al. (2011); Zhao et al. (2011); Ren et al. (2010)
Comparative Studies	Binz et al. (2017); Gul et al. (2016); Quitzow (2015); Gosens et al. (2015); Platzer (2015); Wu (2014); Jang et al. (2013); Wu, Mathews (2012); Grau et al. (2012); Huo et al. (2011)
Network Analysis	Dominguez Lacasa, Shubbak (2016; 2018)

Source: Authors' own elaboration

Binz and Anadon (2016) analysed emergence of the Chinese PV industry based on systemic approach, taking into account four key resources for the industry formation: knowledge, markets, financial investment and technology legitimacy. Their research shows that most of crucial knowledge had international origins. Additionally, instead of trying to satisfy small domestic demand, first entrepreneurs decided to use existing networks and trade infrastructure to enter the European and the Japanese markets with their products. Huang et al. (2016) identified three main factors of rapid development of the China's PV sector: (i) change in institutional set up, (ii) technology transfer, (iii) existence of large European market.

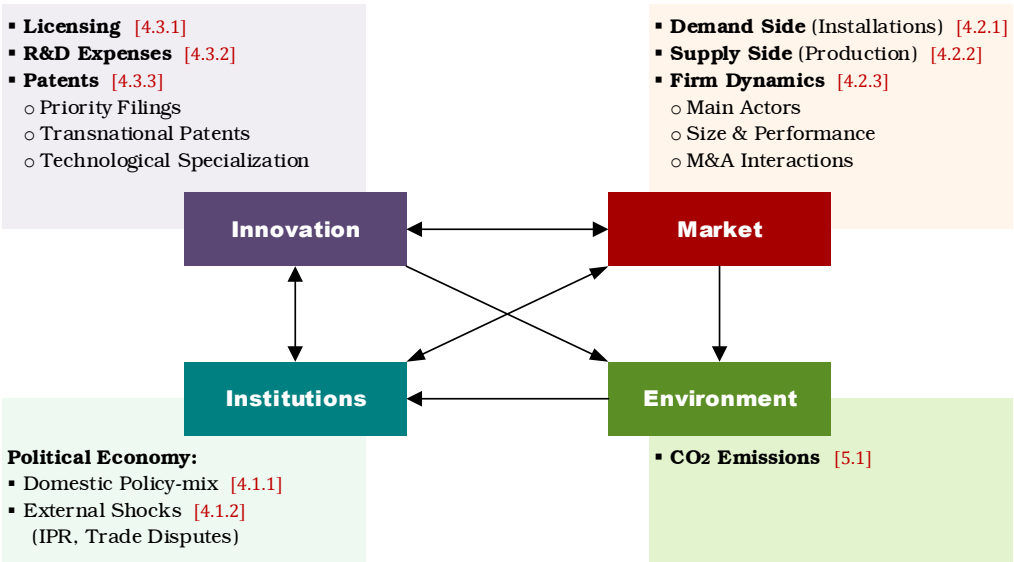
[39] Scholars usually highlight the case of SunTech Power Co, which was the global leader in solar-cell manufacturing in 2010. The company was founded in 2001 by a Chinese scientist (Dr. Shi Zhengrong), who obtained his PhD in renewable energy engineering from the University of New South Wales in Australia before moving back to China and running a PV start-up business benefiting from the networks and knowledge gained from abroad.

While considerable research on PV development in China already existed, it nonetheless mostly considers single aspects of the process at a time. This leaves a crucial part of the story untold. In other words, the dynamic interrelations between different dimensions, as well as the analysis of innovation and environmental aspects had not been adequately addressed in the literature. In this paper, we adopt the TIS framework to incorporate these dimensions. More specifically, we aim to understand the bidirectional interaction between government policy and global market dynamics, and its influence on innovation and environment. The contribution of this paper is twofold: first, it provides a deeper look into the PV system of production and innovation vertically through the different stages of its value chain. Second, it integrates all the building blocks of the TIS concept and expands it horizontally by introducing the system firmodynamics element (with its micro level analysis), and the environmental impact element (considering the specificity of the system and its direct relation to climate change).

3. MATERIAL AND METHODS

To study the PV innovation system in China, we first consider the development of its **building blocks** individually. Therefore, we identify the relevant **technologies** (section 3.1), for which **knowledge base** and innovation capabilities are accumulated throughout the system development (section 4.3). The system **institutions** are discussed from a political economy perspective (section 4.1), in order to detect their interrelations with the market dynamics of supply and **demand** (section 4.2). Furthermore, we identify the main **actors** in the system, both firm (sections 4.2.3, 4.3.3) and non-firm (sections 4.1.1, 4.3.3), along with their market **interactions** with international actors.

Figure 3.1: The Analytical Dimensions of the PV Production & Innovation System



Notes: The relevant subsections are given in square brackets. The arrows show direction of influence. Author's own elaboration.

Finally, we combine the individual building blocks into the complete image of the system (section 5), to understand their interactions and overlapping roles in both: the system development (**variety generation, selection**, and windows of opportunity), and environment protection. Figure 3.1 summarizes the main dimensions of the present study. The remaining subsections of this chapter introduce the definitions, data sources, and indicators used along the paper.

3.1. PV technologies and components

To determine innovation activities associated with solar PV technologies, we use the definition and patent identification scheme developed by Shubbak (2017). The classification offers a comprehensive definition of different components along the production value chain of the so-called PV large technical system. It defines six main patent groups for the PV system: (i) solar cells, (ii) solar panels, (iii) electronics, (iv) monitoring and testing, (v) energy storage, and (vi) portable devices for lighting, heating and cooling purposes.

These groups comprise subcategories with more details regarding specific technologies. For instance, the first group 'solar cells' represents an active research field in physics, photo- and electro-chemistry. It includes three technology generations with five families differing in their semiconductor materials and manufacturing processes (figure 3.2). These are the relatively mature first-generation 1G technologies of **crystalline silicon (c-Si) cells**; the second-generation 2G technologies of **thin-film technologies** (such as CdTe, CIGS, and Amorphous- Si) and **single-junction Gallium Arsenide (GaAs) cells**; as well as the third-generation 3G technologies of the high efficient **multi-junction cells** and the **emerging/organic PV cells** (NREL, 2016; Hegedus & Luque, 2010). These families widely differ in both manufacturing complexity and power conversion efficiency, and thus in their costs, and practical applications.

Figure 3.2: Technology Generations and Families of Solar PV Cells

Author's own elaboration.

For example, c-Si cells (with cell efficiency[40] records η ≈ 21-27%) and thin-film cells (η ≈ 14-23%) are the two families available in mass production. They are commonly used in electronic portable devices, residential solar panels, or utility power plans. On the other hand, the expensive high-efficient technologies of GaAs (η ≈ 27-29%) and Multi-junction cells (η

[40] The conversion efficiency of a solar cell (η) is calculated as the portion of the incident sunlight power on cell surface that is converted into electrical energy. In this paper, cell efficiencies source is (NREL, 2016).

≈ 31-46%) are mostly used for space power applications (Hubbard, et al., 2009). Organic and emerging technologies (η ≈ 11-12%) are still under development phase in research laboratories. Despite their lower efficiency, the emerging technologies are considered promising due to their low manufacturing costs and additional applications such as transparent cells.

In terms of production share, c-Si cells are dominant in the market with 93% of the total produced capacity in 2015 (69% multi-crystalline cells and 24% mono-crystalline), while thin-film technologies form only 7% of the total production. Furthermore, China's PV cell production is mostly focused on c-Si technology.

The production of c-Si PV cells goes through three main groups of purification and fabrication processes. In the first, raw materials of quartz sand (SiO_2) and coal[41] (C) are processed inside electric arc oven to generate metallurgical-grade silicon, which undergoes further hi-tech processes in several reactors to produce solar-grade polysilicon. The second group of purification processes comprises crystal growth methods, where mono and multi-crystalline ingots are produced. The outcomes of both process groups are called purified silicon feedstock. The ingots are then sliced into wafers to be doped with p-n impurities and soldered with conducting surfaces, which together compose the solar PV cell. Solar panels are produced by wiring and encapsulating arrays of PV cells together. Within all these stages of the value chain, the production of purified silicon feedstock is considered the core technology. It contributes to 40% of the total cost and 82% of the final profit of each solar panel (de la Tour, et al., 2011).

3.2. Market dynamics and firm level data

To analyse the market dynamics of the system, two levels are considered. First, macro-level data, where indicators are measured per countries. Under this category, three indicators are used: (1) The net charges for using intellectual property (NCIP) through licences based on World Bank, world development indicators database. (2) The market demand-side represented by PV installed capacity based on British Petroleum (BP) statistical review of world energy 2016 dataset. (3) The market supply-side represented by cell production capacity based on the dataset of (Brown, et al., 2015).

Second, micro-level data, where indicators represent the characteristics of individual companies. Under this category, we employ four indicators: (1) Silicon-feedstock production shares of top producers globally, compiled from various resources shown under figure 4.2. (2) Global PV cell shipments of top manufacturers, compiled from various resources shown under figure 4.3. (4) Firm size, performance, and R&D expenses for the main actors in the system, based on Bureau van Dijk (BvD) - Orbis database (version 129.00). (4) M&A deals for main global and Chinese firms based on BvD-Zephyr Database (version 30.0).

[41] Carbon raw material used in this process usually consists of metallurgical grade coal along with charcoal, and coke (Ciftja, et al., 2008, pp.9-12).

3.3. Patent Indicators

Despite the well-known limitations for using patents as an indicator of technological innovation (Archibugi, 1992), it is undeniable that patent filings act as a key link between successful inventive activities and commercial markets. Patent data covers large temporal and spatial scope, and it includes detailed technical information about the inventions along with their legal and intellectual owners (patent applicants and inventors respectively). Therefore, it provides rich insights into the accumulated knowledge stocks, flows, as well as cooperation activities in the sake of knowledge creation. In this paper, two types of patent applications are considered from the EPO Worldwide Patent Statistical (PATSTAT) Database 2015:

(1) ***Priority patent filings*** developed by (de Rassenfosse, et al., 2013) are used to capture the complete landscape of patenting activities per inventor country. Priority filings offer a proxy of the total number of patent families marked by their earliest publications regardless of the issuing authority. Therefore, it can capture a wider scope of patenting activities with various economic and technological values with no restrictions to a specific market domain.

(2) On the other hand, ***transnational patent indicator*** developed by (Frietsch & Schmoch, 2010) covers patent applications only enforceable across national borders. Those are applications filed at the European Patent Office (EPO), and international applications filed under the Patent Cooperation Treaty (PCT)[42]. Therefore, transnational patents are usually expected to be of higher economic and technological value, for which applicants seek protection in several markets across the national borders.

Furthermore, to comparably capture indigenous inventive capabilities, patent applications are fractionally counted and disaggregated by country where inventors are located, e.g. Chinese transnational patent applications indicate patents of Chinese residents that are filed under the international or European patent systems. The fractional counting means that patents, with multiple inventors from different countries, are partly attributed to each country (OECD, 2009, p. 64).

To capture the relative technological specialization of China in patenting activities, we use the ***Revealed Technology Advantage (RTA) index*** (Balassa, 1965; Soete & Wyatt, 1983). RTA is calculated as the ratio between two shares. The nominator is the share of a country's patent applications in a specific technological field over its total patents. The denominator is the share of the worldwide patents in the field over the worldwide patents in all fields. This can be represented by the following formula:

$$\mathrm{RTA} = \frac{P_{ij}/P_{iT}}{P_{Nj}/P_{NT}}$$

[42] Transnational patent indicator is calculated avoiding double counting of applications that belong to the same family.

Where P: is the number of Patent applications, i; represents the inventor country under consideration, N: represents all inventor countries, j: represents the technological field under consideration, and T: represents all technological fields.

Laursen (2015) introduces adjustment to the index to become symmetric around its neutral value by using the formula for symmetric RTA (sRTA): $sRTA = (RTA - 1)/(RTA + 1)$

Accordingly, a positive sRTA indicates that the country has a relative advantage in the technological field compared to other countries. In other words, it means that the concentration of patenting activities by the country in the field j is larger than the world's average. On the other hand, a negative sRTA means the opposite.

4. THE PV TECHNOLOGICAL SYSTEM OF PRODUCTION AND INNOVATION IN CHINA

To understand the PV technological system of production and innovation in China, the paper considers three levels of analysis (figure 3.1). First, we investigate the institutional side of the system. Second, we consider the market dynamics of production and deployment from the macro to the micro level, identifying the main firm actors (producers) and their characteristics. Finally, for the third analytical level, we study the innovation related activities within the system, identifying the main innovators along with their technological specialization.

4.1. The Institutional Framework

The first analytical dimension to consider is the institutional framework. Adopting a political economy perspective, we first review the main policies and laws promulgated by the Chinese government regarding PV technologies development and deployment over time. Second, we highlight the external shocks in terms of institutional dynamics, trade disputes, and decisions taken by international parties and their impact on the system of production and innovation in China.

4.1.1 Domestic Policy-Mix

China's commitment to develop and deploy renewable energy technologies has long been institutionalised in government strategies. To analyse the role of the Chinese state in the PV technological system, we consider its main plans, laws, projects, and policies during 1993-2017 (Table 4.1). We distinguish between four types of institutional instruments. First, plans and targets set by the government. Second, 'supply-push' policies aimed for supporting development of PV technologies through scientific research, R&D, and facilitating business activities of PV manufacturers (with financing support, materials/equipment duty-free, enterprise income-tax reduction, and investor subsidies). Third, 'demand-pull' policies aimed for supporting deployment of PV technologies through electrification programs, value-added tax reduction, feed-in tariffs (FITs), technology-adoption subsidies, and grid infrastructure development. Fourth, regulatory instruments such as laws and standards.

