Geographical interdependence, international trade and economic dynamics: the Chinese and German solar energy industries

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Oil price increases, European gas supply interruptions and the global climate impacts of greenhouse gas emissions are making renewable sources of energy of increasing importance. Photovoltaic (PV) technologies have emerged as a central plank in the establishment of a low carbon energy system. There are however striking differences in the geographies of production and use of photovoltaic systems. In 2000-10 Germany was the most important market, while China emerged as the most important manufacturer.

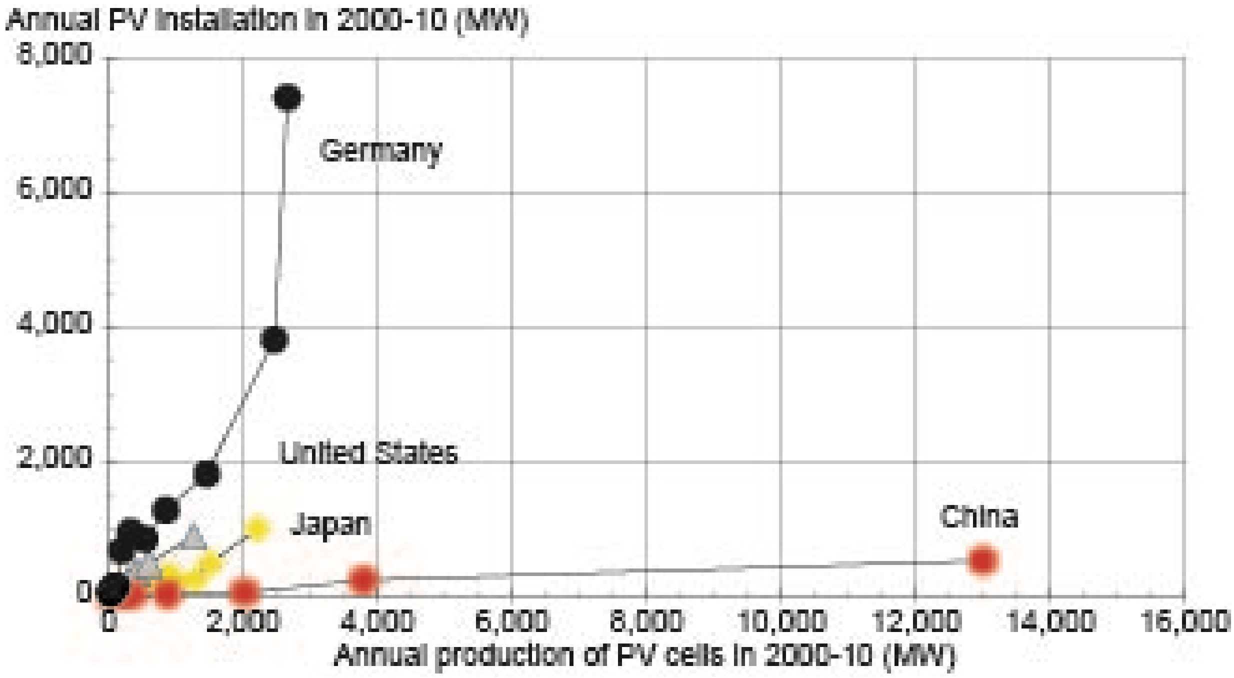
The aim of this paper is to explore and explain these contrasting geographies of demand and supply drawing on a set of concepts designed to explain geographies of trade and development of the PV sector. Much of the recent geographical literature has concentrated on the development of clusters, agglomerations, innovation, value chains and evolutionary ideas (Storper, 1995; Smith et al. 2002; Coe et al, 2004; Martin, 2011). In this paper we shall draw on some of these concepts. We shall argue however for a re-engagement with a political economy of trade and development. More specifically, we shall concentrate on three drivers of the geography of industrial development: market creation; investment and investment finance; and innovation and competitiveness. We shall also emphasise the importance of the specific characteristics of the sector, and a context and set of interactions marked by the presence of an initial market leader (Germany), a country that embarked on catch-up and may overtake the initial leaders (China) and a set of trade disputes.

In 2000-2010 worldwide solar power output has increased more than 100 times to reach 27.2 GW. In the last five years output growth was most rapid in China and Taiwan Republic of China. In 2010 China and Taiwan accounted for nearly 48 and 13 per cent of total output respectively (Photon

International, 2011). As China and Taiwan rose as manufacturing centres for PV components, Europe and Japan declined in relative importance to account for 13 and 8 per cent respectively. The United States (US) accounted for less than 5 percent.

The geography of use is quite different from the geography of manufacture. In 2010 annual installations were less than output (27.2 GW), standing at around 16.6 GW compared with 7.3 GW in 2009. Cumulative installations reached 39.5 GW. Of these totals Germany alone accounted for 45 and 43 per cent respectively (EPIA, 2011). German market expansion has given a very substantial stimulus to the development of the industry and of the wider value chain in Germany. In a globalised world, however, it is has also created a market for competitors in China and East Asia. These competitors pose a serious challenge to Germany's own domestic manufacturing sector and indeed to the manufacturing sector in other developed countries. In 2011 some of these advanced country rivals sought trade protection.

Figure 1 Photovoltaic demand and supply trajectories, 2000-10. Source: elaborated from Earth Policy Institute, 2010; European Photovoltaic Industry Association, 2011 for installed capacity; Photon International for 2010 production.



These simple facts permit the identification of a number of distinct trajectories in the development of the industry (Figure 1) of which those of Germany and China are the subject of this paper. Germany has seen the rapid growth of market demand, and strong increase in production especially in the less developed eastern half of the country. In Germany production was for the domestic market and for export: German exports[1] expanded from $524 million in 2000 to $8,097 million in 2010. Chinese growth was export-driven. Exports grew from $178 million to $25,179 million. In 2010

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[1] These data refer to sector 854140 in the HS 1996 Classification. HS 854140 comprises photosensitive semiconductor devices, including photovoltaic cells whether or not assembled in modules or made up into panels and light emitting diodes.

Chinese PV exports to Germany, worth $7,637 million, were almost equal to total German PV exports. Until the implementation of some recent massive domestic solar installations only about 5 percent of Chinese production was for domestic consumption. China's export success was however a source of trade frictions with developed countries.

Geographies of production and international trade are mainly explained by two sets of theories. Theories of comparative advantage attribute specialisation and trade to national resource endowments. The new geographical economics, seeks to explain the ways in which resource endowments and relative competitiveness are created rather than endowed (Dunford, Yeung, Liu and Liu, 2012).

In this paper we shall examine the creation and evolution of endowments and competitiveness, but in ways that seek to overcome two of the limitations of these models. The first is the widely recognised lack of attention to institutional factors. The second is the lack of explicit attention paid to money and to the demand side drivers of trade and industrial dynamics. In Keynesian type models money and credit are the starting point for economic development and drive economic activity: credit creates deposits, expenditure creates income, and capital advanced drives capital accumulation and growth (Dunford, Yeung, Liu and Liu 2011). In the emergence of the PV sector and the adoption of PV technologies the creation of markets and effective market demand were crucial drivers as were a variety of financial investment subsidies.

