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Evolution of innovation ecosystem in Emerging Industries: A Case Study of China's Photovoltaic Industry#

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ABSTRACT

Since 2001, China's photovoltaic (PV) industry has evolved from a latecomer to the global leader. Grounded in innovation ecosystem theory, this paper examines the development of China's PV industry through four stages characterized by technology, market, finance, and policy dynamics: Pre-commercialization R&D accumulation stage (prior to 1995), Initial commercialization stage driven by rapid international market expansion (1996-2008), Technology and industrial chain integration stage accelerated by domestic market growth (2009-2017), Intense competition and phase out stage under widely technological diffusion and overcapacity (post-2018). This study reveals that policy tools should strategically coordinate technological, market, and financial elements to guide innovation ecosystem participants, thereby facilitating the evolution of the whole innovation ecosystem in different development stages. This coordinated governance mechanism proves critical for achieving leapfrog development in emerging industries.

Keywords: China's photovoltaic industry, innovation ecosystem, key resources, development stages, leapfrog development

1. INTRODUCTION

With the challenges of global climate change and energy transformation, renewable energy technologies, particularly photovoltaic (PV) systems, have emerged as a key pathway for nations worldwide to achieve their "dual - carbon" objectives. China, as a latecomer in the PV industry, has remarkably accomplished a leapfrog advancement from a technological follower to a global leading country within 20 years. This achievement not only has significantly reshaped the global energy competition landscape but also serves as an example for understanding the evolutionary mechanisms of innovation ecosystem in emerging industrial economies.

Most of the existing studies focus on the static analysis of the innovation ecosystem in developed countries, or explain the logic of passive catching-up of late-coming countries based on the technology gap theory[1]. However, they pay less attention to the dynamic evolution process in the innovation ecosystem from the view of key resources interaction such as technology, market, institution etc[2]. Taking industrial innovation ecosystem theory as a framework, this paper analyzes the four-stage evolution of China's photovoltaic (PV) industry. Additionally, it works to answer the following core questions: How can China build a globally competitive innovation ecosystem step-by-step with the initial conditions of lacking technology, market, finance? What are the implications of the China case for the emerging countries? The study reveals the composite path of late-coming countries' accumulation of technology capability, development of domestic market ecology embedding in global value chain through policy orientation. We try to provide a theoretical reference for emerging economies to break through and achieve industry upgrading.

2. ANALYTICAL FRAMEWORK AND METHODOLOGY

Based on the theory of industrial innovation ecosystem, this paper analyzes across two dimensions: first, the key resources of the industrial innovation

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ecosystem and second, the evolutionary stages.

2.1 Key resources of the industrial innovation ecosystem

As shown in Figure 1, the key resources of the industrial innovation ecosystem include technology, market, finance, and policy[3][4]. The dynamic evolutionary process of the entities in the ecosystem acquiring these resources through their decentralized behaviors[5][6], can be divided into four stages.

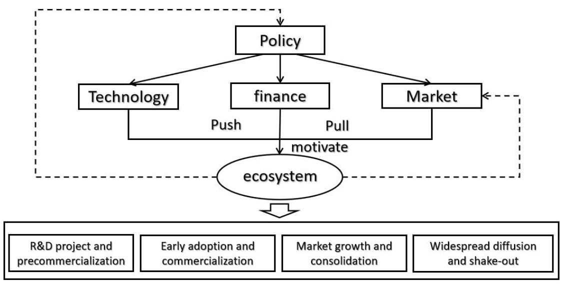

Figure 1 Interaction mechanism and evolution of key resources in innovation ecosystem

2.2 Four evolution stages of the innovation ecosystem

As shown in Figure 2, we can see the development scale of the PV industry and we take key policies, technologies, finance, and market as milestones. The four development stages of China's PV industry are as follows:

1.R&D and Pre-commercialization (1980 –1995)

2.Early Adoption and Commercialization (1996 –2008)

3.Market Growth and Consolidation (2009 –2017)

4.Widespread Diffusion and shake-out (2018 –2022)

