Analysis of the Photovoltaic Market in China: Optimization of Industrial Chain and Prospect Forecast Under the 'Double-Carbon' Background

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Abstract. Since the Paris Agreement was signed in 2016, the development of renewable energy has become a strategic consensus of all countries in the world. Since 2020, China has officially put forward the goals of "peak carbon dioxide emissions" in 2030 and "carbon neutrality" in 2060, and actively responded to the global proposition of sustainable development goals and carbon emission reduction in Paris Agreement. According to the statistics of the National Energy Administration, fossil energy such as coal, oil and natural gas accounts for more than 80% in China's current energy consumption structure, while clean energy such as hydro power, wind power and natural gas accounts for only 25.5%. At the same time, China's energy consumption is increasing year by year, with the total consumption reaching 5.24 billion tons of standard coal equivalent in 2021, and the reform of energy consumption structure is imminent. The new energy represented by photovoltaic is expected to become the main industry to achieve the goal of carbon neutrality in 2030. Based on the investigation of national and local statistical data, combined with the current development of clean energy and photovoltaic industry, this paper analyzes the operation status of leading photovoltaic enterprises, deconstructs the photovoltaic industry chain, extracts data, grasps the future development direction of photovoltaic industry, and reveals the shortcomings and loopholes in the development of photovoltaic industry. At present, the photovoltaic industry is subject to many industrial chain structures, and the market fluctuation between upstream and downstream industrial chains changes periodically. However, in the long run, the photovoltaic industry is on the rise. If the specific links in the industrial chain can be optimized and cost reduced, the coordination capacity within the industrial chain can be increased, the integration of the industrial chain can be realized as soon as possible, meanwhile, the coverage area of photovoltaic power stations can be promoted, the high-quality sunshine conditions in the western region can be fully utilized, and the regional economy can be driven by the development of photovoltaic industry, so that the promotion of green energy industry can be realized, the economic vitality of the western villages and towns can be developed, and the double cycle of domestic and international economy can be promoted.

Keywords: Photovoltaic Industry, Industrial Chain, Industrial Analysis, New Energy, Strategic Research, Photovoltaic Market.

1. Introduction

Energy is an important support for economic development, and the choice of energy is undoubtedly crucial for sustainable development. In China, the current energy structure is still dominated by coal and oil, accounting for more than 80%, and energy consumption results in a large amount of carbon dioxide emissions[1]. However, under the strategic layout of global sustainable development, China must continuously promote the adjustment of industrial structure and energy structure and vigorously develop renewable energy. Only in this way can we improve the global competitiveness of industry and economy. At the same time, in order to realize the long-term plan of "peak carbon dioxide emissions" in 2030 and "carbon neutrality" in 2060, energy structure transformation is its inevitable requirement. Hence, renewable energy has received growing support in recent years (e.g., wind power,

hydropower, etc.) [2, 3]. Solar energy resources are abundant and widely distributed throughout the world, and Solar photovoltaic(PV) power generation technology is the most promising technology of renewable energy power generation technology. PV is a technology that directly converts solar energy into electricity by using the photovoltaic effect of semiconductor interface. It is safe, clean and efficient[4].

China’s PV industry has experienced a momentous change in recent years and its development has considerably increased the installed capacity (CNESB, 2020). Photovoltaic industry is unique among new energy sources. Its installed cost has dropped by 81%, and the cost of leveling electricity has dropped by 85%, making it the biggest dark horse and potential stock among all new energy sources. From 2010, it ranked the bottom among all new energy sources, and it ranked the third in 2020, surpassing geothermal, sea breeze, biomass energy, light and heat, second only to land breeze and hydro power. In academic circles, the research on photovoltaic and photovoltaic industry has gradually become a hot topic.

However, China’s PV industry is driven and restricted by many factors[5]. China has vigorously developed the PV industry since 2006. The Chinese PV industry is economically vulnerable due its dependence on foreign countries in sourcing silicon and other PV products which are exacerbated during international developments such as the 2008 global financial crisis and the 2013 “anti-dumping and anti-subsidy” investigation in Europe and the United States[6]. Demand, policy, market conditions, and other factors have a significant impact on the PV industry. Such complex driving and limiting factors of the PV industry pose a difficulty in development planning. Currently, China’s PV industry is facing a major transformation, and its development path and the determination of its future direction are challenges that need attention.

In this study, Based on the investigation of national and local statistical data, combined with the current development of clean energy and photovoltaic industry, this paper analyzes the operation status of leading photovoltaic enterprises, deconstructs the photovoltaic industry chain, extracts data, grasps the future development direction of photovoltaic industry, and reveals the shortcomings and loopholes in the development of photovoltaic industry.

2. Development of China’s PV

2.1 Development of China’s PV market

In recent years, China’s energy consumption has increased in volatility (Figure 1), while in the energy consumption structure that needs to be optimized urgently, clean energy is increasing year by year, which has a very broad development space (Figure 2). At the same time, there is a certain correlation between GDP growth rate and energy consumption growth rate (Figure 3).

