8. The Compressed Development of the Renewable Energy Industry in China: The Case of Photovoltaics

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1. Introduction

Until recently, Japanese manufacturers were the leading force in the global photovoltaic (PV) industry, accounting for half of the global production of PV cells in 2004. They started developing PV cells during the 1960s and 1970s, and had been the main force in transforming them from a marginal device to supply electricity to machinery that had no access to the power grid—such as satellites and lighthouses—to one of the most prospective sources of energy in the future, by which, hopefully, mankind may be able to reduce its reliance on fossil fuels for energy and prevent the global warming process. But when Japanese manufacturers were about to harvest the fruits of their long development efforts, many Chinese entrepreneurs jumped into the manufacturing of PV cells and have taken away Japan's leading position in the industry, accounting for half of the global production in 2010. The Chinese PV industry is the most recent, and perhaps the most dramatic, case of "compressed development" (Whittaker, Zhu, Sturgeon, Tsai, and Okita, 2010). This paper explores how this was possible.

Photovoltaics, or solar cells, are a kind of semiconductor. Accordingly, China's rise in the global PV industry has certain factors commensurate with its rise in the global electronics industry: the modularity of product architecture, which made it easy for latecomers to enter the global value chain by specializing in the production of a certain module; and the shift of production technology from device manufacturers to equipment manufacturers, making it possible for latecomers to improve their technological capabilities rapidly simply by buying state-of-the-art production equipment. Besides these, two additional factors are notable in the case of China's PV industry: the fund-raising strategy and the technology strategy. The former two factors, namely, modularity and technology shift to equipment makers, can only explain why Chinese PV manufacturers could catch up with the forerunning Japanese manufacturers. The latter two, fund-raising and technology strategies, are the critical factors that explain the reason that Chinese entrepreneurs were able to surpass their Japanese forerunners. This paper will discuss these points in detail.

In addition, this paper will discuss two points that will be relevant in comparing the case of the Chinese PV industry with other cases of "compressed development." The first is the role of the state. The Chinese Government by no means acted as a "developmental state" (Johnson, 1982) in the development of the PV industry. Then, what has been the role played by central and local governments? The second is the role of "lead firms." In the literature on global value chains, the dominant role of "lead firms," which are typically headquartered in developed countries, in shaping the structure of value chains and in assigning the role that suppliers must play seems to be taken for granted (Gereffi, Humphrey, and Sturgeon, 2005). In the case of the PV industry, however, lead firms in major markets had only limited roles in shaping the structure of the value chain, and they are smaller in size than their suppliers in China. This observation leads us to an interesting question: what determines the power balance between lead firms and suppliers?

The remainder of this paper is structured as follows. In the second section, we introduce a framework to evaluate the technology strategy of PV manufacturers. The third section briefly reviews the development of the global photovoltaic industry. The fourth section discusses how Chinese entrepreneurs have made their way into the global PV industry and become leading manufacturers. This section also discusses the central and local governments' role in Chinese PV industry development. The fifth section describes the relationship between the lead firms in major PV markets such as Germany and PV suppliers in China, and discusses the factors that shape the power balance between lead firms and suppliers. The sixth section concludes the paper.

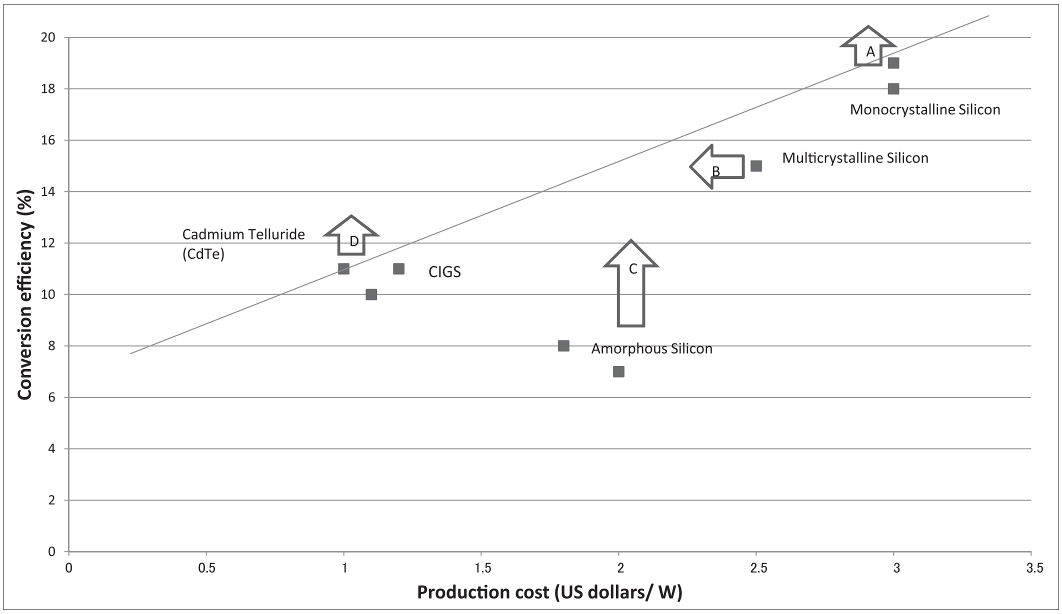
2. Choice of Technology

The growth of PV production in China is triggered by the expansion of demand for PV systems in Europe, the United States, and Japan. China is the world's largest supplier of PV modules, which are connected with inverters and monitors and constructed into PV systems on the roofs of houses or on the ground. The Chinese PV industry constitutes a part of the global value chain of PV systems, which consists of system integrators and various module suppliers. Therefore, we will pay attention to the three key factors that, according to Gereffi, Humphrey, and Sturgeon (2005), determine the type of global value chain governance, namely, 1) complexity of transactions, 2) ability to codify transactions, and 3) capabilities in the supply base, in our analysis of the Chinese PV industry.