We consider four periods that are similar to China's five-year plans (FYP). In the first period (1995-1999), the focus was on building a knowledge base for science and technology as well as regulating electric power production and developing devices for rural electrification purposes. Furthermore, China signed the Kyoto Protocol in 1998.

In the second period (2000-2004), the government continued with rural electrification programs and introduced supporting policies to the establishment of solar panel production through tax reduction on PV manufacturing equipment and products. Moreover, the 10th FYP (2001-2005) aimed to enhance the industrial structure and competitiveness, raise R&D funding to 1.5% of GDP, and strengthen science-technology-innovation capabilities.

Government policy in the third period (2005-2009) was mainly production and export-oriented. The solar PV industry was included in the catalog of Chinese high-technology products for export in 2006, and a component of the launch of a science and technology cooperation program in 2008. The program motivates Chinese firms, research institutes, and universities to acquire high-tech knowledge through long-term cooperative partnerships and joint R&D centres with leading countries in the field to stimulate technology transfer.

Later in 2008, the central government launched a recruitment programme for global experts entitled 'Thousand Talents Plan'. Offering full-time positions (with high salaries and benefits) at research institutes, universities, and national industrial parks, the programme was successful in attracting 4,180 experts by mid-2014. Many of them were overseas Chinese who obtained their higher degrees at western universities. Ball, et al. (2017) highlight the role of the programme in attracting back prominent researchers in PV cell technologies that are less developed in China (e.g. 2G technologies) to trigger catching-up capabilities[43].

Table 4.1: The Chinese Policy-Mix for PV Technology over 1993-2017

Year	Policy	Type
1993	Science and Technology Law	Law
Period 1		
1995	9th five-year plan: speed up the establishment of a modern enterprise system, support education, focus on scientific and technological research (plan period: 1996-2000)	State Plan
1995	The China Electric Power Law	Law
1996	Brightness Electrification Program	Electrification
1997	National Basic Research Program (973 programmes)	Research
Period 2		
2001	10th five-year plan: enhance the industrial structure and competitiveness, raise R&D funding to 1.5% of GDP, and strengthen STI capabilities	State Plan
2001–2003	Reduced Value-Added Tax for Renewable Energy	Tax Reduction
2002	Township Electrification Program	Electrification
2003-2007	Preferential Tax Policies for Renewable Energy	Tax Reduction SP

[43] e.g. Zhengxin Liu (expert in Heterojunction with Intrinsic Thin-layer HIT cells from Japan), Xudong Xiao (CIGS cells from USA), and Deliang Wang (CdTe cells from Germany). (Ball, et al. 2017, p. 86)

Period 3		
2006	11th Five-year Plan: wider openness in science & technology. Energy-saving and environmental protection. PV power plants in remote areas.	State Plan
2006	Catalog of Chinese High-Tech Products for Export includes PV industry	Strategy
2006	Renewable Energy Law	Law
2006	Renewable Energy Price Subsidies and Cost-sharing Management Pilot Scheme	Subsidies
2007	National Climate Change Program	Strategy
2008	International Science and Technology Cooperation Program for Renewable Energy	Strategy
2008	Energy Conservation Law	Law
2008-2018	Thousand Talents Plan: Recruitment Program of Global Experts	Strategy
2009	Renewable Energy Law (Amendment) (scientific and technological research to be commissioned by government)	Law
2009	Renewable Electricity Surcharge	Subsidies
2009	Concession Program for Large-Scale Solar PV Power Plants	Subsidies
2009	Solar Rooftop Subsidy Program	Subsidies
2009	Golden Sun Demonstration Program	Electrification
Period 4		
2010, 2011	12th five-year plan: raise renewable and solar energy generation capacity	State Plan
2010	Building Integrated Solar PV Program	Subsidies
2010	Taxation preferential policies for renewable energy related enterprises	Tax Reduction SP
2010	Interim Feed-in Tariff for 4 Ningxia Solar Projects	Feed-in Tariff
2011	Nationwide Solar PV National Feed-in Tariff	Feed-in Tariff
2012	12th Five-Year Development Plan for the Solar Photovoltaic Industry	State Plan
2012	Interim Measure of Distributed Solar Power Generation On-grid Service Agreement: State Grid Cooperation for China (SGCC) announced a plan to allow small-scale distributed solar power generators to connect to the grid.	Grid Infrastructure Development
2013	Renewable Electricity Generation Bonus	Subsidies
2013	Code of practice of the PV manufacturing	Standards
2013	The State Development and Reform Commission's notice on promotion of PV industry by exert the price leverage effect	Strategy
2013	Distributed photovoltaic power generation service guide of China Southern Power Grid Company Limited (Interim)	Grid Infra. Development
2014	National certification and Implementation Supervision Commission, Energy Bureau on strengthening the photovoltaic products testing and certification	Standards
2014	Notice on issues concerning SGCC to buy distributed PV power generation projects' electricity products invoice; taxation procedures facilitation	Tax Procedure Facilitation SP
2014-2020	Energy Development Strategy Action Plan: aims 100 GW installed capacity by 2020	State Plan

2014-2020	Poverty alleviation project by installation of solar PV panels in poor households	Electrification
Recent Policies		
2015	13th Five-Year Plan: increase the share of non-fossil fuel energy to 15% by 2020, and reduce carbon intensity by 18% by 2020, as compared to 2015	State Plan
2016	Feed-in Tariff reduction (≈10%)	Feed-in Tariff
2017	Feed-in Tariff reduction (≈30%)	Feed-in Tariff

Author's elaboration. Source: data compiled from Climate Policy Database (NewClimate Institute); China Internet Information Center (both accessed in February 2017); (Zhao, et al., 2011; Zhang & He, 2013; Iizuka, 2015).

By the end of 2009, the focus of Chinese government policies was shifted towards demand-pull and domestic deployment of the PV technology through the Concession Program for Large-Scale Solar PV Power Plants, Solar Rooftop Subsidy Program, and Golden Sun Demonstration Program, where subsidies up to 70% of the total investment were provided by the government. Both the Renewable Energy Law in 2006 and the Energy Conservation Law in 2008 have clearly set the obligations of different parties connected to the grid, laying down the basis for feed-in operations.

In the fourth period (2010-2014), this institutional transformation was reflected by the 12th FYP with targets to raise solar generation capacity to 21 GW and set up 1,000 'solar energy model villages'. Policies increased in the direction of subsidizing the deployment of Chinese PV panels domestically through introducing FITs, developing grid infrastructure, and implementing a six-year poverty alleviation programme aiming for electrification and raising living standards of poor households through installation of PV panels.

Further policies aimed for supporting the industry through preferential taxation, code of practice for manufacturers, and products testing and certification. The 'China Development Bank' (controlled by the central government) authorized an unprecedented 31.35$ billion in total credit facilities to the leading Chinese PV producers during 2005-2013 (most were accredited in 2010) (Ball, et al., 2017, p. 53). Other state and commercial banks extended debt to PV manufacturers during the same period. Despite the relatively expensive debt (in terms of interest rates compared to that in USA), it nonetheless enabled Chinese companies "to access plentiful debt… at a time when, in the midst of the global financial crisis, most Western solar manufacturers were unable to do the same" (Ball, et al., 2017, p. 51). Chinese PV manufacturers actually borrowed only 14% of the authorized credit facilities. They used the money to expand production capacity and undertake acquisitions in industrialised countries prior to 2010, and for surviving the severe recession and overcapacity problems during 2010-2012.

Moreover, a specific FYP for PV industry was issued in 2012 aiming for the construction of 10,000-ton high-purity polysilicon production lines. The PV plan also encouraged the diversification of cell manufacturing by building capabilities in 2G and 3G technologies. In 2015, China signed the Paris Agreement for greenhouse gases emissions mitigation. Accordingly, given the country's problems with air quality, its 13th FYP in 2015 aimed for increasing the share of non-fossil fuel energy to 15% and reducing carbon intensity by 18%

by 2020. The plan was accompanied with launching a carbon emission-trading scheme in seven pilot regions in 2016. Recently in 2016 and 2017, the Chinese government announced reductions in the FITs up to 30%. However, its subsidy for distributed solar PV remains unchanged. This dramatic FITs reduction can nonetheless open a new chapter in the Chinese PV story in the next few years.

4.1.2 External Shocks

The dramatic growth of the Chinese PV industry and its share in the global market led to significant conflicts with the incumbent leaders, what is often referred to as the PV 'solar wars'. In July 2010, the German Renewable Energy Sources Act was amended, reducing FITs in the country in response to the sharp drop of PV panel prices in 2009.[44] In addition to its normal annual depreciation, the FIT's reduction varied between 8-16% based on the installation type. Besides that, the amendment set new constraints on utility-scaled installations, limiting their size to maximum of 10 kW, and excluding installations on agricultural fields from FITs (Gründinger, 2015). Moreover, in 2011, several European governments reduced their PV subsidy programs because of the high deficit from the 2009 financial crisis recovery.

Consequently, and since the European countries were accounted of more than 70% of the global annual installations, the international PV demand declined significantly. In the meanwhile, the production supply was still rapidly increasing. This situation led to a huge overcapacity in the entire PV industry, causing a dramatic drop in prices across the PV value chain. For example, solar module prices dropped about 70% between the fourth quarters of 2010 and 2012 (Wang, et al., 2014).

Another chapter of the solar wars had emerged in the form of intellectual property right (IPR) disputes. In 2011, Westinghouse Solar Inc. (USA) filed a complaint against Canadian Solar (Chinese subsidiary) and Zep Solar (American PV panels company that licenses technologies to some Chinese firms) alleging them of patent infringement. Zep Solar responded with a lawsuit against Westinghouse Solar and four other parties. Although a final settlement of the legal disputes was announced in 2012, the PV IPR became the subject of extensive debate in the USA when two government financially aided companies filed for bankruptcy. Solyndra and Evergreen Solar Inc. received more than $600 million from the USA government as loans and financial aid packages. They owned several patents in CIGS and string-ribbon c-Si cell technologies before their bankruptcy in 2011.[45]

Further, in 2011, a group of solar PV manufacturers filed a trade case against Chinese PV producers for dumping the market with products subsidized by the Chinese government. They claimed that due to the Chinese activities, more than 20 American producers closed or went bankrupt. Following to trade investigation, the USA Commerce Department (DOC) began imposing high tariffs on Chinese imports in 2012. Consequently, the USA imports of solar

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[44] The rapid development of a large solar industry in China led to an international decline in PV module prices by approx. 30% in 2009.

[45] When a company undergoes bankruptcy, its patents are usually liquidated, or they expired when nobody pays their maintenance fees.

cells and panels from China declined from $2,804 million in 2011 to $1,144 million in 2013 (Platzer, 2015). Later in 2014, DOC announced additional anti-dumping duties (AD) of around 27-78% and anti-subsidy duties (Countervailing duties CVD) of around 28-50% on importing solar panels made in China (Cardwell, 2014). In 2013, the European Union (EU) imposed duties of around 48% on Chinese PV imports due to similar trade disputes. In response, China issues AD duties up to 57% on solar-grade polysilicon imports from the USA and EU in 2013-2014.

These external shocks affected the Chinese PV industry from both sides. First, Chinese cell manufacturers lost large shares of the international demand, as their prices became less competitive in an already shrinking market. Second, the supply costs of raw materials (purified silicon feedstock from USA) increased according to the Chinese government duties. The critical situation could have led to a collapse in the solar PV industry in China, unless the Chinese government had intervened by stimulating the domestic market (section 4.1.1).

Interestingly, a recent trade petition in the USA was filed by cell manufacturing firms (Suniva and SolarWorld Americas) in April 2017, seeking 'global safeguard relief' in the form of tariffs on imports of c-Si PV cells regardless of the exporting country. However, what is different this time is that the Solar Energy Industries Association opposes the petition considering any additional tariffs as a threat to the broad PV industry in the country and its 260,000 jobs, which are mostly focused on sales and installation, not manufacturing. The decision on that case, expected to be announced in 2018, might thus have an impact on the PV sector in the USA.

4.2. The Market Dynamics

The second dimension of analysing the Chinese TIS in PV technologies is to understand the global PV market dynamics focusing on the position and progress of China in it. On the way to obtain this understanding, this section reviews the demand side of the system represented by the PV installed capacity, along with the supply side represented by the PV cell production. After that, section 4.2.3 discusses the system's firm dynamics by identifying the main Chinese firms and analysing their economic performance.

4.2.1. Demand Side (PV Installed Capacity)

Reviewing countries' share of annual installed capacity in the period 1996-2015 (Figure 4.1a), three major shifts can be noticed. In years 1996-2003, the largest share of annual installations was accounted to Japan (ranging between 25-50%). The second shift was towards Europe, where Germany became the largest market for PV cells during 2004-2012.[46] The peak of German annual installations was reached in 2010. Such high rate of installations in Germany lasted for three years with an average of 7,500 MWp then it declined dramatically.

[46] In the period 2004-2012, Germany was the largest market for PV cells except for years 2008 and 2011, when Spain and Italy became one-year leaders respectively.

The third major shift was towards China. Starting from 2009, the annual installed capacity in China has experienced a notable growth (from less than 40 megawatts in 2008 to 15,150 megawatts in 2015). This growth was mainly due to the construction of several PV power plants around the country along with a wide expansion in the residential use of PV panels.

The major PV power plants in China (Table 4.2) were established in 2009-2011, and they entered the service in 2013-2015. Interestingly, since 2015, China has become the world's leader of PV installations with cumulative capacity of over 43 GW. 83% of the 101.8 GW installed capacity in China by mid-2017 are in utility-scale.