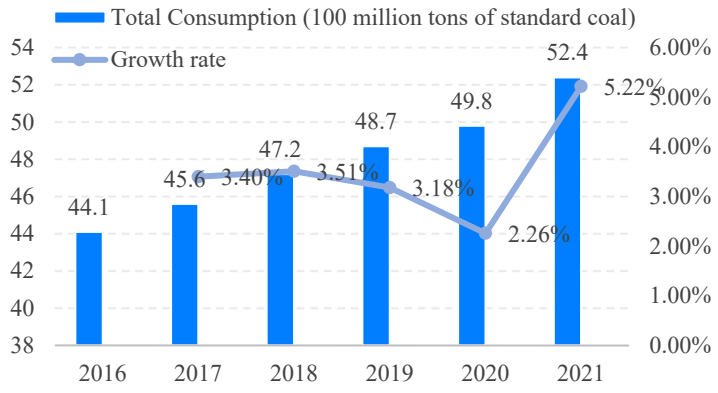

Fig. 1. Total Energy Consumption and Growth Rate from 2016 to 2021

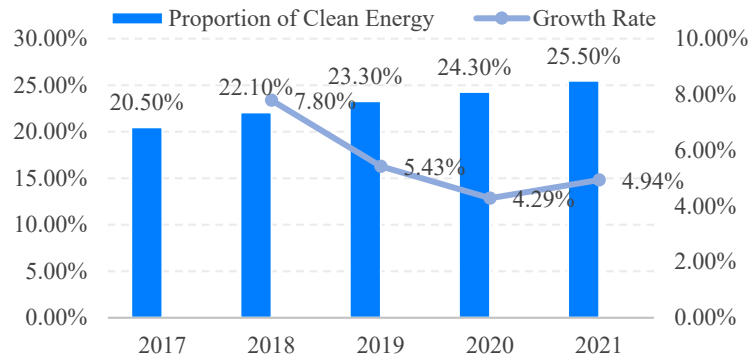

Fig. 2. Proportion and Growth Rate of Clean Energy from 2017 to 2021

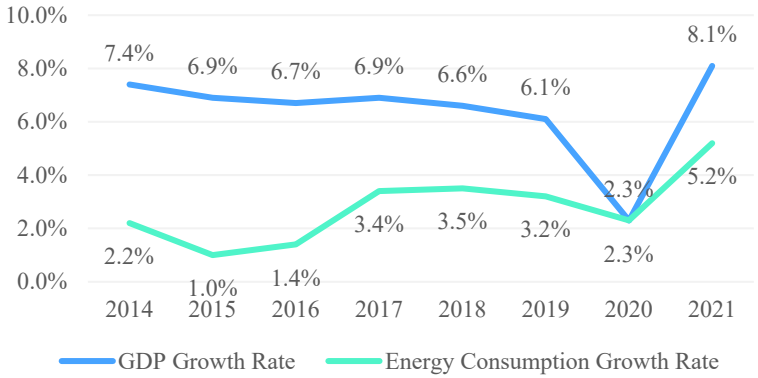

Fig. 3. Growth rate of GDP and energy consumption from 2014 to 2021

From the above three figures, we may as well see that after the first outbreak of the epidemic in 2020 suppressed the market, the growth rates of the three categories in 2021 all rebounded to varying degrees. Therefore, the market growth trend and prospect in the post-epidemic era are obvious to all.

2.2 Development of photovoltaic literature in China

The study is also based on an extensive literature list. The data of all the main topics published by CNKI under the entry of "Photovoltaic" from 1965 to now are compiled into a word cloud map, and the following results are obtained (Figure 4).

Fig. 4. Cloud Map of Key Words of CNKI "Photovoltaic" Entry Research

From the above figure, it can be concluded that photovoltaic power generation under the discipline of "electric power industry" and photovoltaic industry under the discipline of "industrial economy" are the main research directions. We searched the term "photovoltaic industry" and got the following figure (Figure 5). At the same time, We made a rectangular tree diagram to show its research proportion (Figure 6).