However, these factors, which are largely in common with the cases of various segments of the global electronic industry, may only explain the reason that a modular value chain has emerged in the PV industry and why Chinese PV cell suppliers have succeeded inserting themselves into the PV value chain. Some other factors must be added in order to explain why Chinese manufacturers, which started as small ventures only recently, have been able to outcompete their Japanese rivals, which are vertically integrated and horizontally diversified conglomerates that have long experience in the PV industry. The main factor that we believe explains the reversal is the technology strategy adopted by Chinese and Japanese manufacturers. The difference in fund-raising strategy, which is also an important factor that led to the reversal, is related to technology strategy. Therefore, we will develop a framework to evaluate the technology strategies for PV cell manufacturers in the following.

A PV cell is a device that converts light into electricity by a process known as the photovoltaic effect. The effect can be created by making a p-n junction of P-type and N-type semiconductors. In this sense, a PV cell is quite akin to an integrated circuit (IC). The difference is that while most ICs use monocrystalline silicon as the material to make P-type and N-type semiconductors, PV cells can use various materials to make semiconductors. *Monocrystalline silicon* will make PV cells with high conversion efficiency, that is, the proportion of sunlight energy converted into electrical energy, but its production cost is the highest among the major production technologies. *Multicrystalline silicon* will make PV cells that cost less and consume less energy during the production process than monocrystalline silicon PV cells, though their conversion efficiency is lower than the latter. Thin-film silicon PV cells using *amorphous silicon* can be even cheaper, because instead of casting ingots of crystalline silicon and slicing them into wafers, thin films of amorphous silicon are made by vapor disposition. This technology enables the manufacturer to economize the production cost, and to reduce the consumption of silicon materials to only 1% of the amount necessary to make crystalline silicon cells. There are other types of thin film PV cells that use other materials to make P-type and N-type semiconductors, such as *gallium arsenide* (GaAs), *cadmium telluride* (CdTe), *copper indium gallium selenide* (CIGS), and even *conductive organic polymers* (Saito, 2009). Because PV cells are usually expected to have only one function—to generate electricity—there is almost no room for product differentiation by adding other functions to PV cells.[1] But, as mentioned above, there are several technological approaches using different materials to realize the function of generating electricity.

Figure 1: Conversion Efficiency and Production Cost of Various Types of PV Cells



Source: *Nikkei Electronics*, Feb. 8, 2010

[1] There have been some attempts by PV manufacturers to add properties to PV cells to increase their applicability. For example, some Japanese manufacturers developed flexible PV cells that can be attached to curved surfaces.

These technologies can be evaluated by their conversion efficiencies and production costs.[2] Figure 1 shows the conversion efficiency and production cost as of 2010 of the five most widely produced types of PV cells. Generally speaking, there is a trade-off between conversion efficiency and production cost; the higher the conversion efficiency is, the higher the production cost is. The envelope of the most cost-effective technologies, which is indicated by the straight line in Figure 1, represents the frontier of current technologies. PV cells using technologies that are far below the technological frontier, such as amorphous silicon in Figure 1, will find it difficult to compete with cells using technologies near the frontier, unless they have other useful properties. How, then, will the cells using technologies near the frontier be selected by their users?

Consider a photovoltaic power station that is going to erect a new PV plant in a limited space. The station is considering which type of PV cell to use in the new plant. The condition for the new plant to recover the initial investment and to earn profits can be written as

$$mypT \geq xm + Y(m) \ , \qquad (1)$$

where *m* denotes the size of the plant in terms of the amount of PV cells used in the plant, *y* denotes the wattage that a single PV cell can generate in one hour, *p* denotes the price of electricity (per watt-hour) that the PV plant can expect to earn, and *T* denotes the duration (in hours) for which the PV plant is expected to operate. The left-hand side of the equation denotes the total revenue that the PV plant can earn during its operation. The right-hand side indicates the total cost of building the plant, in which *xm* denotes the cost of PV cells and *x* denotes the unit price (production cost) of the PV cell, and *Y(m)* denotes other costs necessary for installing and operating the plant, including the cost of ancillary equipment such as inverters, construction cost, and maintenance cost. These costs will increase as the size of the plant increases, but because there is scale economy, they will not increase proportionately with the plant size. Hence, $Y'(m)>0$, $Y''(m)<0$.

