Paper to be presented at the DRUID Academy 2013

on

DRUID Academy 2013
at Comwell Rebild Bakker, Rebild/Aalborg

Public Policy & Industry Evolution: The Evolution of the Photovoltaic Industry in Germany

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Abstract

Preliminary, please contact the authors before citing or quoting

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Renewable technologies are a main topic in the current energy discussion and in this context photovoltaic is seen as one promising technology. In its first decades the photovoltaic industry in Germany was characterized by a slow evolution. Due to the length of time until the life cycle started the term ?arrested development? will be implemented. Numerous efforts by public policy were then undertaken to stimulate the industry. Thus the course of industrial evolution cannot be understood without reflecting on the impact of public policy. By this, it is the main task of this paper to embed public policy into theories on industrial life cycles. After an overview about the development of this industry in Germany, the existing industrial life cycle theories will be discussed regarding which is applicable to explain the development of this industry. Public policy as a possible trigger of industrial evolution will be discussed.

[Key words: Industry Dynamic, Shakeout, Submarket, Photovoltaic Industry]

Jelcodes:L22,L11

1 Introduction

Until today the photovoltaic industry emerged to a significant industry in Germany, especially in Eastern Germany. For long this technology just occupied niche applications and it took decades to get it where it is nowadays: the production of electricity out of photovoltaic systems is seriously discussed as a pillar for future energy systems. In Germany 3.1 % of total electricity demand was supplied by photovoltaic in 2011 (BMU, 2012). This significant share in application was accompanied by a change in the industrial development, given that attempts to push the use of this technology were always paralleled by the aim to build up a new industry. The years of evolution show distinct characteristics regarding the number and types of firms involved, regarding the policy support intensions and schemes, regarding the technology focus and regarding the scope of applications and diverse market segments. Major changes in the industry can be explained by policy impact.

Seen from the lens of industrial life cycle theories, the evolution of the photovoltaic industry in Germany shows some parallels to those of the laser industry in Germany as well as in the USA. This concerns the fact that the shakeout was not observable for a long time (Bünstorf, 2007). Only recently signs for a beginning shakeout can be observed, as numerous producers face the threat of or already went into insolvency.

The research stream in management theories as well in economics to find regularities in industrial life cycles started at the end of the 1970s with the analysis of the automobile industry in the United States (Abernathy, 1978; Abernathy & Utterback 1978; Gort & Klepper, 1982; Abernathy & Clark, 1985). Different studies in the last 30 years show that industries pass through different stages or cycles in their evolution (Klepper, 1997). In the last years different approaches of industrial life cycle theories were developed (Utterback & Suárez, 1993; Jovanovic & McDonald, 1994; Klepper, 1996; Klepper & Thompson, 2006; Bhaskarabhatla & Klepper, 2011) to understand why industries evolve in a certain way and the authors pointed to different influencing factors. Mostly old industries like the automobile industry in the USA and the tire industry were in the focus of these analyses. Compared to these industries the photovoltaic industry is a young industry. Its development started about 60 years ago but significant dynamics regarding the foundation of new companies and the build-up of an encompassing industrial value chain occurred only in the last 20 years (Dewald, 2012). The dynamics in this industry can by large be attributed to efforts of policy makers in designing different support schemes for this technology. Especially, the Renewable Energy Sources Act (EEG) of 2000 triggered the industrial evolution in Germany, although it was preceded by a series of different funding approaches in the decades before (Jacobbson & Lauber, 2006). Thus, public policy plays an important role in the evolution of the firm population of the photovoltaic industry. But until now, not much attention has been given to public policy as a possible trigger of the evolution of an industry by industrial life cycle scholars. Thus the main conceptual aim is to point out the role of public policy in these theories. Furthermore we will discuss the existing industrial life cycle theories regarding which fits best to explain the developments in the photovoltaic industry. According to this we will apply the model of Bhaskarabathla & Klepper (2008), because the model offers most potential to integrate public policy as a catalyst for industrial dynamics. Our analysis focuses on the German photovoltaic industry, in particular on the development of solar cell production as a core step in the value chain.

In section 2 we will give basic information on different technological designs, submarkets and policy related to photovoltaic technology. Section 3 gives an overview about existing life cycle theories and furthermore investigates the role of public policy therein. In section 4 the data and a descriptive overview of the evolution of the firm population will be presented. Empirical results concerning the predictions built up on the model of Bhaskarabathla & Klepper (2008), based on patent data will be discussed in section 5. The paper ends with a conclusion and some routes for further research will be identified.

2 Technology, submarkets and policy

Solar electricity generation is based on the production of direct electric current by capturing the photonic energy of light on semiconductor materials (Goetzberger & Hoffmann, 2005). Although today turnkey production lines for solar cells exist, the production process is complex and merges a multitude of different cross-sectional technologies. Two main different technological designs can be distinguished: crystalline and thin-film technology. Both pass through distinct steps during the production process, as roughly illustrated in Fig. 1:

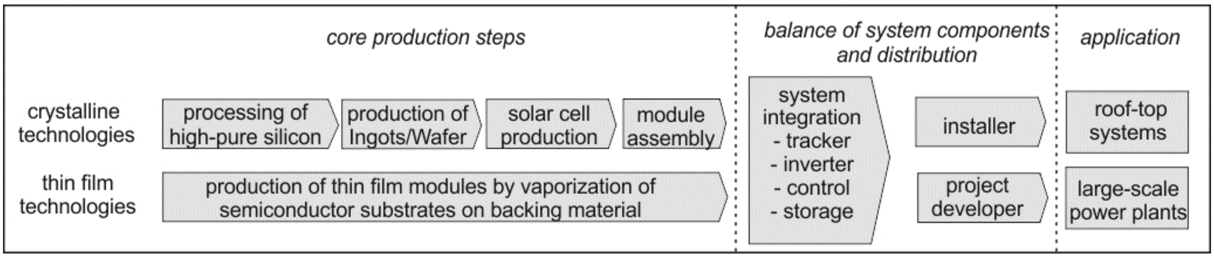


Fig. 1: Value chain of photovoltaic production

Crystalline technologies are based on the production and processing of ingots made of single-crystal or multi-crystalline silicon material, which is then wired into wafers. These wafers are then assembled to solar cells through different treatments like thermal diffusion, screen printing technologies, laser preparation of surfaces, just to denote the complexity of the production process. Against this, thin film modules are produced using chemical vapor deposition to precipitate layers on a backing material like glass. Within crystalline and within thin-film photovoltaic different technological variants exist concerning the purity (in the case of crystalline photovoltaic) or the type of semi-conductor-materials (in the case of thin-film technologies) (Goetzberger & Hoffmann, 2005).

