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

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Abstract
The trajectories of the German and Chinese photovoltaic industries differ significantly yet are strongly interdependent. Germany has seen a rapid growth in market demand and a strong increase in production, especially in the less developed eastern half of the country. Chinese growth has been export driven. These contrasting trajectories reflect the roles of market creation, investment and credit and the drivers of innovation and competitiveness. Consequent differences in competiveness have generated major trade disputes.

Keywords
China, Germany, industrial dynamics, international trade, photovoltaic industry

Oil price increases, European gas supply interruptions and the global climate impacts of greenhouse gas emissions are increasing the importance of renewable sources of energy. 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 PV systems. Between 2000 and 2010 Germany was the most important market, while China emerged as the most important manufacturer.

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The aim of this article is to explore and explain these contrasting geographies of demand and supply and their implications for relationships between Germany, Europe and China. The analysis itself 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 between the summer of 2010 and end of 2011.

The article is divided into five sections. In the first section we present a series of stylized facts relating to the trajectories of the PV sectors in Germany and China and the nature of the relations of complementarity, competition and interdependence between Germany and China that the article seeks to explain. The second section develops a theoretical framework and includes an account of the structure of the PV value chain. In the third section we provide an explanatory account of the dynamics of the German PV sector and its interaction with China. The fourth section deals with the Chinese case. In the fifth section we examine further the asymmetric interaction of these two national industries and national development trajectories. We consider their empirical and theoretical implications for an understanding of relations between, in particular, Germany and Europe and, in general, advanced economies and emerging economies such as China.

The emerging geographies of production and consumption in the photovoltaic sector

In 2000–2010 worldwide solar power output has increased more than 100 times to reach 27.2 GW. In the last 5 years output growth was most rapid in China and Taiwan Republic of China. In 2010 China and Taiwan accounted for nearly 48% and 13% of total output, respectively (Photon International, 2011). As China and Taiwan rose in importance as manufacturing centres for PV components, Europe and Japan declined in relative importance to account for 13% and 8%, respectively. The USA accounted for less than 5%.

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%, 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 globalized world, however, it is has also created markets 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.

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 article. Germany has seen a rapid growth in market demand and a 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 $8097 million in 2010. Chinese growth was export driven. Exports grew from $178 million to $25,179 million. In 2010 Chinese PV exports to Germany, worth $7637 million, were almost equal to total German PV exports. Until the implementation of some recent massive domestic solar installations, only about 5% of Chinese production was for domestic consumption. China's export success was, however, a source of trade friction with developed countries.

Theories of geographies of trade and development and the photovoltaic chain

Analysing these different trajectories and roles involves drawing on a set of concepts capable of explaining geographies of PV sector trade and

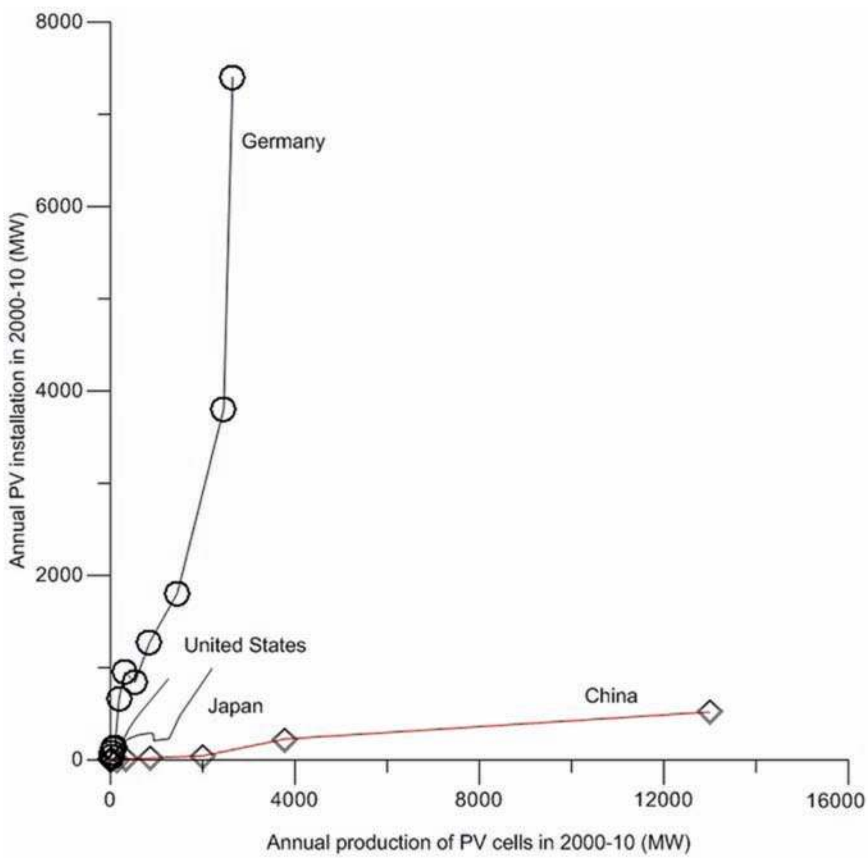

Figure 1. Photovoltaic demand and supply trajectories, 2000–2010.
Elaborated from Earth Policy Institute, 2010a, 2010b. European Photovoltaic Industry Association (2011); Photon International.

development. The recent geographical literature has largely concentrated on the development of clusters, agglomerations, innovation, value chains and institutional and evolutionary ideas (Coe et al., 2004; Martin, 2011; Smith et al., 2002; Storper, 1995). We shall draw on some of these concepts, but shall argue, however, for a greater concern with geographical interdependence and a re-engagement with a political economy of trade and development.