As was discussed earlier in this section, there is a trade-off between the conversion efficiency and production cost of various types of PV cells around the frontier of current technologies. Assuming that there is a linear relationship between conversion efficiency and production cost at the frontier for simplification, we can write the relationship as *fx,* and since the wattage that the PV cell can generate per hour is proportional to its conversion efficiency, $y = Afx$, where *A* is a constant. Therefore, we can rewrite equation (1) as

$$mAfxpT \geq xm + Y(m) \ . \qquad (2)$$

The first-order condition to maximize the profit (that is, the left-hand side minus the right-hand

[2] Another important point in evaluating the technologies is the durability of PV cells. Cells using conductive organic polymers are less durable than cells using inorganic materials (Saito, 2009), but there seems to be no evidence about the durability of cells using various inorganic materials such as silicon, GaAs, CdTe, and CIGS. We assume that there is no difference in the durability of various types of cells compared in the following.

side of equation (2)) is

$$\frac{\partial(mx(AfpT-1)-Y(m))}{\partial m}=x(AfpT-1)-Y'(m)=0\ ,$$

$$\text{or}\ \ x=\frac{Y'(m)}{AfpT-1}\quad .$$

This condition means that as $Y'(m)$ decreases as m increases, the optimum unit price of PV cells is lower in large-scale PV plants than in small-scale PV plants. In other words, an expensive type of PV cell, even if it were on the technological frontier, will only be adopted by small-scale plants.

Evidence that PV plant owners are actually selecting the type of PV cells according to the above calculation is found in the prices of PV modules (that is, packaged and connected sets of PV cells) in major PV markets. In Japan, where most of the PV plants are residential PV systems installed on the rooftops of houses, the price of a typical module was 4.3 US dollars in 2010. In Spain, where most of the PV plants are large-scale power stations, module prices ranged from 1.8 to 2.6 US dollars. In Germany, where there are both the small-scale rooftop plants and large-scale stations, module prices ranged from 2.6 to 4.7 US dollars (IEA-PVPS, 2011).

The above discussion indicates that there are several choices for PV cell manufacturers to be competitive in the PV industry. The following technology strategies have actually been adopted by one or some of the global PV manufacturers.

The first strategy is to adopt the most efficient technology and devote R&D resources to improve its conversion efficiency. This strategy is shown by the arrow "A" in Figure 1, and it has been pursued by Sanyo (later to merge with Panasonic). Sanyo has a proprietary cell technology, which is called a HIT (heterojunction with intrinsic thin layer) cell, that combines monocrystalline silicon semiconductors with amorphous silicon layers. With this technology, Sanyo produces PV cells that have the highest conversion efficiency among the mass-produced cells in the world. But because of its high production cost, a HIT cell will be an optimal choice only for small-scale residential PV plants. Therefore, the size of the market for high-efficiency PV cells remains small.

The second strategy is to adopt a technology that is easily accessible, and decrease its production cost by low input costs and large-scale production. This strategy is shown by the arrow "B," and has been pursued by Chinese PV manufacturers.

The third strategy is to select a technology that is not on the current technological frontier but has potential for improvement and devote R&D resources to improve its efficiency. This strategy is shown by the arrow "C," and was pursued by Sharp during 2007-2008.[3] This strategy will be effective if the manufacturer succeeds in improving the technology's efficiency dramatically and/or if the technological frontier moves downwards. During 2006-2008, the price of polysilicon,

[3] *Nikkei Microdevices*, August 2008.

which is the material to make monocrystalline and multicrystalline PV cells, soared from 66 US dollars per kilogram in 2005 to 300 US dollars in October 2006, and to 450 US dollars in April 2008.[4] With the steep rise in the polysilicon price, the production costs of PV cells using silicon were expected to rise, which would push the frontier downwards and give advantage to technologies that could economize the consumption of silicon.

The fourth strategy is to create a proprietary technology for making PV cells and let nobody else follow the technology by protecting it with intellectual property rights and vertical integration of equipment fabrication. This strategy is pursued by First Solar, which specializes in CdTe PV cells and modules.

A manufacturer may pursue two or more strategies at the same time, but in most cases, their focus is on one strategy. Therefore, the rise and fall of a PV manufacturer is closely related with the rise and fall of a particular technology.

3. The Development of the Photovoltaic Industry

Photovoltaic cells were invented by Bell Laboratories of the United States in 1954. Until the 1970s, PV cells were mainly used as a means to supply electricity to machinery that operated at places where no other means of electricity supply was available, such as satellites in space, or lighthouses and radio relay stations at places remote from the power grid. In those days, the *energy payback time* of monocrystalline PV cells, which is the period of operation that is necessary to generate the equivalent amount of energy consumed for the production of the PV cell, was nineteen years (Hamakawa, 1981, p. 27). This meant that unless the PV cells worked for more than nineteen years, producing PV cells was a sheer waste of energy. The leading force of the PV industry in those days was US manufacturers, accounting for 75% of the global production of PV cells in 1981 (Denki gakkai taiyo denchi chosa senmon iinkai, 1985, p. 282). Since the 1980s, Japanese PV production grew by expanding the fields of applying PVs to calculators, watches, trickle chargers, and other portable electronic products. Since these products require only small power, amorphous silicon is extensively used for the PV cells installed in them. Japanese PV manufacturers accounted for 45% of the global PV production in 1987 (Maycock, 1994). The share of Japanese manufacturers in global PV production has declined since then because of the saturation of PV cell markets for consumer electronic goods.