As can be seen from tab. 1, the shares of these different technological designs remained relatively stable over the covered years, although some shifts can be observed from year to year. Strikingly, Cadmiumtellurid based thin film technology experienced a growth, but a deeper investigation of firm structures and trajectories highlights the role of single companies. In this case US-based company First Solar successfully managed the up scaling of thin-film production and developed to the world's third largest producer in year 2010 (Jäger-Waldau, 2011). Although crystalline technologies dominate production technologies with a constant share of more than 80 percent, this example indicates that there remains a window of opportunity for producers in niche production technologies.

	cell technologies (in %)	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
crystalline technologies	*monocrystalline silicon*	40,8	37,4	34,6	36,4	32,2	36,2	38,4	43,4	42,2	38,3	37,8	33,2	30,9
	polycristalline silicon	42,1	48,2	50,2	51,6	57,2	54,7	52,3	46,5	45,2	47,7	43,2	52,9	57
	string-ribbon	4,1	4,3	5,6	4,6	4,4	3,3	2,9	2,6	2,2	1,5	1,4	1,2	0
thin-film technology	*CIS*	0,2	0,2	0,2	0,2	0,6	0,4	0,2	0,2	0,5	1	1,7	1,6	2,4
	amorphous silicon/ micromorphous silicon	12,3	9,6	8,9	6,4	4,5	4,4	4,7	4,7	5,2	5,1	6,1	5	3,4
	cadmiumtellurid	0,5	0,3	0,5	0,7	1,1	1,1	1,4	2,7	4,7	6,4	9	5,3	5,5
	others	0	0	0	0	0	0	0,1	0	0	0	0,9	0,8	0,8

Tab. 1: Competing photovoltaic production technologies 1999-2010 (Photon, 2012)

Considering the application of solar modules, highly diverse submarkets evolved since the invention of the solar cell. In industrial life cycle theories submarkets describe that firms belonging to the same industry can be distinguished concerning different factors, e.g. the technology they use, the targeted customer segments, the regions (geographic areas) in which the firms are active for example (Klepper & Thompson, 2006).

Following this, a closer look on different applications for the technology during the last decades is required. Over time different submarkets occurred in Germany and were affected by different inventions. The first submarket was the ´space´submarket (off-grid space application) which dominated the years 1957-1973. The second submarket was the ´off-grid-submarket´ (terrestrial off-grid applications) in the years 1973-1995. Follwed by the occurrence of the third submarket, the ´on-grid-submarket´ (grid-connected roof-top-systems) since the beginning of the 1990ies. As a fourth one large-scale ´power-plants´-as on-grid systems emerged since 2000 (Breyer et al., 2010).

The basic invention of the solar cell dates back to 1954, when a first solar cell was developed at Bell Laboratories, US (Perlin, 1999). With the start of the moon race and big aerospace research programs, some industry players in the US started to invest into R&D, given that photovoltaic was seen as the superior technology against other options for power generation (Perlin, 1999). The space market served also as the origin impulse for some German companies to start R&D in photovoltaic technology (Räuber, 2005). Following Jacobsson et al. (2004) this was due to US export restrictions on the European Space Agency, leading to own aerospace programs in European countries. The BMFT announced the first German space program in 1962, and AEG-Telefunken as one of the large German electronics companies was involved as an industry partner therein. AEG-Telefunken started to build up research facilities and a pioneering production line from the middle of the 1960s and in 1969, the first German satellite AZUR was powered with solar cells developed by AEG-Telefunken (Jacobsson & Lauber, 2006). Other industry players like Siemens started early operations as well in the context of the space program (Jacobsson et al., 2004). This first market was important in delivering access to broad public funding for the basic development of a production process.

A next submarket emerged in the context of the oil crises and with the formation of the environmental movement during the 1970ies. Photovoltaic technology first moved to terrestrial off-grid applications, where it was able to compete against fossil-fuel-based energy supply technologies. Installations for telecommunication devices, watering pumps and other off-grid applications were explored. Later on, projects were realized in the context of development aid for countries in the third world. German company AEG for example carried numerous projects during the 1970ies (Dewald, 2012). But as well, photovoltaic systems served to power remote locations like cottages in the home markets of the producers. Production costs remained high, due to a poor level of industrial automation and the low size of markets (Jacobsson & Lauber, 2006). Research was still heavily depending on public funding. From 1974 till 1984, yearly research funding by the federal state grew from 24 million to 274 million EUR (BMU, 2010).

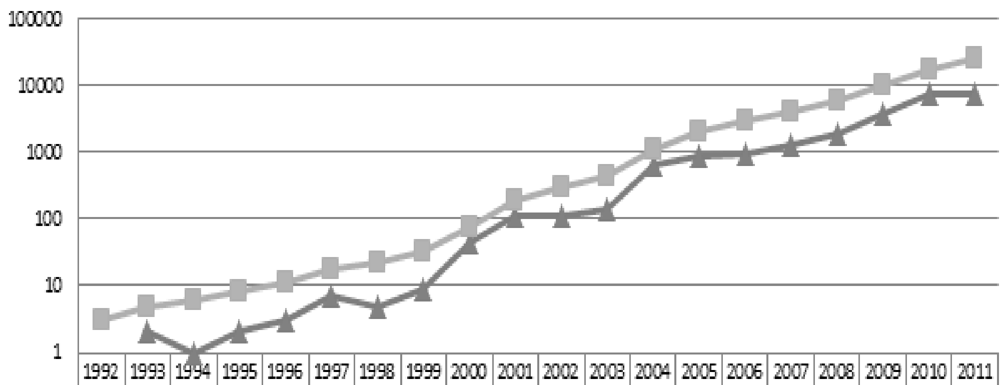
Due to disappointing results of the hitherto funding with its focus on industrial based research, existing schemes were complemented by demand-oriented funding. This fundamental change went along with a shift from centralized large-scale applications to decentralized small-scale applications. Mainly from the beginning of the 1990ies the now most important sub-market for on-grid installations emerged. This new market was publicly funded by a multitude of programs from the local over the federal ("Bundesländer") to the state level. The emergence of on-grid-installations was accompanied by a fundamental shift from technology- to demand-oriented-funding schemes. With the 1000-roofs-program by the BMBFT (Federal Ministry of Education, Research and Technology) a total installation of about 2400 decentralized roof-top systems was realized between 1991 and 1995 (Erge et al., 2001), by then the largest support program worldwide (Jacobsson et al., 2004). For roof-top systems of 1-5 kWp installed capacity a maximum of 70 % of the total system prices where subsidized by the state. It was accompanied by a comprehensive monitoring program and especially focused basic aspects of system integration like the development of inverters and architectural integration (Erge et al., 2001).

Beside this program, diverse subnational activities contributed to the demand funding as well. The growing support coalition stemming from the green movement acted on the utilization of photovoltaic technology. A network of local initiatives started to introduce cost-covering payments, a basic mechanism of the later EEG, at the local level (Dewald & Truffer, 2011). As well, utilities introduced small-scale funding programs based on soft loans and remunerations. Beside these activities, some federal states like Northrhine-Westfalia started support programs as well. Combined, these funding schemes at different spatial scales took effect in pushing market development strongly in direction of decentralized roof-top applications and they secured continuous market formation especially in between the 1000-roofs-program and the later 100.000-roofs program.