3. EMPIRICAL STUDY: THE FOUR EVOLUTION STAGES OF CHINA'S PHOTOVOLTAIC INDUSTRY INNOVATION ECOSYSTEM

3.1 Stage 1: R&D and Pre-commercialization (before 1995)

Public policy, with central government investment in R&D, was the main driving force for technological innovation in PV during this period. Before 1980, there was little demand for PV in China. China's photovoltaic technology progress was mainly due to the Chinese National R&D support for the satellite program as energy supply system. In 1980, under the promotion of the world's solar photovoltaic industry, the former State Science and Technology Commission of China launched the R&D project for solar photovoltaic technology breakthrough[7], and established the China Optical and Electronic Technology Center to initiate research on the application of mono-crystalline silicon solar cells, poly-crystalline silicon solar cells and photovoltaic systems[8]. In addition, PV technology R&D also began to enter the three major R&D programs in China -- Science and Technology Support Program, "863" and "973" and other programs, although the overall scale of funding is far less than that of the United States, Germany and Japan[9].

In addition to R&D support between 1980 and 1990, the central and local governments strengthened the very small and weak solar cell industry through application demonstration projects by state owned companies[10], such as the Tibet Sunshine Program, the Tibet Ali Solar Project, and other small scale rural programs related to optical fiber communication power supply, village radio and televisions, and household photovoltaic power supply systems. In addition, due to these policies, from 1990 to 1995, the cumulative installed solar PV capacity in China increased from 1.78MW to 6.63MW, less than 1% of the world [7].

During this stage there was also some activity in China's photovoltaic manufacturing: some factories were built by state-owned companies and the equipment was constantly updated. For example, Yunnan Semiconductor Device Factory imported a world-advanced mono-crystalline silicon solar cell production line from the US company SPIRE in 1984. It became the largest solar cell manufacturer in China at that time. Other factories established by state-owned companies include Ningbo Solar Cell Plant, Kaifeng Solar Cell Plant, Qinhuangdao Huamei Plant Harbin-Corolla Plant, Shenzhen Yukang Plant and Shenzhen Daming Plant[10].

Overall, technological development during this period was very dependent on the central policies, and all the manufacturing, which was at a small scale, was conducted in factories of state-owned companies. These companies had low incentive for technology innovation[11]. In summary, during this stage the main actors in China were the ministries allocating government R&D funds, scientific research institutes (both universities and government labs) as the main institutions conducting the research on solar PV, and state-owned manufacturers conducting early technology exploration supported by small scale demonstration and rural government programs.

3.2 Stage 2: Early adoption and commercialization (1996-2008)

In 1996, the World Solar Energy Summit was held in Zimbabwe. In 1997, The Kyoto Protocol was adopted. Following the deployment of PV technology in the United States, Japan and Europe, the Chinese government actively advocated the development of the photovoltaic industry during this time through national projects and international projects[12]. For example, the Chinese State Planning Commission created the "China Bright Project" plan in 1996 as the Chinese government responded to the Zimbabwe Summit. It was China's largest application of wind and solar energy in remote areas at that time, supported by the national budget with a total investment of 10 billion RMB. Another example of international project is the program supported by credit financed by the World Bank offered subsidies of $1.50 to $2 per Watt to accredited PV system companies in China to nurture a market for solar home systems in remote rural areas[12]. As a result of these projects, China's cumulative installed capacity increased from 19 MW in 2000 to 52 MW in 2003. The vast majority of these systems were installed in off-grid applications, mainly rural applications and applications in the telecommunications sector[13], showing the importance of niche markets in this early phase.

After 2004, European countries increased their spending on renewable energy. Although China's annual Solar PV installed capacity was 10 MW in 2004 and increased to 40 MW in 2008, its share in the world's Solar PV installed capacity was still 0.73% in 2008[14].

The 1995-2008 period saw a sharp increase in global demand for solar PV opening the manufacturing market, spurring China's photovoltaic manufacturing capabilities and exports.

China's policies were focused on deliberately promoting international technology transfer as well as strengthening R&D to reduce the costs of deploying and using technology from abroad in China. For example, in 1998, the central government introduced a tax exemption policy for imported equipment with key technologies to encourage technology transfer, and value-added tax on imports has been exempted. Starting in 2003, the central government issued a catalogue of high-tech products in which the product can get policy support from R&D project, demonstration, fiscal taxation, product prices, marketing and sales, import and export taxation and other policies[7]. Projects from MOST gave more to firm led collaboration with research institutes, universities and joint R&D centers with leading countries[15]. During this stage, in the mid-2000s, the scale of commercial PV cell production in China reached over 10MW. The efficiency of general commercial cells made in China reached 13%, the large-scale production capacity of amorphous Si thin-film cells reached 10MW, and the cost of PV cells dropped from 40 RMB/watt in 1996 to 27 RMB/watt in 2004[16].