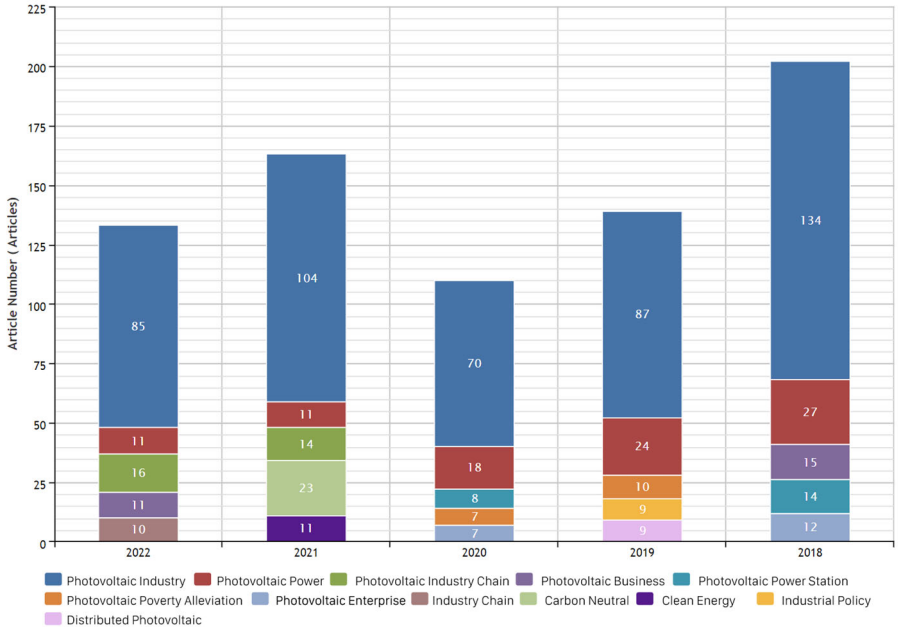

Fig. 5. Figure of the number of documents published under the theme of "photovoltaic industry" of CNKI from 2018 to 2022

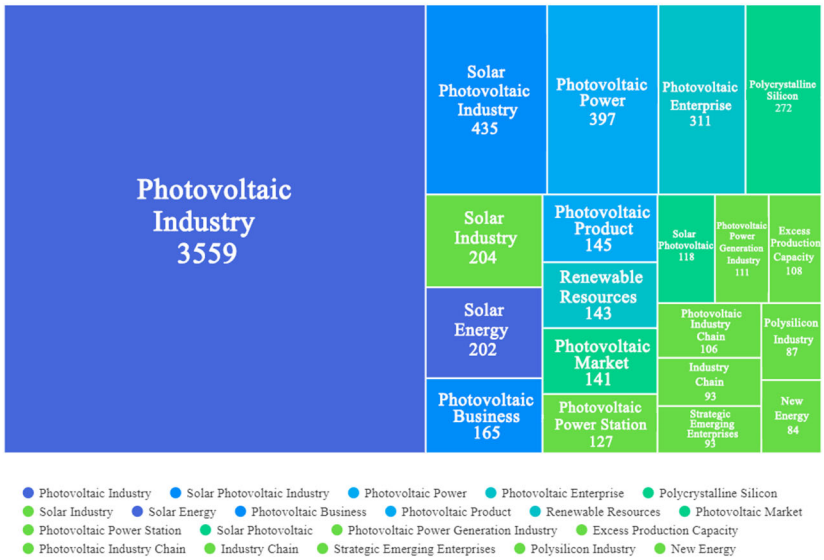

Fig. 6. Rectangular tree diagram of research topic of "Photovoltaic Industry" in CNKI

Only seven months have passed since 2022, and the number of articles published by CNKI under the theme of "Photovoltaic Industry" this year has exceeded the sum of 2020, which is expected to exceed the total number of articles published in 2021 in the second half of the year. At the same time, the downward trend in 2018-2020 and the sharp rebound in 2021 are also found in the GDP growth rate, energy consumption growth rate and clean energy proportion growth rate. Therefore, in 2022, We think it's quite possible to speculate that the market will continue to rebound in the post-epidemic era and keep growing.

2.3 Development of photovoltaic industry chain in China

The increasing trend of photovoltaic industry year by year is reflected not only in research, but also in the photovoltaic industry. According to disclosure, the domestic silicon market supply increased steadily in the first quarter of 2022, and it is expected to maintain the growth trend in the second quarter, with an expected monthly growth rate of 3%~6% (Figure 7).

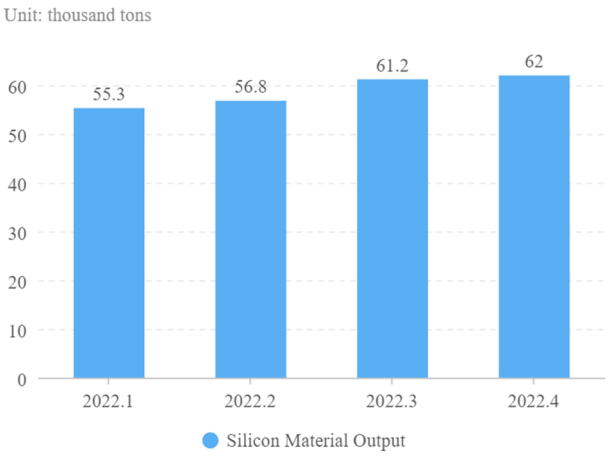

Fig. 7. Output of silicon materials from January to April 2022

3. Analysis of industrial chain

However, even the dark horse of photovoltaic, a new energy source, has been troubled by how to continue to reduce the cost of electricity. To explore this problem, we need to first analyze the relationship between the structure of photovoltaic industry and the inside of industrial chain, so as to have a more intuitive understanding of photovoltaic industry.

