Analysis of the Evolution of Photovoltaic Industry Technology Track Based on Patent Citation

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Abstract: Based on the patent data of the photovoltaic industry, this paper uses technology life cycle analysis and main path analysis to study the trajectory evolution process and characteristics of the global photovoltaic industry technology development. The study finds that: (1) The development of photovoltaic technology is divided into three stages, namely the embryonic period from 1998 to 2001, the growth period from 2002 to 2013 and the mature period from 2014 to 2021. From the perspective of patent owners, Japan and South Korea are in the leading position in the world; (2) The technological development of the photovoltaic industry has formed two more complex paths, which have experienced the process of technology integration-technology separation-technology reintegration. With the evolution of the main path, the focus of research has shifted from the construction of hardware facilities such as light-emitting devices and their supporting devices to the research and development of high-performance materials with obvious advantages in transmission efficiency and device service life. (3) The technological orbital evolution of the photovoltaic industry has three characteristics, namely, the coexistence of the gradual route and the radical route in the evolution path, the diversification trend of the upstream and downstream leading technologies of the industrial chain, and the evolution of the technology track is affected by many factors of the external environment such as market demand, policy system, and energy status.

1. Introduction

In the context of global warming, green and low-carbon has become a global consensus, and countries around the world have actively introduced policies and measures to promote the development and utilization of renewable energy, and more than 170 countries around the world have proposed "zero carbon" or "carbon neutral" climate goals. The development of new energy is the key to promoting the low-carbon transformation of the industry and achieving "carbon peak and carbon neutrality". China's energy sector has introduced a series of plans and policies, forming a strategic planning system to promote the energy revolution, and the energy consumption structure has undergone positive changes, with the proportion of coal consumption falling from 68.5% in 2012 to 56% in 2021, and the proportion of clean energy consumption rising from 15.5% in 2013 to 25.5% in 2021. As a product of scientific and technological development, technology is not only a representative of the latest scientific and technological achievements, but also an important indicator of the development of social productive forces, and technological development has become an important force driving national economic growth.

Affected by the conflict between Russia and Ukraine and inflation, the price of traditional energy has risen sharply, the economy of photovoltaic power generation has gradually become prominent, the enthusiasm of photovoltaic construction has increased significantly, and overseas installed demand is expected to maintain high growth. According to the EU's latest REpowerEU action plan released in May 2022, the EU will increase its overall renewable energy target from 40% to 45% in 2030, and plan to install more than 320GW of photovoltaic capacity by 2025 and reach 600GW by 2030, with an average annual increase of 46.8GW.

2. Literature Review

Thomas Kuhn first mentioned the new concept of technological paradigm in his book "The Structure of Scientific Revolution" in 1962, and then a large number of scholars introduced it into the study of innovative development such as the generation, development, and evolution of technology. Dosi [1] clarified the definition of technology track on this basis, he believes that the technology and economy in the technology paradigm work together to create the evolution trajectory of technology, and also believes that breakthrough innovative technologies can achieve new technology tracks, and changes in technology tracks are also created by progressive technological innovation.

Different scholars have different opinions on the nature and development direction of the technical track. Hua [2] believes that the key attributes of the technology track include: continuity, finiteness, systematicness, exclusivity and diversity. Jenkins & Floyd [3] focuses the three key attributes of the technology track on energy, power, and uncertainty. Energy and power represent the impact and impetus of technological progress, respectively, while uncertainty emphasizes early competitive technologies. Geels [4] believes that technological change occurs because of the interplay between technology and various elements of society, including policies, regulations, and standards. Fu et al. [5] believe that scientific and technological progress, technology accumulation and market demand determine the direction of the technology track.

Later, many scholars began to comprehensively use patent analysis and statistics, bibliometrics and other methods, drawing on the quantitative indicators of those patent data, and opened up new methods for identifying technical tracks. In order to explore the trend of technological development and change and describe the technology trajectory, Lee et al. [6] constructed a formal conceptual model based on patent data. Huang [7] explored and predicted the development trajectory of lithium battery and fuel cell technology from three aspects: the increasing number of patents, the speed of technology update and stakeholders. Miao et al. [8] constructed patent indicators and statistical comparisons to interpret the competition between technology tracks in the automotive industry.