Meanwhile, the local governments began to play an active role as investors in manufacturing firms. For example, in 2005, the Xinyu municipal government invested 200 million RMB in the newly established LDK Solar which became the municipal government's largest taxpayer by 2011. In 2001, Wuxi Suntech, a start-up solar company established by a returning talent from Australia, received 39 million RMB from the local Wuxi government's venture capital firm[17]. Some other local governments also helped new PV manufacturers to sign preferential land contracts.

During this period, new enterprises—as opposed to the state-owned enterprises that had been the main private actors engaged in PV in the previous stage—began to introduce foreign technology and improve it[18]. Suntech imported manufacturing equipment from Europe, the US and Japan to establish production lines. Baoding Yingli Energy, a start-up company built in 1998, imported production equipment from abroad, including China's first crane ingot furnace, multi-wire saw cutting machine, and oil heating laminating machine. Due to the advanced manufacturing equipment adopted by both enterprises, when Suntech and Yingli's 10MW and 3MW cell and module production lines were put into operation in 2002 and 2003, their module conversion efficiency reached 14%. Trina Solar introduced the most advanced production lines from the United States and Germany and creatively adjusted the production line structure with domestic advanced equipment. In 2007, Canadian Solar, another Chinese company built in 2001, successfully overcame the technical bottleneck of manufacturing solar cells based on refined metallurgical silicon, and made the conversion efficiency reach 15%, close to the level of conventional crystalline silicon cells[19]. During this period, the leading companies went to the US stock market for financing support. By 2008, 9 Chinese photovoltaic companies were listed abroad, with a global market share of more than 30%[14].

China's Renewable Energy Law was implemented in 2006. It defined legally the principles to be used to support the development of renewable energy, including "cost sharing," "full purchase," and "quota trading". Shortly after, in 2006, the National Development and Reform Commission (NDRC) launched the FiT (Feed-in-Tariff) policy, marking the end of the