Geographies of production and international trade are mainly explained by two sets of theories. Theories of comparative advantage attribute specialization 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 et al., 2012).

In this article 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 lack of attention to institutional factors. We shall emphasize the importance of international, national and local social foundations of economic growth (Figure 2). The second is the lack of explicit attention paid to money and the demand-side drivers of trade and industrial dynamics. In Keynesian models, money and credit are the starting point for economic development and drive economic activity: credit creates deposits, deposits permit expenditure, capital advanced creates income, and

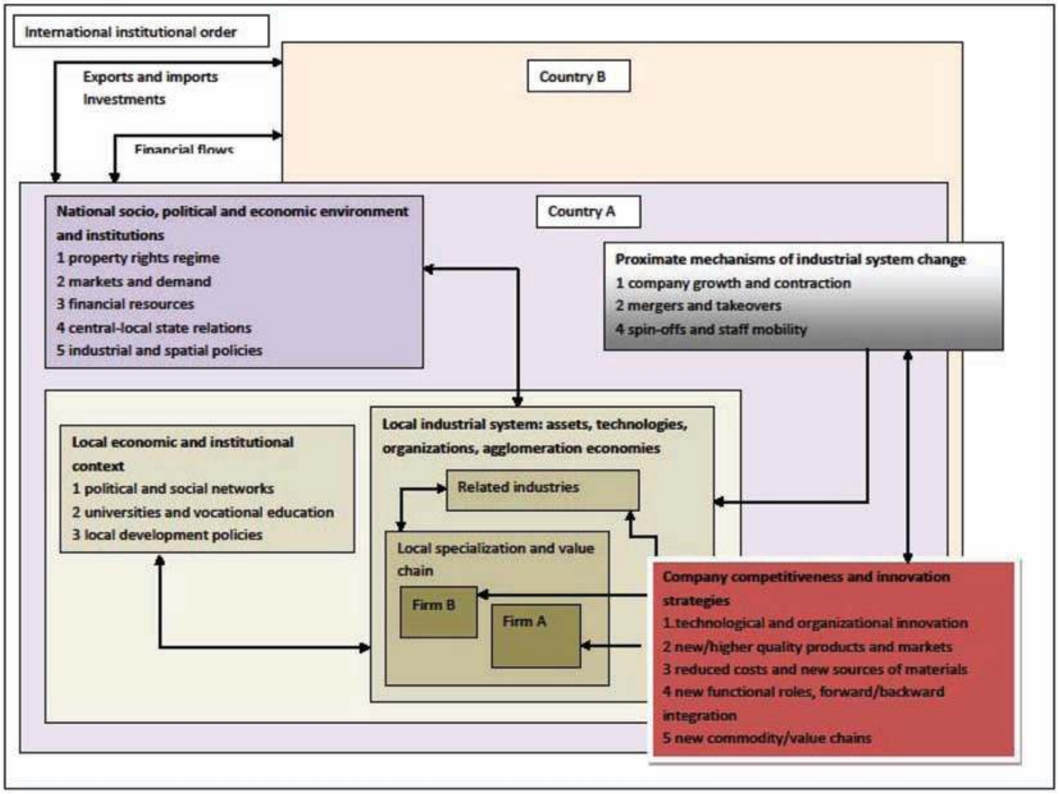

Figure 2. A conceptual framework: industrial dynamics in a global context.
Elaborated from Liu and Dunford (2012).

income creates further expenditure, which together drive capital accumulation and growth (Dunford et al., 2011). In a sense, the argument is close to the idea of a circuit of capital. Each firm in Figure 2 has its own circuit (Figure 3), which starts with the advance of money as capital to purchase material and human resources. These expenditures create money income for producers and wage earners. The expenditure of these incomes is a source of effective demand. Once produced, goods and services are offered for sale in the market place: if successful, income is earned and costs are recovered. These revenues are re-advanced, restarting the circuit, the size and character of which can change over time as enterprises pursue innovation, growth and competitiveness strategies to compete successfully with their domestic and international rivals (Figure 2). In this type of model capital expenditure, credit and investment subsidies and the creation of markets are crucial drivers of industrial dynamics.

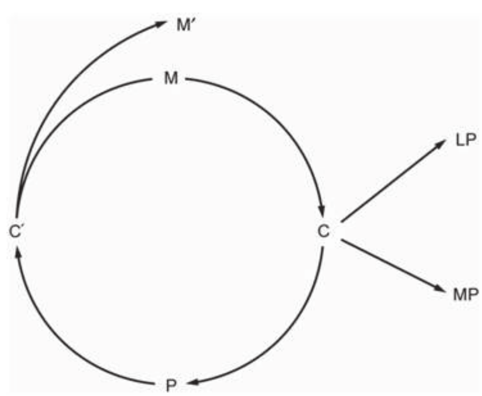

Figure 3. A firm's circuit of money capital.