Van de Ven and Garud (2000, 493) have argued that industrial development is underpinned by three functional sub-systems: an instrumental subsystem (applied R&D, manufacturing and assembly, and marketing and distribution), a resource procurement subsystem (scientific or technological knowledge, financing and a pool of competent human resources), and an institutional subsystem (governance structures and industrial support). Combining this argument with our conception of the role of money and credit as drivers of trade and economic development leads to a modification of their analytical framework to identify three drivers, of which the third combines the resource procurement and instrumental sub-systems. More specifically we shall argue that geographies of the emergence and comparative development of industrial activities in general and of the PV sector in particular can be seen as a result of three sets of drivers: (1) market creation as a result of investment decisions of users of electrical energy shaped by institutional configurations and policy regimes, (2) investment in production driven by investment finance and credit creation and (3) the drivers of innovation, cost reduction and value chain upgrading.

To explain and compare the trajectories of Germany and China a number of further theoretical considerations are required. In the case of Germany the development of solar energy involved the establishment of a new industry and new products. New industries and products are examined in the product life cycle literature. According to Vernon's (1966) simple model (which classifies the phases of a product cycle as new products, maturing products, and standardised products in accordance with a degree of standardisation) the manufacture of products that reach a state of maturity moves to cheaper locations. In the case of China however the development of the solar industry was driven by Chinese companies and not by the relocation of investment by companies involved in the new product phase. To examine this situation, theories relating to catch-up, latecomer development and developmental states play a significant explanatory role.

The simple life cycle idea also requires some modification to reflect the specific characteristics of different industries (Pavitt, 1984). Cell and module manufacturing are just parts of a wider value chain. Cell and module manufacture involves the manufacture of equipment (mainly in Germany, Japan and the US). The next step involves the capital-intensive manufacture of poly silicon, ingots, wafers and cells and labour-intensive manufacture of modules (see Table 1 which also records the share of value added by each of these stages). A complete system also requires the manufacture of inverters. On completion the system is installed. Once operational some PV electricity is sold to utilities. Installation accounts for a significant share of value added and is appropriated in the areas where the products are sold. In the United States in 2009 a module cost $3, an inverter $0.5 and installation $4 giving a total of $7 per watt (McGehee, 2009). As is clear from these data, the manufacture of cells and modules accounts only for three sevenths of the overall value added per watt.

Table 1 Solar cell and module value chain. Sources: KNREC (2009), ECJRC (2010), BSW (2010), Solar & Energy (2011)

	Poly silicon	Ingots	Wafers	Cells	Modules	Inverters and rest of system
Minimum efficient scale	Very high	High			Low	
Factor-intensity	Capital-intensive				Labour-intensive	
Added value	26%	29%		23%	22%	
Number of firms in 2010						
China				At least 100	At least 300	
Germany				More than 200		

The crystalline silicon (c-Si) cell PV sector[2] on which we shall concentrate is a largely scale-intensive sector. In 2010 the realisation of scale economies in cell manufacture was considered to require an annual production capacity in the order of 300 MWp. As in Pavitt's (1984) classification, users are sensitive to prices rather than performance, process innovation and cost reduction are very important, sources of innovation are internal (R&D and learning by doing) and external (equipment producers) and appropriability is through secrecy and patents. These specific characteristics play an important role in explaining geographies of production and use.

As indicated earlier, the aim of this paper is to examine the roles of market creation, investment and credit and the drivers of innovation and competitiveness in shaping the development of the PV sector. These drivers will be examined in the light of these specific characteristics of the sector and in the context of the emergence of an initial market leader (Germany) and a country that embarked on catch-up (China). Attention will also be paid to the way in which the asymmetric interaction of

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[2] There are three technologies in the PV industry: crystalline silicon (c-Si); thin film; and others (Boyle, 1996). Of these crystalline silicon solar cells accounted for about 83 per cent of the world PV market in 2010. A major advantage is that complete production lines can be purchased, installed and started in a relatively short space of time. In 2005-9 however temporary shortages of silicon and the market entry of firms offering turn key production lines for thin-film solar cells saw large increases in investment.

national industries has shaped the contrasting trajectories of these two countries and the geography of comparative development.

The analysis in this paper derives from several sources. The first is the construction of a series of statistical databases dealing with trade, production and markets in China, Germany and the rest of the world. The second is a series of interviews with companies, industry organizations, research institutes and government officials conducted in Germany and China in a period starting in the summer of 2010 and ending in 2011.

The paper is divided into three sections. In section 2 we shall provide an explanatory account of the dynamics of the German PV sector and its interaction with China. Section 4 will deal with the Chinese case. In Section 5 we shall examine further the interaction of these two development trajectories and then conclude.

The German case: market creation and the rise of German manufacturing

Understanding the development of the German PV sector requires awareness of the historical steps in the emergence of the PV sector. The photovoltaic effect was discovered in 1839. In 1954 the first modern silicon solar cell was invented. German scientific and applied research institutions including the Max Planck Society (MPS) founded in 1948 and the Fraunhofer Society founded in 1949 played a major role in PV scientific and technological development. After 1958 a commercial space satellite market emerged (Wolf, 1972). In the 1960s due to US restrictions on exports to the European Space Agency, Telefunken (AEG-Telefunken) and Siemens' started to develop silicon solar cells (Jacobbson et al., 2004). In the 1970s the oil crisis stimulated many PV energy experiments. As a result the silicon-type of solar cell emerged as what Utterback (1994) would call a 'dominant design': Utterback insisted that product life cycle theory pay attention to the emergence of specific products from among competing designs. In the 1980s, special off-grid PV markets gradually increased to provide electricity in remote areas. In Germany major change came however after the 1986 Chernobyl disaster. Opposition to nuclear power soared, the Social Democratic Party (SPD) and the Green Party committed themselves to phasing out nuclear power (Lauber and Mez, 2004), and Förderverein Solarenergie (Solar Promotion Association) and Eurosolar were established to promote solar PV energy.

The outcome was three significant attempts aimed at creating solar PV markets in Germany. The first was the 1989 1,000 roof programme which saw the installation of 2,250 grid-connected roof-mounted installations with a capacity of 5.3 MWp by 1993 (Lauber and Mez, 2004), and the development of new inverters for feeding decentralized power into the network grid (Jacobbson et al., 2004). The second was the approval by all parliamentary political parties of the Electricity Feed-in Law of 1990. This law adopted the concept of a cost covering payment for relatively expensive renewable energy as originally proposed by Förderverein Solarenergie and Eurosolar (Lauber and Mez, 2004). This law required electric utilities to connect renewable energy generators to the grid, and to buy the electricity at rates of 65 to 90 percent of the average tariff for final customers. If grid connection is completely unviable the utilities must share the costs of the renewable installation. The grid connection requirement was an especially important driver of market expansion (Chrometzka, 2011).

The new law saw the wind energy market explode, but the price of nearly 17 pfennig (approximately 9 Euro cents) per kWh was too low to cover the costs of solar energy (Lauber and Mez, 2004). The growth of the PV sector derived rather from a third set of sub-national initiatives. The so-called Aachen model under which local governments imposed ‘cost covering contracts’ with renewable generators on municipal utilities spread to dozens of cities in Germany and some Land governments subsidised solar installations. Due to these local-level initiatives, the German PV market continued to grow throughout the 1990s, even though the 1,000 rooves programme ended in 1993 (Lauber and Mez, 2004; Jacobbson et al., 2004).