A new turning point came in 1994, however, when Sharp developed a residential PV system. In the same year, the Japanese Government introduced a subsidy program that would subsidize households constructing residential PV systems. This program lasted until 2005, as many as 254 thousand households received subsidies, and the total capacity of the PV systems installed using the program amounted to 932 MW (Sangyo taimuzusha, 2007, p. 185). The electricity generated by the PV systems would be primarily consumed by the household that installed the system, but net billing was offered by the electricity utilities under a voluntarily scheme called the "excess

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4 *21-shiji jingji baodao*, February 20, 2009.

electricity buying menu." The initial investment is large for a household (a 5.2-kW PV system cost 3.5 million yen, including the construction fee, in 2002), but the investment can be recovered partly by government subsidy, partly by the reduction in expenses for buying electricity, and partly by the sales of excess electricity. These policies stimulated the spread of PV systems among Japanese households. Japan had the largest cumulative installed capacity of PV systems in the world until 2004 (IEA-PVPS, 2007). The expansion of the PV market in Japan triggered the growth of Japanese PV manufacturers. Japan's share in world PV production was only 24% in 1994, but since then, it started to expand, reaching 55% at its peak in 2004.

The severe deficit of the Japanese Government's budget, however, did not allow the subsidy program to continue. The end of the program in 2005 led to a decline in domestic demand for PV systems after 2006 (Table 1), though subsidy programs run by local governments continued. With the wane of the Japanese market, the main market for PV systems shifted to Europe. Germany's annual installed capacity of PV systems surpassed that of Japan's in 2004 (Table 1), and its cumulative PV system capacity has been the largest in the world since 2005. Germany accelerated the introduction of renewable energy resources since 2000, when the country decided to abolish nuclear power plants in the future and promulgated the Renewable Energy Sources Act. This act obliges power utilities to buy all the electricity produced by renewable energy sources, such as wind power and solar energy. Utilities must buy such electricity at a price fixed by the law. The price is adjusted every year, but for an individual plant, the selling price of electricity is fixed for twenty years from its establishment. The price was very favorable for an investor in a PV power plant: in 2006, for example, the selling price was 0.518 euros/kWh, when the retail price of electricity for households was 0.18 euros/kWh. This was a very favorable condition for PV system investors compared to that in Japan. In Japan, the selling price of electricity produced by PV plants was 24 yen/kWh (approximately 0.16 euros) in 2006, which was the same as the retail price of electricity for households. Utilities buy only the excess electricity that the household does not use by itself. There was no guarantee for the duration of this buying scheme, so investors were uncertain of whether they could recover their initial investment or not. The Renewable Portfolio Standard Act promulgated in 2003 obliged utilities to use renewable energy sources up to a certain percentage of their total procurement of electricity, but since this obligation was very low (it was 1.35% in 2010, for example), utilities were reluctant to buy electricity from large-scale PV plants and wind power generators. Therefore, most of the PV power plants in Japan are small-scale residential PV systems. There were 719 thousand residential PV plants at the end of March 2011, the average capacity of which was 3.8 kW.[5] Faced with the stagnation of the growth of PV system installations and the decline of the Japanese PV industry, the Japanese Government tried to boost PV demand by doubling the price of electricity made by PVs in November 2009 and by obliging power utilities to buy electricity at this price for ten years from 2009. This policy led to the recovery of PV installations in Japan (Table 1), but because this policy was applied only to

[5] These data are calculated on the basis of the information provided on the Renewable Portfolio Standard Act website, Agency for Natural Resources and Energy.

Table 1: Annual Installations of Photovoltaic Power by Selected Countries

(Unit: MW)

Country	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Germany	7	5	9	44	110	110	143	635	906	951	1,274	1,955	3,799	7,411
Japan	32	42	75	122	123	184	223	272	290	287	210	225	483	991
United States	12	12	17	22	29	44	63	101	103	145	207	338	448	918
Spain	0	0	0	0	2	3	5	11	25	99	557	2,758	60	392
Korea	0	1	1	1	1	1	1	3	5	22	45	276	167	131
Italy	1	1	1	1	1	2	4	5	7	13	70	338	723	2,321
China	-	-	-	-	6	-	10	10	5	10	20	40	160	500
All IEA PVPS Countries	62	74	116	207	288	371	481	1,058	1,367	1,639	2,465	6,146	6,265	14,195

Source: International Energy Agency, *Trends in Photovolatic Applications:Survey Report of Selected IEA Countries* between 1992 and 2010. Report IEA-PVPS T1-20:2011.

Note: The total capacity of PV power in India as of September 2011 stood at 45 MW.

small-scale residential PV plants, the size of the Japanese PV market fell far short of Germany's. The new Feed-in Tariff Law, which was approved by the parliament in August 2011 and will be effective in 2012, will boost the installations of PV systems in Japan, because this law will enable not only small-scale residential PV plants but also utility-scale PV plants to sell all the electricity they produce to power utilities at a fixed price for a duration of fifteen to twenty years.