Table 1. Solar cell and module value chain

	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		

KNREC (2009), ECJRC (2010), BSW (2010), Solar & Energy (2011).

Van De Ven and Garud (2000: 493) have argued that industrial development is underpinned by three functional subsystems: 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 subsystems. 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 principal sets of drivers: (1) market creation and growth 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, marketing and distribution in enterprise value chains.

To compare and explain the different trajectories of Germany and China several further theoretical considerations relating to the structure and evolution of the industry value chain 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 standardized products in accordance with the degree of standardization) 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. This case involves consideration, therefore, of theories relating to catch-up, latecomer development and developmental states.

The simple life cycle idea also requires some modification to reflect the specific characteristics of different industries (Pavitt, 1984) and of their value chains (Figure 4 and Table 1). In the case of the crystalline silicon (c-Si) chain,[2] on which we shall concentrate, cell and module manufacture involve the manufacture of equipment (mainly in Germany, Japan and the USA). The next step involves the capital-intensive manufacture of polysilicon, ingots, wafers and cells and the labour-intensive manufacture of modules. 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. This value is appropriated in the areas where the products are sold. In the USA, in 2009 the costs of a module, an inverter and installation were $3, $0.5 and $4 per watt, respectively, giving a total of $7.5 per watt (McGehee, 2009). The manufacture of cells and modules accounts only for three-sevenths of the overall value added per watt.

The c-Si cell PV sector is largely a scale-intensive sector. In 2010 the realization of scale economies in cell manufacture was considered to require an annual

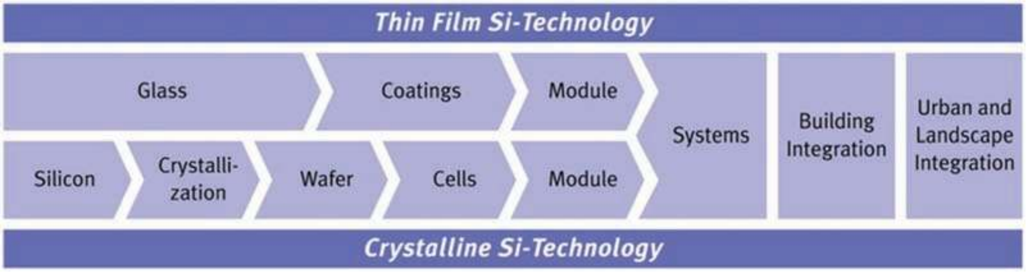

Figure 4. The photovoltaic value chain.

production capacity in the order of 300 MWp (megawatt-peak). As in Pavitt's (1984) classification, users are sensitive to price rather than performance; process innovation and cost reduction are very important; not, sources of innovation are internal (R&D and learning by doing) and external (equipment producers); not, and appropriability is through secrecy and patents. These specific characteristics play an important role in explaining geographies of production and use.

The aim of the next two sections is to examine the roles of market creation, investment and credit and the drivers of value-chain innovation and competitiveness in shaping the development of the PV sector. These drivers will be examined in the light of the specific characteristics of the sector. Attention must also be paid, however, to a set of international relationships marked by the presence of an initial market leader (Germany), a country that embarked on catch-up and may overtake the initial leaders (China), a set of institutionally mediated trade disputes deriving from international competition and trade flows. These interdependencies and their implications for studies of German and European development will be considered in the conclusions.

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

The German PV sector is a new industry, and therefore its development requires awareness of the historical steps in the emergence of the PV sector. These steps involved significant institutional choices. The PV 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, owing 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, out of which the silicon-type of solar cell emerged as what Utterback (1994) would call a 'dominant design': Utterback had 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 to create solar PV markets in Germany (market creation factor). The first was the1989 1000-roof programme, which saw the installation of 2250 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 65–90% 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.[3]

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 subnational initiatives, which saw the Aachen model spread to dozens of German cities. Under this model local governments imposed 'cost-covering contracts' with renewable generators on municipal utilities. In addition, some Land governments subsidized solar installations (Jacobbson et al., 2004; Lauber and Mez, 2004). Owing to these local-level initiatives, the German PV market continued to grow throughout the 1990s, even though the 1000-roof programme ended in 1993 (Lauber and Mez, 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 that 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 (Lauber and Mez, 2004), 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 RWE Schott Solar and Solar World, which 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-roof programme in 1993 was not supported by the ruling Conservative–Liberal government (Jacobsson and Lauber, 2006). 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 marked out Germany 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).[4] In 2002 the Nuclear Energy Phase-Out Act was adopted and increased 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 lifetime of a capital-intensive PV system (BSW, 2011; Jacobsson and Lauber, 2006; Lauber and Mez, 2004). In Germany an annual degression of 5% 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 downwards 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 euro cents per kWh in 2000 to around 25 euro cents per 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 grid parity will be achieved (Figure 5). Germany has relatively high electricity costs, but sunshine is not especially abundant.