These initial demand side measures created a German market that encouraged the first generation of German PV firms to expand. Siemens and ASE (Applied Solar Energy: Angewandte Solarenergie) acquired US PV firms which had state-of-the-art PV technology (Jacobbson et al., 2004). In 1998 ASE started a new factory with an annual production capacity of 20 MW, and Royal Dutch Shell entered into the German solar cell industry with a 9.5 MW plant (Lauber and Mez, 2004). Capacity however exceeded the size of the domestic market: after 2000 these plants were taken over by a RWE Schott Solar and SolarWorld, who were members of a new generation of PV firms.

The feed in law faced strong opposition from electricity utilities with investments in coal and nuclear technologies. In the face of opposition a Eurosolar proposal for a 100,000 rooves programme in 1993 was not supported by the ruling Conservative-Liberal government. Attempts to go further and reduce feed-in rates were however narrowly blocked (Jacobsson and Lauber, 2006). In 1998 the election of a Red-Green (SDP-Green) coalition saw a major change of course that marks Germany out from other countries. In January 1999 the new government started the 100,000 roof programme. Second, and more importantly, in March 2000 it adopted the Renewable Energy Source Law (Erneuerbare Energien Gesetz: EEG).[3] In 2002 the Nuclear Energy Phase-Out Act was adopted increasing the importance of alternative renewable energy policies (Lauber and Mez, 2004).

The new renewable energy law increased the feed in rate from 17 to 99 pfennig (approximately 50 Euro cents) covering the cost of PV electricity. In addition the new rate was guaranteed for 20 years to enable recovery of the capital outlay over the life-time of a capital-intensive PV system (Jacobsson and Lauber, 2006; Lauber and Mez, 2004; BSW, 2011).In Germany an annual degression of 5 per cent was applied: the aim was to create a mass market and to create a situation where the scaling up of production would drive down costs to users. In 2004 the tariff was amended downward and since the end of 2007 it has been subject to nearly constant renegotiation as the industry developed faster and costs declined faster than expected. A July 2010 adaptation saw a large cut in remuneration structure with further change at the start of 2011. Overall the feed-in rate for PV electricity decreased from 50.6 Eurocents/kWh in 2000 to around 25 Eurocents/kWh in 2011

The ultimate aim of course is grid parity: a situation in which solar energy is at least as cheap as grid power. For solar energy it depends on several factors: the greater the abundance of sunlight, the higher the costs of grid electricity and the lower the costs of solar energy, the quicker it will be achieved (Figure 2). Germany has relatively high electricity costs but sunshine is not especially abundant.

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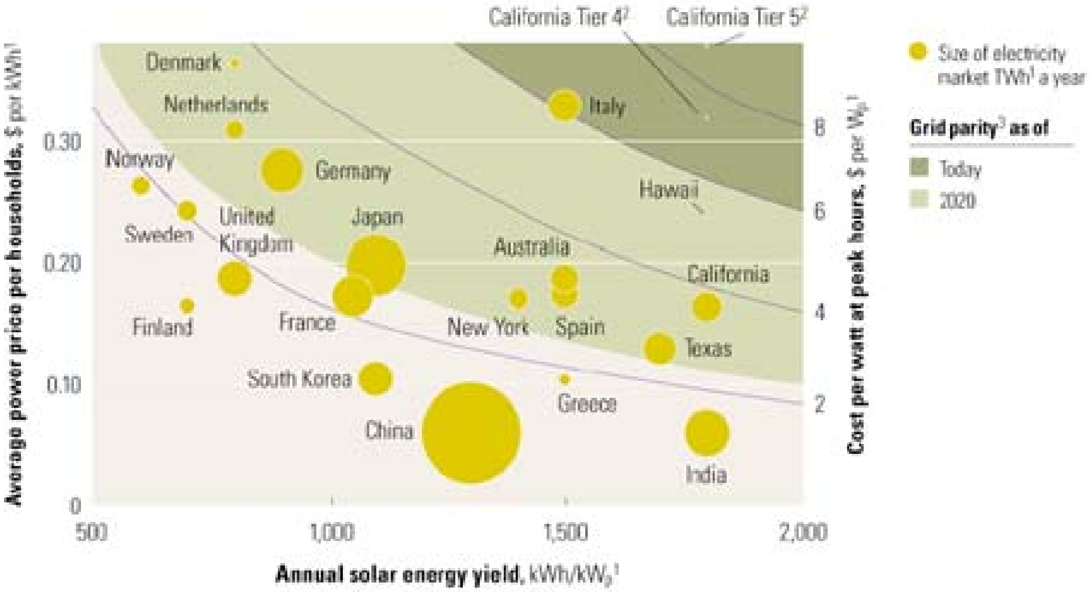
[3] A feed-in tariff scheme relies more on non-market than on market mechanisms. Market-oriented tradable certificates and renewable portfolio standards were adopted in the UK and in many states in the US.

Figure 2 Grid parity and its drivers. Source: McGehee, 2010



The new law saw the German market explode: it grew from 42 MW in 2000 to 7,408 MW in 2010. Demand also increased in other countries especially Spain which also adopted a feed-in tariff. At the same time a number of new companies entered the market either through mergers and takeovers or through new investment (Figure 3). The Schott group, one of the largest glass manufacturers, entered the PV industry in 2002. Siemens Solar was taken over by Shell Solar in 2002, and was acquired by SolarWorld in 2006. In addition, the Bosch group entered the PV sector through the acquisition of Ersol Solar in 2008.

Figure 3 Growth of the German PV sector Source: elaborated from Lee, 2011

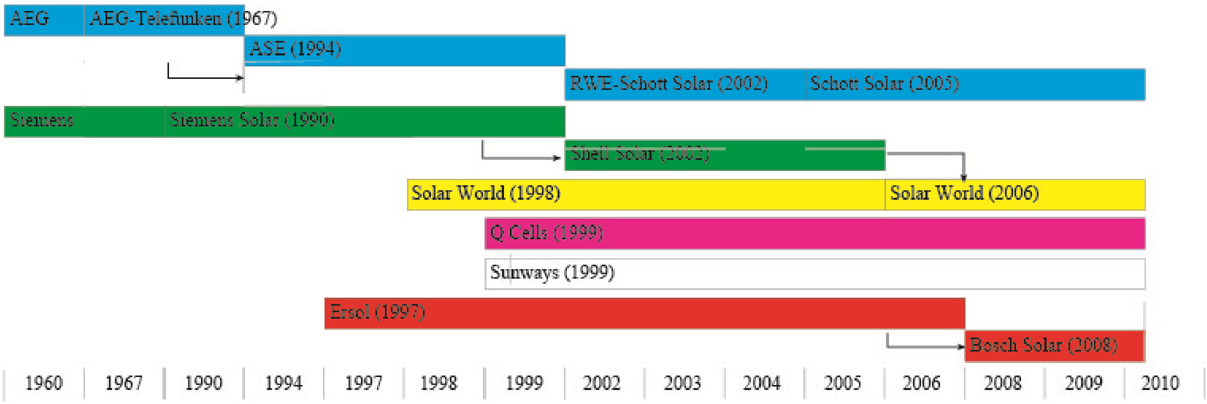


Table 2 Top ten companies of solar cell equipment industry Source: VLSI Research, 2008