The PV systems market in some other countries has been very unstable since 2008. The sudden expansion of PV installations in Spain in 2008 was an outcome of a fluctuation of policy. Spain introduced a generous feed-in tariff scheme for PV plants in 2007, with a national cap of PV installations of 400 MW per year. The government considered in 2008 raising the cap and then lowering it. While the government was considering the new rule, investors tried to install as many projects as they could before the new rules were set. Faced with the unexpected expansion of PV installations, the Spanish Government dramatically shrunk the incentives for PV plants in 2009 (Wong, 2009). The sudden rise of Italy in 2010 also has a similar reason. Italy started an incentive program for PV installations in 2005. The third phase of the program announced in August 2010 led investors to expect that feed-in tariffs would be reduced from 2011, triggering a sharp increase in the number of installations (IEA-PVPS, 2011).

The big fluctuations in demand for PV systems since 2004, together with the shift of the main market from Japan to Europe, may have been one of the reasons for the decline of Japanese PV manufacturers. The size of PV installations in 2010 by the Photovoltaic Power Systems Program (PVPS) members of the International Energy Agency, which consists of twenty-five countries that cover all the important PV markets in the world, was more than thirteen times larger than that in 2004. The annual growth rate of PV installations was 54%. Japanese PV manufacturers did respond to the shift in the market by expanding exports: in 2002, 68% (186 MW) of the PV cells they produced were sold in Japan, but in 2008, 79% (884 MW) were exported. However, this was not enough to fulfill the steep rise in demand in Europe. This gave room for new entrants to expand their sales.

In 2007, Sharp lost its leading position in global PV cell production, which the company had

Table 2: PV Cell Production by Major Manufacturers (Unit: MW)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Suntech (CH)				28	82	158	327	498	704	1,584
JA Solar (CH)						25	113	277	509	1,464
First Solar (US)			3	6	20	60	207	504	1,011	1,400
Yingli Solar (CH)					10	35	143	282	525	1,117
Trina Solar (CH)						7	37	210	399	1,116
Q-Cells (GER)		8	28	75	166	253	389	570	537	939
Gintech (TW)							55	180	368	800
Sharp (JP)	75	123	198	324	428	434	363	473	595	745
Motech (TW)	4	8	17	35	60	102	176	275	360	715
Kyocera (JP)	54	60	72	105	142	180	207	290	400	650
Hanwha-SolarOne (CH)							88	173	220	532
Neo Solar (TW)							36	102	200	530
Canadian Solar (CH)							8	72	326	523
SunPower (US)					23	63	100	237	398	520
Sun-Earth (CH)							8	80	260	421
E-TON (TW)							60	95	225	420
Sanyo (JP)	19	35	35	65	125	155	165	215	260	405
China Sunergie（CH）							80	111	160	336
Schott (GER, CZ)	21	30	42	63	95	93	79	145	102	320
Mitsubishi (JP)	14	24	42	75	100	111	121	148	120	210
Kaneka (JP)	8	8	14	20	21	28	43	52	40	25
Total	371	542	749	1,199	1,782	2,459	3,710	6,823	10,660	23,889

Source: PV News Vol.29, No.5, Vol.28, No.4

kept for seven years in a row since 2000, to Q-Cells of Germany, which was a new entrant to the industry. Q-Cells was established in 1999 and started producing PV cells in 2001. Q-Cells was a specialized PV cell manufacturer until recently, but the company can now supply PV systems as a whole. Its technology strategy is the “B” type according to our classification in Figure 1. The company has adopted easily accessible technologies, such as monocrystalline and multicrystalline silicon, and reduced production costs by erecting a manufacturing plant in Malaysia. In 2009, First Solar of the United States became the top PV cell manufacturer in the world. First Solar’s strategy is the “D” type according to our classification: the company has a proprietary technology of CdTe cell production, and has achieved high conversion efficiency with low production costs by continuous research and development. This is not to say that CdTe technology is monopolized by First Solar; in fact, Panasonic (Matsushita) produced CdTe cells in the early 1990s (Maycock, 1994, p. 698). But Japanese manufacturers were reluctant to pursue CdTe technology because it used cadmium, which would be very harmful to human health. They were surprised when the European market, which was believed to be strict on harmful substances, accepted the import of First Solar’s PV cells on a large scale (Nikkei Microdevices and Nikkei Electronics, 2008, p. 95). In 2010, Suntech of China became the largest manufacturer of PV cells in the world. In this year, four of the top five PV cell manufacturers were Chinese companies (Table 2). The reason that the Chinese manufacturers could reach this position so rapidly is the topic to be discussed in the next section.