3. Data Sourcing and Preprocessing

The Derwent World Patent Index database contains the original patent data of more than 40 patent offices around the world, contains more than 100 million patent documents worldwide, and is one of the most trusted sources of patent information in the world, used by researchers. This paper takes the patent data of the global photovoltaic industry as the research object, and selects the Derwent patent database as the data source. Drawing on the search keywords of Zhao [9], Tang [10] and others and integrating the core technical terms of the photovoltaic industry chain [11]: silicon materials, silicon wafers, silicon rods, chips, cells, battery modules, photovoltaic glass, monocrystalline silicon, polysilicon, amorphous silicon films, etc., the search formula is determined as: TS=photovoltaic OR TS=photovoltaic power generation OR TS=photovoltaic solar cell OR TS=photovoltaic industry OR TS=distributed photovoltaic generation OR TS=photovoltaic system OR TS=PV system OR TS=photovoltaic glass OR TS=PV glass OR TS=distributed PV generation OR TS=PV power generation OR TS=PV solar cell OR TS=PV industry OR TS=battery module OR TS=solar cell OR TS=siliceous material OR TS=silicon pellet OR TS=silicon ingot OR TS=polysilicon OR TS=single-crystal silicon OR TS=amorphous silicon membrane. The search time range was determined from 1998 to 2021, the search date was December 1, 2022, and all patent information was exported, a total of 287,520 patent data, each patent included the patent inventor, Derwent main collection number, IPC, Derwent classification code, Derwent manual code, cited patent, designated country, etc.

The original patent dataset was processed as follows: (1) Referring to the screening strategy of combining IPC number and keyword adopted by Zheng [12], Lin [13] and others, the IPC number contained in the original patent dataset was screened twice, and the IPC code with relatively small correlation with the photovoltaic industry was eliminated. Such as A01g-009/24(Heating, ventilation, tempering or watering devices for greenhouses, contributing to hotbeds or the like), A61b-005/00(Measurements for diagnostic purposes), B08b-001/00(Utilize the cleaning method of a tool, brush or similar), G01d-021/02(Devices that measure two or more variables that are not included in other separate subclasses), G06q-010/06(business planning; Organizational model), G07c-009/00(Single input or output register); (2) Clean the data and remove duplicate and missing data. Finally, we obtained 203545 patent information of the photovoltaic industry, including 102012 Chinese patent information and 101532 patent information of other countries, which we used as the patent dataset of the photovoltaic industry for research.

3.1. IPC Number Analysis

The IPC classification code can reflect the technology distribution and research hotspots in the photovoltaic industry so far, and the patent IPC classification symbols of China and other countries are counted and ranked respectively, as shown in Table 1. As can be seen from the table, the main distribution of patents in China's photovoltaic industry is: Semiconductor devices and components manufacturing, packaging (H01L-031), for solar cell installations (H02J-007), movable or adjustable support structure (H02S-020) and exposure recharge lighting (F21S-009). Among them, the largest number of patents is made for methods or equipment dedicated to manufacturing or handling semiconductor devices or their components, with a total of 10,326, indicating that research on this technology is more likely to generate patents.

Table 1 Patent IPC classification numbers and records of the top ten domestic photovoltaic industry.

IPC number	Technical note	Number of records
H01L-031/18	A method or apparatus specifically suited for the manufacture or handling of a semiconductor device or its components	10326
H02S-020/30	Removable or adjustable support structure for photovoltaic modules	8698
H01L-031/048	Packaging of photovoltaic conversion modules	6771
H02J-003/38	Parallel feeder	6670
H02J-007/35	A device with a photosensitive cell	6365
F21S-009/03	With lighting device that is recharged by exposure	4641
H01L-031/0224	Semiconductor electrode components	4158
H02S-020/32	Movable or adjustable support structures dedicated to solar tracking	3574
H01L-031/042	A photovoltaic module or array of individual photovoltaic cells	3342
H02J-007/00	Devices for charging/powering or depolarizing battery packs	3339