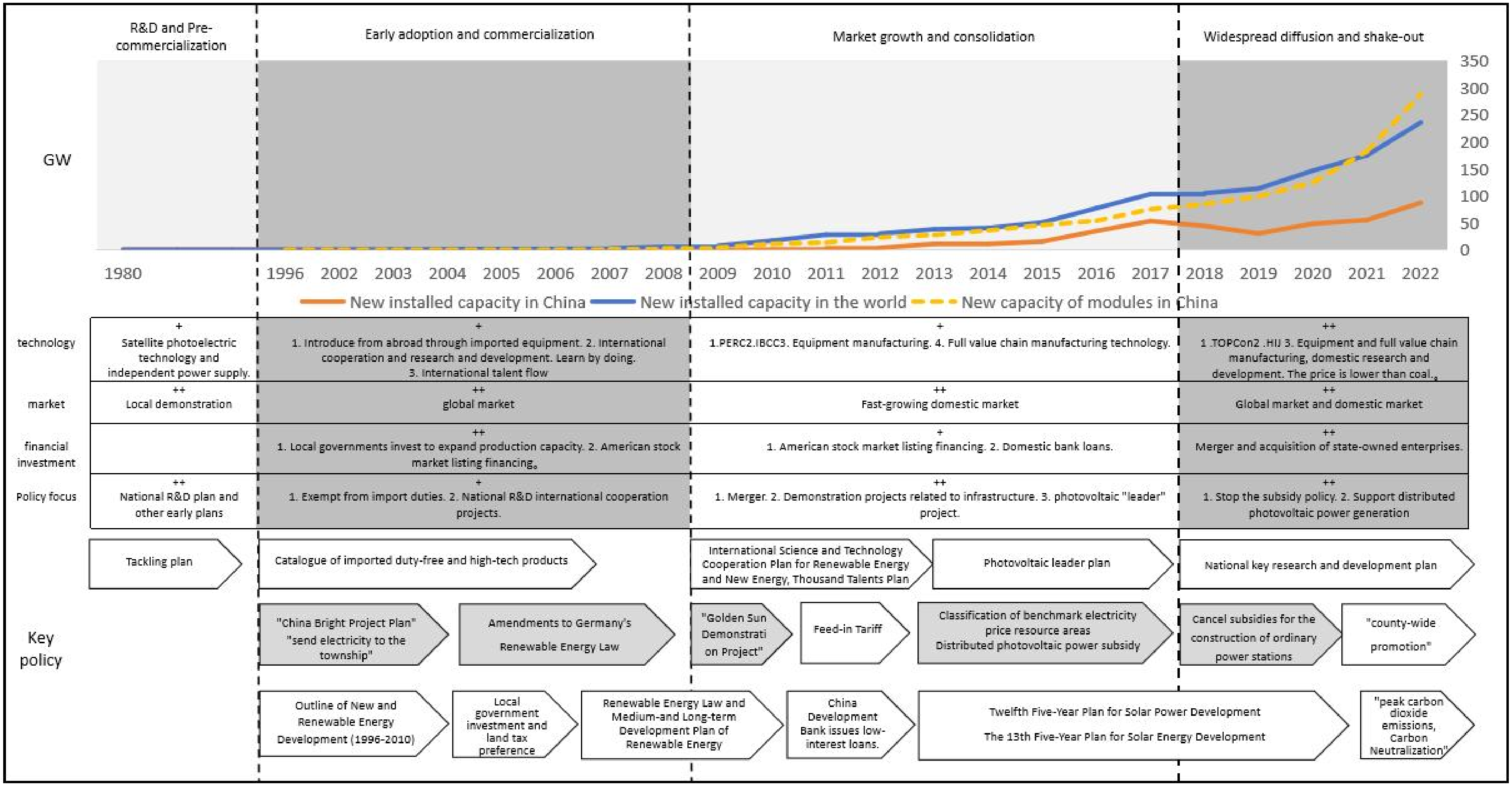

Figure 2: The four development stages of China's PV industry and the key resources including technology, market, financial investment and policies

Note: + indicates that the resource plays a weak role, ++ indicates an important role. Source: According research reports, government statistics, news information, et second stage of industrial development.

3.3 Stage 3: Market growth and consolidation (2009-2017)

During this stage, the scale of the Chinese market for PV installation expanded rapidly. In 2009, China launched the "Golden Sun Project", which provided an initial investment subsidy of 50% for grid-connected photovoltaic power generation and 70% for off-grid systems. From 2009 to 2013, the actual installed capacity of central government-led projects reached about 5 GW, and the total subsidy was about 50 billion RMB[20]. Domestic demand was at that time in line with the international market.

The FiT policy greatly expanded the domestic market. China's installed photovoltaic capacity increased from 12.92GW in 2013 to 53.06GW in 2017, with an average annual growth rate of more than 40%, becoming the largest PV market globally[20].

With the rapid growth of the Chinese market, the government has begun to further strengthen technology R&D and transfer. In 2008, China launched a large-scale global expert recruitment program, which played an important role in attracting outstanding Chinese researchers in PV cell technology to bolster the country's absorptive capacity in the sector[16]. National R&D programs supported international collaboration for key product research. For example, Yingli collaborated with the Netherlands' National Energy Research Center and Amtech, the world's leading photovoltaic equipment and automation system manufacturer, to make joint technological breakthroughs for N-type monocrystalline silicon solar cells in May 2009, and successfully raised the average conversion efficiency of "Panda" cells to 19% in 2010, which was the highest in China.

During this period, China's technology continued making progress: in March 2012, Suntech's "Pluto" solar cell technology achieved a conversion efficiency of 20.3% in mass production of cells using standard commercial grade P-type silicon wafer. This established another world record resulting from the collaborative R&D with Australian Solar Thermal Research Institute[21]. In 2013, Trina successfully developed IBC crystalline silicon solar cells with the highest electrical conversion efficiency at that time based on several years of cooperation with foreign partners, including the Solar Energy Research Institute of Singapore and Australian National University[22].

While the technology was improving, China's production further expanded. In 2012, China's total production of photovoltaic modules was 23GW, accounting for 61.8% of the global output. The total output value of the industry exceeded 300 billion RMB[23]. In the same year, global polysilicon production reached 234,000 tons, with China ranking first in the world with 71,000 tons.