Program	*Aim*	*Type of subsidies*	*Years*	*volume/inst. capacity*
1000-roofs program	test program to explore the technical feasability of decentralized roof-top systems by the state	Subsidy: 70 percent of total investment sum	1991-1994	2250 system, 6,15 MWp
REN-Programm	Broad funding program for renewables by Northrine-Westfalia	Government grants per installed kWp by federal state	1988-2003	25 MWp (till 2000)
100.000-roofs-program	Broad market support program for pv	State/KfW, soft loans	1999-2003	~50 MWp, till 2000, 345,5 MWp till 2003
Cost-covering payments	Remunerations at level of municipalities, utilities	Cost-covering payments by apportionment to grid subscibers	1994-2000	~40 municipalities*
200-roofs program Hamburg	Equipment of 200 roofs in Hamburg by HEW (=utility of city of Hamburg);	Purchasing of pv-systems by rents from HEW, which were paid to roof-owners	1997	
Shareholder programs By municipalities, utilities (Bayernwerk)	Purchase of shares by individuals	Yearly payback according to amount of shares respective produced kWh	From 1994	ca 0,35 MWp
Tender of BEWAG Berlin (utility)	Tender to subsidy efficient and cost-effective systems	Grant + remuneration	1996-2000	2,275 MWp
Bulk purchasing – program by Stadtwerke München (utility)	Low-priced purchase of do-it-yourself-kits by bulk purchases	Lower prices for systems in combination with local remuneration and shareholder model	1996	225 systems, 0,52 MWp
Green pricing schemes of providers, RWE und EnBW	Financing of pv systems installations by green tariffs	Voluntary payment of additional price per kWh by customers	1998-2000 (RWE) 2000 (EnBW)	1,05 MWp (RWE)
„Sonne in der Schule"	Demonstration program at	Investment grant of 60 % by utility	1994-1997	544 systems 0,61 MWp

Tab. 2: Different funding schemes preceding the EEG (Source: Dewald 2012, based on IEA-PVPS 2002)

With the victory of the red-green coalition in the 1998 elections the political conditions in Germany again changed considerably. In 1999 the 100.000-roofs-program was introduced, a funding scheme based on soft loans by state-owned bank KfW (Kreditanstalt für Wiederaufbau) (Jacobsson & Lauber, 2006). Shortly after that the Renewable Energy Sources Act (EEG) was introduced. The basic mode of the feed-in-tariff is a fixed remuneration for operators of renewable energy plants, which is paid for twenty years in the case of the German EEG. The costs are apportioned to all customers within the respective national grid, except large-scale industrial producers with high power consumption. Thus, the success of the EEG – as indicated in Fig. 2 – is based on long-term planning reliability in combination with a sufficient payment. In combination of both EEG and 100.000-roofs program secure funding conditions were realized and a considerable boom in the German market started (IEA-PVPS 2012).



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
yearly inst. cap. (MW)	0	2	1	2	3	7	5	9	44	110	110	143	635	906	951	1274	1955	3799	7411	7500
cum. inst. cap. (MW)	3	5	6	8	11	18	23	32	76	186	296	439	1074	1980	2931	4205	6160	9959	17370	24800

Fig. 2: Market development in Germany 1992-2011 (Source: IEA-PVPS (2012))

By this it can be seen, that the emergence of sub-markets is directly linked to the type and design of policies, while small-scale roof-top installations were targeted in these programs. Only from 2004, an amendment of the EEG led to an opening for large-scale applications, mostly as ground-mounted systems on agricultural areas.

It has to be pointed out that in the EEG no restrictions regarding the technology design were integrated. It thus created a competitive environment, were companies with different backgrounds both in crystalline and thin-film technologies were founded (Jacobsson et al., 2004).

3 Theories

Evidence on the industrial life cycle: Gort and Klepper (1982) describe empirical regularities how industries delivering new products evolve. Their work can be seen as the origin of a number of industrial life cycle theories. Gort and Klepper (1982) point out that it is possible to distinguish between five stages in these regularities. Right in the beginning (stage I) the market consists only of a few firms. In the second stage the number of firms (producers) grows rapidly. In stage III there is stagnation in the number of firms which will be followed by exits in stage four (negative net entry - shakeout). Shakeout describes the fact that the number of firms highly decreases, while the output of the market still grows. The last stage (V) features the equilibrium. This stage will last until the industry is confronted with some fundamental changes. It is pointed out that technical change is important for the evolution of an industry (Gort & Klepper, 1982). The evolution of an industry in this way is possible, but in fact it is not obligatory (Klepper, 1997).

In the last years different approaches were developed to further refine this basic approach of industrial life cycles. Different factors which influence the evolution of the firm population in certain industries were pointed out. The theories can be arranged to different categories. On one side there are the shakeout theories (Utterback & Suárez, 1993; Jovanovic & McDonald, 1994; Klepper, 1996) and on the other side there are submarket theories (Klepper & Thompson, 2006). A third field of research tries to merge these theories (Bhaskarabhatla & Klepper, 2011). These theories will be discussed in this section. We are going to ask for the impact of public policy in these approaches and which of these theories is useful for explaining the evolution of the photovoltaic industry in Germany.

3.1 Shakeout Theories

There are different approaches that try to explain the industrial life cycle and the shakeout of industries of which the most important are the approaches by Utterback & Suárez (1993), Jovanovic & McDonald (1994) and Klepper (1996).

In the four-stage-industrial-life-cycle-model of Utterback & Suárez (1993) it is assumed that a dominant design leads to a shakeout in an industry. The dominant design is a product that is adopted to a large extent by other firms and the occurrence of this product leads to a change in the innovation patterns within firms and industry and furthermore in the competition dynamics. Utterback & Suárez (1993: 17) say *"The dominant design which emerges is not necessarily the result solely of technical potentials, but also of timing, collateral assets and other circumstances. Once a degree of standardization is accepted, however, major innovations from within an industry seem less and less likely to occur short of a wave of new entrants and increasing competition."* At a certain point of time in the life cycle of an industry a creative synthesis of new product innovations from one or more firms in this industry leads to a monopoly. This impermanent monopoly is linked with high prices and high profit margins. The product is first placed in some niche markets. After a certain time

the demand as well as the production grows and new firms will enter the market with certain variants of the product. These variants are developed through innovation.
In this approach it is assumed that not the size of a firm is of great importance but rather that innovative firms from outside the market enter in the market. Through the emergence of a dominant design the firms shift their efforts to process innovations and process integration, the rate of product innovations decline. The inability of incumbents to change the internal structure and practices is seen as the major source of failure. So the shakeout in the industry is triggered by the emergence of the dominant design. It is assumed that in certain markets the market becomes stable as well as the sales and the market shares and only a few large firms offer standardized product which at the utmost differ only slightly. When a major discontinuity appears it is possible that through this maybe a new cycle starts (Utterback & Suárez, 1993).

The model constructed by Jovanovic & McDonald (1994) builds on Gort and Klepper (1982). Central in this theory are two inventions. The first one starts the formation of the industry. Furthermore they improve the model by introducing a refinement, the second invention in this model. Jovanovic & McDonald (1994) assume that an invention from outside the industry is implemented by the firms and this leads to an increase of the output on firm-level. The firms innovate and at a certain point of time a refinement will be made. This refinement leads to an increase of the optimal scale of each firm that implemented this refinement before. After this scale-enhancing innovation is introduced the price of the product will decrease and the firms will start to exit the market (shakeout). This can happen in a rapid process or in a more or less gradual process. After this the number of firms stabilizes (Jovanovic & McDonald, 1994).