3.2. Technology Life Cycle Analysis

The technological life cycle is a pattern of technological change characterized by periodic changes, reflecting the life process of the research field from birth to maturity and finally disappearance [9], and this concept has been widely used in political, economic, social and other directions. Based on this, we separately count the annual patent applications and patent inventors of the global photovoltaic industry from 1998 to 2021, and draw a technology life cycle map of the photovoltaic industry, as shown in Figure 1. According to the technology life cycle theory, this paper divides the technological development of the photovoltaic industry into three stages: embryonic stage, growth period and mature stage. They were 1998-2001, 2002-2013 and 2014-2021. In the embryonic period, the number of patent applications and patent inventors was small, and the growth rate was low, and the number of patent applications was only 978 as of 2001. In the growth period, technology continues to innovate, gradually involving various application scenarios, attracting the attention of a large number of enterprises and researchers, in these more than ten years, the average annual growth rate of patent applications exceeds 100%, the number of patent inventors has an average annual growth rate of more than 68%, and the photovoltaic industry has expanded rapidly. At present, it is in a mature period of technological development, R&D technology is relatively mature, invention patents are still emerging, but the growth rate has slowed down, there is a certain threshold for enterprises to enter the market, and the number of patent inventors shows negative growth.

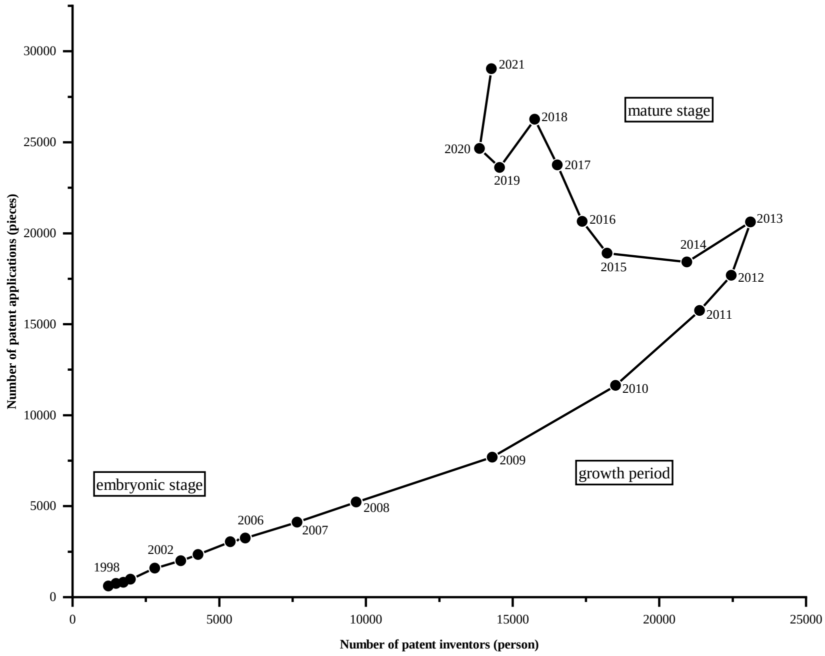

Figure 1 Technology life cycle of photovoltaic industry.

3.3. Analysis of Major Patentees

As of 2022, the ten companies with the most patent rights in the global photovoltaic industry are shown in Figure 2. Japan occupies five seats, which are SHARP KK, SANYO ELECTRIC CO LTD, KYOCERA CORP, MITSUBISHI ELECTRIC CORP and KANEKA CORP, with SHARP leading the list with 3,519 patents. South Korean companies LG ELECTRONICS INC, LG CHEM LTD and SAMSUNG ELECTRONICS CO LTD occupies three of the seats, with LG ELECTRONICS in the third place. Merck Patents AG ranks second with 2,811 patents, while State Grid of China ranks eighth. It can be seen that Japan and South Korea have highlighted their global leading position in the ownership of photovoltaic patents.

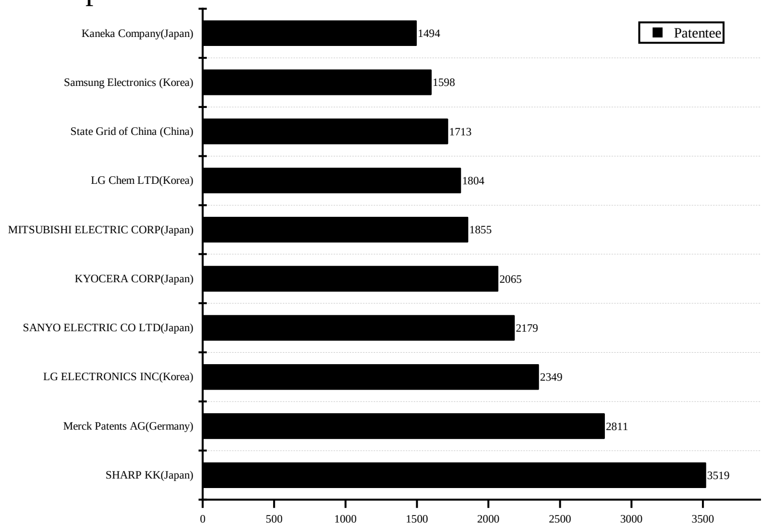

Figure 2 Major patentees of global photovoltaic patents.