After 2013, the central government began to promote industrial integration to enhance competitiveness. The government publicly stated that the country would promote industrial mergers and reorganizations, support leading enterprises to master core technologies, and raise the permission of qualification for building new solar PV manufactures. By 2017, the top five enterprises accounted for more than 80% of the national output. This period of consolidation has a parallel in the EV case, as we will see in 4.3, since in 2017 the top firms in 10 battery manufacturing accounted for 70% of the national output. Around this time, the Chinese government started to implement the three-phase PV Leader Program, which had as a main goal to reduce PV costs, improve industry and technology development, and eventually achieve grid parity. The program required the use of "leader" advanced technology products in national electricity consumption projects and PV power generation projects supported by central and local government procurement. This top-level plan, aimed to promote the transformation of the photovoltaic industry from the pursuit of scale expansion to the focus on quality and efficiency, has begun to force the upgrading of photovoltaic technology[12].

Since 2013, major manufacturers have made technological breakthroughs in the whole industrial chain through independent R&D, and carried out technological integration around the mainstream route. For example, Longi Green Energy, which was built in 2002 in Xi'an[24], focuses on the upstream silicon wafer field, made breakthroughs in single crystal growth and diamond line slicing technology successively, took the lead in introducing PERC cell technology into production lines on a large scale[25]. In 2017, through in-depth research on the mechanism of light decay jointly with partners such as the University of New South Wales, Longji solved the problem of high initial light decay of single crystal PERC and opened LIR technology to the industry. In December 2016, Trina Solar set another world record for single-crystal PERC cells with a conversion efficiency of 22.61%[26]. In 2018, JinkoSolar, a silicon wafer manufacturing company built in 2006 and transformed into a solar PV manufacturer in 2010, announced that its P-type single-crystal PERC multi-gate cell achieved 23.45% efficiency which integrates several advanced technologies[27]. During the last stage, described in 3.4, the cost of PERC components continued declining, and the market share increased from 33% in 2018 to 87% in 2020.

Benefiting from the development of PERC technology, domestic equipment manufacturers began to support production equipment for this technology. Here we have a new private sector actor that became actively engaged following domestic improvements in a novel technology. Since 2011, domestic Fengsheng Equipment, Ideal Energy and 48 institutes of China Power Science and Technology have all put PECVD equipment off-line successively.

At the end of this period, China had leading firms in the PV solar manufacturing supply chain. For example, Longji broke through the monocrystalline silicon cutting process to surpass the polycrystalline silicon route and change the whole industry to become the world's largest monocrystalline supplier. In 2016, Trina's module scale ranked first. In addition, in 2015, Sunshine Power, the leading Chinese inverter company established in 1997, announced its new inverter product which inverter efficiency exceeded 99%, beginning to lead the world of photovoltaic inverters[28].

3.4 Widespread diffusion and shake-out (2018 to date)

On May 31st 2018, China launched the so-called 531 policy, which clearly accelerated the phase-out of solar PV power generation subsidies, and no longer arranged the construction of ordinary power stations supporting it with state subsidies[29]. China's photovoltaic power stations could recover costs in about five years without relying on subsidies. On December 29, the largest "photovoltaic leader" project in China was completed on time, and the first large-scale affordable on-grid photovoltaic project in China was officially connected to the grid in Golemu, Qinghai Province. It drove an average electricity price of 0.316 RMB/kWh, lower than the benchmark on-grid electricity price of thermal power, which revealed that the replacement of coal power by solar power is economically feasible. Various studies show that starting in 2019, 344 cities in China were able to produce solar PV electricity at a price lower than the price supplied by the grid (user-side price) without subsidies and that about 22% of the urban solar power price can compete with the desulfurized coal benchmark price[30]. At the end of 2018, the cost of PV installation decreased to about 4.5 RMB/Watt, a decrease of more than 30% compared with that in 2017. These milestones can be interpreted as the point at which China's PV industry and production have reached relative maturity in terms of technology and cost.

Globally, during this time, driven by China's photovoltaic industry, the global photovoltaic comprehensive price index fell by more than 30% from May to October 2018. Solar PV has become the cheapest source of electricity in some overseas markets with high electricity prices, good solar irradiation conditions and low non-technical costs. The cost of photovoltaic power generation in Greece, Germany, India, Brazil and other countries has been lower than the local thermal power price[31].