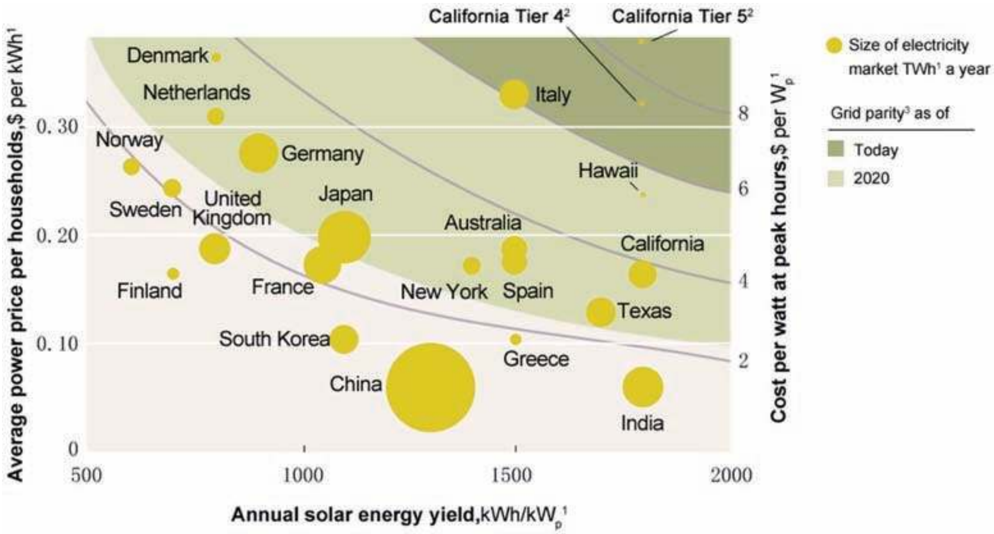

Figure 5. Grid parity and its drivers.
McGehee (2010).

The new law saw the German market explode: it grew from 42 MW in 2000 to 7408 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 through either mergers and takeovers or new investment (Figure 6).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, which was later acquired by Solar World in 2006. The Bosch group entered the PV sector through the acquisition of Ersol Solar in 2008.

The development of manufacture was closely associated with the development of the German equipment industry. Of the top 10 equipment suppliers in the world, six are German (Table 2). As

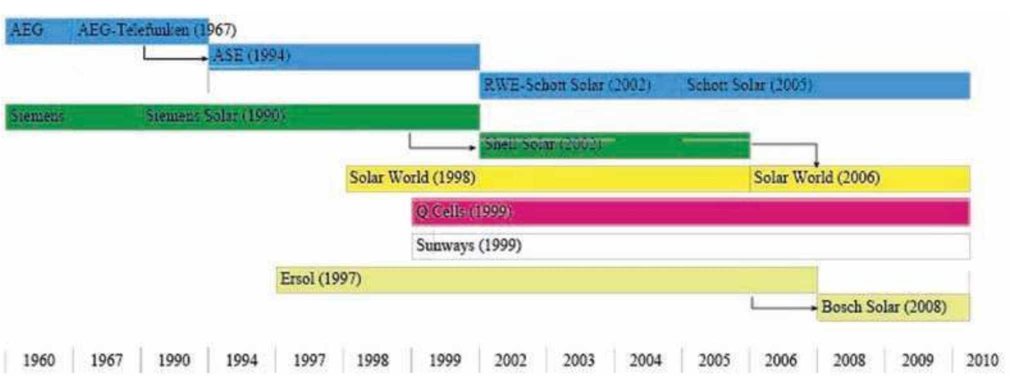

Figure 6. Growth of the German photovoltaic sector.
Lee (2011).

Table 2. Top 10 companies of the solar cell equipment industry

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

VLSI Research (2008).

the industry expanded, their sales increased rapidly from €0.2 billion in 2005 to €2 billion in 2009 (BSW, 2010) with the export proportion rising from 31% to 79%. As most production processes of PV cells are automated, equipment suppliers play a significant role in improving productivity.

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 Solar World nearly 500 MW by 2009 (Table 3). Scale-driven cost reductions have been accompanied by cost reduction through improved technologies. First, over 4–5 years from 2003 Q-Cells and Solar World reduced wafer thickness from 330 μm to 180 μm, reducing the consumption of polysilicon material by about 45%. The adoption of string ribbon technology also affords reductions, in this case of 30% to 35% by cutting waste. Second, cell efficiency has been increased from 14% in 2002 to 18% by 2008 or 2009.

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 5 years from April 2006 end-customer prices declined by nearly one-half, from €5000 to €2546 per kWp (Figure 7).The German Solar Industry Association's (BSW's) 'PV-Roadmap 2020' anticipates a further drop in the price of PV systems to €1500 per kWp by 2017 (Roland Berger

Table 3. Annual production capacity (MW)

	Value chain	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Q-Cells	Cells			22	63	170	292	420	645	860	800	1100	950
Solar World	Poly-silicon (tonnes)						2	810	1200	2250			
	Wafers	32	55		120		180	245	385	600	900	1000	1000
	Cells			30			60	185	205	260	450	775	800
	Modules		10		50	54	90	140	185	310	500	940	850

Q-Cells, annual reports; Solar World, annual reports.