4. Identification of the Main Path of Technology Track Evolution

4.1. Technology Track Identify

Dosi [1] believes that the evolution of technology has progressive innovation and breakthrough innovation, the former is the continuous improvement of existing technology on the basis of existing technology, the latter is breakthrough innovation on the basis of existing technology, thereby changing the original technological evolution direction of technology, and the technology track is the process of continuous improvement of progressive innovation and fundamental breakthrough innovation combined with each other. Each patent can be seen as an individual carrying technology, and the critical path that encompasses the inheritance between technologies represents the backbone of technological progress. Scholars have proposed a series of algorithms for identifying critical paths, with SPLC and SPNP being the most common. The SPLC algorithm is suitable for the derivative development of research paths [14], while SPNP is often used to identify high-value patent nodes on the evolutionary main path and screening path, such as intermediate patents, endpoint patents, and convergence patents [15]. Therefore, we first clean the data, sort it into the data format of inter-patent citations, and obtain a total of 541358 pairs of citation relationships, then use txt2Pajek software to convert the file into Pajek importable net format, and finally use the more suitable SPNP algorithm in Pajek software to calculate the SPNP value of each node, identify the critical path of the photovoltaic industry patent citation network, and obtain the photovoltaic industry technology track, as shown in Figure 3.

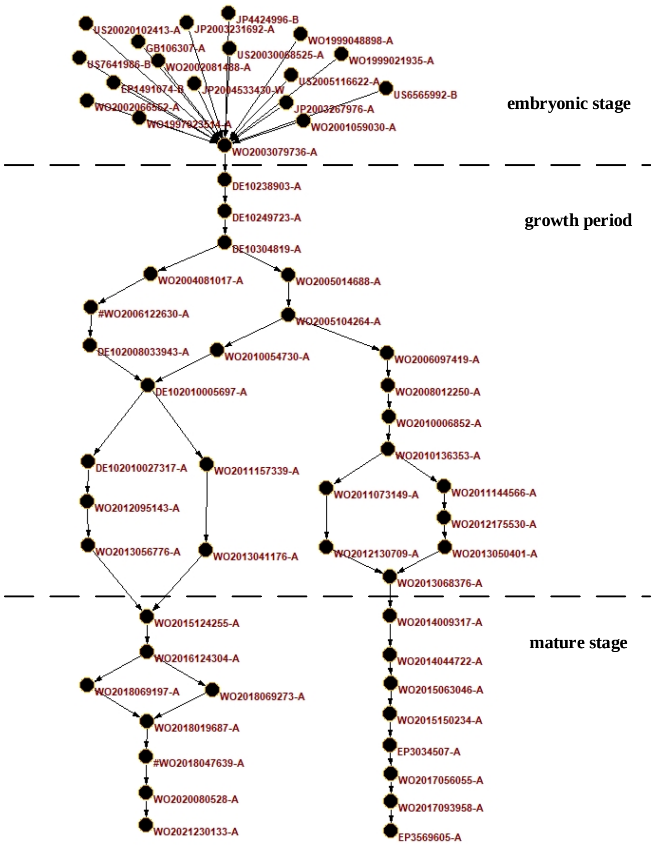

Figure 3 Photovoltaic industry technology track (1998-2021).

Overall, the technical track of photovoltaic industry technology development contains a total of 59 patents, photovoltaic technology originated from different technical branches, and its development has experienced the process of technology integration - technology separation - technology reintegration, and finally formed two different technical directions.

(1) Embryonic stage. The embryonic photovoltaic industry technology track contains 18 patents, with a number of different starting points, and finally converges into patent WO2003079736-A.