The international market once again had high demand for products from China's solar PV industry. In the second half of 2018, China's export volume of photovoltaic modules increased significantly. From June to November, the total export volume reached 20.69GW, up 57.23% year on year, and the export volume reached more than 200 countries.

With the emergence of the commercialization of photovoltaic power generation at home and abroad, state-owned enterprises with financial strength, financing convenience, policy and personnel advantages began to enter the photovoltaic field through acquisition, merger and capital injection in the photovoltaic industry. In 2019, Huaneng acquired a 51% stake in GCL New Energy, making it the world's second-largest investor. Yingli also became a state-owned company through a share purchase. SOEs in the energy sector of China, essentially entered the sector and became significant players again in this last stage[32].

In 2019, China proposed replacing the benchmark FiT system with a market-oriented bidding system. In June 2021, China stopped the FIT policy for photovoltaic projects, entered the stage of comprehensive marketization. At the same time, China officially launched the whole county (city, district) roofs to promote the development of distributed photovoltaics, guiding the development of a new domestic market for PV deployment. During this period, as the efficiency of mainstream single-crystal PERC cells approached the theoretical limit, and HJT cells and TOPCON cells with higher conversion efficiency became a new theoretical technology trajectory. Big enterprises, e.g. JinkoSolar and JA Technology, considerably increased R&D investment to gain a leading edge in the new competition[33].

With their rapid increase in R&D investments, those two private enterprises made breakthroughs in technology. In 2018, the maximum efficiency of n-type TOPCon battery independently developed by JinkoSolar reached 24.19%. Trina Solar's self-developed i-TOPCon technology broke laboratory records in both large-area cells, achieving conversion efficiencies of 24.58%. At the same time, TOPCon's technologies are diverse, and equipment manufacturers have their own focus areas. Many manufacturers have launched their own technical solutions to upgrade PERC technology to TOPCon. This indicates that China's indigenous innovation ecosystem has been equipped with the ability to select technologies and implement industrialization. In 2023, China's PV patent applications accounted for more than 50% of the world's total applications[34].

At this stage, leading enterprises beyond module manufacturers began to operate internationally. Tianhe, Jinko, JA Solar focused on the international market and established a distribution system around the world covering more than 60 countries, with their distributors covering more than 60 countries.

4. CONCLUSION

Based on the theory of industrial innovation ecosystem, this paper reveals the dynamic mechanism and key driving factors of catching up of emerging industries in late-developed countries through the analysis of the evolution path of China's photovoltaic industry. It is found that the rise of China's PV industry is essentially the result of the synergistic evolution of policy, technology, market and financial resources. The innovation ecosystem presents differentiated characteristics at four stages.

At the first stage, the Chinese government policy began to support PV technology based on the following strategy, which focused on R&D projects. The key players in this stage were research institutes and SOEs. The goal in this stage was that China had the PV technology and could make PV cells.

At the second stage, when the global market had formed, the manufacturing industry developed, the private firms emerged quickly based on technology transfer by equipment import, R&D collaboration projects. The local government was a key player in financing the development of the industry which can be seen as an early investor in China. The commercialization began and increased quickly based on the global market. Meanwhile, the leading players (technology providers/manufacturers) went to the US stock market for financing support.

During the third stage, the domestic market increased enormously thanks to China's domestic FiT policy. Meanwhile, the central government started to pick-winners using the Leader Project policy. Only the best players (with the 'best technology') qualified to supply the national policy-oriented market. The key product PERC became the dominant product. Meanwhile, the domestic equipment manufacturing and material manufacturing developed quickly; these companies supported the innovation and development of PV manufacturing. Then China developed the whole manufacturing value chain technology.

At the last stage, China's policy shook-out its key subsidy policy and opened the distributed solar market. Both the global market and the domestic market played central roles in shaping China's PV industry. Meanwhile, in the domestic market, the key electricity SOEs came back into play using M&A as the main mechanism. At this stage, due to the development of China's PV industry, the cost of solar energy is lower than traditional coal-based energy, which formed a new global market pattern.

In summary, the policy-oriented dynamic evolution of China's PV industry ecosystem is a good case for countries to raise their emerging industry.

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