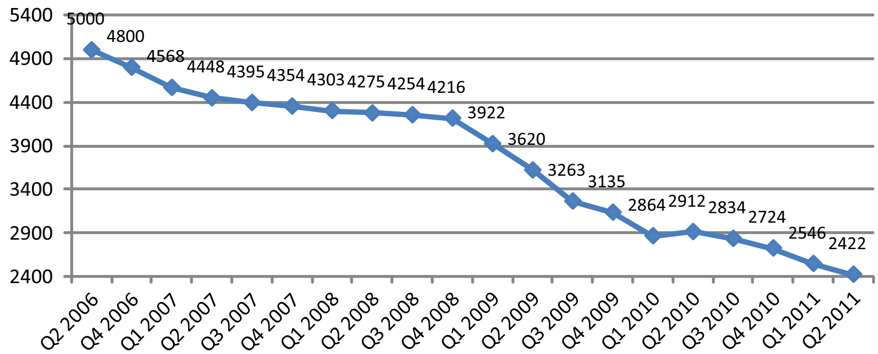

Figure 7. Average end-customer prices for installed roof-mounted systems of up to 100 kWp per kWp. BSW (2011).

Strategy Consultants and Prognos AG, 2010). If prices fall this far, house-roof PV system installations will be affordable for house owners without any government support.[5]

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% of personnel in Sunways, 7.8% in Q-Cells, 6% in Schott and 4.5% in Solar World),[6] 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 (presently Sovello), to develop and commercialize string ribbon technology. Most of the projects with universities and research institutes were designed to improve c-Si 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 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% of the capital of Norwegian REC (Renewable Energy Corporation), the world's foremost manufacturer of polysilicon 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 adopted a different strategy: it chose 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, Solar World established a plant in Hillsboro, Oregon, and Schott Solar followed suit with a plant in Albuquerque, New Mexico, in the USA.

In Germany production growth remained healthy. In 2010, however, few producers significantly expanded the capacity of their European facilities. Instead they chose to either utilize existing capacity or 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 'Conclusions').

The German case: finance and investment

Credit and investment capital play a fundamental role in driving industrial development (see 'Theories of geographies of trade and development and the photovoltaic chain' section). The creation of a market in Germany stimulated investment decisions that required a mobilization 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 €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 1994–1999 East Germany received ECU 13.6 billion (Wishlade, 1996: 49). Additional resources arrived in 2000–2006 and for the period 2007–2013. These funds helped finance generous regional government investment incentives in East Germany.

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% of German PV turnover and 75% of German production of solar cells, afforded 10,000 direct PV jobs and housed four of the top 10 companies in the world. Association members include 29 global PV companies, nine renowned research organizations and four universities (Liebe, 2010; Solarvalley Mitteldeutschland, 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% or 50% of eligible investment costs, and Länder R&D subsidies cover 50–80% of expenses. The Länder also cover 80–100% of employee training and qualification costs (LEG, 2009).

In a 5-year period a total budget of €150 million was allocated to 98 joint projects. One-half of these were 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 indicate that public subsidies from the European Union and the state government accounted for 35% of the initial financing of Deutsche Solar AG (a current Solar World AG company) in 1994 (Woditsch, 2011).[7] Sachsen-Anhalt's state subsidy influenced strongly 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 indicate that Solar World was provided with €73 million for the expansion of solar factories in Freiberg in Saxony in 2003, and Q-Cells received a grant of approximately €21 million for the construction of factories in Thalheim in 2004.

Table 4. Main photovoltaic companies in Solar Valley Mitteldeutschland

State	Wafers	Cells	Modules
Thuringia	Bosch Solar in Arnstadt Schott Solar in Jena PV Crystalox in Erfurt	Bosch Solar in Erfurt Sunways in Arnstadt	Bosch Solar in Erfurt Schott Solar in Jena
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: Lee, 2011

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 Chinese growth is export orientated, relies on catch-up rather than initial mover advantages and enjoys access to cheap capital as well as, in common with Germany, strong government financial support.

In China solar cell research dates from at least 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 organizations 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 (CRED, 2000; Stone et al., 1998). 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, including 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: 63–64). Internationally, the Chinese government collaborated with a number of organizations 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).

A particularly important policy initiative was the 'Transmission of 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).[8] Aided by a host of preferential policies and incentives, installed PV system capacity in China increased, with annual growth rates around 27% in 1993–1998. Annual installed PV capacity was, however, still low: 2.3 MWp in 1997 and 3.0 MWp in 1998, up from 900 in 1993 (Dai and Shi, 1999). In 1997 installed production capacity stood at about 4.5 MWp (CRED, 2000).

Another extremely important initiative starting in the 1990s was the widespread use of solar water heating technologies. China's annual solar water heater production capacity stood at 500,000 m^2 in 1992, 15 million m^2 in 2005 and 49 million m^2 in 2010. In 2005 the total surface area reached 8000 m^2 (58% of the global total). In 2010 it reached 168 million m^2 (60% of the world total, and 123.5 m^2 per 1000 people). In the National Development and Reform Commission's 2007 long-term renewable energy development plan (可再生能源中长期发展规划: Kezaisheng nengyuan zhong changqi fazhan guihua – Medium and long-term renewable energy development plan) the use of solar energy for heating was identified as a major priority. For solar water heating, targets for 2010 and 2020 were set at 150 million m^2 and approximately 300 million m^2, respectively. Combined with other thermal applications of solar energy these alternative energy sources would provide 30 and 60 million tonnes of coal equivalent.