4. The Rise of the Chinese PV Industry

In 1984, the first PV cell in China was produced by a state-owned electronics manufacturer based in Nanjing.[6] The growth of the PV industry in China, however, started with the establishment of Suntech Power in 2001. The company was created by a Chinese engineer named Shi Zhengrong, who had earned a Ph.D on photovoltaic engineering at the University of New South Wales. Dr. Shi returned to China in 2000 with a plan to manufacture PV cells. He asked Shanghai City and his hometown Yangzhong City, Jiangsu Province, whether they were interested in investing in his venture. Finally Dr. Shi managed to persuade Wuxi City Government to invest 6 million US dollars in his venture, while he himself invested 2 million US dollars, of which 1.6 million dollars was his "contribution of technological capital" to the venture, which was based on an assessment of his expertise (Dai and Kishimoto, 2011). In 2002, Suntech created a PV cell-manufacturing line with an annual capacity of 10 MW. This was the first mass production line of PV cells in China. The total PV cell manufacturing capacity in China before the launch of Suntech's production line was 2.7 MW per year.[7] Suntech's success in exporting its PV cells and modules to the European market, and the listing of its stocks on the New York Stock Exchange (NYSE) in December 2005, by which the company raised almost 400 million US dollars in its initial public offering (IPO), has stimulated the emergence of many followers in China. As can be seen in Table 2, many Chinese companies have started the production of PV cells since 2005 and have aggressively expanded their production volume.

The rapid rise of Chinese PV manufacturers was made possible, firstly, because production technology shifted from PV manufacturers to equipment manufacturers. Japanese PV manufacturers had tried to keep their production technology to themselves by fabricating the production equipment on their own, except for the initial stage of mass production (Watagi, 2008, p. 14). But gradually, equipment manufacturers absorbed the production technology and marketed PV manufacturing equipment to new entrants. Some equipment makers, such as Applied Materials, Ulvac, and OC Oerlikon Balzers, even provide "turn-key solutions" of PV cell manufacturing, which makes it very easy for new entrants to start production if they have the money to buy such solutions (Kawai, 2008). Lacking experience in PV production, new entrants may produce PV cells that are inferior in their conversion efficiency than the products of incumbent manufacturers. But Figure 1 suggests that, even if the efficiency of the PV cells produced by the new entrant is one percentage point lower than those made by incumbent manufacturers, the new entrant can still be on the technological frontier if it succeeds in cutting production costs by 0.25 US dollars per watt. Therefore, Chinese PV manufacturers can easily make marketable cells by taking advantage of low input costs. Japanese PV manufacturers were reluctant to erect PV cell plants outside of Japan because they were afraid of leakage of technology. This decision has created room for new entrants to have an advantage in production costs over Japanese manufacturers. It is reasonable for

[6] Based on the author's interview with Mr. Xu Ruilin of Jiangsu Photovoltaic Industry Association, August 24, 2011.
[7] Based on the author's interview with Mr. Chen Xiaodong of Suntech Power Holdings, August 23, 2011.

Chinese manufacturers to select an accessible technology and try to reduce production costs by mobilizing cheap inputs and by enlarging the production scale, namely, the “B” strategy discussed in Section 2.

Chinese PV manufacturers need to raise the funds to expand production capacity because most of them are private ventures that receive little, if any, support from the government. Suntech’s success in raising 400 million US dollars by listing its stock on the NYSE has become a model case that virtually all major PV manufacturers in China have imitated. Among the eight Chinese manufacturers listed in Table 2, all of them except for Sun-Earth have their stocks listed either on the NYSE or on the NASDAQ. Such globalization of fund-raising is also found in other new industries of China, such as economy hotel chains, semiconductors, and internet services. Because the domestic stock exchanges in China give priority to state-owned enterprises, more and more private ventures go directly to foreign stock exchanges, in particular to the United States, to raise funds by IPO. Chinese PV manufacturers invested most of the funds raised in the United States in the expansion of production facilities in China. With this new route of raising funds, Chinese PV manufacturers have never given way to their Japanese rivals, which are vertically integrated and horizontally diversified conglomerates, in the race for production expansion.

The critical year was 2007, when new incentives created a surge of demand for PV systems in Germany and Spain, and the global production of PV cells recorded a 51% growth. The sudden growth in PV cell production led to a shortage of photovoltaic-grade polysilicon and a steep rise in its price. Before then, PV cells used the waste of semiconductor-grade polysilicon, because while semiconductors require very pure (99.999999999%) polysilicon, PV cells can be made with less pure (99.99999%) polysilicon. But as demand for PV cells increased, waste polysilicon would not be enough to fulfill demand. Polysilicon manufacturers invested in new plants for making photovoltaic-grade silicon, but before these new capacities started operation, its supply remained tight. Chinese PV manufacturers did their best to procure polysilicon because with insatiable demand for PV cells at that time, the only bottleneck PV manufacturers faced was the shortage of polysilicon. Suntech entered a ten-year agreement in 2006 with MEMC, an American silicon wafer maker, to buy 5-6 billion US dollars of silicon wafers in total. At this time, Japanese manufacturers were less aggressive in procuring polysilicon than their Chinese and European rivals. This was because they faced tighter cash constraints than their rivals. Chinese PV manufacturers and Q-Cells could raise the cash to procure polysilicon directly from the stock markets through IPO. But since Japanese PV manufacturers are divisions of diversified conglomerates, they need to go through internal procedures for the allocation of funds within the corporation. The headquarters of Japanese conglomerates would not increase the allocation of funds to the PV division so quickly, because such decision would sacrifice their other lines of business. Because of the shortage of polysilicon, Japanese PV manufacturers suffered from low growth rates compared to the world average in 2007 (see Table 2).