These patents located at the starting point can be roughly divided into four categories, the first category is patent US20020102413-A, which studies plasma curing based on porous low-dielectric eddy thin film materials; The second category is the patent GB106307-A, which creates a new construction process with an illuminated digital dial; The third class is patent US6565992-B, which provides a phosphide oxygen pressure sensor comprising a stable polymer skeleton and phosphorescent dyes; The fourth category consists of the remaining 14 patents such as WO2002081488-A, US2005116622-A and JP2003231692-A, which provide phosphorescent organometallic dendritic polymers that can be used in light-emitting devices, such as light-emitting diodes or photovoltaic devices. These four categories of inventions eventually converged into a light-emitting device invented by the University of St. Andrews in the United Kingdom, which contained at least a layer of metallic cations of phosphorescent organometallic dendritic polymers. In general, the patents at this stage are mainly based on the research and development of light-emitting devices and their devices, and due to the immaturity of the technology, a variety of phosphorescent organometallic dendritic polymers with different structures are used to compare luminescent performance. From the perspective of patent owners, they are mainly divided into two categories, one is the highly innovative multinational companies represented by 3M Company of the United States and Merck OLED Materials Co., Ltd. of Germany, and the other is the world's famous universities represented by the University of Oxford, the University of St. Andrews and Kanagawa Institute of Science and Technology. It can be seen that at this time, the research and development of photovoltaic technology is concentrated in universities and scientific research scholars, and the production and manufacturing of key devices rely on large semiconductor companies or comprehensive companies with high innovation efficiency.

(2) Growth period. The photovoltaic industry technology track in the growth period contains 25 patents, which has undergone a process of multiple technology separation and technology integration, and finally formed two main paths.

The growth phase begins with the continuous improvement of the emitting layer of photovoltaic devices to make them more efficient at high brightness, making them more suitable for use with light-emitting diodes. The main path is then divided into two directions, one direction is composed of WO2004081017-A, WO2006122630-A and DE102008033943-A patents, mainly involving the invention of new metal complexes and the improvement of organic electronic devices, which are often used as functional materials for electron transport in the emitting layer. Therefore, this direction is the improvement of spectral devices from the hardware. The other direction consists of WO2005014688-A and WO2005104264-A patents, mainly involving mosaic conjugated copolymers bound to static parts, this creative material has higher efficiency, longer service life and reduced operating voltage. Therefore, this direction is the optimization of light-emitting diodes from the performance point of view. Subsequently, the DE102010005697-A patent on the main path of the technology track fused the improved results of light-emitting devices and materials to further derive two relatively mature main paths. One is represented by WO2012095143-A and WO2013056776-A patents, involving the preparation of organic light-emitting devices of aromatic nitrogen heterocycles and triphenylene compounds, and the other is represented by WO2013041176-A patent, involving the preparation of organic light-emitting devices of carbazole derivatives. At the same time, WO2006097419-A and other patents have also derived a main path, these inventions mainly involve the application of compounds in electronic devices, these compounds have excellent solubility and film-forming properties in organic solvents, if used in light-emitting diodes, the charge migration efficiency is high, and can remain stable at high temperatures. Over the next three years, researchers continued to improve the energy conversion efficiency, manufacturability, and stability of these light-emitting devices in solar cells and photodiodes.

From the perspective of patent applicants, the main path of this stage is divided into two camps, one is German Merck, which has 14 core patent technologies, and the second is BASF AG, which has 11 core patent technologies through the acquisition of Swiss Ciba Refining Holdings Co., Ltd. It is worth noting that both companies are German enterprises, indicating that the development of the photovoltaic industry at this time is completely led by Germany, expanding towards the production and preparation of light-emitting devices and high-performance materials, and initially opening the application of organic semiconductors in solar cells.

(3) Maturity period. The mature photovoltaic industry technology track is relatively single, consisting of two main paths. One is represented by 8 patents such as WO2015124255-A and WO2016124304-A, using polycyclic aromatic compounds with novel structures as materials for organic electroluminescent elements, and these inventions focus on the luminous efficiency of materials and the service life of components. The other is represented by 8 patents such as WO2014009317-A and WO2014044722-A as the continuous improvement of technology, using

metal compounds as charge transport materials or host materials for phosphorescent emitters in electroluminescent devices, providing higher efficiency, stability, manufacturability and spectral characteristics, while reducing the driving voltage of electroluminescent devices.

From the perspective of patent applicants, applicants on the main path represented by WO2015124255-A transitioned from Merck KGain of Germany to JNC Co., Ltd. of Japan and SK Materials of South Korea. The other main path, represented by WO2014009317-A, transitioned from BASF AG to Demitsu Kosan Co., Ltd. It can be seen that the countries occupying the core position of the photovoltaic industry have shifted from Europe to emerging countries in Japan and South Korea, and key patented technologies are mastered by cutting-edge LED and semiconductor companies.