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 (1981–1985) and Seventh (1986–1990) Five-year Plans (FYPs) (Cui et al., 1990). In the Eighth (1991–1995) and Ninth (1996–2000) FYPs, funds for increasing the efficiency and reducing the cost of renewable energy reached 60 and 82 million RMB (approximately US$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 Programme for China New and Renewable Energy for the 1996–2010 period (CRED, 2000) that saw the installation of mass production lines for poly c-Si solar cells, the upgrading of production lines for mono c-Si solar cells and R&D into new types of high-efficiency and low-cost solar cells (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 penalized 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 losses (Bradsher, 2010). In the case of solar energy a limited feed-in tariff was introduced in Jiangsu Province (Wei, 2010).[9] 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 Taiyang)’ project to facilitate the deployment of large-scale PV plants of no less than 500 MWp within 2–3 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/RMB per kWh for approved solar projects in 2011, compared with 50.6 euro cents 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 3782 MWp of PV modules, but installed only 228 MWp domestically (Figure 1). By entering global markets Chinese firms were able to secure the volumes required to achieve economies of scale.

The Chinese case: technology and costs

To establish an industry and subsequently enter global markets Chinese companies had to 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 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); subcontracting; 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 and started to produce mono c-Si 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 c-Si solar cells in 1979) (CRED, 2000). Costs were high (400 RMB or US$206) per watt-peak in 1976 (Cui et al., 1990) and output was low, reaching merely 0.5 kW, 1 kW and 2 kW 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 USA and the UK with help from the State Science and Technology Commission (CRED, 2000; Dai and Shi, 1999). In 1989, the Huamei PV Equipment Company of Qinhuangdao (Hebei) entered the solar cell sector (CRED, 2000; Dai and Shi, 1999). 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 400 KWp (Cui et al., 1990).

The gap between the four mono c-Si 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 per watt-peak. Chinese PV modules were therefore some 10% more expensive than foreign products, despite lower costs of plant construction and labour (CRED, 2000; Dai and Shi, 1999). 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% (CRED, 2000; Cui et al., 1990; Dai and Shi, 1999). Average photoelectric efficiency of Chinese commercialized silicon solar cells was 10–12%, compared with 14–16% in developed countries (CRED, 2000; Dai and Shi, 1999). The quality of Chinese solar modules fell short of competitors on the domestic and international markets. Wafer thickness was about 400 μm compared with 250 μm in foreign firms because of differences in cutting technologies that raised silicon feedstock usage and production costs (Dai and Shi, 1999). In the case of amorphous silicon modules, Chinese manufacturers produced only single-junction modules, whereas most foreign firms produced double- 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). Moreover, most users were 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, owing to poor credit ratings and uncertainty about the solar cell market (CRED, 2000; Dai and Shi, 1999).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 helped increase foreign investment. This investment included the establishment of several PV sector joint ventures: Harbin-Chronar Solar Power Company in 1991 and Shenzhen Yukang Solar Energy Ltd in 1992, although the latter was closed in 1997 (CRED, 2000; Dai and Shi, 1999). In the mid-1990s the annual domestic PV market reached over 2 MWp. 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 because of the above-mentioned northern and western province electrification programmes (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, 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).

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

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 establish a reputation for credible and cheap products. Successful completion of these steps enabled them to overcome barriers to enter European markets (Chen, 2010).[10]

To overcome the technological gap, Chinese companies imported turn-key equipment and expanded

Table 5. Production capacity of top photovoltaic companies in China (MWp)

	Capacity									Production	Rank by capacity
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2010	2010
JA Solar					75	175	600	875	2100	1463	1
Suntech Power	10	30	60	150	270	540	1000	1100	1800	1585	2
Trina Solar Energy			6	6	28	150	350	600	1200	1050	3
Yingli green energy		30	50	100	100	200	400	600	1000	980	4
Solarfun/Hanwha Solar One						240	360	420	500	500	10
China Sunergy				32	192	192	320	320	400	400	13
Sun Earth					100		200		450		
Total	10	60	116	288	665	1457	3030	3915	7000	5978	

Annual reports, company websites, interviews and Photon International (2011).

their know-how via learning by doing. By the early 2000s, c-Si solar cell technology had matured, so most state-of-the-art technologies were embodied in production equipment.[11] At first, turn-key-based equipment was imported from Germany, the USA and Japan. As production took place, a rapid process of learning by manufacturing was set in motion (Lee, 2010).[12] Manufacturing experience enabled these companies 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% share of the Chinese PV equipment market (Chen, 2010; Lee, 2010; Xu, 2010; Yang, 2010; Zhu, 2010).[13] 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 (Chen, 2010; Lee, 2010). The other

Table 6. Top 10 solar cell and solar module manufacturers in 2010

Rank	Name	Home country	Annual solar cells production (MWp)		Home country	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

Photon International (2011).

was merger and acquisition activity. Suntech, for example, acquired for list that follows MSK Corporation, a leading PV module manufacturer; Building-Integrated PV (BIPV) company in Japan in 2006; and KSL-Kuttler, a German company specializing 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 led mainly by scientists who studied state-of-the-art PV technology in foreign countries (especially in 2002 Nobel Laureate Professor Martin A. Green's centre in the University of New South Wales in Australia). 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 experiments, but sometimes lacked experience in manufacturing. In contrast, technicians who had worked in factories for a long time had deep tacit knowledge of mass production, but knew little about new technologies.