Rank	Company	Home country	Sales in 2008 (US $ million)
1	Applied Materials	US	455
2	Roth & Rau AG	Germany	275
3	Centrotherm GmbH	Germany	270
4	Oerlikon Balzers AG	Switzerland	250
5	Ulvac Inc.	Japan	240
6	Manz Automation AG	Germany	140
7	Schmid GmbH	Germany	125
8	Von Ardenne GmbH	Germany	120
9	Rena Sondermaschinen GmbH	Germany	85
10	Swiss Solar Systems	Switzerland	70

The development of manufacture was closely associated with the development of the German equipment industry. Of the ten top equipment suppliers in the world six are German (Table 2). As the industry expanded, their sales increased rapidly from 0.2 billion Euro in 2005 to 2 billion in 2009 (BSW, 2010) with the export ratio rising from 31 to 79 per cent. As most production processes of PV cells are automated, equipment suppliers play a significant role in improving productivity.

3.2 Value chain dynamics and the rise of German manufacturing

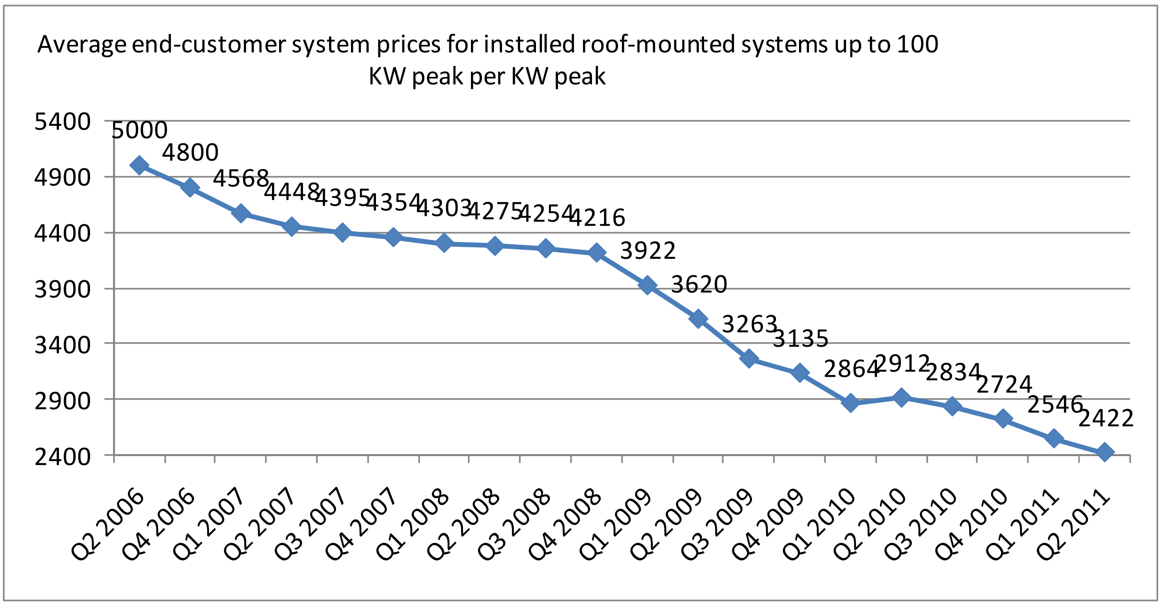
As costs depend largely upon scale, German companies have made major efforts to expand capacity with Q-Cells reaching 800 MW and SolarWorld nearly 500 MW by 2009 (Table 3). Scale-driven cost reductions have been accompanied by cost reduction through improved technologies. First in four to five years from 2003 Q-Cells and SolarWorld reduced wafer thickness from 330 μm to 180 μm reducing the consumption of poly silicon material by about 45 per cent. The adoption of string ribbon technology affords also affords reductions in this case of 30 to 35 per cent by cutting waste. Second cell efficiency has also been increased from 14 per cent in 2002 to 18 per cent by 2008 or 2009.

Table 3 Annual production capacity (MW) Sources: Q-Cells, Annual Reports; SolarWorld, Annual reports)

	Value chain	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Q-Cells	Cells			22	63	170	292	420	645	860	800	
Solar World	Poly-silicon						2	810	1,200	2,250		
	Wafers	32	55		120		180	245	385	600	900	
	Cells			30			60	185	205	260	450	
	Modules		10		50	54	90	140	185	310	500	

These developments and the consequent cost reductions in Germany were also a result of external pressures deriving from reductions in feed-in rates and Chinese and Asian competition which we shall shortly consider. In the five years from April 2006 end-customer prices declined by nearly one-half, from 5,000 Euro/kWp to 2,546 Euro/kWp (Figure 4). The German Solar Industry Association's (BSW) 'PV-Roadmap 2020' anticipates a further drop in the price of PV systems to 1,500 Euro/kWp by 2017 (Roland Berger SC and Prognos AG, 2010). If prices fall this far, house-rook PV system installations will be affordable for house owners without any government support (Chrometzka, 2011).

Figure 4 Average end-customer prices for installed roof-mounted systems of up to 100 KW peak per KW peak. Source: BSW, 2011



The improvements in technology that permit these cost and price reductions derive not just from scale changes and internal R&D (which accounts for 10.4 per cent of personnel in Sunways, 7.8 per cent in Q-Cells, 6 per cent in Schott and 4.5 per cent in Solar World)[4], but also from public and private co-operation. German companies have had important co-operation programmes with research institutes and universities (Konstanz and Freiberg), applied research institutes (CSP Fraunhofer Center for Silicon PV and the ISE Fraunhofer Institute for Solar Energy Systems), technical service agencies, other companies and equipment suppliers. These projects may involve participation in government programmes, contracts with applied research institutes and technical agencies, joint ventures or participation in the capital of other companies, as for example when Q-Cells and US Evergreen Solar established a joint venture, EverQ GmbH (present Sovello), to develop and commercialise string ribbon technology. Most of the projects with universities and research institutes were designed to improve crystalline-silicon PV technology. The development of new thin film technologies relied more on co-operation with other companies.

To maintain competitiveness, German companies have formed various strategic partnerships and relocated parts of their production lines overseas. For instance, Q-Cells has concentrated on the rapid expansion of solar cell production capacity. At the same time it has tried to establish stable customer-supplier relationships via strategic partnerships. For example, it acquired 17 per cent of

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[4] Interview data revealed that the initial wage of an engineer with a Master's or PhD degree in PV firms is around 30,000 or 40,000 Euros/year respectively (Seifert, 2011). This figure is much greater than that for engineers in Chinese enterprises.

the capital of Norwegian REC (Renewable Energy Corporation) which the world's foremost manufacturer of poly silicon and silicon wafers. These steps also contribute to its strategy of vertical near-integration. Cost considerations also led however to movement offshore to lower cost locations: in 2008 Q-Cells established a production facility in Malaysia; while Schott Solar operates a factory at Valašskè Meziříčí in the Czech Republic.