Looking at the main path of the three periods of the photovoltaic industry, it is found that the focus of the first phase of photovoltaic industry technology is the structural research and development of light-emitting devices and their supporting devices, which enable light-emitting devices to operate, but the photoelectric transmission capacity is weak. The second stage is to simultaneously innovate in device hardware and material properties, and the goal of this stage is to improve the preparation of organic light-emitting devices and improve their performance in solar cells and photodiodes. In the third stage, photovoltaic technology focuses on more materials that can be used for electrical transmission than the previous stage, and focuses more on material transfer efficiency and device service life in different application scenarios.

4.2. Analysis of Technical Characteristics

Each leap in the technological track represents the gradual development of technology on the basis of the original technology, and its advanced and complex are higher than the original technical foundation. Technology tracks are often continuous, phased, adaptable and open, and predictive. Based on the analysis of the technical trajectory evolution of the photovoltaic industry, we conclude that its technical evolution has the following characteristics:

(1) Technical track evolution route. In the above technical trajectory analysis, we can observe two technological evolution routes, one is the gradual route represented by Merck KGa, and the other is the radical route represented by BASF AG and Japan's Idemitsu Kosan Co., Ltd.

Traditional large-scale comprehensive enterprises began the development and industrial layout of photovoltaic technology as early as the rise of the photovoltaic industry, and the technological evolution took a more conservative and gradual route. In the early stage, it focused on the development of photovoltaic devices such as light-emitting diodes and photodetectors, and the materials required for these devices can also be used in high-tech fields such as liquid crystals, OLEDs and integrated circuits, thereby improving the overall technical level of the company's development in the direction of electronic technology. This route progresses to the entire electronic device manufacturing by gradually developing the different types of metal compounds required for the emitter layer of electroluminescent devices. The reason for adopting this route is that on the one hand, comprehensive enterprises have matured technical and management experience in other fields, and at the same time, high R&D investment has formed a source of power in the development process of photovoltaic technology and products; On the other hand, the R&D results can be fully integrated with the company's existing products and applied to the market faster.

In contrast to traditional comprehensive enterprises, chemical manufacturing companies represented by BASF and Idemitsu Kosan have adopted an aggressive route of entering the photovoltaic industry through acquisitions and mergers and acquisitions at the beginning of photovoltaic technology development. From the beginning of its entry, we have begun to develop high-efficiency and manufacturable light-emitting devices, and pursued the landing of high-efficiency products. In this regard, the Guofu Factory at Idemitsu Kosan was once the largest PV panel manufacturing plant in the world at the time, but due to severe operating conditions and low prices for photovoltaic panels by rival Chinese companies, the Guofu Plant ceased production in June 2022. In contrast, BASF has participated in a number of smart energy storage power station and distributed photovoltaic power plant projects through the "Buy & Manufacture" initiative, putting the world's leading technology into use.

(2) Direction of technical track evolution. Technology evolution is not achieved overnight, but gradually formed after a long period of technological accumulation, and branches of the technical track will appear in the process of accumulation [2]. By comparing the branches of technology and their technical attributes, we can predict the future direction of technology to a certain extent.

Due to the different technical paths of the upstream and downstream of the photovoltaic industry, the direction of technological evolution has also been further refined and improved in each branch. From the perspective of electronic devices, the invention involves organic electronic devices with multilayer structures or new polymers, and the charge mobility of devices with these new structures as materials continues to increase. From the perspective of solar cells, the invention of organic perovskite, thin-film perovskites and other materials production and applications, and even the doping of DNA molecules into perovskite crystals as a carrier has also proved effective in charge and heat transport. From the perspective of photovoltaic power generation system, the system needs to monitor the operation status and power generation of the entire power plant and individual modules, identify and display faulty solar modules, and perform the control data upload and download process between the relay terminal and the remote terminal of the integrated management site.

(3) Technical track drivers. The technical track is dynamically evolving, which needs to continuously transmit information with the external market demand, policy system, energy status and other environments, and is also affected by the interference and transformation application of the external environment. The survival and continuation of technology is not only related to the properties of the technology itself, but also affected by the entire technology ecosystem.