According to the analysis of the listing prospectus of PV companies in China, we can roughly know the main business of a PV company (Figure 8), and through the detailed disclosure of the PV module production process, we can know the overall process flow of its PV industry and make the PV industry chain diagram (Figure 9).

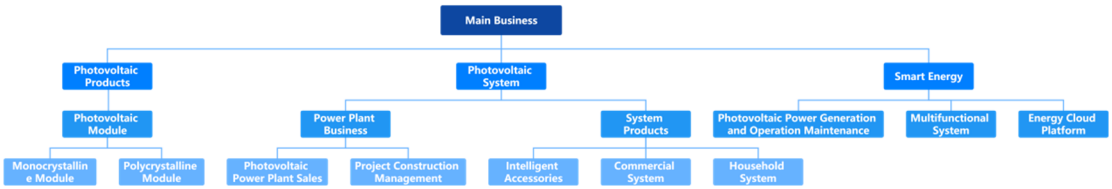

Fig. 8. Main business diagram of a PV company

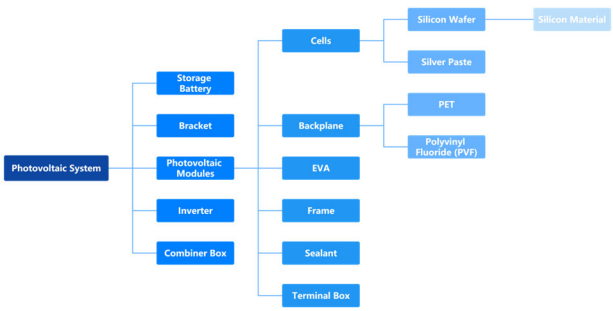

Fig. 9. Photovoltaic Industry Chain Diagram

Among them, photovoltaic module is the main raw material industry chain, and storage battery, bracket, inverter and junction box are the auxiliary materials industry chain. According to the CHINA PV INDUSTRY DEVELOPMENT ROADMAP, we can know the cost composition of photovoltaic system (Figure 10) and photovoltaic modules (Figure 11) and the detailed proportion of each part.