Sharp was the most extreme example. The company is one of few cell manufacturers that experienced negative growth in 2007. This was not only the result of the company’s failure to procure polysilicon, but also the result of the company’s technology strategy. With the steep rise in the polysilicon price, Sharp expected that amorphous silicon cells would be an economical choice for PV plants.[8] The company started the construction of a 1-GW amorphous silicon cell plant (Nikkei Microdevices and Nikkei Electronics, 2008, p. 36). Sharp expected that the shortage of polysilicon would continue for a while, and that this fact would push the technological frontier downward. On the other hand, the company expected that it would succeed in enhancing the conversion efficiency of amorphous silicon cells to more than 10% by 2010.[9] Sharp adopted the "C" strategy according to our classification in Figure 1.

As things turned out, both expectations were wrong. The sharp reduction of incentives for PV plants in Spain in early 2009 led to the stagnation of demand for PV cells in Europe. Besides this, several photovoltaic-grade polysilicon plants started operation during 2008-2009 (Fuji Keizai, 2009, pp. 151-156). These facts caused the spot price of polysilicon to drop from 450 US dollars per kilogram in April 2008 to only 65 US dollars per kilogram in May 2009. Besides this, the conversion efficiency of amorphous silicon cells did not improve as Sharp expected. Another unexpected incident was the growth of First Solar that specialized in CdTe cells. The efficiency of First Solar's cells improved from 10.4% in 2007 to 11.3% in 2010 while the production cost of modules dropped by 45% during the same period, which pushed the technological frontier upward, leaving amorphous silicon technology far below the frontier. Suntech also had an amorphous silicon cell plant, but faced with the drop in the polysilicon price and competition with CdTe cells, the company stopped operation of the plant in 2010,[10] while Sharp remained indecisive about amorphous silicon technology.

There was little involvement by the central government in the development of the PV industry. The national five-year plans never referred to the PV industry until the current Twelfth Five-Year Plan (2011-2015), in which photovoltaic power generation is referred to as one of the "strategic new industries," along with wind power generation, new-energy vehicles, and many other industries. When the plan was drafted, China was already the top PV producer in the world. The government's involvement in the PV industry is in sharp contrast with that in wind power generation. The government obligated wind power stations to procure windmills that had a local content of more than 70% between 2005 and 2009. This policy induced the growth of domestic windmill manufacturers such as Sinovel, Goldwind, and Dongfang Electric, all of which are more or less state-owned. By contrast, all of the major PV cell and module manufacturers in China, with the exception of Sun-Earth, are private companies. They raised funds abroad because they were underprivileged in the domestic capital market. The government did not make requirements regarding the local content of PV plant equipment. In fact, there was virtually no market for PVs in China until recently (see Table 1). The PV industry is one of the few industries in China in which few state-owned enterprises are involved, and the domestic market has not been important.

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[8] Mr. Mikio Katayama, president of Sharp, said in an interview in April 2008 that "thin-film silicon cells will be very cost effective. It is also a technology in which Sharp can show its advantage" *Nikkei Electronics*, May 5, 2008.
[9] Interview with Mr. Tetsuro Muramatsu, cited in *Nikkei Microdevices* August 2008.
[10] Suntech Power Holdings Co., Ltd, *2010 Corporate Report*; interview with Mr. Chen Xiaodong, Suntech Power Holdings.

Some local governments have played a slightly more positive role than the central government in the development of the PV industry. Wuxi Municipal Government mobilized eight state-owned enterprises under its control to invest 6 million US dollars in Suntech. This was a great help for Suntech to get started, but the initial investment by the state sector in the venture is dwarfed when compared with the 4 million US dollars raised by the company on the NYSE. Shangrao City, Jiangxi Province, has given preferential treatment to Jinko, a PV manufacturer, in the provision of land and electricity.[11] However, these are only generic preferential policies that will be extended to all kinds of high-tech ventures. It is not that these local governments have targeted the PV industry as a "developmental state" would do.

Only after 2009 did the central government start to promote the expansion of photovoltaic applications in China. Since 2009, the government has launched several large-scale solar power plant projects, as if to adjust the excessive reliance of the domestic PV industry on exports. In August 2011, the government announced the selling price of electricity generated by PV plants to be 1.15 yuan/kWh (0.125 euros) for the first time. This announcement will trigger the growth of domestic PV installations, because PV plants can now be certain that the electricity they produce will be bought by power utilities, though the selling price is very low, compared to the prices in Germany and Japan. These positive policies may be the result of lobbying conducted by major PV manufacturers.[12] Insertion into the global value chain of PV systems has led to the dramatic expansion of the PV industry in China. And the growth of the PV industry in China, which was beyond the expectations of the government, is now in turn promoting the application of PVs in China. Without the growth of the domestic PV industry, the Chinese Government would not be interested in installing PV plants, because their cost of generating electricity is still much higher than conventional power plants and windmills, and because China has not yet committed itself to a reduction in CO2 emissions. Compressed development of the PV industry induced the compressed development of PV application in China.