The model of Klepper (1996) is a further development of the model which was developed by Klepper & Graddy (1990). The model considers innovation as an important factor of industrial evolution. Right in the beginning there are no restrictions respective if the number of potential entrants rises or falls, because it is assumed that this differs concerning single industries. For simplicity it is assumed that all firms produce the same product. In each period incumbent firms decide whether they stay and also the potential entrants decide if they should enter. All firms own innovative expertise, which cannot change over time. The success of the R&D efforts is influenced by the experience of the firms in R&D. Concerning their experience the firms differ. A distinctive product innovation is developed by the successful product innovators in each period and combined with the standard product to a unique product which can be put on the market. The variant of the industry product can be sold at a higher price but it is only demanded by a new class of buyers. In the period after the introduction the rivals can introduce an imitation because they are able to monitor the other firms. Through this the firm has only a one-period monopoly of the new product. When the output increases the costs decrease. By this larger firms have a competitive advantage. It is assumed that the average costs are determined by process-R&D. Through process-R&D the average costs can be reduced. The returns of the process-R&D efforts increase and because of this the early entrants have a competitive advantage. The market shares of the firms change rapidly. Over a specific period of time the output of the market still grows, regardless there is less entry, and also there is more exit than entry. In this context product innovations as well as the diversity decline. The producers convert their product innovation efforts into process innovation efforts. The firms try to improve the production process and over time the market shares stabilize (Klepper, 1996). While the incumbent firms grow, the price of the product declines. Because of this entry might become unprofitable for other firms and furthermore some of the smaller firms are forced to exit the market (Klepper, 1997). This point in the industrial life cycle is called the shakeout (Klepper, 1996). After the shakeout the industry evolves towards an oligopoly, which is mostly dominated by the early entrants with the best capabilities (Klepper, 2002). Important in this model is that the process innovation is not a single event but rather a gradual process that can happen in all periods and finally leads to the shakeout (Klepper, 1996, 1997).

3.2 Submarket theory

The patterns of industry evolution as described above are possible but not obligatory for all industries. For a long time it was just ignored in these theories that firms can also belong to more than one submarket. Also the fact that a firm may enter and then exit again one special submarket while the firm is still on top in another submarket, as well as that one submarket may become important only for a certain time and then declines (Bhaskarabhatla & Klepper, 2011) was ignored for a long time. Furthermore not all industries experience a shakeout (Klepper & Thompson, 2006).

Firms often do not operate only in one market, but rather are producers of several products and so they act also in several markets (Dunne et al., 1988). These aspects considering a submarket model were developed by Klepper and Thompson (2006). In this model it is assumed that the moving power for change in an industry is the creation and as well the destruction of submarkets. An industry is built up on different submarkets, but it starts with only one submarket. Over the time new submarkets are created. The life of each submarket is limited. Furthermore a submarket consists of different firms which have different market shares which can also vary. There are numbers of potential entrants and the probability to enter the market is equal for all firms. The firms differ concerning the number of submarkets in which they are active, when e.g. the geographic markets decline or the technology change the submarkets vanish. When a firm is only involved in one submarket, it is assumed that the firm dies, when the submarket dies. The survival of a firm is positively related to its number of submarkets. The evolution of an industry is affected by the creation and destruction of submarkets (Klepper & Thompson, 2006).

3.3 A unified model

Bhaskarabhatla & Klepper (2011) developed a model that integrates the shakeout and submarket theories. The model works as described in the following. Right in the beginning there are potential producing firms. In the first period (period 0) the first product and through this the concerning submarket is created. In each of the following periods new submarkets can arise. All firms have the same probability to enter a new submarket. New submarkets occur, when a new variation of a product is developed that attracts a new group of buyers. These new products are no perfect substitutes to the existing products. In each period the same probability exists that through a technical advance, possibly exogenous, a new product and through this, a new submarket arises. It is assumed that no new submarket will occur, if the price P is so low, that new submarkets are not profitable anymore. As long as the submarkets are small the firms do not investigate in process R&D. Furthermore as long as the price of the product in one submarket is not lowered enough the different submarkets do not compete with each other. When the price is lowered extremely the product can attract potential customers from other submarkets. At a certain point of time, the growth of one submarket, triggered by an exogenous technical advance, can lead to such a high growth so that it is cost-effective for firms to invest in cost-reducing R&D (process R&D). Through this the price of the product in one submarket decreases and furthermore the demand as well as the output in the industry rises. Through the competition smaller firms as well as latecomers from other submarkets are forced to leave the (sub-)market and, if they produce only in one submarket are furthermore forced to leave the industry. Possibly other submarkets also disappear because the customers are attracted by the cost-efficient submarket and the submarkets lose their output. Through this the shakeout is triggered (Bhaskarabhatla & Klepper, 2011).

3.4 Theoretical considerations –Public policy in industrial dynamics

All these theories above are centered on technological change as the driving force for the evolution of industries (Bünstorf, 2007). In the technological approach of Utterback & Suárez (1993) the shakeout is triggered by the appearance of a dominant design. In this way public policy could be integrated as a trigger for the emergence of a dominant design. In this context standardization could be used as a policy instrument to create an artificial dominant design. Through this the shakeout could be triggered by public policy. Industrial dynamics in the model of Jovanovic & McDonald (1994) are triggered exogenously. An innovation based on an invention from outside the industry leads to the shakeout (Jovanovic & McDonald, 1994). The evolution of the firm population and the shakeout in this approach are explained through technological impact. Possibly the invention from outside is triggered by public policy, e.g. through technology diffusion or through public research. By this public policy may impact the evolution of the industry, precisely because public policy could lead to an invention which furthermore leads to an innovation in the industry. Through this it could lead to the shakeout. Klepper (1996) focused in his research on the evolution of "technologically progressive" industries. In the concept of the industrial life cycle knowledge and innovation are very important. In this model public policy is not really considered. However it could be that a subsidization of process R&D could possibly lead to a faster shakeout. In this way public policy could be considered as a trigger of industry evolution.

Utterback & Suárez (1993), Jovanovic & McDonald (1994) and Klepper (1996) developed theories that explain how industries evolve and in the last step they identify different triggers that lead to a shakeout in an industry. Public policy efforts are not considered but may be included as shown above. In the cases above public policy is only considered in the case of R&D-related policy tools. But regarding the case of photovoltaic technology, (1) until today no dominant design occurred (c.f. Fig. 2). Neither a product was adopted to a large extent by other firms nor a product led to a change in innovation and competition patterns of single photovoltaic firms as well as the whole industry. No technology came up to the top until today. (2) The invention of the solar cell started the industry. There are innovations that support the development of the product, but there is no major invention from outside the industry, that led to a refinement. The major inventions in photovoltaic technology come from inside the industry. (3) The model of Klepper (1996) points out that gradual process innovation lead to an early shakeout in the industry. (4) Furthermore the opportunity that an industry consists of more than one market is also not considered in these approaches. Over time different submarkets occurred and were affected by different major inventions.
According to this, these three theories seem not to be suitable to explain the developments in the photovoltaic industry because of the different listed reasons. Despite all, these theories might explain the happenings in the photovoltaic industry. By highlighting different circumstances these three theories point out, that an early shakeout in the industry is observable. So we will test the following prediction, regardless the listed reasons, whether the theories possibly explain the evolution of the photovoltaic industry.

(P1) An early shakeout is observable in the industry.

In the model of Klepper and Thompson (2006) the trigger for change in the evolution of an industry is the process of creation of submarkets on the one hand and destruction of submarkets on the other hand. Coincidence leads to new submarkets, but the circumstances are not clearly defined – public policy is not mentioned in this model. But in fact it could possibly play an important role. The industry in this model evolves through the creation and destruction of submarkets.