Solar World has adopted a different strategy as it hose to integrate vertically dealing in-house with all manufacturing steps from silicon to module manufacture. To circumvent trade barriers and take advantage of local subsidies, SolarWorld established a plant in Hillsboro, Oregon and Schott Solar followed suit with a plant in Albuquerque, New Mexico in the US.

In Germany production growth remained healthy. In 2010 however few producers significantly expanded the capacity of their European facilities. Instead they chose either to utilize existing capacity or to rely on contract manufacturing or offshore production to serve market demand. These trends were a portent of the increased competitive pressures that in 2011 would be translated into increased tensions over international trade and East Asian competition (See Section 4).

2.3 German case: finance and investment

As mentioned in Section 1 credit and investment capital play a fundamental role in driving industrial development. The creation of a market in German stimulated investment decisions that required a mobilisation of financial resources to invest in production capacity and distribution channels. Some of these resources were raised on German financial markets, from bank loans and from the German Stock and Corporate Bond markets. For instance, in 2005 Ersol and Q-Cells raised some Euros 153 million and 240 million respectively through initial public offerings (IPOs) on the Frankfurt Stock Exchange. A significant share of resources came however from grants and subsidies available from the European Union's Structural and Cohesion Policies and the German government's development funds targeted at the economically less developed eastern part of Germany. After the unification of Germany, the new Länder were designated as Objective 1 or Convergence regions. In 1994-9 this region have received ECU 13.6 billion (Wishlade, 1996, p. 49). Additional resources arrived in 2000-06 and for the period 2007-13. These funds helped finance generous investment incentives offered by regional governments in East Germany.

Table 4 Main PV companies in Solarvalley Mitteldeutschland

State	Wafers	Cells	Modules
Thuringia	Bosch Solar in Arnstadt	Bosch Solar in Erfurt	Bosch Solar in Erfurt
	Schott Solar in Jena	Sunways in Arnstadt	Schott Solar in Jena
	PV Crystalox in Erfurt		
Sachsen	SolarWorld in Freiberg	SolarWorld in Freiberg	SolarWatt in Dresden
			SolarWorld in Freiberg
Sachsen-Anhalt	PV Crystalox in Bitterfeld	Q-Cells in Thalheim	
		Sovello in Thalheim	

Source: Solarvalley Mitteldeutschland, 2010

To stimulate investments in solar energy, three east German Länder (Thüringen, Sachsen, and Sachsen-Anhalt), with the support of the Federal Ministry for Education and Research (Bundesministerium für Bildung and Forschung), established Solar Valley Central Germany

(Solarvalley Mitteldeustchland). In 2008 this area accounted for 43 per cent of German PV turnover and 75 per cent of German production of solar cells, afforded 10,000 direct PV jobs and housed four of the top ten companies in the world. Association members include 29 global PV companies, 9 renowned research organizations, and 4 universities (Solarvalley Mitteldeutschland, 2010; Liebe, 2010). To support the PV sector the association offers investment grants, R&D subsidies and assistance with operating costs. Investment grants can cover up to 30 to 50 per cent of eligible investment costs, and Länder R&D subsidies cover 50 to 80 per cent of expenses. The Länder also cover 80 to 100 per cent of employee training and qualification costs (LEG, 2009).

In a five-year period a total budget of 150 million Euros was allocated to 98 joint projects. One-half was financed by the public sector (Solarvalley Mitteldeutschland, 2010). Q-Cells, Sunways, SolarWorld, and Schott Solar participated in these projects. With regard to investment grants, these subsidies were more helpful for start-ups and expansions. Interview data indicates that public subsidies from the European Union and the state government accounted for 35 per cent of the initial financing of Deutsche Solar AG (a current SolarWorld AG) company in 1994 (Woditsch, 2011). Sachsen-Anhalt's state subsidy influenced strongly on the decision of Q-Cells to locate in Thalheim, when it was looking for a site to construct a large solar cell factory in 2000 (Seifert, 2011). Annual report data indicates that SolarWorld was provided with 73 million Euros for the expansion of solar factories in Freiberg of Saxony in 2003, and Q-Cells received a grant of approximately 21 million Euros for the construction of factories in Thalheim in 2004.

3.1 The Chinese case: market creation

The Chinese case differs from the German case in a number of respects: although the general drivers are similar, their form differs in that it growth is export-oriented, enjoys access to cheap capital and relies on catch-up rather than initial mover advantages. As in Germany the industry has received significant government financial support.

In China solar cell research dates at least from 1958. The first application and the first market had however to await China's second space satellite project in 1971 (Cui et al., 1990; Zhao, 2001). Terrestrial applications followed. In the 1990s the Chinese government and a number of international organisations implemented a series of programmes to provide electricity to 80 million people who lived in rural areas in western China, and who, in 1995, had no access to grid electricity (Stone et al., 1998; CRED, 2000). At a national level the National Eight-Seven Poverty Alleviation Programme, the China Brightness Programme and the Project to Raise Income Levels of the Poor by Introducing Electricity resulted in the distribution of household PV systems to meet the needs of peasants and herdsmen in five provinces of southwest China, Inner Mongolia, and Tibet. A number of PV systems (including wind/PV, wind/diesel, and wind/diesel/PV hybrid systems, and small independent PV and solar PV generation systems) were installed in regions rich in solar energy potential, such as Tibet, Xinjiang, Qinghai, Gansu, Ningxia, Shanxi, and Inner Mongolia. For instance, six county-level PV stations with a capacity of 250 kW were installed in Tibet at the end of 1998 (CRED, 2000, p. 63-4). Internationally the Chinese government collaborated with a number of multinational organisations to deploy PV systems in China. Examples include the US Department of Energy (DOE) Project, the Netherlands' Shell Project, the Eldorado Program (a Sino-German project), the World Bank and Global Environment Facility (GEF) Project, the United Nations Development Programme (UNDP) Project, and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Project (CRED, 2000).

One of the most important policy initiatives was the 'Transmission Electricity to Village (Song Dian Dao Xiang)' programme carried out in the early 2000s. These government programmes increased domestic demand for PV systems and created a market for newly established PV firms, such as Trina solar and Yingli enabling them to accumulate experience on domestic markets (Wei, 2010; Yang, 2010). Aided by a host of preferential policies and incentives, annual installed PV system capacity in China increased at some 27 per cent per year in 1993-8. Annual installed PV capacity was however still low: 2.3 MWp in 1997 up from 900 in 1993 and 3.0 MWp in 1998 (Dai and Shi, 1999), although 1997 production capacity stood at about 4.5 MWp (CRED, 2000).

Government support for R&D increased significantly over the course of time. To address energy issues the Chinese government provided PV R&D funds in the Sixth (1981-85) and Seventh (1986-90) Five-Year Plans (FYPs) (Cui et al., 1990). In the Eighth (1991-95) and Ninth (1996-00) FYPs, funds for increasing the efficiency and reducing the cost of renewable energy reached 60 and 82 million RMB (approximately USD 9.2 and 12.6 million), respectively (CRED, 2000). In 1995, the State Planning Commission (SPC), the State Science and Technology Commission and the State Economic and Trade Commission jointly formulated the Development Program for China New and Renewable Energy during the Year 1996 – 2010 (CRED, 2000) that saw the installation of mass production lines of poly-crystalline-silicon solar cells, upgrading of production lines of mono-crystalline-silicon solar cells and R&D into new types of high-efficiency and low-cost solar cells were carried out (CRED, 2000).