Table 4.2: Top Photovoltaic Power Plants in China

Photovoltaic Power Plant Name	Capacity [MWp]	Year	Previous Phases
Longyangxia Dam Solar Park	850	2015	Phase I (2013): 320 MW
Huanghe Hydropower Golmud Solar Park	600	2015	Phase I (2011): 200 MW
Yanchi Solar PV Station	380	2016	
Cixi solar farm	200	2017	
Gonghe Industrial Park Phase I	200	2013	
Zhongli Tenghui solar farm	150	2015	
Tengger Desert Solar PV Power Plant Project	100	2014	
Chengde PV Project	100	2013	
Jiayuguan PV power plant	100	2013	

Data Sources: (Lenardic, 2016; Publicover, 2017). Author's elaboration.

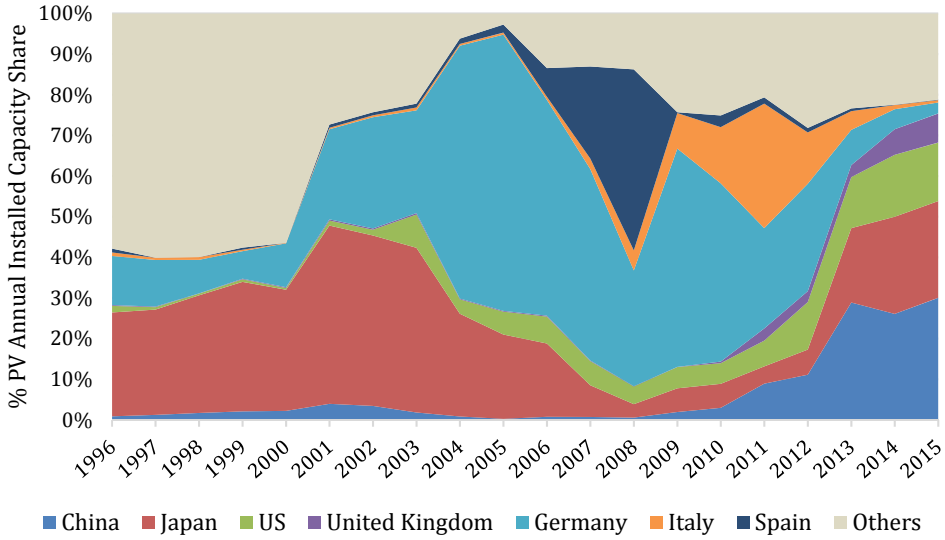
4.2.2. Supply Side (PV Cell Production)

On the supply side, prior to 1995, the annual PV cell production was less than 70 megawatts largely dominated by USA and Japan. Germany entered the scene in 1999. These three countries continued leading the market until 2005, when new players started gaining notable shares. Figure 4.1b shows the global landscape of PV cell production in the period 1995-2013.

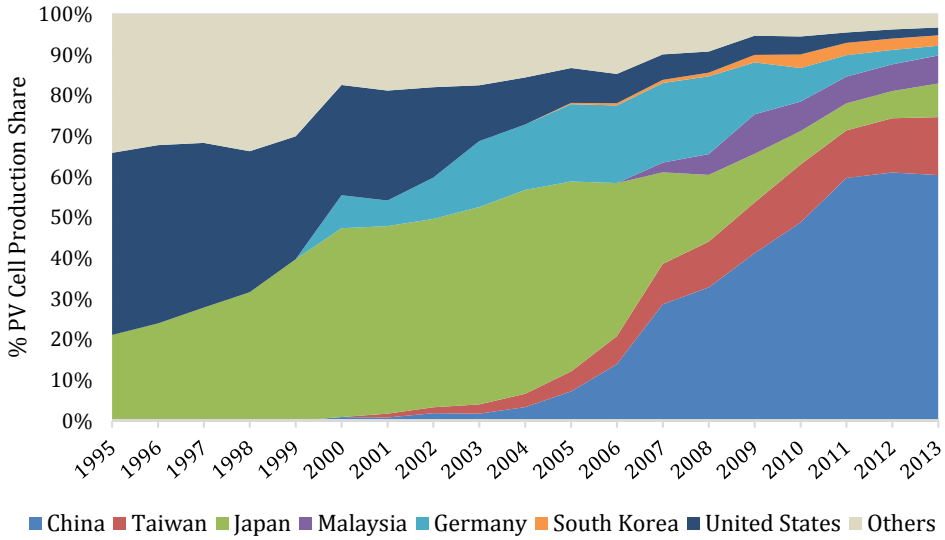
Three shifts in the industrial leadership can be noted, from USA to Japan in 1999, to Germany in 2007, and finally to China since 2008. China's share in the global market has been growing dramatically from less than 1% in 2003 (with 13 MW) to around 60% in 2013 with around 27 GW of production capacity.

Figure 4.1: Global Market Dynamics of the PV sector

a) Demand Side: Share of Global Annual PV Installed Capacity by Country*



b) Supply Side: Share of Global PV Cell Production by Country**



Data Sources *BP Statistical Review of World Energy 2016 **dataset of (Brown, et al., 2015).
Author's own elaboration

4.2.3. System Firm Dynamics

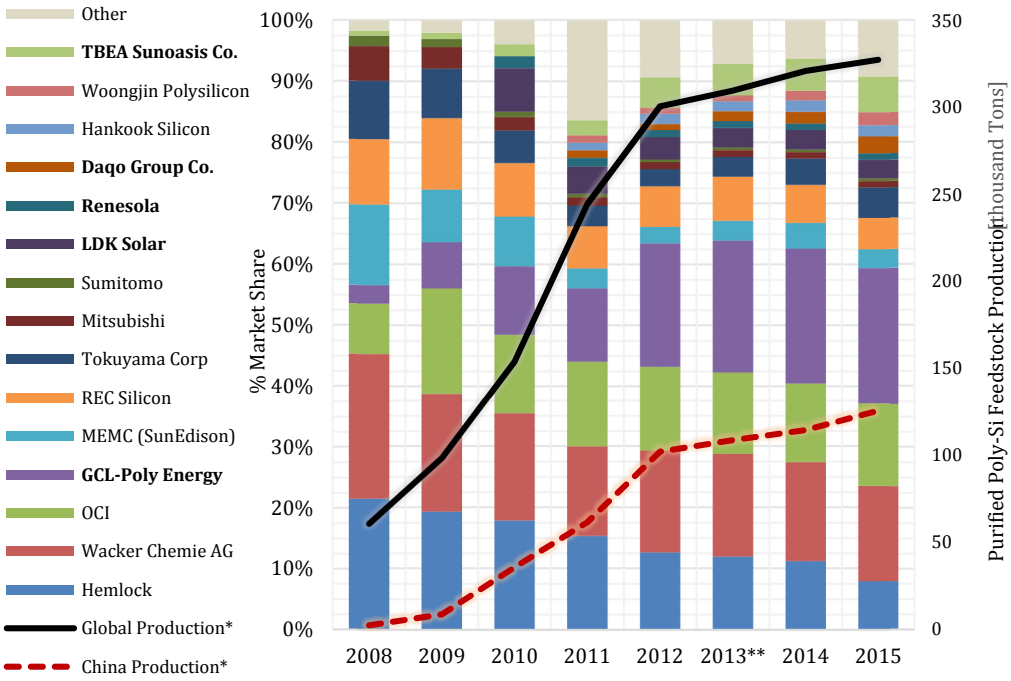
The next step in studying the Chinese PV system is to identify the main firm actors along with their economic performance over time. In the paper, we will refer to this analytical level as the system firmodynamics. To study it, we first observed the PV market from a global perspective, analysing the main silicon-feedstock producers and solar-cell manufacturers

according to their market shares. Subsequently, we identified the emergence and development of Chinese firms in the global industry landscape. Having a list of the main Chinese firm actors, we dynamically analysed their size, performance, and international involvement. A complete list of these actors is provided in Table A in the appendix.

Main Silicon Feedstock Producers

Zhao et al. (2011) stated that in 2007, more than 95% of China's polysilicon feedstock relied mainly on importing from overseas. This heavy dependence on international suppliers formed a big hurdle for the Chinese PV industry at its initial stage (Fischer, 2012). However, considering the recent stages, our results show a breakthrough in accumulating indigenous capabilities in running the Silane process for producing solar-grade polysilicon, and finally producing mono and multi c-Si ingots. China's share of the global Silicon feedstock has dramatically increased from around 4% in 2008 to 38% in 2015 (in light of the government's 12th FYP for PV industry and the global trade actions discussed in section 4.1.2.)

Figure 4.2: Market Share of the Top Silicon Feedstock Producers over 2008-2015



*Figures for Global and China Si-Feedstock Production are given in secondary axis. **Data of 2013 is estimated. **Data sources:** Compiled from (Yu, et al., 2016; Roselund, 2016; Park & Kim, 2012); BvD-Orbis database; Bloomberg L.P. data; Companies' websites, annual reports and fact books (accessed in February 2017). **Author's own elaboration.**

Figure 4.2 pictures the feedstock production landscape during 2008-2015. Until 2009, the global silicon feedstock market was dominated by six international firms located in USA,

Germany, Norway, Japan, and South Korea.[47] The six firms were accounted for around 86% of the global production. However, since 2010, five Chinese companies (noted in bold in figure 4.2) were able to catch-up, expand their production capacity, and gain a notable market share[48].

Two further notable features of figure 4.2 are that global silicon production experienced a fast growth during 2008-2012, after which it stagnated as due to over-supply in the past period. Second, China's feedstock production, despite obvious progress, still is behind the Chinese dominance in PV cell production.

Main PV Cell Manufacturers

The global PV market was relatively small before 2000 with around $2.5 billion (Statista, 2016). Moreover, the annual PV shipments globally were less than 200 MWp (Brown, et al., 2015) with a rate of change of only 30 MWp p.a. during 1995-1999. However, since the beginning of the 21st century, the market experienced a dramatic growth. Empirically, three main stages can be identified since then. First during 2000-2004, the market was growing with a rate of 192 MWp/yr. reaching for the first time the level of 1 GWp in 2004. In the second stage 2005-2009, the rate increased 8-fold to reach the level of 1,652 MWp/yr. Finally, since 2010, the rate reaches the level of 5,311 MWp/yr. with more than 50 GWp shipments in 2015.

Figure 4.3 shows the market shares of the top ten cell manufacturers over 2000-2015. During the first stage, the market was mainly dominated by six firms located in Japan, EU, and USA[49]. Those traditional leaders together were accounted for more than 60% of the global market.

The market landscape changed gradually in the second stage, with new firms from other countries (mainly Korea, Taiwan, and China) entering in 2006. Consequently, the share of the traditional leaders declined into less than 20% in 2007, and even to 4% in 2011 (third stage) with many of them leaving the market. In the third stage, the market became even less concentrated with several firms from emerging economies gaining notable shares.

Analysing the market landscape (figure 4.3), eight Chinese PV manufacturers (noted in bold in the figure) can be identified during the latest two stages of market development[50]. In 2013, they were accounted for 42% of the global cell production, which comprises 70% of the production in China.

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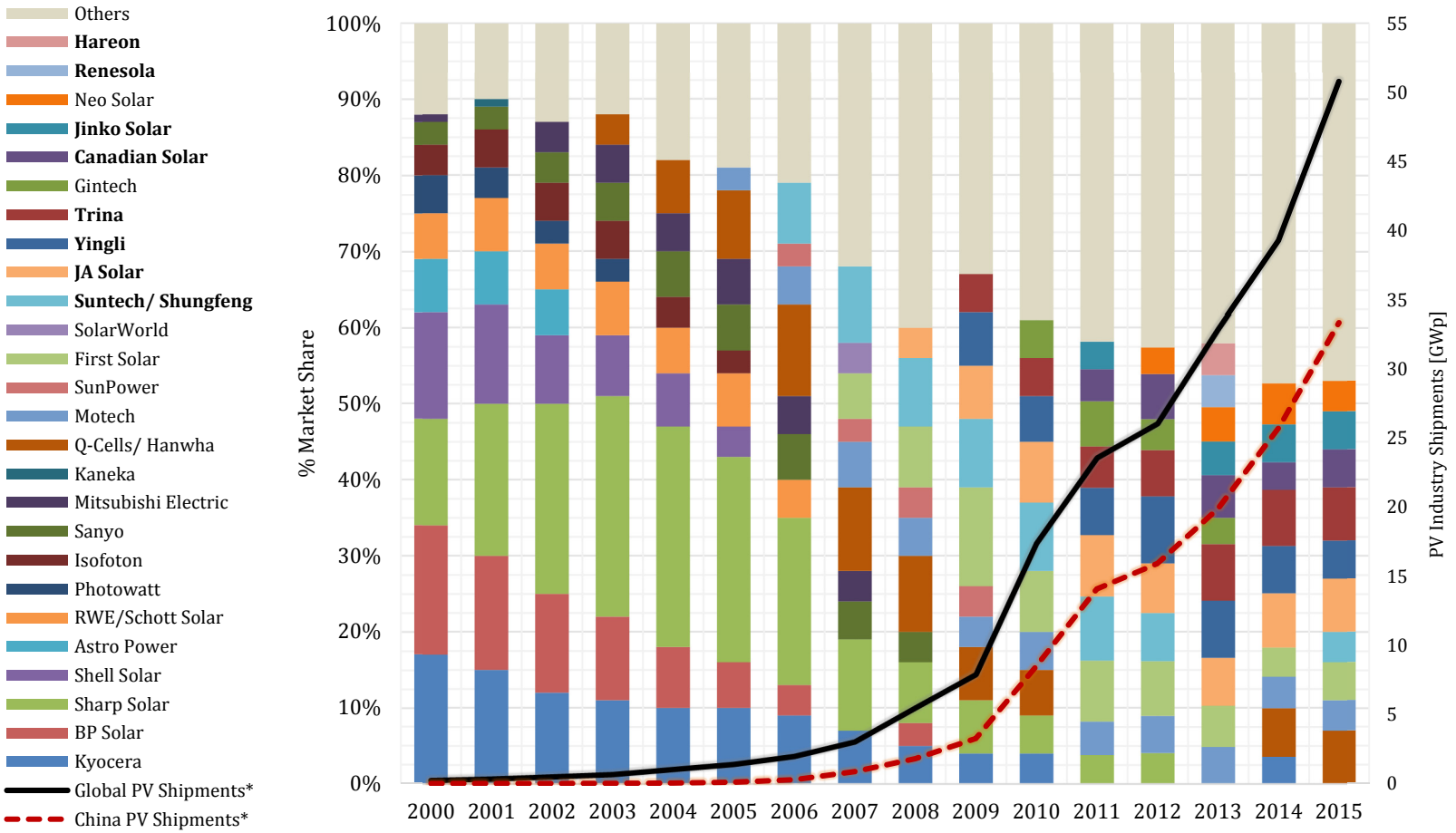
[47] These silicon feedstock leaders are Wacker Chemie AG (DE), Hemlock (USA), MEMC (USA), REC Silicon (NO), Tokuyama Corp (JP), and OCI (KR).