(P2a)The industry evolves over time through the creation and destruction of submarkets.

(P2b) No shakeout is observable in the industry.

In the model of Bhaskarabhatla & Klepper (2011) the impact of submarkets on the evolution of industries is analyzed. Submarket dynamics are used to explain regularities like entry, exit and growth in the industrial life cycle. The growth in the submarkets is triggered by an exogenous shock. The shakeout process is triggered by a certain technology in one submarket that leads to a change from product to process innovation. Public policy as a trigger is not considered in this approach. But it could possibly be considered. E.g. through demand subsidies an artificial demand could be created and lead to the growth of one submarket. In this way the exogenous shock for growth would be public policy which created the artificial demand. The model of Bhaskarabhatla & Klepper (2011) might fit to explain the evolution of the cell producers as a main part of the core value chain of the photovoltaic industry in Germany. Built on the model of Bhaskarabhatla & Klepper (2011) which explains the shakeout through an exogenous shock we posit just one extension. It is public policy, that drives exogenously the growth in the submarkets and leads furthermore to the new technology that finally triggers the shakeout. To check if the model is applicable to explain the dynamics in the photovoltaic industry the following predictions concerning the model of Bhaskarabhatla & Klepper (2011) are made.

(P3) The evolution of the photovoltaic industry was triggered by public policy.

(P4) Increasing output leads to an increase in the number of innovations in the industry.

(P5) The form of innovations shifts over time from product to process innovations and larger firms should have more process innovations relative to other firms.

(P6) Large firms have comparatively more innovations than small firms. Large firms are those with a high output level.

4 The firm population

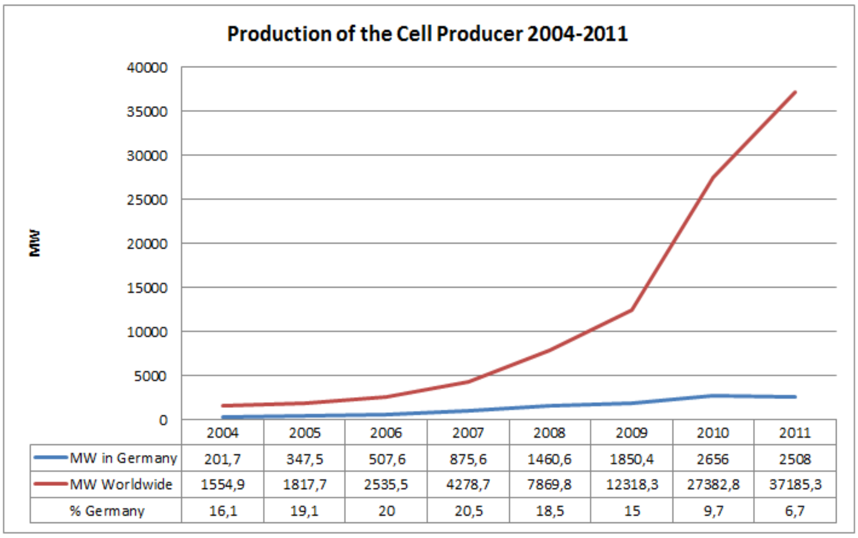
4.1 Evolution of the firm population

In the mid1970s to mid 1980s external impacts led to a change in industrial development. With the oil crises in the 1970s, a broad discussion on secure energy production started, with considerable effects on public research funding and industry dynamics. First, and parallel to the first stage, some large-scale companies in the electronics and/or energy sector started operations in photovoltaic technology, with a shift to terrestrial applications. Companies like MBB, Nukem – a subsidiary of one of the major German utilities RWE – and Wacker joined the field of the industrial players with large and mostly public funded research programs. New technological approaches like thin-film photovoltaic technology were focused, thus the technological spectrum diversified. Observers of the early technological development point out that research was nearly exclusively concentrated at large companies (Pfisterer & Bloss, 1989) and driven by convictions that this applied research would rapidly lead to the production of efficient solar cells (Räuber, 2005). Beside some university research groups, the foundation of Fraunhofer ISE in Freiburg in 1983 was a first account to diversify the R&D-landscape. Still, effects in terms of broader market diffusion remained low, although market development occurred in small consumer markets and in off-grid applications and was thus broadened from the ongoing satellite market to terrestrial applications. At the end of this stage, again an external event affected the development trajectory. The Chernobyl accident in 1986 pushed the formation of an influential green movement and affected the direction of public policy. In the course of this, discussions about photovoltaic technology as an on-grid power source were intensified. Shortly after this event, research institutes were founded in several federal states ("Bundesländer"). Parallel to this the 1980s saw the installation of first on-grid demonstration systems, again funded by the federal government (Jacobsson et al., 2004). Several large-scale applications were installed to test the modules, often in corporation by utilities and accompanied by monitoring programs (Räuber, 2005).

Until 1998 the industry saw distinct changes both in funding, in market formation and in the development of the industry. But what was the effect on industrial development? Although these first demand-oriented support schemes were introduced the industrial development at that time was characterized by a consolidation. Apparently the market demand was not strong enough to stimulate broader investments in upstream segments of the value chain (Jacobsson et al., 2004). Even the opposite was the case: After several decades of intense funding, the two major players in Germany closed their production lines or threatened to do so. Siemens acquired a US company and shifted production there, and ASE, a company that merged former photovoltaic activities of NUKEM, DASA and MBB, was close to follow Siemens to the promising US market (Dewald, 2012).

In the years 1998 until 2010 several important developments occurred. In line with this first growth, a considerable boom at all levels of the value chain occurred in Germany. This industrial growth was based on mainly three sources. First, some of the still existing players extended their operations, like ASE. Partly, these already existing companies extended upstream and/or downstream. For example, SolarWorld as one of the major German producers developed from a mere project developer in the late 1990s to a vertically integrated photovoltaic company by acquiring the wafer production of chemistry giant Bayer. Subsequently it started solar cell and module production shortly after the introduction of the EEG. Second, new start-ups were founded. These emerged from sometimes decade-long research activities at universities or research institutes and profited from easy access to venture capital for technology-oriented start-ups at the end of the dot-com-bubble. As a third source of industrial rise, investors from abroad chose Germany to start production facilities due to promising market conditions. All this led to strong industrial growth, and German producers of solar cells reached a global market share of about 20 percent in 2005, the highest share after the introduction of the large market formation subsidies (Dewald, 2012). The industrial growth did not only occur in the core value chain. Due to the large market, producers for system integration components like inverters or trackers entered the industrial landscape. Later on, the boom led to the entry of numerous mechanical engineering companies, who supplied production lines for solar modules. Combined, this stage was characterized by parallel growth of the market and the industry and thus deviates from the earlier development. Although evaluations of the EEG led to strong reductions of the feed-in-tariffs, efforts in industrial production compensated these and secured the ongoing market growth.

Only the last years since 2010 are characterized by a new situation. Although the feed-in-tariffs again dropped considerably, years 2010 and 2011 experienced the highest market growth in the history of photovoltaic technology in Germany (Bundesnetzagentur, 2012). But, and different to the former stage, this market growth was not accompanied by an ongoing growth of the industry and the output, as can be seen from fig. 3. The share of German producers contracted over the last years, and from 2010 to 2011 even a drop in absolute terms occurred.