In China a Renewable Energy Law passed in 2005 came into effect in 2006. All electricity users are charged a renewable energy fee, and grid operators are reimbursed for the extra cost of renewable energy. In addition grid operators are penalised financially if they fail to connect renewable energy sources to the grid notwithstanding the fact that renewable sources are often in remote places and incur substantial transmission loses (Bradsher, 2010). In the case of solar energy a limited feed-in tariff was introduced in Jiangsu Province (Wei, 2010; Zhu, 2010). In 2009 the adverse effects of the 2008 global financial crisis on PV companies and renewable energy targets saw the central government (the Ministry of Finance, the Ministry of Science and Technology, and the National Energy Administration of the National Development and Reform Commission) launch 'the Golden Sun (Jin Tai Yang) Project' to facilitate the deployment of large-scale PV plants of no less than 500 MWp within two to three years (MOST, 2009). In 2011 China announced the provisions for a feed-in-tariff (CREDP, 2008; EPIA, 2010). Although the rates are lower than in Europe (up to 1.15 Yuan per KWH for approved solar projects in 2011, compared with 50.6 Eurocents per KWH in 2000 and 25 in 2011 in Germany), Chinese land and installation costs in areas with large amounts of sunlight are low.

The significance of the Chinese market for the solar industry is obviously growing. To date however government demand-pull policies were not enough to absorb the output of the Chinese PV industry. As a result the surplus output of the Chinese solar industry was largely exported to European markets: in 2009 China produced around 3,782 MWp of PV modules but installed only 228 MWp domestically (Figure 1). By entering global markets Chinese firms were able to secure volumes for the economies of scale.

3.2 The Chinese case: technology and costs

To establish an industry and subsequently enter global markets Chinese companies had overcome 'two sets of competitive disadvantages' faced by latecomer firms (Hobday, 1995). The first is a technology gap, deriving from isolation from the main international sources of technology. The other is a marketing disadvantage because the latecomer firm is dislocated from the mainstream international markets. However, latecomer firms may have substantial cost advantages over leading firms. As Hobday (1995) argued, there are various routes to overcoming these disadvantages: joint ventures; licensing; original equipment manufacture (OEM); own-design and manufacture (ODM); sub-contracting; foreign and local buyers; informal means (overseas training, hiring and recruiting returnees); overseas acquisition/equity investments; and strategic technology partnerships.

In the 1970s solar cells were produced in three small Chinese state-owned former semiconductor plants: Kaifeng Solar Cell Factory in Henan (which was established in 1964 started to produce mono-crystalline silicon solar cells from 1975; Ningbo Solar Power Source Factory (now called Sun Earth Solar Power which was founded as a semiconductor plant in 1966 and made cells and modules from 1978); and Yunnan Semiconductor Devices Factory in Kunming (which was established in 1977 and started to produce mono-crystalline silicon solar cells in 1979) (CRED, 2000). Costs were high (400 RMB or US$ 206) /Wp in 1976 (Cui et al., 1990) and output was low, reaching merely 0.5 kW, 1kW and 2kW in 1976, 1977 and 1978 respectively (Cui et al., 1990).

In the 1970s Chinese companies lagged well behind their western counterparts. In the 1980s their relative position improved as a result of the one-off imports of solar cell equipment from the US and the UK with State Science and Technology Commission help (Dai and Shi, 1999; CRED, 2000). In 1989, the Huamei PV Equipment Company of Qinhuangdao (Hebei) entered into the solar cell sector (Dai and Shi, 1999; CRED, 2000). R&D cooperation between manufacturers and research institutes increased, and more than 200 engineers and technicians were employed in the four companies. In 1989 China’s annual production of PV cells reached 400KWp (Cui et al., 1990).

The gap between the four mono-crystalline solar cell manufacturers and their counterparts in developed countries nonetheless remained large. In the late 1980s costs remained high at around 40 RMB or US$ 11/Wp. Chinese PV modules were therefore some 10 per cent more expensive than foreign products, despite lower costs of plant construction and labour (Dai and Shi, 1999; CRED, 2000). The investments in new equipment were one-off investments (CRED, 2000). Capacity was not sufficient to take advantage of economies of scale, while capacity utilization rates were around 50 per cent (Cui et al., 1990; Dai and Shi, 1999; CRED, 2000). Average photoelectric efficiency of Chinese commercialised silicon solar cells was 10-12 per cent, compared to 14-16 per cent in developed countries (Dai and Shi, 1999; CRED, 2000). The quality of Chinese solar modules fell short of competitors on domestic and international market. Wafer thickness was about 400 µm compared with 250 in foreign firms due to differences in cutting technologies raising silicon feedstock usage and production costs (Dai and Shi, 1999). In the case of amorphous-silicon modules, Chinese manufacturers produced only single-junction modules, whilst most foreign firms produced double-junction or triple-junction modules (CRED, 2000). Although R&D activities increased most PV R&D projects were small in scale, as government funding was limited, and spread across a large number of applicants, while the R&D projects themselves seldom resulted in successful commercialization (Dai and Shi, 1999). Most users were moreover people in remote and poor areas who cared little about the technical performance or the efficiency of the systems, so the companies received little feedback or pressure to improve performance from the domestic market (Dai and Shi, 1999). AS a result solar cell firms had difficulty in making ends meet and Chinese banks were reluctant to lend due to poor credit ratings and uncertainty about the solar cell market (Dai and Shi, 1999; CRED, 2000). The limited availability of external finance in turn meant that China’s traditional PV firms could not afford to invest in R&D and process innovation in this period (CRED, 2000).

In the 1990s China’s Open Door Policy saw an increase in foreign investment, including the establishment of several joint ventures in the PV sector: Harbin-Chronar Solar Power Company in 1991; and Shenzhen Yukang Solar Energy Ltd in 1992, although it was closed in 1997 (Dai and Shi, 1999; CRED, 2000). In the mid-1990s the annual domestic PV market reached over 2MWp. Also in the 1990s some firms including the Yunnan factory and Harbin-Chronar Solar Power Company started to export solar cells and modules (CRED, 2000). Towards the end of the decade a wave of foreign solar cell companies (British Petroleum, Shell, Siemens Solar, Sharp, Sanyo and SEC) arrived expecting a large volume of sales partly due to the above mentioned electrification programmes of the northern and western provinces (Dai and Shi, 1999).

In 1997 Trina Solar Energy was founded (Table 5). This step was the first of a series that resulted in the emergence of a new generation of PV firms in China. Today there are over 100 solar PV companies. Six of these new companies grew dramatically rapidly with annual production capacity quickly reaching over 300 MWp, as did the state-owned Ningbo plant (Sun Earth) which was at least initially more directed at the national market (ECJRC, 2009).

Table 5 Production capacity of top PV companies in China (MWp) Sources: Annual reports, company websites, interviews and Photon International, 2011b.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2010	
JA Solar					75	175	600	875	2100	1463	
Suntech Power	10	30	60	150	270	540	1,000	1,100	1800	1585	
Trina Solar Energy			6	6	28	150	350	600	1200	1050	
Yingli Green Energy		30	50	100	100	200	400	600	1000	980	
Solarfun/Hanwha Solar One						240	360	420	500	500	
China Sunergy				32	192	192	320	320	400	400	
Sun Earth					100		200		450		
Total	10	60	116	288	665	1,457	3,030	3,915	7000	5,978	

Growth was so fast that these companies quickly joined the top producers in the world (Table 6). As moreover there is a definite trend towards vertical integration in the industry the top cell producers are also top module producers.