[48] These companies are GCL-Poly Energy, LDK Solar, TBEA Sunoasis, Daqo Group, and Renesola Ltd.

[49] These traditional leading companies in PV cell production are Kyocera (JP), BP Solar (UK), Sharp Solar (JP), Shell Solar (NL), Astro Power (USA), and RWE/Schott Solar (DE).

[50] These Chinese 'star' firms are SunTech, JaSolar, Yingli, Trina, Canadian Solar (CSI-Cells), Jinko Solar, ReneSola, and Hareon.

Figure 4.3: Market Share of the Top 10 Solar PV Cell Manufacturers over 2000-2015



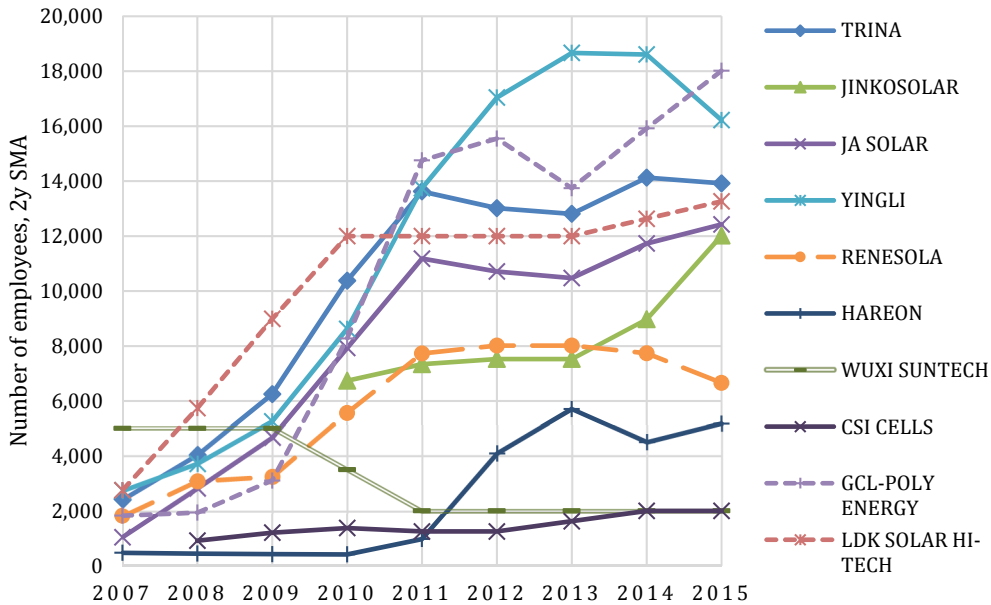
*Figures for Total PV Shipments are given in secondary axis **Data sources:** Renewable Energy World (Mints, 2014; 2016); dataset of (Brown, et al., 2015).
Author's own elaboration.

Size of Main Manufacturers

PV production and deployment represent a relatively large industrial sector in China with more than 1.7 million employees in 2015 (IRENA, 2016). It takes advantage of the low labour cost in the country (average annual costs per employee varying from $500 to $4,000 in Chinese PV firms comparing to $25,000 in Taiwan and $80,000 in Germany[51])

To better understand the dynamics of the PV production system in China, the development of manufacturers' size is considered (figure 4.4). The analysis shows a common trend in the number of employees during 2007-2015. Most of the Chinese manufacturers experienced a sharp growth until 2011. The rapid growth was followed by a stagnation period. Starting from levels around 2,000 employees in 2007, the cell manufacturers Trina, JaSolar, and Yingli, as well as the feedstock domestic producers GCL and LDK, all grow to reach levels of more than 10,000 employees in 2011. Yingli achieved the highest growth and became the largest cell manufacturer in China since 2011. Only two exceptions can be seen in the trends: SunTech[52] and CSI-Cells. In the case of SunTech, the company was considered the largest cell manufacturer in the world before 2009. The size of its main manufacturing unit in Wuxi was 5,000 employees until the financial problems it faced in 2010. Since then, it declined to 2,000 employees in 2011. On the other hand, CSI-Cells, which is a subsidiary of the Canadian Solar Inc., had a stable size around 1,500 employees over the period of consideration.

Figure 4.4: Chinese PV Firms Size: Number of Employees 2007-2015



Data Source: Bureau van Dijk - Orbis database (version 129.00). Author's own elaboration.

[51] Costs of employees were calculated for the main PV producers using data from BvD Orbis database.

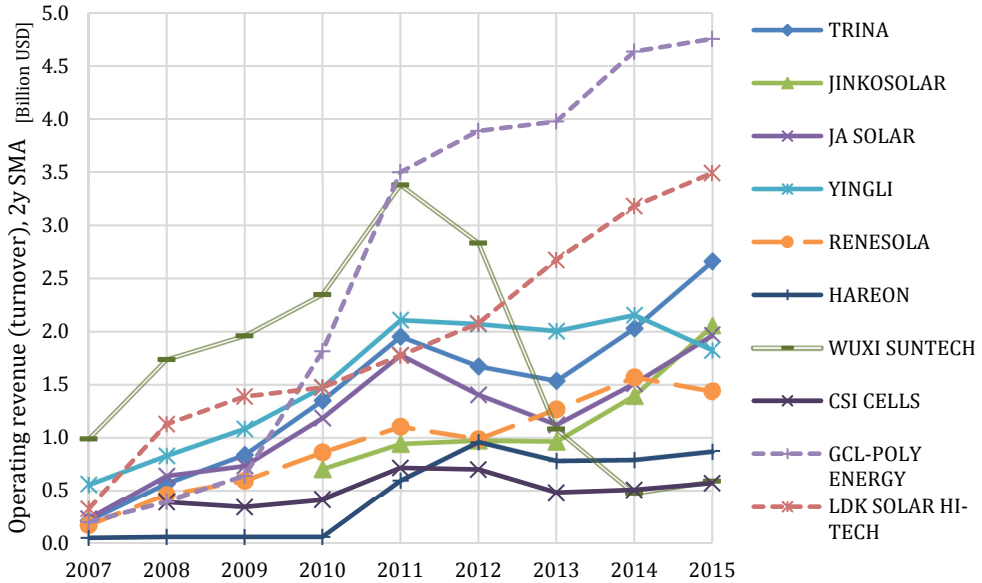
[52] Due to limitations of the database, data for SunTech in figures 4.4 and 4.5 are only for the company's main production unit in Wuxi, China.

Economic Performance of Main Manufacturers

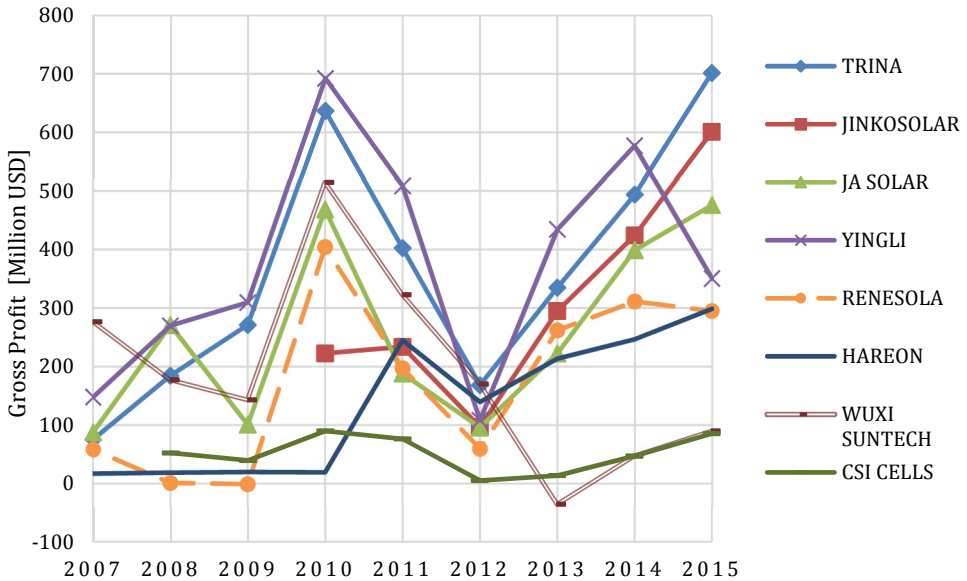
In examining the economic performance of the main actors, we consider two indicators: the turnover and gross profit (figure 4.5).

Figure 4.5: Chinese Firms Economic Performance (2007-2015)

a) Operating Revenue (Turnover) Trends



b) Gross Profit Trends



Data Source: Bureau van Dijk - Orbis database (version 129.00). Author's own elaboration.

Figure 4.5a shows the trend of firms' turnover as a two-year moving average during 2007-2015. Despite the general ascending trend, a clear turning point in 2011 can be noticed for the cell-manufacturing firms. With the only exception of SunTech, the Chinese cell-manufacturers were able to start recovering in 2013. SunTech reached a historical peak of $3.5 billion in 2011, then experienced a sharp decline into the level of $500 million in 2014 (seven times less). On the other hand, the revenue of feedstock producers (GCL and LDK) was always growing. The turnover of GCL and LDK in 2015 was around $4.8 and $3.5 billion respectively.

Observing the gross profit (figure 4.5b), the image becomes even clearer. The solar PV industry in China entered a down cycle in the first quarter of 2011 until the end of 2012 then it recovered rapidly. The declination reached its worst case in 2012, with companies registering very low profits. This sharp collapse of profits was common among all cell manufacturers in China. The gross profits declined from levels of $400-$700 million in 2010 into lower than $150 million in 2012. SunTech experienced large losses of $36 million in 2013. However, the analysis shows a rapid recovery of the industry, Trina, JinkoSolar, and JaSolar experienced high profits in 2015.

International Involvement

To test whether China serves as an offshore platform for PV production, we consider the FDI and M&A activities in the field. First, if China's PV cell manufacturing is a consequence of other countries technologies, we expect high ***inward flows of FDI*** to Chinese subsidiaries of foreign firms. To check this hypothesis, we analysed the available data on foreign subsidiaries and M&A actions taken by the traditional leaders in cell and feedstock production as well as the international firms with high patenting activities in China (Table B in appendix). 11 of the 18 deals took place in the period before 2007. Moreover, 15 of the 18 were joint-ventures with Chinese firms. This result not only confirms the well-known regulatory issues on FDI in China that still favour joint-ventures over pure subsidiaries, but also gives an indicator about the direction of technological capabilities transfer during that period.

Starting in 2000, a joint-venture by the German chemicals company BASF with a group of Chinese petrochemical producers in Shanghai Chemical Industry Park was announced. Later in 2003, BASF established another joint-venture company to produce crude Methylene diphenyl diisocyanate (MDI)[53]. In 2002, the American company DuPont[54] announced via its main unit in China an agreement with a Japanese producer to set up production venture for copolymer acetal resins[55]. In 2003, Kyocera (Japanese) announced a joint-venture to import fine ceramics and electronic components, and another one to produce solar panels in China. In 2004, a joint-venture between Samsung Electronics (Korean), Haier Group (Chinese), and

[53] Among its other industrial applications, MDI is widely used for producing rigid polyurethane for solar panel encapsulation, and can be also used for the manufacturing of Dye-sensitized solar cells.
[54] DuPont is one of the top patent applicants for Chinese inventions in solar-cell common elements and panel encapsulation materials with 10 transnational patent applications.
[55] Copolymer acetal resins can be used, among their several applications, for PV panel encapsulation.

Sanyo Electric (Japanese) was formed in Shanghai to operate maintenance and development services for electrical appliances.

The Taiwanese company, AU Optronics[56] entered the Chinese market in 2006 with a joint-venture to produce backlight modules. Mitsubishi Electric (Japanese) established joint-ventures with Chinese companies to produce electric switches, inverters, and equipment in 2006-2013. Other leading firms such as Honeywell (American) and Shin-Etsu Chemical (Japanese) also established joint-ventures with Chinese firms in 2010-2011.

On the other hand, to test whether China had obtained its technological capabilities in the PV field through international involvement by ***outsourcing and acquiring foreign firms***, we analyse the M&A deals made by Chinese manufacturers (Table C in appendix). 14 of the 17 deals took place after 2007. Most of them (82%) were in form of acquisition of assets and business of foreign firms.