Almost all of 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 assembly was less complex technologically and subsequently integrated backwards. All undertook each stage of production from ingot and wafer to cell production. Yingli in 2009 added the polysilicon 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 around two-thirds of those of foreign companies. China's competitiveness rested on several factors. First, labour costs are low, especially considering the quality of labour. The average salary of workers in the industrial sector was 26,599 RMB (approximately US$3900) per year in 2009 (NBSC, 2010). In Jiangsu, in 2009 the monthly salary of PV factory workers was between 1000 and 1500 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: in part, there are fewer breakages than in automated process (Zhu, 2010).[14] To reduce the number of breakages Chinese firms train workers carefully, but also employ penalty systems that connect breakages to salaries (Chen, 2010; Lee, 2010; Xu, 2010; Zhu, 2010). The second advantage is customization. A customization strategy is important in the PV sector because there is demand for different sizes of PV modules, and this type of production 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 2000 RMB (approximately US$300) 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% of all first university degrees awarded in China (National Science Board, 2002, cited in Marigo, 2009). The average initial monthly salary of engineers with a Master's degree in the PV industry is around 3000 RMB (approximately US$430).

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

China: finance and investment

Cheap finance and the provision of land and infrastructure at low costs were other major drivers of the competitive success of the Chinese solar industry. Wang (2010)[15] estimates that the cost of setting up a 25-MWp production line with mixed local and foreign equipment was around one-half that of foreign companies (Wang, 2010). One reason for this difference 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 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 was slow, making it difficult to raise finance. Chinese products were also of insufficient quality to compete on the markets that did exist. New Chinese companies, nonetheless, grew owing to local and especially city (shi) government assistance and guarantees in securing bank loans, and funding from state-owned enterprises (SOEs) (Chen, 2010; and Park, 2009).[16] 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).[16]

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 as 'local state corporatism'. This tendency itself reflects strong incentives to facilitate the growth of local industries because of 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.[17]

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 and in the same year JA Solar and China Sunergy were listed on Nasdaq.[18] 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 liberalized, 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, reduce manufacturing costs to levels well below their peers' and 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.

Conclusions : geographical interdependence and growth

The years up to 2010 witnessed unfettered solar energy industry growth in Germany and China.

Recent growth was, however, 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 capacity increases. These investments will increase global overcapacity and contribute to low overall rates of capacity utilization.

In 2010 and 2011 prices fell by more than one-half, in part as a result of learning curve effects, but mainly because of 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, and these pressures will accelerate the ongoing transformation of the industry: the geography of markets and demand will continue to change, vertical integration will increase, as will 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. In spite of these cuts, new capacity in 2011 was expected to exceed 7.5 GWp. To reduce the volume of new installations in the face of opposition to solar energy from large electricity producers and claims that the tariff was driving up electricity costs, in 2012 the German government pushed forward with further reform of the Renewable Energy Sources Act (EEGÄG) cutting support in January 2012 and again in April 2012. These measures are expected to stop planned investments and substantially reduce the pace of installations with potentially negative effects on Chinese producers in the upstream part of the solar value chain.

In contrast, market growth is stronger in China and India – where the governments plan significant increases in installed capacity – and in the USA, especially in California. In China, government energy revitalization plans envisage subsidizing 300 large-scale projects. The geography of market demand is therefore changing, with the fastest growth found not in Europe but in Asia and the USA.

German PV companies have excellent technological capabilities yet confront a difficult market and competitive situation. In 2011 Q-Cells reduced its workforce of 2500 by almost 1000, and reported a €846 million loss. A Bank Sarasin study considers German companies to be ill prepared for currently unfolding difficulties, and anticipates that 'only about one-half of Germany's 50 or so larger solar power companies will survive in the next five years'. At the start of April 2012 Q Cells filed for bankruptcy. Two sets of factors are at work.

The first difficulty relates 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 10 companies is increasing strongly. Critical mass and scale in production and sales are a significant advantage. Moreover, 80% of the capacity of these firms is 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 contrasting 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, Solar World 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 aluminium and polysilicon, tax exemptions, massive loans at below-market rates of interest and discounts on land, power and water. The petition was prompted by several factors. One was the bankruptcy of Solyndra, a solar panel maker that received a $0.5 billion US federal government loan, and two other companies. Another was soaring Chinese imports rising from $21.3 million in 2005 to $2.65 billion in 2011. These increases saw the market share of Chinese companies reach 47%. In December 2011 the US USITC upheld the complaint, opening the way for the US Department of Commerce to impose proposed antidumping and countervailing duties. In March 2012 relatively small tariffs of 2.9–4.73% were proposed though antidumping decisions remained to be made.

In December 2011 the 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 USA of measures that violate World Trade Organization rules and lower the competitiveness of Chinese products in the US market. The CPIA argued that overseas companies led by the USA more than doubled polysilicon imports to reach 47,500 tonnes in 2010 and plan further increases to reach 60,000 tonnes in 2011 and significantly reduce prices to bankrupt their Chinese competitors. In the third quarter of 2011, many Chinese polysilicon factories stopped or reduced production, and more than 2000 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 hydroelectric power sectors.