Table 6 Top 10 solar world cell and solar module manufacturers in 2010. Source: Photon International, 2011

Rank	Name	Nationality	Annual solar cells production (MWp)		Nationality	Annual solar modules production (MWp)
1	Suntech Power	China	1584	Suntech Power	China	1558
2	JA Solar	China	1464	First Solar	US	1400
3	First Solar	US	1400	Yingli Green Energy	China	1061
4	Yingli Green Energy	China	1117	Trina Solar	China	1060
5	Trina Solar	China	1116	Sharp	Japan	1022
6	Q-Cells	Germany	939	Canadian Solar	Canada	804
7	Jintech	Taiwan	800	Hanwha-SolarOne	China	798
8	Gintech	Japan	745	Kyocera	Japan	650
9	Motech		715	REC	Norway	491
10	Kyocera	Japan	650	Sanyo	Japan	405

The remarkable success of these companies involved several steps. First they had to overcome the barriers faced by latecomers. Second they had to exploit the cost advantages of manufacture in China.

To enter European markets these companies had to establish marketing channels, acquire European certification such as TÜV and IEC certificates, provide the required 25-year guarantees and the establish of a reputation for credible and cheap products. Successful completion of these steps enabled them to overcome barriers to entry into European markets (Chen, 2010; Lee, 2010).

To overcome the technological gap, Chinese companies imported turn-key equipment and expanded their know-how via learning by doing. By the early 2000s crystalline-silicon solar cell technology had matured, so most state-of-the-art technologies were embodied in production equipment (Bae, 2009). At first, turn-key based equipment was imported from Germany, the US, and Japan. As production took place a rapid process of learning by manufacturing was set in motion (Lee, 2010; Peschke, 2010). Manufacturing experience enabled these companies themselves to select the best equipment for each production process and install it themselves. As the volume of domestic demand for PV equipment grew, local equipment suppliers emerged. The PV producers collaborated with these local equipment suppliers> Domestic equipment suppliers provided lower-priced capital goods and by 2009 or so secured a 50 per cent share of the Chinese PV equipment market (Lee, 2010; Chen, 2010; Xu, 2010; Zhu, 2010; Sun, 2010; Yang, 2010). These developments were supported by a rich variety of complementary assets (Teece, 1986) available in China: machine tools, semiconductor and electronics industries, and a large supply of people with knowledge of PV technologies implemented in the first generation of PV firms (Chen, 2010).

Two other channels played a role in the acquisition of technological capabilities. One was OEM manufacturing (Lee, 2010; Chen, 2010). The other was merger and acquisition activity. Suntech for example acquired MSK Corporation, a leading PV module manufacturer, and Building-Integrated PV (BIPV) company in Japan in 2006, and KSL-Kuttler, a German company specialising in equipment automation in the printed circuit board industry in 2008.

A particularly distinctive feature of this Chinese process of technological learning was that it was mainly led by scientists who studied state-of-the-art PV technology in foreign countries (especially in

2002 Nobel Laureate Prof Martin A Green's centre in the University of New South Wales). These scientists worked in conjunction with technicians (occupying high positions in the new companies) who had manufacturing experience in traditional Chinese PV firms (Chen, 2010; Zhu, 2010). A complementary relationship between these two groups played an important role in innovation. The scientists had a good knowledge of state-of-the-art technology and laboratory-level experiments, but sometimes lacked experience of manufacturing. In contrast, technicians who have worked in factories for a long time have a lot of tacit knowledge of mass production, but knew little about new technologies.

Almost all the Chinese PV firms included in the survey except JA Solar adopted vertical integration strategies. As knowledge accumulated, vertical integration was seen as a way of securing raw materials and components and reducing transaction costs (Williamson, 1971). Yingli, Trina Solar, and Solarfun started as module assemblers, as it was less complex technologically and integrated backwards. All undertook all stages of production from ingot and wafer to cell production. Yingli in 2009 added the poly silicon stage. Suntech and China Sunergy were founded by scientists with expert knowledge of state-of-the-art solar cell technologies. To reduce transaction costs, and expand earnings, the firms' boundaries were extended to embrace module production.

As these obstacles facing latecomers were overcome China could exploit its cost advantage: Chinese manufacturers were able to sell their products at prices that were around two thirds of those required by foreign companies. China's competitiveness rested on several factors. First of all, labour costs are low especially considering the quality of labour. Average salary of workers in the industrial sector was 26,599 RMB/year (approximately $3,900 USD) in 2009 (NBSC, 2010). In Jiangsu in 2009 the monthly salary of PV factory workers was between 1,000 and 1,500 RMB (approximately $146 and 220) (Lee, 2010).

Second, as wages were low, some production processes such as welding and arraying of solar cells in the module production process are still carried out manually by workers. The manual process has two advantages. One is cost-effectiveness compared to the automated process in part as breakages are lower (Xu, 2010; Zhu, 2010). To reduce breakages Chinese firms train workers carefully but also employ penalty systems which connect breakages and salaries (Lee, 2010; Chen, 2010; Zhu, 2010; Xu, 2010). The second advantage is customisation. Customisation strategy is important in the PV sector, because there is demand for different sizes of PV modules, and is much cheaper if a manual process is used (see also Zeng and Williamson, 2007).

A third cost advantage is low costs of people with engineering and technical skills reducing in-house R&D, production and quality control costs. Traditional PV firms are one source of skilled workers with low wages. For example, a senior engineer, working for Suntech, originally worked at the Yunnan factory on a monthly salary of around 2,000 RMB (approximately $300 USD) in the 1990s (Chen, 2010). Chinese tertiary education is the second source. In 2002 more than 300,000 scientists and technologists graduated from Chinese universities. These degrees accounted for 73 per cent of the total of first university degrees awarded in China (National Science Board, 2002, cited in Marigo, 2009). The average initial monthly salary of Master's degree engineers in the PV industry is around 3,000 RMB (approximately $430).

Fourth, as in Germany collaborations between PV firms, local universities and domestic research institutes such as Shanghai Jiatong University, Sun Yat-sen University, and the Chinese Academy of Science increased facilitating innovation at low cost (Zhu, 2010; Xu, 2010).

3.3 China: finance and investment

Cheap finance and the provision of land and infrastructure at low costs were other major drivers of competitive success of Chinese solar industry. Wang (2010) estimated that costs of setting up a 25 MWp production line with mixed local and foreign equipment was around one-half of the costs for foreign companies (Wang, 2010). One reason why is that local government could provide land at preferential rates. Another was the availability of government subsidies and abundant and cheap finance.