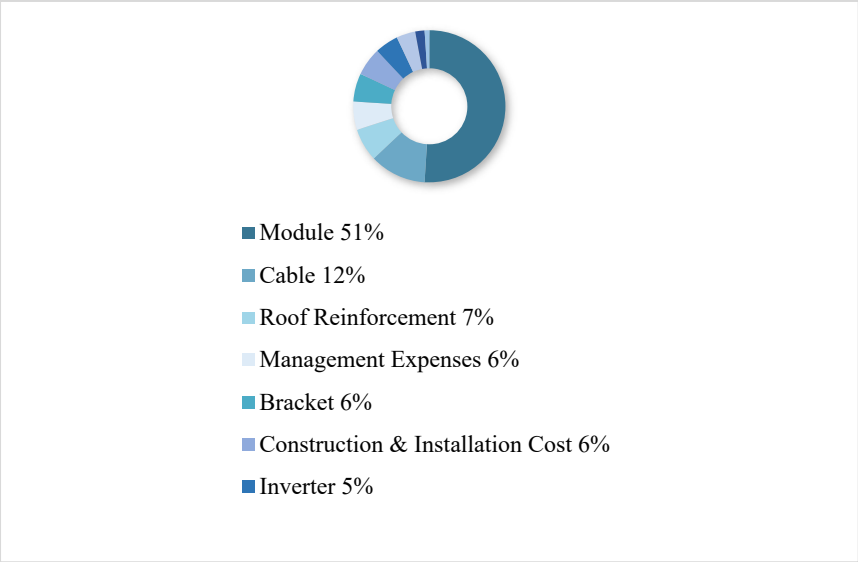

Fig. 10. Cost Composition of Photovoltaic System

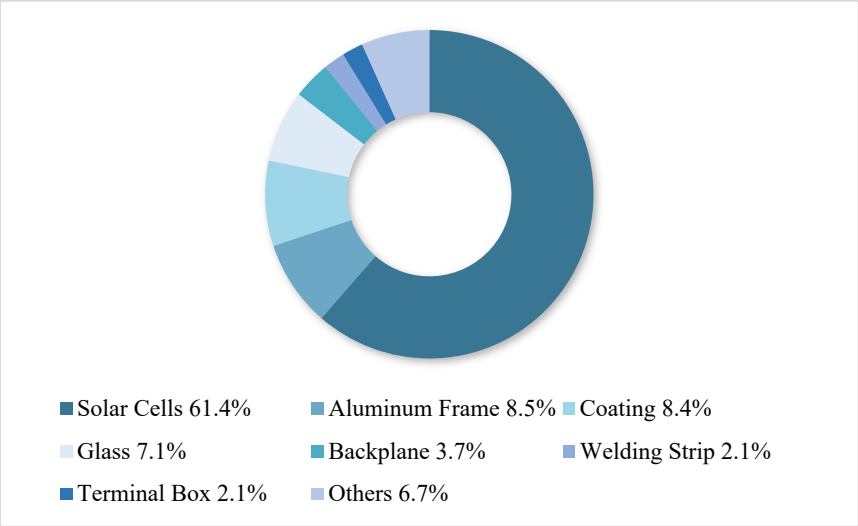

Fig. 11. Cost Composition of Photovoltaic Modules

By analyzing the data disclosed in CPIA's Photovoltaic Industry Development Roadmap CPIA 2021, this study presents the cost composition and detailed proportion of the entire industrial chain through multiple pie charts (Figure 12).

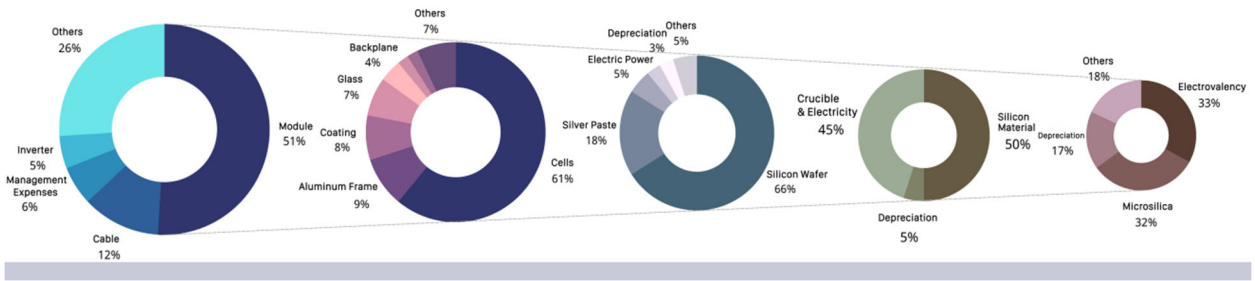

Fig. 12. Cost Composition of Photovoltaic Industry Chain

By analyzing the cost structure of photovoltaic industry chain, we can find that the cost of photovoltaic system is mainly determined by the main raw material industry chain, and the cost of the main raw material industry chain is mainly determined by the raw materials, that is, the price of silicon materials. From the layout of the whole industrial chain, according to the total production capacity and the number of enterprises, the whole industrial chain presents a pyramid form (Figure 13). The upstream silicon material is at the top of the pyramid, which has become an important factor in determining the price of photovoltaic modules.

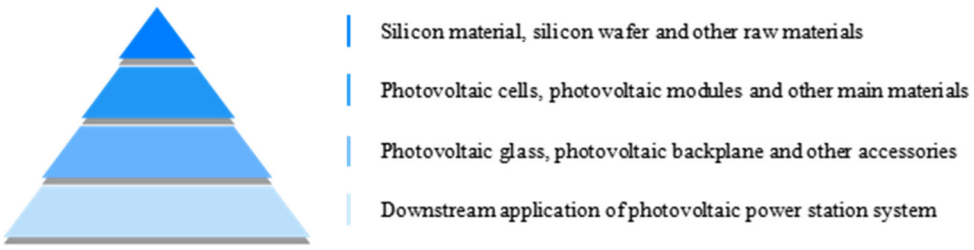

Fig. 13. Structure of Photovoltaic Industry Chain

4. Cost optimization and economies of scale

After knowing the cost composition of each link in the photovoltaic industry chain, we have to think about how to improve the industry chain to achieve the purpose of reducing costs. The profit of a company can be expressed by profit / investment, and when investment is difficult to measure, it can be expressed by unit profit. Unit profit = unit income - unit cost. When making a unit, the unit cost can be expressed by LCOE leveling electricity cost, so unit profit and unit income should also be measured by electricity profit and electricity income. Thus: electricity profit = electricity revenue - electricity cost.

In the market, the competitors of new energy are fossil energy, which accounts for over 80% of the energy consumption structure, and the most representative one is coal. Whether the overall optimization of photovoltaic industry can be achieved is mainly whether it can catch up with coal in the profit of electricity generation. According to the 2021 Notice of National Development and Reform Commission on Further Deepening the Market-oriented Reform of On-grid Electricity Price of Coal-fired Power Generation, there are four reform contents and four safeguard measures on the price of coal-fired power generation. It can be known that the on-grid electricity price of power generation enterprises is gradually determined by the market, that is, by competition. Therefore, the photovoltaic industry is facing a competitive market. In a competitive market, when the costs of the two enterprises are different, the competition leads to the cost of the low-cost enterprise approaching the cost of the high-cost enterprise as much as possible to be the amount of income, so as to squeeze the market space of the other party.