	2004	2005	2006	2007	2008	2009	2010	2011
MW in Germany	201,7	347,5	507,6	875,6	1460,6	1850,4	2656	2508
MW Worldwide	1554,9	1817,7	2535,5	4278,7	7869,8	12318,3	27382,8	37185,3
% Germany	16,1	19,1	20	20,5	18,5	15	9,7	6,7

Fig. 3: Production of the Cell Producers 2004-2011 (Source: Photon 2001-2012)

Quite the contrary, the last years were characterized by consolidation and closing-down of operations and the stars of the growth phase like Q-Cells – once the world leader in cell production – or Conergy face a drastic restructuring.

4.2 Data

For studying the evolution of the photovoltaic industry in Germany an original dataset is required. Due to the fact that the photovoltaic industry is a young industry the evolution of the industry is more or less observable in real time. In reverse there is only limited secondary data and compilations on the history are rare.

Our empirical analysis is based on a dataset including the full population of German photovoltaic firms, namely the cell producers. We have data on firms, patents and output on the level of the cell producers. The principal source of information is the leading trade publication Photon that has been published since 1996 and represents a good source for numerous of different information. It offers an annual market overview for cell producers. In addition Photon provides from 2000-2012 an annual production overview of the cell producers worldwide. Furthermore Photon provides an annual worldwide market overview for the module producers (including the cell producers) for the years 2004 until 2008. Additionally there is literature available dealing with the history of the solar industry. Especially in the first years (around 1950), there were only few large firms (with a small photovoltaic division). By this it was possible to identify the firms of the first hour (c.f. Räuber, 2005). Beside the data of Photon we also collected the entry dates of the firms by observing the firm histories at homepages. If we did not find data for the start of cell production in the cell production overview of Photon we used the entry date at the homepages. Despite this to make it reproducible and comprehensible we use as the entry date for all firms that entered after 2000 the first time the firm occurred in a cell production overview of Photon, except for those firms, we found clear evidence in firm-histories, that they entered before. For the firms, that entered before 2000 we made an Internet based search.

Altogether we identify 44 entrants (cell producers) into the German photovoltaic industry from 1950 to 2011.

4.3 Empirical results

In contrast to other industries the photovoltaic industry started its evolution arrested.

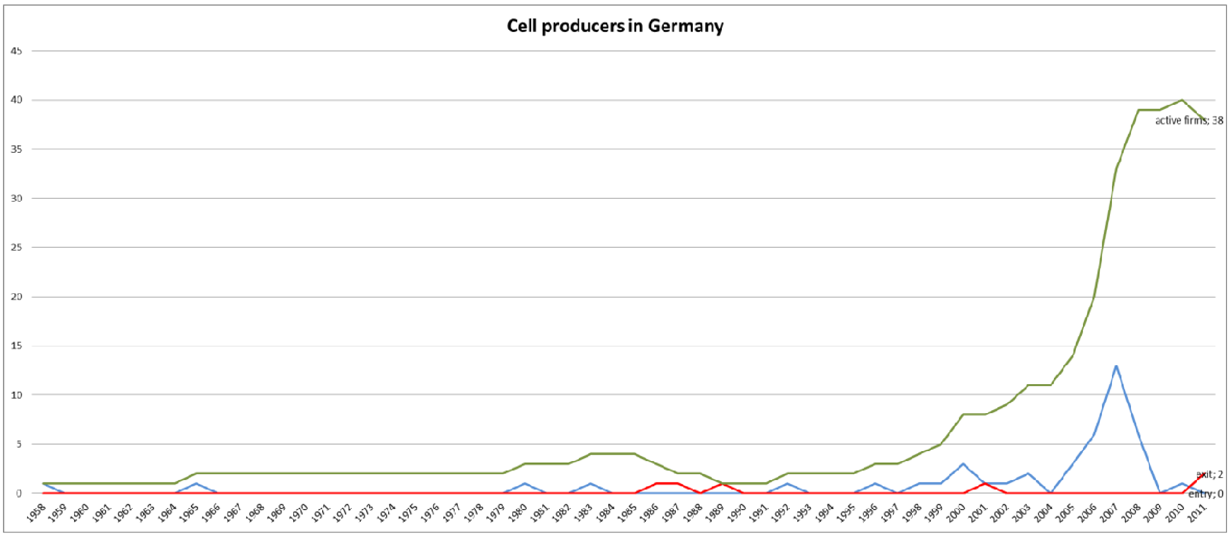


Fig. 4: The evolution of the cell producers in Germany

As described in the history overview only few market entries in this industry between 1950 and 1990 were observable. The first years of this industry were unimpressive. In the early years the active firms consisted only of a few big firms like Siemens and AEG-Telefunken. Although the first firms entered the market in the 1950s, a real start of the industry can be found in the middle of the 1990s. As described before in the overview, there was an industrial stagnation until 1998. This development will be defined as "arrested development". Arrested evolution describes the fact that for over 40 years the firm activities in this industry were on a low level. More or less neither entries nor exits happened. The starting point of the industrial life cycle is not close to the invention of the product.

The shakeout theories assume that an early shakeout in the industry is observable. Concerning this we cannot confirm prediction 1. Consequential the theories of of Utterback & Suárez (1993), Jovanovic & McDonald (1994) and Klepper (1996) are not applicable to explain the evolution of the photovoltaic industry in Germany.

Fig. 4 shows that from 1998 to 2004 a moderate rise in the number of cell producers is observable, while between 2004 and 2008 a fast rise is observable. The peak number of 40 active cell producing firms was reached in 2010. After this year more exits than entries occured - the number of firms decreases. In the German photovoltaic industry no shakeout has occurred to date, but Fig. 4 indicates that the shakeout is in the making.

Taking a closer look on the photovoltaic industry it is observable that there are different submarkets – space, off-grid and on-grid. Until today no submarket was destroyed. Neither the space submarket nor the off-grid submarket triggered the shakeout. No shakeout has happened to date, but more exits than usual are observable in the on-grid market. Despite, the incidents indicate that a shakeout is in the making. Prediction 2a and 2b are made up to test whether the model of Klepper and Thompson (2006) is suitable to explain the evolution of the photovoltaic industry. According to the data, prediction 2a and 2b cannot be proofed true. Consequential the theory of Klepper and Thompson (2006) is not applicable to explain the evolution of the photovoltaic industry in Germany.