To finance rapid expansion and the rapid realization of scale economies in largely capital-intensive sectors, two strategies were pursued. In the initial investment stage up to 2004 domestic demand was limited, the world market was small and growth slow making it difficult to raise finance. Chinese products were also of insufficient quality to compete on the markets that did exist. And yet the new Chinese companies grew due to local and especially city (shi) government assistance and guarantees in securing bank loans, and funding from state-owned enterprises (SOEs) (Chen, 2010; Xu, 2010; Wei, 2010; and Park, 2009). In the case of Suntech:

'In 2002 Suntech built a 10 MWp production capacity. In 2003 Dr. Zengrong Shi, the CEO, tried to expand it to 30 MWp. Most senior executive officers and major stockholders objected because PV markets were uncertain and the firm was far from profitable. Sometimes salaries for senior executives and engineers were not paid by the firm. Some engineers therefore left the firm. But, he convinced Wuxi City government and local state-owned companies (SOEs) to invest in his firm enabling Suntech to expand capacity to 30 MWp production in 2003' (Interview data: Chen, 2010).

Assistance from local government and local government loan guarantees also enabled companies to secure bank loans and SOE investments. Oi (1999) branded this tendency for Chinese local government to support risky investments 'local state corporatism'. This tendency itself reflects strong incentives to facilitate the growth of local industries deriving from their contribution to local tax revenues and their impact on the evaluation system of cadres and high officials (Arrighi, 2007) on the one hand, and the priority given to high-tech and environmentally friendly industries on the other.

This support was rewarded: Yingli and Solarfun have become the biggest firms in Baoding City (shi) and Qidong County (xian), respectively. Suntech has become the second biggest firm in Wuxi City (shi). Most of the city governments in Jiangsu Province have strongly supported local PV firms: Suntech in Wuxi; Trina Solar in Changzhou; China Sunergy in Nanjing; and Solarfun in Nantong (Wei, 2010).

From 2005 a second important source of finance was exploited. In 2003 and 2004 global demand soared. Under the influence and guidance of returnees and overseas Chinese who knew the global financial market well, these new companies (along with companies in other sectors) were able to raise capital through IPOs on foreign stock markets In 2005 Suntech was listed on the New York Stock Exchange (NYSE); in 2006, Trina Solar and Solarfun were listed on the NYSE and Nasdaq, respectively; in 2007, Yingli followed suit by joining the NYSE; in the same year JA Solar and China

Sunergy were listed on Nasdaq (Xu, 2010). Subsequently, all of these companies were able to draw on overseas capital markets to expand their production capacities very rapidly, helping China to emerge as the world's largest PV manufacturing nation by 2008.

In part because the Chinese financial system was not liberalised China was affected by the financial crisis only as a result of negative impacts on export markets, while the Chinese government's fiscal and monetary stimulus contributed to the availability of vast reserves of low-cost capital from Chinese state banks. These resources have also allowed Chinese companies to scale up capacity and reduce manufacturing costs to levels well below their peers enabling to gain market share. Another result is that a growing number of American, European, and Japanese firms employ Chinese module producers in an OEM capacity and sell these modules under their own brand names.

4 Conclusions: geographical interdependence and growth

As a whole the years up to 2010 witnessed unfettered growth in Germany and China. In the last few years however, growth was greatest in China and Taiwan, and the margins of German producers have been squeezed. German and more generally western manufacturers remain significant but are adding less capacity. Chinese (and Taiwanese) cell and module manufacturers conversely plan large increases in capacity. These investments will increase global overcapacity and contribute to low overall rates of capacity utilization.

In the last two years prices have already fallen by more than one-half due in part to learning curve effects but mainly due to excess capacity. Chinese costs are about one-half of those in Germany. Chinese and other Asian low cost producers can reduce prices to increase demand and market share. The strong downward pressure on prices will therefore continue.

These pressures will accelerate the ongoing transformation of the industry: a changing geography of markets and demand, increased vertical integration, downstream integration, contract manufacture, offshore production, acquisitions and mergers, and market exits.

In 2011 and 2012 the German government started to make significant cuts in feed-in tariffs reigning in demand. At the same time proposed reforms to the Renewable Energy Act will remove subsidies. In contrast growth is stronger in China and India, whose government's plan significant increases in installed capacity, and in the US, especially in California. In China the government (Energy Revitalization) plans to subsidize 300 large-scale projects. The geography of market demand is therefore changing with the fastest growth not in Europe but in Asia and the US.

German PV companies have excellent technological capabilities. A Bank Sarasin study however considers them ill-prepared for the difficulties unfolding at present and anticipates that 'only about half of Germany's 50 or so larger solar power companies will survive in the next five years'. Two sets of factors are at work.

The first relate to several characteristics of the external competitive environment, and the second to the characteristics of German firms. As far as the environment is concerned, the market share of the top ten companies is increasing strongly. Critical mass and scale in production and in sales is one significant advantage. 80 per cent of the capacity of these firms is moreover in Asia where costs are one-half of those in Germany. As a result more German companies will offshore production to low-cost countries. Small companies that retain production onshore will therefore face a threefold threat of low-cost competition from Asian and offshored western companies, a more sluggish domestic market and a limited presence in the world's growth markets. Many small German companies are ill-placed to confront these challenges: many are too small to achieve scale economies in production and do not have access to all market channels (of which project channels are particularly important). A shake out, mergers and co-operative ventures are therefore highly probable as German companies seek to adjust cost structures, increase scale, acquire sufficient capital and improve market access.

At the end of 2011 these diverse geographies of production and consumption were the source of increasing international trade frictions in the still depressed economies of Europe and North America. In October 2011 Solar World AG's US subsidiary, SolarWorld Industries America, fronted a petition filed by a group of US companies with the US Department of Commerce and the US International Trade Commission (USITC) alleging that Chinese companies are selling solar cells and modules at prices below costs of production and have received 200 government subsidies including cut-price raw materials such as aluminum and polysilicon, tax exemptions, massive loans at below-market rates of interest and discounts on land, power and water. The petition was prompted in part by the bankruptcy of Solyndra, a solar panel maker that received a $ 0.5 billion US federal government loan. In December 2011 the US USITC upheld the complaint (2010 imports were estimated at $1.2 billion) opening the way for the US Department of Commerce to impose proposed antidumping and countervailing duties of up to 249.96 percent

In December 2011the China Photovoltaic Industry Alliance (CPIA) asked the Chinese Ministry of Commerce to conduct a dumping and subsidy investigation into US sales of polysilicon, a vital component of solar cells and into the adoption in the US of measures that violate World Trade Organization rules and lower the competitiveness of Chinese products in the US market. The CPIA believes that overseas companies led by the US more than doubled polysilicon imports to reach 47,500 in 2010 and plan further increases to reach 60,000 tonnes in 2011 and significantly reduced prices to bankrupt their Chinese competitors.In the third quarter of 2011 many Chinese polysilicon factories stopped or reduced production and more than 2,000 jobs were lost in one province alone. In China the Ministry of Commerce responded by setting up an investigation into six US projects not just in solar energy but also in the wind and hydro power sectors. If the US complaint is upheld moreover several Chinese companies plan to relocate some operations outside of China, while US equipment makers fear that the dispute will adversely affect sales in the Chinese market (Diao Ying and Du Juan, 2011; Du Juan and Ding Ying, 2011).

The outcome of these conflicts will have significant impacts on future geographies of PV production and markets and indicate the significance of institutional contexts and rules in shaping the geographies of market creation, investment and investment finance, and of innovation and competitiveness.

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