In 2006 and 2008, SunTech was very active in acquiring foreign firms. It started with acquiring the Japanese company, MSK Corporation (one of the top-ranking companies in building-integrated-PV). Later, SunTech acquired German and American firms, and formed a joint-venture in the USA to finance PV projects.

In 2008, GCL-Poly acquired the British Virgin Islands based company, Joint Loyal Holdings to get shares in Duolun Golden Concord (DGC). DGC owns a coalmine under construction in Inner Mongolia, with a design output capacity of 1.2 Mtpa. The indirect acquisition provided GCL-Poly with a steady source of coal supply for its purification process of polysilicon. The second feedstock company, LDK was also active in M&A activities during 2009-2011. It established a joint-venture with the German (back then[57]) cell manufacturer Q-Cells in 2009 and acquired high shares in Italian and American firms.

The Chinese companies JaSolar, Huawei, Aiko Solar, Hareon, and Hisense Electric, completely acquired foreign firms and subsidiaries located in the British Virgin Islands, the UK, Germany, and Mexico during 2011-2015. Through its activities to accumulate technological capabilities for power grid infrastructure, State Grid Corporation of China acquired seven high-voltage electricity transmission assets in Brazil in 2012, and established a joint-venture with a Russian power company in 2014.

4.3. The Innovation Side

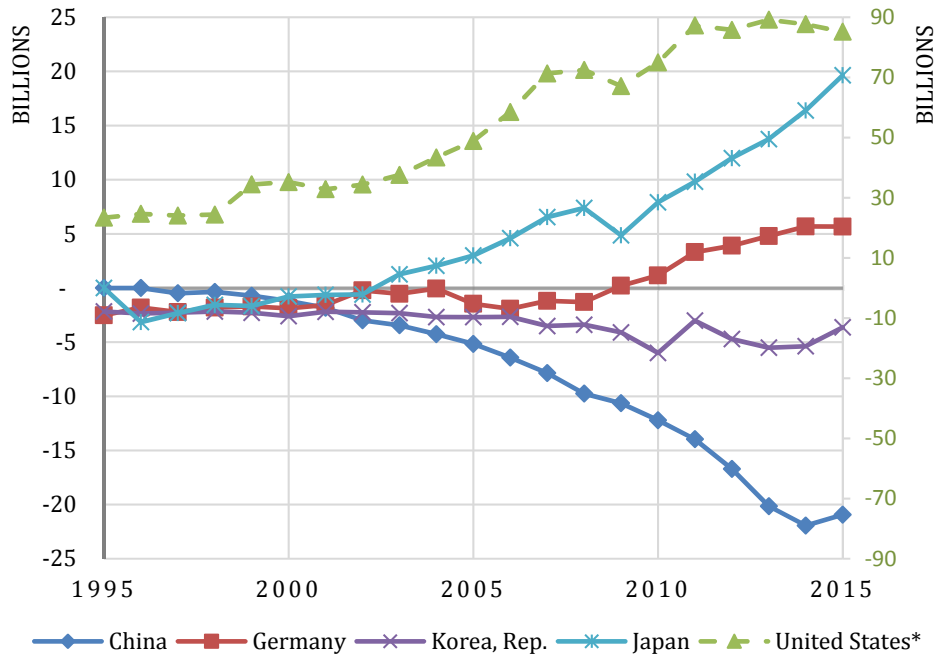
The third analytical dimension to consider is the innovation side of the system. We review the licensing activities by Chinese actors to access foreign IPR, the R&D expenses by main Chinese manufacturers, and their patenting activities.

[56] Au Optronics was the top patent applicant for Chinese inventions in PV cells and panels with 45 transnational patent applications during 2010-2014.
[57] The Korean conglomerate company, Hanwha Group totally acquired the German company Q-Cells in 2012.

4.3.1 Net Charges for the use of intellectual property (NCIP)

To further test whether China obtained its technological capabilities in PV through international involvement, we check the volume of licensing activities by Chinese residents to use IPR of foreigner innovators. The indicator NCIP is used to compare China with the USA, Germany, Japan, and Korea over 1995-2015 (Figure 4.7). While USA has a huge positive NCIP (around $90 billion during the last five years), Korea and China have negative net charges indicating more payments than receipts. On the other hand, Japan and Germany are considered as main suppliers of IPs globally with $20 billion and $5 billion NCIP in 2015 respectively.

Figure 4.6: Net Charges for the use of IPR (BoP, current US$)



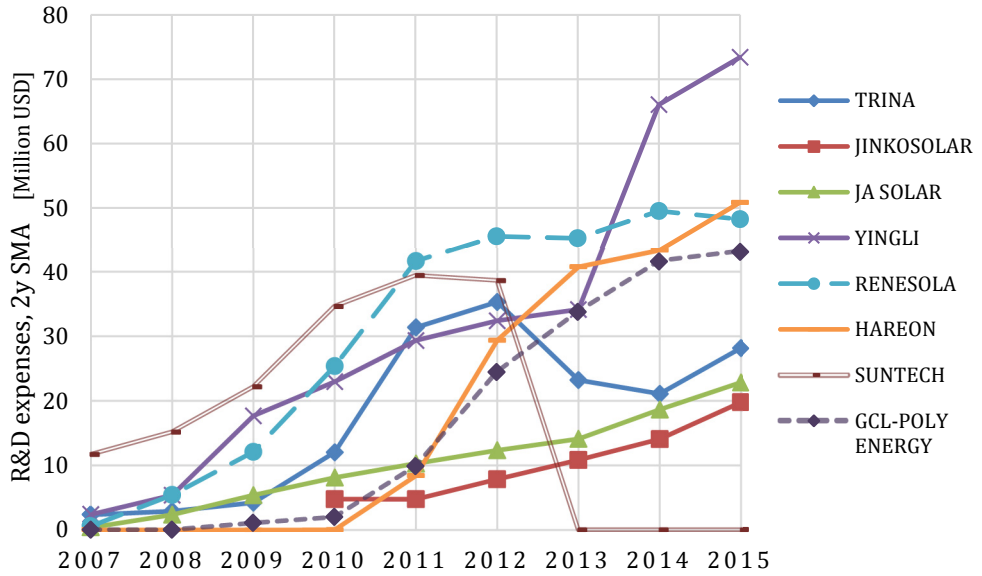
*Figures for United States are given in secondary axis. **Data source:** The World Bank, World Development Indicators Database. Accessed in February 2017. **Author's own elaboration.**

Considering NCIP for China as a general indicator aggregated for all industries, total payments have increased dramatically since 2001. This shows a large growth in licensing agreements signed by Chinese firms for the authorized use of IPRs (such as patents, designs, copyrights, and trademarks) owned by international parties. However, in the clean energy sector, licensing is not considered as the main channel for technology transfer. Karachalios et al (2010, p.58) found that only 17% of surveyed international leading organisations in the sector have frequently or occasionally entered into licensing agreements. In the case of PV technology in China, licensing has played no significant role in cell and panel producers, where in-house R&D activities were more common (de la Tour, et al., 2011; Lema & Lema, 2012). However, Zhao, et al. (2011, p.4966) noted high tendency of Chinese manufacturers to purchase Si-purification technology licenses from overseas.

4.3.2 Companies' R&D Expenses

The second indicator to consider within the innovation side of the system is the R&D activities done by the main Chinese actors (Figure 4.7). Starting from less than $2.5 million in 2007, the R&D expenses increased by all firms until 2011. After that, they took three different trends. Some companies continue their R&D growth (either with similar rate e.g. JinkoSolar and JaSolar, or with even a higher speed e.g. Yingli, Hareon, and GCL). Other companies reduced their expenditure on research, e.g. Trina and SunTech (In the case of SunTech, although it has the highest R&D expenditures before 2011, the company shut down its R&D units since 2013). The third trend is noticed in the case of Renesola, where the R&D expenses reached a stagnation level of $45 million since 2011. Yingli is the Chinese leader in R&D since 2014, with more than $73 million spent in 2015.

Figure 4.7: R&D Expenses of Chinese PV Firms 2007-2015



Data Source: Bureau van Dijk - Orbis database (version 129.00). Author's own elaboration.

4.3.3 Patenting Activities

Priority Patent Filings

Regarding innovation throughput, the first indicator we consider is the patent priority filings (defined in section 3.3). As illustrated in Figure 4.8a, China experienced a notable growth in priority filings since 2005. Within few years, the country was able to introduce and accumulate a large stock of patents protected by its national patent office. Starting from a very late position behind Japan, Korea, USA, Germany and Taiwan, and having an average of 9 filings per year during 1995-1999, Chinese annual patents exceeded Germany, USA and Taiwan in 2005 with 245 annual patents, and later went beyond Korea in 2010. Of note, the Chinese activities were further able to surpass the traditional leader in PV priority patents, Japan, in 2011.

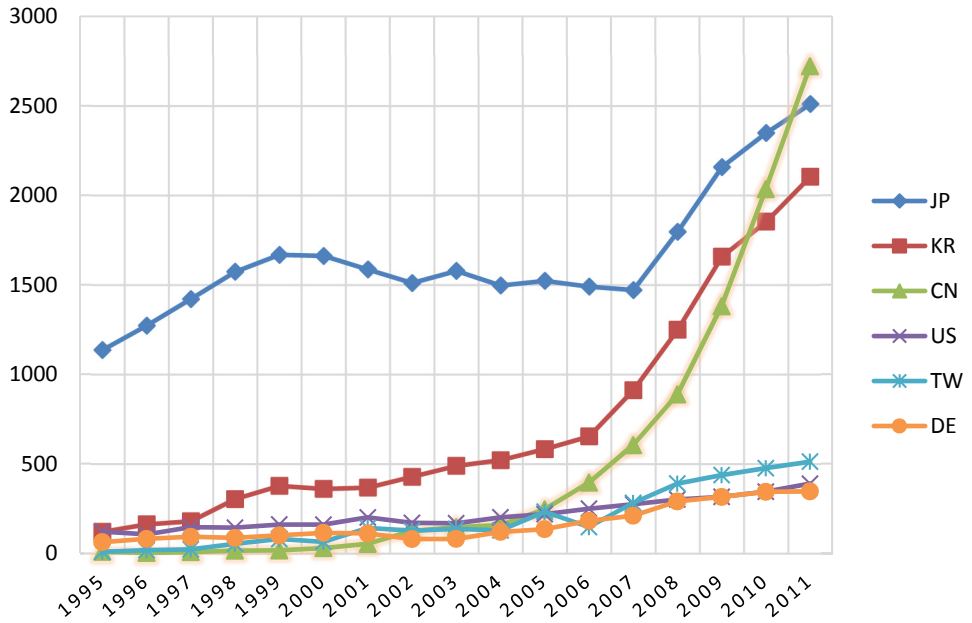
In terms of the accumulated number of priority filings since the earliest PV patent applications were filed in USA and Germany in the 1950s until 2012, China occupies the third place with a share of 12%, following Japan (53%) and South Korea (14%). The final remark in this regard is the fact that only 0.5% of the Chinese priority patents in the field have already expired by 2012, comparing to the Japanese case, where around 37% of the total priority patents have expired. Table D (in appendix) shows the top firm and non-firm applicants for priority patents with at least one inventor located in China during 1995-2014.

Transnational Patent Applications

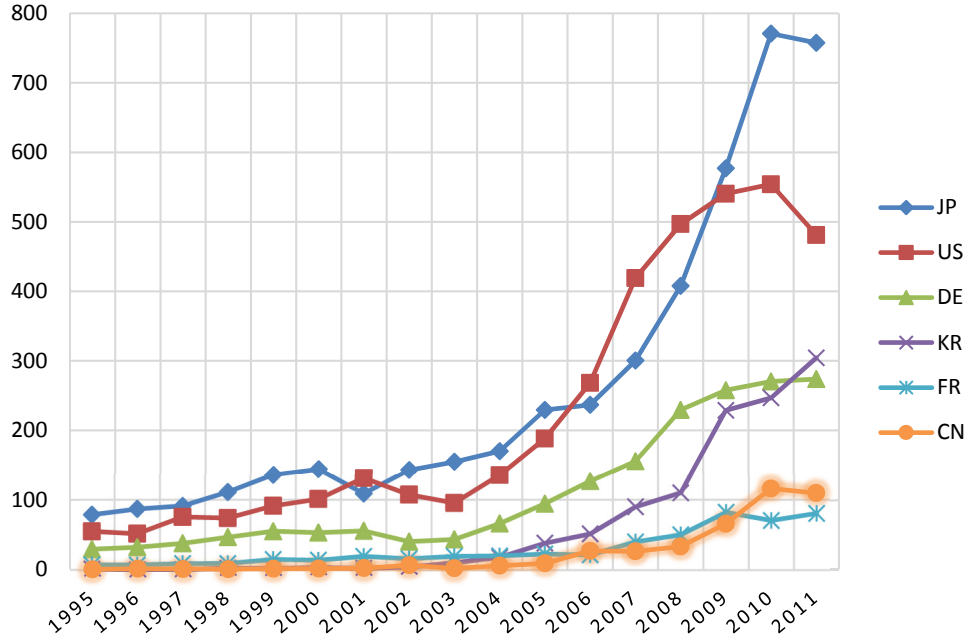
Unlike its performance in priority filings, China has a less significant presence in the transnational patent landscape. The trends in Figure 4.8b shows that China occupies the sixth place in accumulated transnational patent applications in the PV field, after Japan, USA, Germany, Korea, and France respectively. Chinese inventors were involved in only 3% of the total accumulated number of transnational patents during the period 1977-2012. Moreover, China has successfully exceeded France in terms of annual patent counts in the past five years. Starting from a very low level of PV transnational patents in the late nineties, Chinese patent activities have dramatically increased since 2008. Only 0.03% of the Chinese transnational patents in the field have already expired by 2012, compared to 8% of the Japanese and 11% of the American and German patents.