Table 3 shows the evolution of the firm population combined with important developments (laws, support programs, research funding and other happenings witch might be important in this context) in the years 1958-2011. In this overview the arrested development again is observable. Furthermore it highlights that the number of firms starts to increase after the shift from research to market funding in 1990/1991. Between 1990 and 1997 the demand was not strong enough to stimulate broader investments; there was still stagnation in the number of firms. After the implementation of the 1000-roof-program there was stagnation in the programs on federal level. Although the programs on the level of federal states or communities were small programs, these programs led to a support of this industry and prevented a total breakdown of the industrial activities. In 1998 there was a change of government and furthermore these new government set up new, bigger programs then before and introduced the EEG. After these activities a strong growth in the number of firms is observable.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
Entry	1	0	0	0	0	0	0	1	0	0	0	0	0
Exit	0	0	0	0	0	0	0	0	0	0	0	0	0
Active Firms	1	1	1	1	1	1	1	2	2	2	2	2	2
Policy Events					1. German space program								
Other happenings													

Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
Entry	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Exit	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Active Firms	2	2	2	2	2	2	2	2	2	3	3	3	4	4
Policy Events				yearly research funding by the federal state grew from 24 million to 274 million EUR										
Other happenings			Oil crises											

Year	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Entry	0	0	0	0	0	0	0	1	0	0	0	1	0
Exit	0	1	1	0	1	0	0	0	0	0	0	0	0
Active Firms	4	3	2	2	1	1	1	2	2	2	2	3	3
Policy Events							Stromein-speise-gesetz 1000-roofs-program	1000-roofs-program	1000-roofs-program	1000-roofs-program			
Other happenings		Chernobyl accident											

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Entry	1	1	3	1	1	2	0	3	6	13	6	0	1	0
Exit	0	0	0	1	0	0	0	0	0	0	0	0	0	2
Active Firms	4	5	8	8	9	11	11	14	20	33	39	39	40	38
Policy Events		100.000-roofs-program	EEG 100.000-roofs-program	100.000-roofs-program	100.000-roofs-program	100.000-roofs-program	EEG amendment					EEG amendment		
Other happenings	Change of government													

Agenda	laws
	support programs
	research funding
	local programs

Tab. 3: Development of the active firms in the context of the evolution of laws and funding

The table shows, that the EEG has strong influence on the evolution of the cell producing firms of the photovoltaic industry in Germany, while there is no influence of the "Stromeinspeisegesetz", the 1000-roof-program and the 100.000-roof-program as explained before. The influence of these laws on the evolution of the photovoltaic firms is insignificant. Quite important happenings in the history of the energy sector were the oil crises in the 1970ies and the Chernobyl hazard in 1986. These had no influence on the evolution of the firm population of the German cell producing photovoltaic firms. Nonetheless, these events promoted the development of support programs for the industry. This can be explained by the scope, size and mode of the different programs, where only the EEG secured stable investment conditions and thus stimulated a broader market formation. This again shows that public policy can be seen as the main trigger of the photovoltaic industry's lifecycle. Prediction 3 can be proofed true.

We point out that not a technological advance but demand funding (laws) triggers the evolution of the photovoltaic industry in Germany.

5 Patent Data - Testing the predictions of the model

Concerning the existing literature, patents can be used as a proxy for innovations (c.f. Acs & Audretsch, 1989). We collected patent data for the cell producers in Germany. For this a firm name based search in Depatisnet[1] for all 44 producers was made. Patents for 35 firms were found. Family members were removed. Included in the analysis are DE, EP and WO publications. The number of patents is 1317. Some of the patents (382) which were found through the name based search could be identified as being not relevant for the photovoltaic industry. After eliminating those patents there are 935 patents left and 891 (=95,3%)[2] could be gripped for the analysis (Bauckloh, 2012).

Out of these patents we analyzed the most important class for the cell producers. The largest and most important class is H01L, including 591 patents (66,3%) of these firms. Tab. 4 shows the average number of patents per year in class H01L and the average number of patents in all classes. A continous rise in the number is observable.

Year	Average patents/ year (class H01L)	Average patents/ year (all classes)
1950 - 1959	0	0,1
1960 - 1969	0	0,1
1970 - 1979	0,5	1,3
1980 - 1989	3,2	5,5
1990 - 1994	8,2	10,2
1995 - 1999	8	11,2
2000 - 2004	11,2	22
2005 - 2009	51,4	71,6
2010 - 2011	80	122,5

Tab. 4: Evolution of the number of patents in class H01L and all classes from 1950-2011

The output data is based on the trade publication Photon, which offers an annual overview of the production and the capacity of the solar cell producers since 2000. We have output data for 37 of the firms.

5.1 Empirical results

At least there is one theory left which might explain the evolution of the photovoltaic industry. To test whether the model is applicable to explain the happenings in the photovoltaic industry in Germany, different predictions are made up from the model of Bhaskarabhatla & Klepper (2011).

(P4) *Increasing output leads to an increase in the number of innovations in the industry.*

In the analysis of the prediction 37 firms were considered. Tab. 5 shows the cumulative output[3] and the cumulative patent data between 2000 and 2011 for the German cell producers

[1] A service offered by the ´German Patent and Trademark Office (DPMA)´

[2] Some patents are listed without an IPC class. So it was not possible to group them.

[3] Due to the fact, that not all firms reported the output data the table shows a trend.

Year	No of Patents	Output (in MW)
2000	44	16,3
2001	21	35,2
2002	15	59,0
2003	14	115,3
2004	16	201,7
2005	31	347,5
2006	43	507,6
2007	45	875,6
2008	101	1470,6
2009	138	1850,3
2010	161	2656,1
2011	84	2508,3

Tab. 5: 2000-2011: Patent & Output data in the years 2000-2011 (based on Photon 2001 - 2012)

Between the years 2000-2004 the output features a continuous rise, but unsteadiness in the number of patents is observable in 2011[4]. From 2005-2010 a continuous rise in the number of patents as well as in the output is observable. Prediction 4 can be proofed true.

(P5) The form of innovations shifts over time from product to process innovations and larger firms should have more process innovations relative to other firms.

It is expected, that the demand for a product influences the incentive for firms to engage in innovation. In this point it is required to distinguish between product and process innovation. Product innovations tend to attract new buyers, through the addition or improvement of different product features, for a product while process innovations normally lead to a reduction of the average production costs of a firm (Klepper, 1996; Cohen & Klepper, 1996). Over time the form of the innovations should shift from product to process innovations. Furthermore the larger firms should have more process innovations relative to the other firms. To analyze this we will have a closer look at the patents of the cell producers and how they evolve over time.

The patents were grouped in product and process innovations. All patents which raise the ´degree of efficiency´ are counted as product innovations[5]. The patents can be distinguished concerning being relevant for crystalline, thin-film or both technologies and between product and process innovation on the basis of IPC-classes (Bauckloh, 2012).

	Product Innovation (in %)	Process Innovation (in %)
The "five"	40,75	59,25
All other firms	55,61	44,39

Tab. 6: Number of product and process innovations (Proxy: patents)

[4] Due to the disclosure statement it is possible, that we do not gripped all relevant patents in 2011.

[5] We also checked this for the case that the patents which raise the "degree of efficiency" would be grouped to process patents. In this case we would recognize an even higher tendency for process innovations for all firms and still the five large firms would have proportionately more process innovations than all the other firms.

Comparing the five large firms, Q-Cells, Schott Solar, Bosch Solar Energy, Deutsche Cell and First Solar that we have identified before, to the 30 other firms, large firms have cumulated proportionately more process patents than all the other firms.