In fact, as early as 1877, Adams and Day made the first selenium solar cell, but limited by the level of scientific and technological development at that time, the technology failed to achieve breakthroughs for many years. It wasn't until 1941 that Orr discovered the photovoltaic effect on silicon, and has since been used in commercial solar cells, but with a conversion efficiency of only 2%. Human beings have used solar energy as an energy source and power for 400 years, but the real use of technology as a new energy source only began after the 1973 oil crisis, during which many countries around the world strengthened their support for the development of solar energy and other renewable energy sources, such as the US Sunshine Power Project, Japan's Sunshine Plan and China's Bright Project Project. In addition, in the application and development of new technologies, there are also many new laws and social norms formed, and it is foreseeable that laws and regulations will become an important factor in the evolution of the technology track of the photovoltaic industry in the future.

5. Conclusion

The analysis of the technical track of the photovoltaic industry shows that the problems in the technical field have been gradually solved, but the research on the application of scenarios has not yet formed a relatively stable track. Realizing the large-scale commercial application of solar power generation is the mainstream trend of the development of solar photovoltaic power generation technology in the world today, and it is also the mainstream direction of solar cell application in the future. In order to achieve large-scale power generation, we must first solve the problem of how to improve photovoltaic conversion efficiency and reduce production costs. Two completely different paths have been formed at the end of the technology track, which shows that it is not yet possible to judge who can occupy the core technology position of organic compounds and multi-junction technology in the future technology application, which also provides opportunities for innovative research of Chinese enterprises. The conclusion of this article is as follows:

First, Japan has obvious advantages in photovoltaic industry patent technology, which is inseparable from decades of research and development investment by a large number of manufacturers, gradually breaking through the original technology inventions. Although China is a major photovoltaic manufacturing country, the installed capacity has been stabled all year round in the world, but the total number of patents is low, the fundamental reason is that the ability of independent innovation is relatively weak, and a series of photovoltaic technology-related policies need to be introduced to stimulate enterprise innovation. The continuous development of mainstream technologies of a new generation of cells such as TOPCon, HJT, and IBC has brought new opportunities for China's industrialization development. The government should increase investment in scientific research and technology, promote technological progress and disruptive innovation, and establish a demand-oriented mechanism for the transformation of scientific and technological achievements. Among them, the technologies that need to be broken through include the purification technology of polysilicon raw materials, the photoelectric conversion efficiency of photovoltaic cells, the research and development of emerging technologies such as multi-junction and organic cells, and the construction of multi-scenario photovoltaic application demonstration projects. At the same time, the new supply of photovoltaic talents in colleges and universities is less than 1/3 of the needs of the industry, and multidisciplinary compound talents, senior management talents and information talents should be cultivated in a planned manner to ensure that industry-university-research cooperation is not disconnected and does not fall behind.

Second, technology is the key to reducing costs and increasing efficiency, with the two-layer drive of technological progress and market demand, the production cost and power generation cost of China's photovoltaic products are also constantly decreasing, and entered the stage of photovoltaic parity in 2021. At present, the development of large-size, thin-sliced silicon wafer technology, PERC+, perovskite and other battery technologies will effectively improve product power and power generation efficiency. Under the iteration of technology, the production capacity of each link of the industrial chain is gradually released, so it is also necessary to consider the production bottleneck of photovoltaic glass, adhesive film, quartz crucible and other accessories, and be vigilant against the cost pressure caused by the rise in upstream prices caused by the gap between supply and demand. In addition, we must actively promote key breakthroughs in the fields of basic materials and high-performance materials, make up for the shortcomings of the industrial chain, and improve the anti-risk ability of the industrial chain and supply chain.

Third, under the background of the rapid development of new energy, the demand for energy storage facilities in the power system has increased, and new energy has the characteristics of randomness, intermittency and volatility, and large-scale new energy power generation brings new challenges to the traditional power grid. Accelerate the application of energy electronics technology in construction, agriculture, transportation, energy and other fields, promote the development of composite photovoltaic power generation such as agricultural solar complementarity and fishery solar complementarity, and encourage the exploration of emerging photovoltaic business models. Actively deploy photovoltaic large base projects, carry out photovoltaic sand control, pasture-light complementary pilot projects in the northwest region, so that local people can enjoy the dividends of photovoltaic industry development. At the same time, we will encourage distributed photovoltaic installations represented by BIPV, strengthen the integrated design of solar buildings, support the application of photovoltaic curtain walls and photovoltaic roofs, and improve the photovoltaic coverage of new plant roofs.

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