As a latecomer in the photovoltaic energy market, the initial cost is higher than that of coal, and the profit is negative without subsidies. When the cost of coal is less than the cost of photovoltaic, according to the above competitive market theory, the extreme case is photovoltaic cost $\geqslant$ coal revenue > coal cost. Therefore, in the competitive market, it is the cost of electricity generation that determines the profit of electricity generation.

Among them, the cost per kilowatt-hour of coal can be roughly known as 0.28 yuan/kWh, which is calculated as follows: 300 grams of standard coal ≈ 1 kilowatt-hour, 1 ton of standard coal ≈ 3,330 kilowatt-hours. The energy of standard coal is 7,000 kcal, thermal coal is 5,500 kcal. 1 ton of thermal coal ≈ 2,616.43 kilowatt-hours, and the average price of thermal coal in five years is in 700 yuan/ton. According to the national regulations, the medium and long-term coal in Qinhuangdao Port is 5,500 kcal, and the medium and long-term transaction price including tax is 570 - 770 yuan/ton. Assuming that the long-term average price of thermal coal is 730 yuan/ton, the electricity cost of coal = 730 / 2616.43 ≈ 0.28 yuan /kWh.

According to the Road Map of Photovoltaic Industry Development in 2021, we can know the LCOE of equivalent utilization hours of ground photovoltaic power plants and distributed photovoltaic power plants and the future forecast. In 2021, the LCOE of the equivalent utilization hours of the ground photovoltaic power station in 1800 hours, 1500 hours, 1200 hours and 1000 hours under the full investment model is 0.21, 0.25, 0.31 and 0.37 yuan/kWh respectively. Under the full investment model, the LCOE of equivalent utilization hours of distributed photovoltaic power generation system at 1800 hours, 1500 hours, 1200 hours and 1000 hours is 0.19, 0.22, 0.28 and 0.33 yuan/kWh respectively. According to the disclosed data, the LCOE of the current photovoltaic power generation cost of only 1800 and 1500 equivalent utilization hours is less than that of coal, and the photovoltaic power generation cost still fails to fully exceed the coal power generation cost. How will we reduce the cost of photovoltaic power generation? In the photovoltaic power generation system efficiency specification, we can find the calculation formula of LCOE:

$$\mathrm{LCOE} = \left[\mathrm{I}_0 - \sum_{\mathrm{n}=1}^{\mathrm{N}} \frac{\mathrm{I}_\mathrm{t}}{(1+\mathrm{i})^\mathrm{n}} - \frac{\mathrm{V}_\mathrm{R}}{(1+\mathrm{i})^\mathrm{N}} + \sum_{\mathrm{n}=1}^{\mathrm{N}} \frac{\mathrm{M}_\mathrm{n}}{(1+\mathrm{i})^\mathrm{n}}\right] / \sum_{\mathrm{n}=1}^{\mathrm{N}} \frac{\mathrm{Y}_\mathrm{n}}{(1+\mathrm{i})^\mathrm{n}}$$

Where,
i is the discount rate (%).
n is years of system operation.
N is the evaluation period of photovoltaic power generation system, with the unit of year (a)
I_0 is Static initial investment of photovoltaic system, in CNY.
I_t is the deduction of value-added tax of the project, and the unit is CNY.
V_R is the residual value of photovoltaic system, in CNY.
M_n is the operating cost of the year (including labor, maintenance, materials, etc.), excluding interest, and the unit is CNY.
Y_n annual electricity consumption on the internet, in kilowatt hours (kWh)

In short, the cost of power generation is determined by the initial investment cost, operation and maintenance cost and annual power generation. The initial investment cost is the photovoltaic system cost composition in the above figure (Figure 10); Operation and maintenance cost According to the disclosure in the 2021 Photovoltaic Industry Development Roadmap, "In 2021, the operation and maintenance cost of distributed photovoltaic system was 0.051 yuan/W/year, and that of centralized ground power station was 0.045 yuan/W/year, slightly lower than that of 2020. It is expected that the operation and maintenance costs of terrestrial photovoltaic power plants and distributed systems will continue to remain at this level and decrease slightly in the next few years." ; The annual power generation is the product of installed capacity, standard sunshine hours and comprehensive efficiency of the system. Therefore, we can generally know that the operation and maintenance cost can be considered as a fixed value, and we want to reduce the electricity cost, or reduce the investment cost, or improve the conversion efficiency.

At present, the highest cost of generating electricity is the LCOE of the equivalent utilization hours of the ground photovoltaic power station in 1000 hours, which is 0.37 yuan /kWh. We take this as the benchmark of photovoltaic cost. Photovoltaic power cost = 0.37 yuan, coal power cost = 0.28 yuan. Photovoltaic electricity needs to be reduced by 0.09 yuan to be generally lower than the electricity cost of coal. Electricity cost = initial investment cost / power generation, power generation = installed capacity * standard sunshine hours * system comprehensive efficiency (i.e. conversion rate). (0.37 - 0.28) / 0.37 ≈ 24.3%. If only the initial investment cost is reduced, the cost of photovoltaic industry chain needs to be reduced by 24.3% to be generally lower than that of coal. If only the conversion efficiency of photovoltaic is improved, the current conversion efficiency is 24%, which needs to be increased to 31.7% to be generally lower than the electricity cost of coal, with an increase of 32.14%.