5. Relationship between Lead Firms and Chinese PV Manufacturers

Chinese PV manufacturers form a part of the global value chain of PV systems, in which Chinese manufacturers supply PV modules or cells to European companies, and the latter combines them with other parts of the system and sells them through various channels to end-users in Europe. European companies act as lead firms in this value chain. There are two types of division of labor between Chinese suppliers and European lead firms.

First, Chinese suppliers provide PV cells and European firms manufacture PV modules. The modules carry the latter's brand, and are sold directly to EPC (engineering, procurement, and construction) companies, which procure the equipment (including PV modules) and construct PV

[11] Based on the author's interview with Jinko Solar, August 16, 2010.

[12] Jiangsu PV Industry Association, which was organized by Suntech and other major PV manufacturers in Jiangsu Province and headed by Dr. Shi Zhengrong of Suntech, has been lobbying for provincial government support for the PV industry.

plants, or to installers of PV systems through dealers.[13] This is the type of division of labor found between Suntech and Aleo Solar AG of Germany, for example. In this case, an arm's length market relationship is seen between the cell suppliers and module manufacturers. This is because the complexity of the transaction is low, the transaction is easily codified—only a few figures, such as the conversion efficiency and the size, will be sufficient to describe the PV cell—and capabilities in the supply base are high because of the diffusion of cell production technology by equipment manufacturers. In this type of division of labor, end-users may not be aware that they are using PV cells made by Chinese manufacturers.

Secondly, Chinese suppliers provide PV modules and European firms combine them with inverters and other ancillary equipment and provide them to installers. In this case, PV modules are sold under Chinese suppliers' brands. This is the type of division of labor found between Suntech and German companies such as Bihler GmbH and IBC Solar. Again, the transaction is easily codified—the specification of PV modules can be completely described by some figures—and the capabilities in the supply base are high. However, the transaction is somewhat more complex than the first type, because the PV module suppliers offer product warranty to the end-users. Both Bihler and IBC Solar procure PV modules from four suppliers including Suntech. This relationship can be classified as a "modular" type of supply chain governance (Gereffi, Humphrey, and Sturgeon, 2005).

In Europe, Chinese manufacturers including Suntech are acting only as suppliers of PV cells and modules, but, in Japan's residential PV systems market, Suntech is supplying the whole PV system to end-users, by procuring inverters and other ancillary equipment on its own.[14] This fact indicates that Suntech's role in the global value chain is not shaped unilaterally by the lead firms in developed countries. Suntech can become the lead firm itself, as in the case of the Japanese residential market, if it is necessary to assume this role to enter the market. Besides this, Chinese PV manufacturers are not like the suppliers in developing countries that capture only a fraction of the total value of the products they manufacture. Compare the size of total assets and ROA of Suntech and one of its lead firms in Europe, Aleo Solar AG (Table 3). Suntech is much bigger in size, and has almost equally high ROA. How can the component suppliers in the PV industry enjoy high ROA? What determines the power balance between lead firms and suppliers?

It seems that the relative importance of PV cells in determining the technical features and cost of the PV system determines the strong position of PV cell manufacturers. PV cells account for at least 50% of the total cost of constructing a PV plant.[15] Since the competitiveness of a PV system largely depends on the PV cells used in the system, the cell supplier assumes the leading role in the value chain.

[13] Aleo Solar AG, *2010 Annual Report*.
[14] Based on the author's interview with Mr. Yutaka Yamamoto, Suntech Power Japan Corporation, November 28, 2011.
[15] The cost of PV modules accounts for 61.5% of the total cost of building a PV system on the roof of an existing house, while the inverter, other ancillary equipment, and construction cost account for 12.3%, 10.8%, and 15.4%, respectively. The proportion of the latter three will be smaller in the case of large-scale PV plants built on the ground. PV cells account for 81.3% of the cost of modules, or 50% of the cost of building a rooftop PV system. Data are from Fuji Keizai (2009).

Table 3: Comparison of Suntech and Aleo Solar

(Unit: Million US$, percent)

Year	2007	2008	2009	2010
Total Assets				
Suntech	1967	3207	3984	5217
Aleo Solar	148	276	215	239
ROA				
Suntech	14%	10%	9%	10%
Aleo Solar	9%	8%	7%	17%

Source: Corporate Reports

6. Conclusion

The rapid growth of the Chinese PV industry shows how the development path of developing countries can be compressed by insertion into the global value chain. When production technology is easily accessible simply by buying state-of-the-art equipment, developing countries do not need to accept foreign direct investment (FDI) to obtain the latest technology. The only thing they need is the money to buy such equipment. The money can also be raised abroad if domestic entrepreneurs can persuade investors that they have the potential to be competitive. A "developmental state" that mobilizes funds for investment is not necessary. The development of the Chinese PV industry indicates that industrial development in a developing country can take place without a developmental state and without inward FDI. What China had were many entrepreneurs and their experiences and technology, which we have not discussed in detail in this paper. The case of the PV industry also shows that insertion into global value chains does not necessarily mean that the industries in developing countries are placed in an unprofitable position. Depending on the type of product in which the country specializes, the industries of developing countries can even assume the leading role in the global value chain. However, we must be careful in extracting lessons from the experiences of the PV industry, because it is changing very rapidly, affected by policy changes in major markets.

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