Figure 4.8: Patenting Activities of Top Inventor Countries (1995-2011)

a) Priority Filings



b) Transnational Patent Applications



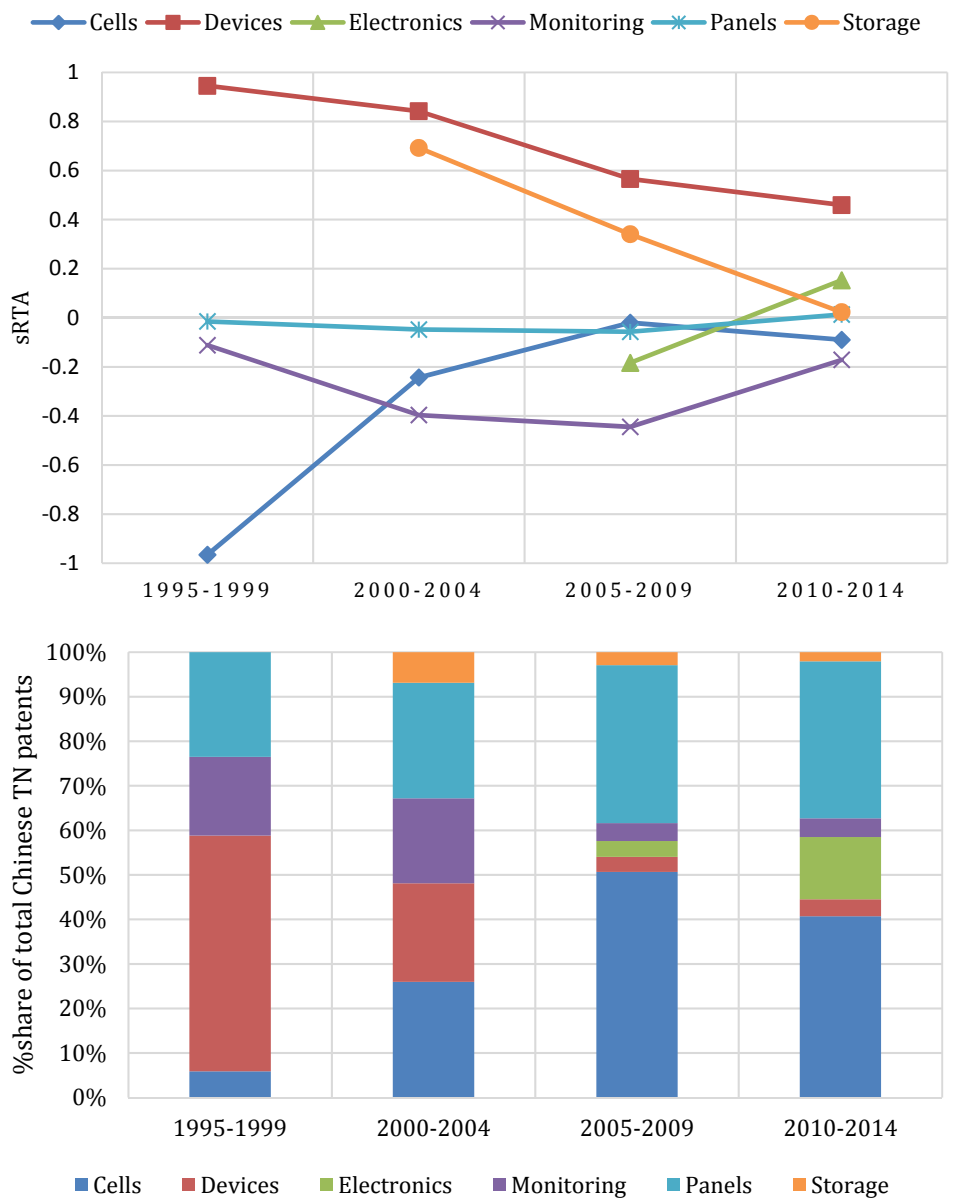
Source: PATSTAT 2015. Author's own elaboration.

Technological Specialization of Chinese PV Inventions

To have a better understanding of the PV inventive activities undertaken in China, we further analyse the technological specialization of its transnational patents over time. Figure 4.9 shows the relative specialization on the level of main PV groups. During the first period, the largest share was associated with portable devices. This can be seen from the absolute share (53%) within the Chinese patents, as well as from the very high sRTA (0.95). However, the analysis shows that both the absolute and relative advantage in the devices field dramatically decreased over the next periods, where panels and cells gained notable scores. In the fourth period, both panel and cell technologies continue to have dominant shares, however, an emerging stream of electronic inventions can be noticed. Although, the absolute share of storage patents is low, it had high sRTA in the second and third periods.

Since cell technologies hold the highest share of patents in the Chinese TIS, we investigate the specialization of their patents to the next level, considering the different cell families along with the Silicon purification methods for producing feedstock. A sharply decreasing RTA for thin-film and multi-junction cell technologies indicates low specialization in them. On the other hand, a high specialization in the 1G technologies is notable since the third period with 46% share and 0.2 sRTA. Furthermore, the analysis shows a steady positive advantage in the polysilicon feedstock technologies over the last three periods.

Figure 4.9: China's Relative Specialization in PV System Technological Groups



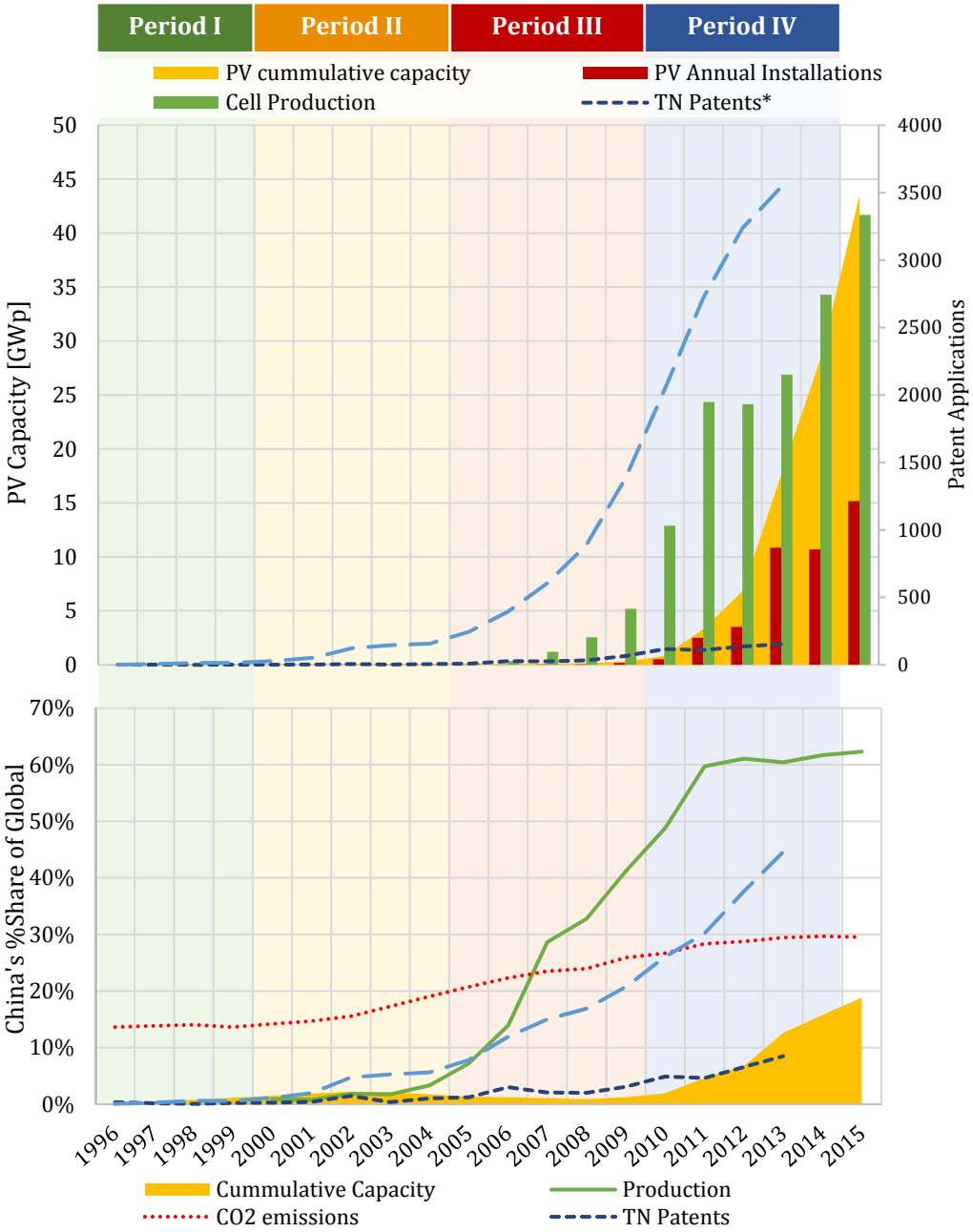
Data source: PATSTAT database 2015. **Author's own elaboration.**

5. DISCUSSION

5.1 The Complete Image

According to the results, the development of the Chinese PV technological system of production and innovation went through four main consecutive periods (figure 5.1).

Figure 5.1: Chinese PV Technological System: The Whole Picture



* The figures of priority filings (PF) and transnational patents (TN) are given in a secondary axis in the upper graph. **Data Sources**: **PV installed capacity data**: BP Statistical Review of World Energy 2016. **PV cell production data**: Dataset of (Brown, et al., 2015). **Patent data**: PATSTAT database 2015, autumn edition. **CO_2 emissions data**: Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.2., European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. **Author's own elaboration.**

Period I (1995-1999): 'Seed Germination'

In this period, Chinese government plans and policies were focused on two main aims. First to build a knowledge base for science and technology, and second, to achieve wider coverage in rural electrification. This government attitude was accompanied with innovation activities for developing portable devices powered by solar PV energy. The inventive activities in this period were individual and appear to have been driven by foreigner firm actors and universities.

In the global PV cell and panel market, China's position was relatively small compared to the dominance of American and Japanese manufacturers. However, a clear tendency towards developing domestic grounds for basic research can be noted.

Period II (2000-2004): 'Vegetative Stage'

In the second period, the government plans became more focused in supporting the establishment of domestic solar panel industry by facilitating the acquiring of manufacturing equipment and supporting R&D activities. Consequently, several PV companies were born either by the end of the first period or in this period, such as Trina, Yingli, Tbea Xinjiang Sunoasis, Hareon Solar, and Wuxi Suntech. Furthermore, an increasing international involvement within the Chinese production and innovation system is also noticed through FDI and joint-ventures for production of chemical materials used in PV systems. Subsidiaries of some of the main international leaders in the PV field were also established in China during this period. The inventiveness activities within the country increased especially in terms of priority patents. The technological specialization of patents was focused on portable devices and PV panels.

On the international market side, in this period, China still had no significant role in both production and installations, which were dominated by Japan, USA, and Europe. Since 2004, the fast growing market for PV panels in Germany became the largest market in the world, and thus the favoured destination of the emerging Chinese panel production.

Period III (2005-2009): 'Flowering'

The success of panel production in the second period and the expansion of international demand on PV systems stimulate a further growth in PV industry in China. Government policies were generously supportive of this growth through several laws, subsidies, and initiatives. The trend toward export-oriented industry was clear in both government policies and firms' performance. Consequently, additional PV companies entered the industry, which expanded vertically to include solar cell production. Most of the Chinese stars were born in this period, such as JaSolar, Jinkosolar, and Renesola. Moreover, additional foreign subsidiaries were established in China to produce PV cells and modules, such as the Taiwanese AU Optronics (Xiamen) and the Canadian CSI-Cells. Consequently, technological specialization of patenting activities notably shifted towards c-Si solar cells. Despite the fact that most silicon feedstock supply for Chinese PV factories was imported from international markets, two Chinese firms (GCL and LDK) entered the market and started building technological capabilities in that field. Both transnational and priority patent

applications for Chinese PV inventions experienced dramatic take-off since 2007. This year (2007) was also a turning point in the international involvement direction, since when Chinese firms started to acquire international companies.

The PV business in China experienced a dramatic growth both in its size (number of jobs) and performance (turnover). The prosperous industry became a labour market for more than 1.5 million employees. Most of the PV production was exported to international markets, where Germany had the largest demand. Having the advantages of lower labour cost, high government subsidies, and less strict environment protection laws, the prices of Chinese PV cells and panels were difficult to compete by international industries.

In this period, the main Chinese PV firms registered their holding companies in Cayman Islands and British Virgin Islands, which served as both tax haven and listing vehicles to undertake Initial Public Offerings (IPO) on NYSE and NASDAQ stock exchanges in the USA. Consequently, the firms raised estimated gross IPO proceeds of more than $1 billion (Binz & Anadon, 2016). Furthermore, the IPO dramatically improved their access to short-term bank borrowing. Being driven by the fast growing European market, Suntech Power, for example, took more than $600 million short- and long-term loans from several Chinese and international banks following its IPO in 2005, which allowed it to dramatically expand its production capacity, undertake series of international acquisitions, and become the global leader.