Since the investment cost constitutes too much, it is difficult to discuss it qualitatively and quantitatively in a short time, so we only discuss the change of power generation here. Power

generation = installed capacity * standard sunshine hours * comprehensive efficiency of the system (i.e. conversion rate), while the newly installed capacity in China is in a fluctuating upward trend. The value of standard sunshine hours in fixed areas is basically stable, and the conversion rate can be disclosed in the 2021 Photovoltaic Industry Development Roadmap (Table 1).

Table 1. Conversion rate and future forecast of different batteries

	Classification	2021	2022	2023	2025	2027	2030
P-type Polycrystalline	BSF P-type Polycrystalline Black Silicon Solar Cells	19.5%	19.5%	19.7%	-	-	-
	PERC P-type Polycrystalline Black Silicon Solar Cells	21.0%	21.1%	21.3%	21.5%	21.7%	21.9%
	PERC P-type Mono Cast Silver Cells	22.4%	22.6%	22.8%	23.0%	23.3%	23.6%
P-type Monocrystalline	PERC P-type Monocrystalline Solar Cells	23.1%	23.3%	23.5%	23.7%	23.9%	24.1%
N-type Monocrystalline	TOPCon Monocrystalline Solar Cells	24.0%	24.3%	24.6%	24.9%	25.2%	25.6%
	HIT Solar Cells	24.2%	24.6%	25.0%	25.3%	25.6%	26.0%
	IBC Solar Cells	24.1%	24.5%	24.8%	25.3%	25.7%	26.2%

Therefore, for the photovoltaic conversion efficiency, it may not reach the ideal situation of 31.8% within ten years. At this time, the photovoltaic cost cannot be completely reduced by the increase of power generation, but the investment cost still needs to be reduced at the same time to achieve the goal that the photovoltaic cost is less than or equal to the coal cost. The reduction of investment cost needs to be solved by optimizing the industrial chain.

We can simply divide the photovoltaic industry into four links, namely, silicon materials, silicon wafers, cells and components, which correspond to the pyramid structure of the industrial chain in the above figure (Figure 13). Through the analysis of the enterprises in the industrial chain, this study found that few enterprises can cover all four links in the industrial chain, while the common situation is that one enterprise only carries out a single link. Moreover, almost no enterprise can monopolize any part of the four links in the industrial chain. This is because the technical barriers of R&D within the photovoltaic industry are thin, and the R&D process is relatively gentle, so the enterprise can't achieve the gap with other enterprises through the one-step R&D progress. Because there is no monopoly enterprise in any link, and it is impossible to obtain the gross profit margin and shipment volume that can replace the full scale and standard of one link, this study uses the leading enterprises in each link as the scale replacement, and studies how to distribute the profits in different links in the industrial chain by analyzing the gross profit per unit scale of the leading enterprises in four links.

The unit scale of the four links in the photovoltaic industry is uniformly expressed by the shipment volume, and the unit is W, so we can use the net profit per watt for comparison. The faucet of silicon is Daqo New Energy (Table 2), faucet of silicon chip is LONGi Green Energy (Table 3), faucet of battery chip is Aiko Solar Energy (Table 4), and the faucet of components is Trina Solar (Table 5).

Table 2. Total Energy Profit and Gross Profit per Watt of Daqo New Energy

Xinjiang Daqo New Energy Co., Ltd.	2018	2019	2020	2021
Gross Profit (100 million yuan)	6.36	5.05	15.37	70.73
Shipment Volume (tons)	22919.12	38109.56	74811.53	75400.00
Gross Profit Per Gram (yuan/g)	0.03	0.01	0.02	0.09
Silicon Consumption Per Watt (g/W)	4.30	3.70	3.20	3.00
Gross Profit Per Watt (yuan/W)	0.13	0.04	0.06	0.27

Table 3. Total profit and gross profit per watt of LONGi Green Energy

LONGi Green Energy Technology Co., Ltd.	2018	2019	2020	2021
Gross Profit (100 million yuan)	9.95	41.56	47.10	46.91
Shipment Volume (MW)	8094.00	25750.00	31835.64	33924.20
Gross Profit Per Watt (yuan/W)	0.12	0.16	0.15	0.14

Table 4. Total profit and gross profit per watt of Aiko Solar Energy

Shanghai Aiko Solar Energy Co., Ltd.	2018	2019	2020	2021
Gross Profit (100 million yuan)	9.91	10.92	10.35	6.15
Shipment Volume (MW)	2854.58	6787.72	13161.89	12500.00
Gross Profit Per Watt (yuan/W)	0.35	0.16	0.08	0.05

Table 5. Total profit and gross profit per watt of Trina Solar

Trina Solar Co., Ltd.	2018	2019	2020	2021
Gross Profit (100 million yuan)	23.46	28.23	32.85	42.74
Shipment Volume (MW)	6598.64	8798.01	13285.00	21084.00
Gross Profit Per Watt (yuan/W)	0.36	0.32	0.25	0.20

We can get the following information by summarizing all the gross profit per watt in a table (Table 6), and make a line chart (Figure 14) that reflects the gross profit per watt in different links of photovoltaic industry.