If the US complaint is upheld, several Chinese companies plan to relocate some operations outside of China. US installers were worried about the impact on sales, and US equipment makers feared that the dispute might adversely affect sales in the Chinese market (Diao and Du, 2011; Du and Ding, 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.

The interdependencies examined in this article are also of wider significance. The rapid growth of China and of a number of other rising powers combined with Europe and the developed world's loss of momentum (Dunford and Yeung, 2011) signify the emergence of challenges to the economic and political leadership of the western world and the need to pay much more attention to global interdependencies in shaping the trajectories of European industries, cities and regions.

The third important set of implications of this article relate to theoretical questions. In this article we have indicated, first, the significance of geographies of interdependence. Second, we have emphasized the importance of the state and a hierarchical institutional order in creating contrasting social conditions for economic life. Third, we have paid considerable attention to demand-side factors alongside the supply-side factors on which much recent economic geography theory has concentrated.

The framework we developed takes the enterprise and its environment as the starting point, and the regional system as a set of enterprises. Over time its ways of organizing production evolves as enterprises seek to innovate, compete and grow (Figure 2 and the idea that innovation and competitiveness is one core driver of development). The relative success of enterprises and an associated set of organizational choices (such as mergers, acquisitions and takeovers) are proximate causes of changes in the structure of the system (Figure 2). However, these changes unfold in a context of interaction amongst regional and national economies: different economies specialize in activities that are sometimes complementary and sometimes competitive, and these interdependencies and the ways they are politically mediated are vital drivers of relative growth and development.

Second, the development of each enterprise depends on the availability of credit and other financial resources (Figure 3). These resources are used not just to invest in plant and equipment, but also to purchase material inputs. In this article, accordingly, we paid greater attention to differences in the availability and cost of credit and, more generally, of financial drivers of development.

Third, the development of the solar sector is crucially dependent on the size and geographical extent of markets. Market creation and expansion is, in part, a consequence of active policy choices that reflect values and interests. In money economies accumulation and growth depend on the scale of effective market demand; market demand depends on expenditure; expenditure depends on income; and incomes are created through the advance of wages and the purchase of material inputs of all kinds. Advances themselves depend on the existence of accumulated wealth, credit and deposits. In other words, economies are driven not mainly by supply-side but by a set of demand-side mechanisms, as recognized in Keynesian and Marxist as opposed to neoclassical models.

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Notes

1. These data refer to sector 854140 in the HS 1996 Classification, comprising photosensitive semiconductor devices, including PV cells whether or not assembled in modules or made up into panels and light-emitting diodes.
2. There are three technologies in the PV industry: crystalline silicon (c-Si); thin film; and others (Boyle, 1996). Of these, c-Si solar cells accounted for about 83% 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 2005–2009, 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.
3. Interview with Thomas Chrometzka, Head of International Affairs in the German Solar Industry Association (BSW), 16 May 2011.
4. A feed-in tariff scheme relies more on non-market than on market mechanisms. Market-orientated tradeable certificates and renewable portfolio standards were adopted in the UK and in many states in the USA.
5. Interview with Thomas Chrometzka, Head of International Affairs in the German Solar Industry Association (BSW), 16 May 2011.
6. The initial wage of an engineer with a Master's or PhD degree in PV firms is around €30,000 or €40,000 per year, respectively (interview with Professor Gerhard Seifert, Solarvalley Graduate School and Martin-Luther University, 17 May 2011). This figure is much greater than that for engineers in Chinese enterprises.
7. Interview with Professor Peter Woditsch, former Chief Executive Officer of Deutsche Solar AG, 10 May 2011.
8. Interview with Xiaozhong (Colin) Yang, Vice President of Public Affairs in Trina Solar, 21 July 2010.
9. Interview with Jun Zhu, Domestic Market Manager in Solarfun, 19 July 2010.
10. Interview with Seok Jin Lee, Vice President of Sales and Marketing in LDK Solar, and a former Chief Operating Officer in Yingli, 7 July 2010.
11. Interviews with Sang Soon Bae, Senior Manager of Hanwha Chemical and former Chief Executive Officer of Nesco Solar, 20 December 2009 and 7 May 2010.
12. Interview with Dr Matthias Peschke, Chief Operating Officer of Masdar PV GmbH, 19 May 2011.
13. Interview with Renbao Sun, Vice Manager in the Development and Coordination Department of China Sunergy, 20 July 2010.
14. Interview with Honghua Xu, Vice Director, Institute of Electrical Engineering, Chinese Academy of

Science, and a former independent director of JA Solar, 6 July 2010.
Interview with Wang, Wenjing, Institute of Electrical Engineering, Chinese Academy of Sciences, 2 August, 2010.
15. Interview with Honghua Xu, and with Professor Qidong Wei, a professor of Nandong University and a director of Jiangsu PV Industry Association, 8 July 2010.
16. Interview with Harry Chen, Group Office Director, Suntech, 16 July 2010.
17. Interview with Professor Qidong Wei, op. cit.
18. Interview with Honghua Xu, op.cit.

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