By 2009, China was accountable for 40% of the global PV production, 20% of priority patents, and only 3% of transnational patents. Interestingly, the growth trend of priority patents has become significantly larger than that of transnational patents. It was rather consistent with the production share trends. This observation indicates a strong competition between the global PV actors taking place in the Chinese market. In the light of the supportive circumstances in China for PV industry, it became difficult for international companies to carry on with a competitive industry outside China. This apparently led to defensive patenting strategies by the traditional leaders, who continue to file transnational patent applications. On the other hand, working under the same supportive circumstances, the differentiation between Chinese manufacturers became restricted in two aspects. First, to gain a larger market share, PV companies in China needed to obtain capabilities for producing more efficient cells, improve their manufacturing processes, or use materials of less cost. Second, such innovations were either achieved internally (and thus protected with domestic patent filings) or obtained via outsourcing activities like licencing and acquisition. In other words, with priority filings, companies aimed at protecting their incremental innovations in order to maintain their competitiveness in the local market.

Although PV systems are considered a clean energy source, they were not environmentally beneficial in China in this period because of the export-oriented strategy. Alsema & de Wild-Scholten (2006) noted that the life-cycle CO_2 emissions of c-Si PV systems are 40 g/kWh on average, comparing to 1000 g/kWh in the case of using hard coal for electricity generation. Analysing the market dynamics with one-year lag between production and installation, our results show that only 7.8% of the Chinese PV production were used domestically. Using coal in the feedstock and cell production, the industry generated around 26,500 kt of CO_2

emissions (0.07% of the total emissions in China in this period). Our calculations show that 8,260 kt of CO_2 were saved because of PV installations in the period, which results in net CO_2 emissions of 18,240 kt caused by the PV industry (negative savings). Thus, the PV industry has posed an additional burden on the air pollution problems in China in this period.

Period IV (2010-2014): 'Getting Back to Roots'

By the beginning of the fourth period, the Chinese PV production system faced severe external shocks. A sharp recession in the global demand due to institutional alterations in the German market in 2010, followed by AD and CVD tariffs on Chinese PV products enforced in both USA and EU. Chinese PV manufacturers, who were already running on their full capacity, faced difficult situation in 2011 and 2012 with huge financial loses that even led to bankruptcy of some important actors, such as SunTech in 2013 being defaulted on $541 million of convertible bonds.

To rescue the huge PV industry with its large labour market and assets, a comprehensive set of policies were introduced by the Chinese government mainly to stimulate the domestic market. The government intervention, despite the complexities underlying the formulation of industrial policies, was highly beneficial from socio-economic and innovative perspectives. On one hand, it rescued the companies and their employees and increased the share of renewable sources in energy production, and on the other, it maintained the growth of R&D and patenting activities.

In this period, around 35% of the Chinese PV production was installed domestically. Although the industry generated around 346,000 kt of CO_2 emissions (0.7% of total emissions in China), the domestic PV installations in this period saved around 482,000 kt of CO_2, yielding positive net CO_2 savings of 136,000 kt, and making the industry environmentally efficient.

On the innovation side, the government intervention indirectly resulted in three positive effects. First, it stimulated learning processes in the system, as illustrated by the performance of Chinese feedstock firms. Such high-tech manufacturing processes formed a hurdle for the Chinese firms in the initial stages. They used to buy polysilicon ingots and wafers from the international market mainly dominated by Japanese, German and American firms. However, with the preservation of the Chinese PV system (as well as the Chinese AD duties on polysilicon imports), some domestic companies succeeded in accumulating technological capabilities and were able to enter the polysilicon global market achieving high shares since 2010. Second, the rescue of R&D activities in cell manufacturers led to the achievement of a global cell efficiency record in multi-crystalline cells by Trina beginning in 2014. Third, it opened up new fields of specialization and development, which are the PV electronics and inverter technologies, as the Chinese state grid companies needed to develop the grid infrastructure to cope with the growing utilisation of solar electricity.

The interrelations between the analytical dimensions of the PV technological system of production and innovation in China are summarized in figure 3.1 and table 5.1. While the institutions, market, and innovation are completely interrelated, the results show different

pattern for environment. Direct influence of environmental aspects was found neither on market nor on innovation. Environment influenced them indirectly through institutions. Similarly, we could not find a direct influence of institutions on environment, its influence nonetheless occurs indirectly via the market dynamics or innovation.

Table 5.1: The interrelations between the analytical dimensions of the PV TIS in China

Source (influencing)	Destination (influenced)	Influence	
		Positive +	Negative -
Institutions	Market	• Supportive government policies (supply push and regulations) • Demand pull policies stimulated domestic market	• External shocks
	Innovation	• Scientific collaboration programs • Supporting R&D and IPR • Attracting overseas experts (e.g. thousand talents plan)	-
Market	Institutions	• Industrial success caused more supportive policies • The down-cycle triggered the stimulation of domestic market (FIT and energy conversion laws)	• Global competition caused external shocks (e.g. AD and CVD)
	Innovation	• Industrial success stimulated R&D and provided financial support for patenting • M&A deals provide access to foreign IPR • The emergence of domestic market horizontally expands the patent portfolio of China (e.g. electronic inverters)	• The down-cycle reduced R&D of some companies (e.g. Suntech and Trina)
	Environment	• Installations reduce CO_2 emission	• Production emits CO_2
Innovation	Institutions	• Success stories (e.g. Suntech's founder) inspired policy (e.g. thousand talents plan)	-
	Market	• Inventiveness, R&D, licensing foster firm competiveness	• Patents by incumbent leaders impede catch-up by latecomers
	Environment	• Increasing cell efficiencies	-
Environment	Institutions	• Climate change, air quality problems trigger remedial policies	

Author's own elaboration.

5.2 China's PV Catching-up Trajectory

Tracking the Chinese development in the PV industry using the catch-up cycles framework introduced by (Lee & Malerba, 2017), the results show that China's 'entry' to the global market occurred over 1998-2005. During 2006-2008, it experienced 'gradual catch-up' processes. In 2008, the country entered the 'forging ahead' stage with 'persistency of leadership' until present. The analysis further shows that the shift in industrial leadership

towards China was mainly driven by institutional and demand 'windows of opportunity'. While the demand played an important role in triggering the catch-up, a public policy window was opened through the government intervention in the midst of the global economic and institutional challenges. The responses of different actors within the sectoral system to the radical discontinuities were instrumental in the catch-up process. Chinese firms successfully took the advantage of the windows of opportunity to forge ahead.

From a technical perspective, the catch-up process in the Chinese case followed a specific trajectory (devices, panels, cells, wafers, polysilicon, and finally electronics). It started with the development of portable lighting devices powered by imported solar cells. It then switched to the assembly of PV panels also based on imported cells from overseas. On the following stage, a domestic cell and wafer industry emerged through acquiring foreign manufacturing equipment, however, it had been dependent on imports of polysilicon from USA, Europe and Japan. Gradually, the domestic industry accumulated technological capabilities and became able to produce polysilicon ingots. Finally, due to the institutionally driven growth of domestic market, further capabilities started to be accumulated in electrical inverter technologies.

Although this trajectory seems to be similar to the catch-up process in pharmaceuticals and software industry in India and in the Taiwanese and Malaysian semiconductor firms (Malerba & Nelson, 2011), one key difference in the Chinese PV case is that technological capabilities in different components of the technical system were accumulated by different firms.

On the other hand, similar to the successful catch-up cases discussed by (Malerba & Nelson, 2011; Mowery & Nelson, 2001), our analysis highlights the importance of learning processes, access to foreign knowledge, skilled human capital, and active government policy in the PV case in China.

5.3 Implications and Lessons

The present case study suggests several implications for China, other emerging and developing economies as well as for developed countries.

In what concerns China, the fast government intervention with supportive policies and subsidies show successful effect in the PV case especially with the stimulation of domestic market. However, to maintain the industrial leadership, Chinese firms should find new markets for utility-scale PV outside China. Two possible candidates could be oil-producing countries in the Middle-East and Africa (given their favourable conditions of solar irradiation and the depletion of oil reserves in the long-term), as well as other emerging economies such as India and Brazil (given their need to stable sources of energy).

As to emerging and developing countries, the Chinese PV case highlights the significant role of public policy in supporting the industry through its development stages. Furthermore, it sheds light on the importance of knowledge transfer through scientific cooperation and the mobility of skilled personnel. Such channels can pave the way for emerging states to accumulate domestic capabilities towards catching-up with forerunners.

In what concerns developed countries and incumbent leaders, the analysis shows the ineffectiveness of punitive policies in enhancing competitiveness nor in supporting domestic industry. Instead of protecting the local industry as intended, the imposed duties on Chinese PV products raised the prices of solar panels in the western markets hindering the adoption rate of the green technology therein. More efficient alternatives in that regard could have been achieved by incumbent leader governments through directly subsidizing their local firms, or by the firms themselves through offshoring their production activities to China maintaining local panel assembly and encapsulation plants. Either way, in such vital sector related to the global challenge of climate change, collaboration would be more useful than trade wars.

6. CONCLUSION

This study analysed the Chinese technological system of production and innovation in the field of solar photovoltaics. Following the systematic approach of the TIS, the paper highlighted the main factors that influenced the production and innovation processes. It inspected the system development from three analytical dimensions: the institutional framework of the system, its market dynamics, and the composition of innovative activities of the main actors. The results show a significant role of government policy instruments in developing indigenous capabilities within the system and rescuing it in the tough situations.

On market level, China has become the world's leader of PV installations since 2015. Likewise, its global market share boosted to around 60% in 2013. This rapid growth can be partially connected with export-oriented policies and the involvement of international actors during 2005-2009. Despite the negative environmental effect of the PV industry in the initial stages (due to the heavily export-oriented strategy), the stimulation of domestic market resulted in effective CO_2 reduction in the last stage.

The patent analysis shows that in spite of their puzzling low activities in transnational patents, the Chinese actors have a notable performance in terms of priority filings. This observation illustrates an interesting role for patents as a market instrument used by leading actors in high-income countries to compensate their potential losses of market shares due to low labour costs in emerging economies.

The results also show that the Chinese system is not isolated from the global technological system of production and innovation in the field. The interactions and events occurring within the global system cast a shadow on the Chinese system dynamics. At some stage, they motivated production processes to very high levels. At other stages, they formed external shocks that caused industry enter down-cycle and resulted in structural change. Interestingly, thanks to successful government intervention, both positive and negative externalities have stimulated, in one way or another, the capability building and innovation activities in China.

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APPENDIX - TABLE A: THE MAIN FIRM ACTORS IN THE CHINESE TIS OF PV TECHNOLOGY

	COMPANY NAME	Ctry.	Year of incorp.	Turnover 2015 th $	Number of employees 2015	Prio-patents	TN patents	TN Patent periods	Specialization
1.	HUAWEI TECHNOLOGIES	CN	1987	59,465,858	140,000	18.7	4.9	III- IV	Telecommunications, electronics
2.	STATE GRID CORPORATION	CN	2003	38,285,791	927,839	259.2	10.0	III- IV	Transmission of electricity
3.	BYD COMPANY LIMITED	CN	1995	12,252,158	200,000	87.2	34.6	III- IV	Automobile, batteries, Poly-Si solar cells and modules
4.	BOE TECHNOLOGY GROUP	CN	1993	7,447,883	42,837	35.4	9.6	IV	Display Devices and electronics, c-Si* PV systems
5.	GCL-POLY ENERGY HOLDINGS	KY	2006	4,545,521	17,705	8.4	0.0	-	Purified Si-feedstock, wafers
6.	LDK SOLAR HI-TECH CO., LTD.	CN	2005	3,490,368**	13,265**	28.6	2	III-IV	Purified Si-feedstock, wafers
7.	TRINA SOLAR LIMITED[1]	KY	2006	3,035,512	13,556	180.5	20.5	IV	c-Si PV cells, modules and panels
8.	DAQO GROUP CO., LTD.	CN	1965	2,637,511**	10,000**	0.8	0.0	-	Purified Si-feedstock, wafers
9.	SHENZHEN CHINA STAR OPTOELECTRONICS TECH	CN	2009	2,520,390	7,500	6.5	6.5	IV	Electronic components, semiconductors
10.	JINKOSOLAR HOLDING CO.	KY	2006	2,476,543	14,035	54.7	1.0	IV	c-Si PV cells, modules and panels
11.	JA SOLAR HOLDINGS CO.	KY	2005	2,083,556	12,550	22.3	2.0	IV	c-Si PV cells, modules and panels
12.	YINGLI GREEN ENERGY HOLDING	KY	2006	1,535,205	14,533	103.5	9.3	III- IV	c-Si PV cells, modules and panels
13.	RENESOLA LTD	VG	2006	1,298,951	5,438	1.7	1.5	IV	Si-Feedstock, c-Si cells, inverter
14.	TBEA XINJIANG SUNOASIS CO.	CN	2000	1,046,171**	5,000**	4.8	0.3	IV	Purified Si-feedstock, wafers
15.	HAREON SOLAR TECHNOLOGY	CN	2000	933,143	6,100	9.5	0.0	-	Poly-Si solar cells and modules
16.	SANAN OPTOELECTRONICS COMPANY LIMITED	CN	1993	741,491	7,135	7.9	13.2	IV	LEDs, multi-junction solar cells for space applications
17.	WUXI SUNTECH POWER CO[2]	CN	2001	620,504	2,000	64.4	23.3	III- IV	c-Si PV cells, modules and panels
18.	CSI CELLS CO[3]	CN	2006	580,397	2,000	72.9	11.7	III- IV	c-Si PV cells, modules and panels

19.	DUPONT CHINA HOLDING CO[4]	CN	1989	522,158**	1,100**	24.8	9.8	II-IV	c-Si, thin-film, organic PV cells
20.	AU OPTRONICS (XIAMEN) CORP.[5]	CN	2005	222,933**	25,000**	54.2	44.8	IV	c-Si PV systems (cells, panels, electronics and monitoring)
21.	OCEAN'S KING LIGHTING SCIENCE AND TECHNOLOGY	CN	1995	136,169	2,682	582.6	16.3	IV	Lighting facilities, organic cells
22.	APPLIED MATERIALS (CHINA) INC.[6]	CN	2002	98,956	200	3.3	3.3	II-IV	Semiconductor, display devices, c-Si and thin-film PV
23.	SILICON CHINA (HK) LTD	HK	2006	n.a.	n.a.	6.7	6.7	III	c-Si PV cells, modules and panels
24.	SOLAR WIDE INDUSTRIAL	HK	1987	n.a.	570	0.2	0.2	I	Portable devices, solar lamps
25.	SOL-LITE MANUFACTURING COMPANY LIMITED	HK	1989	n.a.	n.a.	0.4	0.4	I	Small PV panels for charging electronic portable devices

Data sources: data compiled from BvD Orbis database; PATSTAT database 2015b; Bloomberg L.P.; Forbes lists; companies websites & financial reports (accessed in February 2017). **Author's own elaboration.**

Notes:

- These companies were accounted for 37% of the global PV cell production in 2015 (60% of the PV production in China), and for 33% of all the Chinese transnational patents in the PV field during 1995-2014.
- Companies are sorted by their turnover values (operating revenue) in a descending order.