Table 6. Gross profit per watt of four links in photovoltaic industry in 2018-2021

Gross Profit Per Watt (yuan/W)	2018	2019	2020	2021
Silicon Material	0.13	0.04	0.06	0.27
Silicon Wafer	0.12	0.16	0.15	0.14
Cells	0.35	0.16	0.08	0.05
Modules	0.36	0.32	0.25	0.20

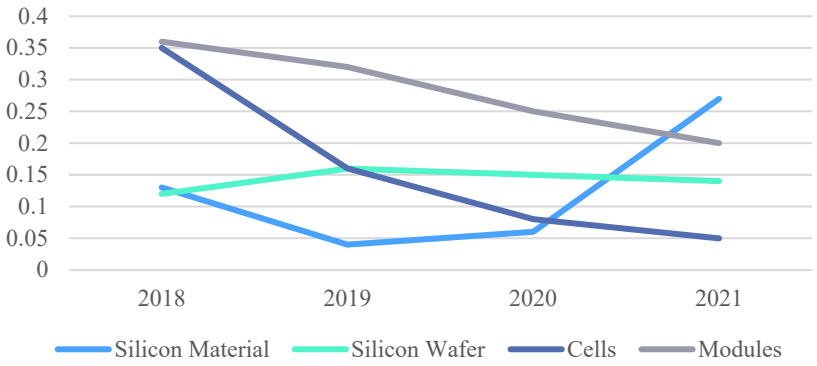

Fig. 14. Structure of Photovoltaic Industry Chain

5. Conclusion

According to the data and line chart, we can see that the gross profit margin per watt fluctuates greatly among different links in the photovoltaic industry. However, after analyzing the corporate financial report and long-term data, we draw the following conclusions. All links in the photovoltaic industry chain are mutually restrained, forming a reciprocal cycle. If the increase of silicon wafers is high, the increase of battery wafers will surely slow down; If the price of silicon powder in the global raw material industry rises, the silicon enterprises will gain a lot. The upstream and downstream of the photovoltaic industry chain are constrained by each other, and there are certain problems in the relationship between supply and demand, which will lead to the cyclical fluctuation of profits. The cooperation between the upstream and downstream of photovoltaic industry is inefficient, and there is often a situation that the downstream demand is surging but the supply of raw materials is short of demand, and the upstream raw materials are supersaturated but the downstream market is depressed and the supply exceeds demand. If the upstream cost is too high for a period of time, the upstream will increase the production capacity, while at the same time, the downstream will reduce the production capacity due to the high cost, resulting in the downstream demand being reduced or even smaller than the upstream supply, resulting in the upstream price being reduced, the downstream profit being increased, and the profit distribution difference being reversed again, finally forming an alternating cycle between upstream and downstream. The photovoltaic industry chain is not long, but the relationship between the industrial chains is very complicated, the coordination between upstream and downstream is insufficient, and the internal efficiency of the industrial chain is low, which often leads to market imbalance. This is the problem of China's photovoltaic industry today.

According to the theory that latecomers enter emerging markets, it is necessary to transform the industrial chain and supply chain to reconstruct emerging industries. In the photovoltaic industry, the specific embodiment is to optimize the specific links in the industrial chain and reduce the cost, and increase the coordination capacity within the industrial chain, so as to realize the integration of the industrial chain as soon as possible. On July 7th, the International Energy Agency (IEA) released the "Special Report on Global Supply Chain of Photovoltaic", arguing that by 2025, the world will almost completely depend on China for the key components used in the production of photovoltaic modules. According to the production capacity forecast under construction, the global production share of polysilicon and silicon wafers in China will reach 95% by then.

As for how to continue to promote the construction and optimization of photovoltaic industry in China, we should make full use of the abundant and sufficient light energy resources in western China, broaden the downstream power generation system of photovoltaic industry, stimulate the economic growth capacity of the central and western regions, deepen the rural revitalization strategy, and help the ethnic groups in the central and western regions play a deep role in China's green industrial system in the new era. On the basis of the downstream extension, the local government will take the lead in relying on the local objective social and natural conditions, investigate the missing parts of the

photovoltaic industry chain and its driving effect on the local economy, set up or build an integrated photovoltaic industrial park, complete the regional centralization of the photovoltaic industry, form an effective scale economy, and form a whole to offset the long-standing fluctuation problem between the upstream and downstream of the photovoltaic industry.

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