* c-Si: Crystalline silicon both mono- and polycrystalline technologies. ** Data is for 2014.

[1] Changzhou Trina Solar Energy Co., Ltd. in Changzhou, China, was incorporated in 1997.

[2] In March 2013, the main subsidiary of SunTech filed for bankruptcy in Wuxi-Jiangsu, China. Followed by the mother company Suntech Power Holdings Co., Ltd. filed for bankruptcy in a Cayman court in November 2013. The primary manufacturing unit: Wuxi SunTech Power Co. Ltd. was sold to mid-size solar manufacturer Shunfeng Photovoltaic International Ltd. for $492 million in November 2013.

[3] The mother company Canadian Solar Inc. was incorporated in Guelph, Canada in 2001.

[4] The mother company E. I. du Pont de Nemours and Company (DuPont) was incorporated in Wilmington in 1915. The American conglomerate is specialized in chemicals manufacturing and science-based solutions.

[5] The mother company AU Optronics Corporation was formed in 2001 in Hsinchu, Taiwan. It entered the green energy industry in 2008 by introducing high efficiency solar PV solutions to the market in addition to its traditional display products.

[6] The mother company Applied Materials Inc. was incorporated in Santa Clara, USA in 1973. It is specialized in semiconductor systems, LCD/LED display, c-Si and thin-film PV cells and panels.

APPENDIX - TABLE B: FDI AND M&A DEALS: FOREIGN FIRMS HAVING ACQUISITIONS AND SUBSIDIARIES IN CHINA

Acquirer Name	Acquirer Country	Target Name	Target Country	Deal Type	Deal Value th EUR	Announced Date
BASF AG	DE	BASF AG AND OTHER JOINT VENTURE PARTNERS' CHEMICAL MANUFACTURING JOINT VENTURE	CN	Joint venture 100%	n.a.	03/07/2000
ASAHI KASEI CORPORATION	JP	RESIN PRODUCTION AND SALES JOINT VENTURE	CN	Joint venture 100%	n.a.	26/03/2002
KYOCERA CORPORATION	JP	KYOCERA (TIANJIN) SALES AND TRADING CO Ltd	CN	Joint venture 100%	126,526.13	01/01/2003
BASF AG	DE	SHANGHAI LIANHENG ISOCYANATE CO., Ltd	CN	Joint venture 100%	310,396.17	31/03/2003
KYOCERA CORPORATION	JP	KYOCERA (TIANJIN) SOLAR ENERGY CO., Ltd	CN	Joint venture 100%	1,801.14	05/06/2003
SAMSUNG ELECTRONICS CO.	KR	DOMESTIC ELECTRICAL APPLIANCE MAINTENANCE SERVICES JOINT VENTURE	CN	Joint venture 100%	n.a.	08/01/2004
EI DU PONT DE NEMOURS & COMPANY	US	GUANGZHOU MONTELLI MATERIAL TECHNOLOGY CORPORATION	CN	Acquisition 100%	n.a.	05/03/2004
SANYO ELECTRIC CO., LTD	JP	NINGBO GP SANYO ENERGY CO Ltd	CN	Joint venture 100%	20,502.50	01/07/2004
SHARP CORPORATION	JP	NANJING SHARP ELECTRONICS CO., Ltd	CN	Acquisition increased	7,160.83	16/10/2005
AU OPTRONICS CORPORATION	TW	DARWIN PRECISIONS (XIAMEN) CORPORATION	CN	Joint venture 100%	14,600.25	13/03/2006
MITSUBISHI ELECTRIC CORPORATION	JP	MISUBISHI ELECTRIC CORPORATION AND BAODING TIANWEI GROUP CO. HIGH-VOLTAGE SWITCHGEAR JOINT VENTURE	CN	Joint venture 100%	11,525.37*	26/07/2006
HONEYWELL INTERNATIONAL	US	LONON INDUSTRY CO., LTD'S BUSINESS AND ASSETS	CN	Acquisition 100%	21,973.69*	08/01/2008
AU OPTRONICS CORPORATION	TW	QINGDAO HAIER OPTRONICS CO., Ltd	CN	Joint venture 100%	5,282.20	29/04/2010
SHIN-ETSU CHEMICAL CO. Ltd	JP	SHIN-ETSU (JIANGSU) OPTICAL PREFORM CO Ltd	CN	Joint venture 100%	494,036.47	27/10/2010
CANADIAN SOLAR INC.	CA	CANADIAN SOLAR INC., SUZHOU NEW DISTRICT ECONOMIC DEVELOPMENT GROUP CORPORATION and SUZHOU SCIENCE AND TECHNOLOGY CITY DEVELOPMENT CO. Ltd' PV cell production factory	CN	Joint venture 100%	n.a.	01/06/2011

HONEYWELL INTERNATIONAL	US	SINOCHEM LANTIAN HONEYWELL NEW MATERIAL CO., Ltd	CN	Joint venture 100%	n.a.	10/10/2011
MITSUBISHI ELECTRIC CORPORATION	JP	MITSUBISHI ELECTRIC LOW VOLTAGE EQUIPMENT (XIAMEN) CO., Ltd	CN	Joint venture 100%	4,730.02	14/12/2011
MITSUBISHI ELECTRIC CORPORATION	JP	HEFEI KINGHOME MITSUBISHI ELECTRIC HOME APPLIANCES TECHNOLOGY DEVELOPMENT CO.	CN	Joint venture 100%	4,740.15	20/06/2013

*estimated value. Data Source: Bureau van Dijk – Zephyr Database (version 30.0) – 2017. Author's own elaboration

APPENDIX - TABLE C: M&A DEALS: CHINESE PV FIRMS ACQUIRING FOREIGN FIRMS

Acquirer Name	Acquirer Country	Target Name	Target Country	Deal Type	Deal Value th EUR	Announced Date
BEIJING ORIENTAL ELECTRONICS TECHNOLOGY GROUP CO., LTD	CN	HYNIX SEMICONDUCTOR INC.'S TFT LCD BUSINESS	KR	Acquisition 100%	354,160.00	27/09/2002
SUNTECH POWER HOLDINGS	KY	MSK CORPORATION	JP	Acquisition 66.67%	84,155.50	02/08/2006
HAIER GROUP CORPORATION	CN	SANYO UNIVERSAL ELECTRIC PCL	TH	Acquisition majority stake	13,807.36*	27/10/2006
SUNTECH POWER HOLDINGS	KY	KSL-KUTTLER AUTOMATION SYSTEMS GMBH	DE	Acquisition 100%	34,100.00	28/01/2008
GCL-POLY ENERGY HOLDINGS	KY	JOINT LOYAL HOLDINGS LTD	VG	Acquisition 100%	14,765.94*	11/08/2008
SUNTECH POWER HOLDINGS	KY	GEMINI SOLAR DEVELOPMENT COMPANY	US	Joint venture 100%	n.a.	02/10/2008
SUNTECH POWER HOLDINGS	KY	EL SOLUTIONS INC.	US	Acquisition 100%	n.a.	02/10/2008
LDK SOLAR COMPANY LTD	KY	Q-CELLS SE'S AND LDK SOLAR CO., LTD'S unnamed PV systems joint venture	DE	Joint venture 100%	n.a.	08/04/2009
LDK SOLAR COMPANY LTD	KY	SOLAR GREEN TECHNOLOGY SPA	IT	Acquisition 70%	n.a.	14/07/2009
LDK SOLAR COMPANY LTD	KY	SOLAR POWER INC.	US	Acquisition 70%	23,227.99*	06/01/2011
JA SOLAR HOLDINGS CO.	KY	SILVER AGE HOLDINGS LTD	VG	Acquisition 100%	133,917.94	01/07/2011
HUAWEI TECHNOLOGY CO.	CN	CENTRE FOR INTEGRATED PHOTONICS LTD, THE	GB	Acquisition 100%	n.a.	25/01/2012
STATE GRID CORPORATION of CHINA	CN	ACTIVIDADES DE CONSTRUCCION Y SERVICIOS SA'S Seven High Voltage Electricity Transmission Assets in Brazil	BR	Acquisition 100%	597,613.96	29/05/2012

AIKO SOLAR ENERGY TECHNOLOGY CO	CN	SCHEUTEN SOLARWORLD SOLIZIUM GMBH	DE	Acquisition 100%	n.a.	12/06/2012
HAREON SOLAR TECHNOLOGY	CN	BRILLIANT HARVEST 003 LTD	GB	Acquisition 100%	2,321.58	13/02/2014
STATE GRID CORPORATION of CHINA	CN	ROSSIISKIE SETI OAO	RU	Joint venture 100%	n.a.	13/10/2014
HISENSE ELECTRIC CO., LTD	CN	SHARP ELECTRONICA MEXICO SA DE CV	MX	Acquisition 100%	19,848.90	31/07/2015

*estimated value. Data Source: Bureau van Dijk – Zephyr Database (version 30.0) – 2017. Author's own elaboration.

APPENDIX - TABLE D: TOP PRIORITY-FILING APPLICANTS OF CHINESE INVENTIONS

	Firm Applicant Name	Number of Applications	Non-Firm Applicant Name	Number of Applications
1.	Oceans King Lighting Science	582.6	University Zhejiang	151.6
2.	State Grid Corp China	259.2	University Tsinghua	112.0
3.	Shanghai Huali Microelect Corp	181.1	Suzhou Inst Nano Tech & Nano B	110.4
4.	Changzhou Trina Solar Energy	180.5	Inst Semiconductors CAS	105.7
5.	Jifu New Energy Tech Shanghai	122.4	University Electronic Science & Tech	93.3
6.	Semiconductor Mfg Int Shanghai	113.2	University Shanghai Jiaotong	90.2
7.	Yingli Solar China Co Ltd	103.5	China Electric Power Res Inst	88.5
8.	BYD Co Ltd	87.2	University North China Elec Power	85.7
9.	Altusvia Energy Taicang Co Ltd	81.3	University Huazhong Science Tech	84.4
10.	Chengdu Juhe Technology Co Ltd	73.7	University Sun Yat Sen	78.7
11.	Suzhou CSI Solar Power Tech.	72.9	University Southeast	76.4
12.	Eging Photovoltaic Tech Co Ltd	70.8	University Shanghai	71.6
13.	Wuxi SunTech Power Co Ltd	64.4	Inst Of Microelectronics CAS	71.0
14.	Hongfujin Prec Ind Shenzhen	59.9	University Nankai	66.9
15.	Jinko Solar Co Ltd	54.7	Shanghai Tech Physics Inst	63.8
16.	AU Optronics Corp	54.2	University Tianjin Technology	54.9

Source: Author's calculations. Data extracted from PATSTAT 2015.

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Personal contributions to the papers of the cumulative dissertation

The Technological System of Photovoltaics: Identification and Analysis with Patent Classes (Ch. 2)

This paper was written by me as a sole author. It is based on my own ideas. I am grateful to the people mentioned in the acknowledgments and the participants of the conferences where I presented this paper.

Drifting Towards Innovation: The Co-evolution of Patent Networks, Policy, and Institutions in China's Solar Photovoltaics Industry (Ch. 3)

This paper was joint work with Iciar Dominguez-Lacasa. I conducted the patent and network analysis, calculated all the indicators, and created all the figures and tables. Regarding the text, Iciar wrote the literature review and conceptual framework sections. I wrote the data, methods and results sections. The introduction and conclusion sections were jointly written by both of us. We are grateful to the people mentioned in the acknowledgments and the participants of the conferences where we presented this paper.

Innovation Capability, Network Embeddedness and Economic Performance: Profiling Solar Power Innovators in China (Ch. 4)

This paper was written by me as a sole author. It is based on my own ideas. I am grateful to the people mentioned in the acknowledgments and the participants of the conferences where I presented this paper.

The Technological System of Production and Innovation: The Case of Photovoltaics Technology in China (Ch. 5)

This paper was written by me as a sole author. It is based on my own ideas. I am grateful to the people mentioned in the acknowledgments and the participants of the conferences where I presented this paper.

Erklärung über die Anfertigung der Dissertation ohne unerlaubte Hilfsmittel

Ich erkläre hiermit, dass diese Arbeit ohne unerlaubte Hilfe angefertigt worden ist und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt wurden.

Ich erkläre ferner, dass die den benutzten Werken wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht wurden.

Eine Überprüfung der Dissertation mit qualifizierter Software im Rahmen der Untersuchung von Plagiatsvorwürfen ist gestattet

Bremen, 21. Februar 2018

Mahmood Shubbak

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