Firm	Product Innovations	Process Innovations	Total Patents	Average process share (in %)
AEG	4	2	6	33,33
Antec	2	5	7	71,43
Arise	1	6	7	85,71
Avancis	4	2	6	33,33
Azur	14	0	14	0,00
Bosch Solar Energy	5	13	18	72,22
Calyxo	4	9	13	69,23
Conergy	22	1	23	4,35
CSG	5	7	12	58,33
Deutsche Cell	25	60	85	70,59
EPV	2	0	2	0,00
Evergreen	11	18	29	62,07
First Solar	77	51	128	39,84
Global Solar	7	4	11	36,36
Innotech	2	2	4	50,00
Inventux	8	1	9	11,11
Malibu	2	2	4	50,00
Masdar	1	1	2	50,00
Nanosolar	3	1	4	25,00
Odersun	4	1	5	20,00
PvFlex	5	2	7	28,57
Q-Cells	36	39	75	52,00
Scheuten	3	1	4	25,00
Schott Solar	64	138	202	68,32
Schueco	11	19	30	63,33
Shell Solar	10	8	18	44,44
Siemens Solar	45	37	82	45,12
Signet	2	1	3	33,33
Solarion	6	12	18	66,67
Solarwatt	10	8	18	44,44
Solibro	4	6	10	60,00
Soltecture	6	10	16	62,50
Sovello	0	2	2	100,00
Sunways	6	0	6	0,00
Würth Solar	9	2	11	18,18
Total	420	471	891	52,86

Tab. 7: Number of product and process patents on firm level

Furthermore a general trend to process innovations is observable on the firm level. 4 of the 5 large firms have more than 50% process patents. Taking a closer look at all the other firms, also a general trend towards process innovations is observable. 13 of the other firms (small firms) have 50% and more patents concerning process innovations. In total 17 out of 35 firms have 50% and more process patents then product patents. Analyzing the relevant patents this pattern is also observable over time for the firms. Tab. 8 shows that over time the number of patents in total increases more for the five large firms than compared to the cumulated number of patents for all the other firms. This pattern is in most parts also observable over time. In 2010 there is a general decline in the number of patents. We suppose that this is influenced by the global economic crises 2007/2008 and its consequences.

The output growths over time for all firms, but the five large firms have comparatively more output over all the time.

Four of the firms with the highest number of patents are also among the first 5 firms with the highest output. There is only one exception. Bosch Solar Energy is on place 3 with the highest output (1330,2MW in total and 450 MW in 2011) but the number of patents is still, compared to the other firms, on a low level. A possible explanation for this is that Bosch Solar Energy bought several solar cell firms like Ersol & Johanna Solar in 2009 and has grown very quickly through this ´shopping spree´. This, combined with own research activities led probably to such a high output and a minor number of patents (position 18).

Tab. 8: Output and patents over time of the “5” large firms compared to the other firms

Firm	Q-Cells		*share of Process Innovations*	Schott Solar		*share of Process Innovations*	Bosch Solar Energy (Ersol)		*share of Process Innovations*	Deutsche Cell (Solarworld)		*share of Process Innovations*	First Solar		*share of Process Innovations*	The "five"		*share of Process Innovations*	All Other Firms		*share of Process Innovations*	All firms		*share of Process Innovations*
total Output 2000 - 2011 (in MW)	2791,60			1355,45			1330,20			1098,50			1011,50			7587,25			3056,19			10643,44		
Output (Position)	1			2			3			4			5											
total number of Patents (all classes; 1950-2012)	75		0.52	202		0.68	18		0.72	85		0.71	128		0.40	508		0.59	383		0.44	891		0.53
Patents (Position)	5			1			9			3			2											
2000 (Output in MW; Product Innovation/ Process Innovation)	N/A	0	0	9,85	5 / 7	0.58	0,90	0	0	N/A	0 / 16	1.00	N/A	0 / 2	1.00	10,75	5 / 25	0.83	5,50	7 / 7	0.5	16,25	12 / 32	0.73
2001 (Output in MW; Product Innovation/ Process Innovation)	0,40	0	0	18,10	1 / 7	0.88	2,30	0	0	N/A	0 / 6	1.00	N/A	0	0	20,80	1 / 13	0.93	14,395	6 / 1	0.14	35,20	7 / 14	0.67
2002 (Output in MW; Product Innovation/ Process Innovation)	9,00	0	0	24,50	2 / 2	0.5	9,00	0	0	1,00	0	0	N/A	0 / 2	1.00	43,50	2 / 4	0.67	15,45	5 / 4	0.44	58,95	7 / 8	0.53
2003 (Output in MW; Product Innovation/ Process Innovation)	28,20	0	0	40,00	4 / 1	0.2	9,00	0	0	17,00	0	0	N/A	0	0	94,20	4 / 1	0.20	21,1	5 / 4	0.44	115,30	9 / 5	0.36
2004 (Output in MW; Product Innovation/ Process Innovation)	75,00	0	0	53,00	1 / 0	0	16,00	0	0	28,00	0 / 1	1.00	N/A	0	0	172,00	1 / 1	0.50	29,706	7 / 7	0.5	201,71	8 / 8	0.50
2005 (Output in MW; Product Innovation/ Process Innovation)	165,70	0 / 1	1.00	82,00	1 / 2	0.67	20,00	0	0	37,50	0	0	N/A	2 / 1	0.5	305,20	3 / 4	0.57	42,304	20 / 4	0.17	347,50	23 / 8	0.26
2006 (Output in MW; Product Innovation/ Process Innovation)	253,10	2 / 3	0.60	83,00	2 / 2	0.5	40,00	0	0	70,00	1 / 4	0.80	0	0 / 6	1.00	446,10	5 / 15	0.75	61,51	12 / 11	0.48	507,61	17 / 26	0.60
2007 (Output in MW; Product Innovation/ Process Innovation)	389,20	2 / 5	0.71	74,00	1 / 2	0.67	55,00	0	0	135,00	4 / 4	0.50	81,00	3 / 2	0.40	734,20	10 / 13	0.56	141,4	13 / 9	0.41	875,60	23 / 22	0.49
2008 (Output in MW; Product Innovation/ Process Innovation)	570,00	11 / 6	0.35	138,00	7 / 22	0.76	143,00	2 / 4	0.67	160,00	7 / 5	0.42	192,00	4 / 0	0	1203,00	31 / 37	0.54	267,6	18 / 15	0.45	1470,60	49 / 52	0.51
2009 (Output in MW; Product Innovation/ Process Innovation)	551,00	11 / 15	0.58	218,00	10 / 18	0.64	200,00	3 / 7	0.70	200,00	2 / 11	0.85	192,50	5 / 3	0.60	1361,50	31 / 54	0.64	488,82	20 / 33	0.62	1850,32	51 / 87	0.63
2010 (Output in MW; Product Innovation/ Process Innovation)	470,00	10 / 9	0.47	320,00	4 / 21	0.84	385,00	0 / 2	1.00	200,00	9 / 9	0.50	238,00	33 / 7	0.18	1613	56/48	0.46	1043,1	27 / 30	0.53	2656,10	83 / 78	0.48

The data shows that there is a shift from product to process innovation over time and that those large firms have more process than product innovations compared to ´small´ firms. Prediction 5 can be proofed true.

(P6*) Firms with a high output level have comparatively more innovations than firms with a low output level.*

In the model the prediction is made, that larger firms have a greater incentive to invest in innovations. So it is predicted that large firms have comparatively more innovations than small firms. Large firms are those with a high output level. Considering the 35 firms of our sample it is observable, that the 5 large firms have in average more patents than the other firms. The large firms own 57 % off all patents.

Firma	total Output 2000-2011 (MW)	Output (Position)	No of patents (all classes; 1950-2012)	Patents (Position)
Q-Cells	2791,6	**1**	75	**5**
Schott Solar	1355,45	**2**	202	**1**
Bosch Solar Energy	1330,2	**3**	18	9
Deutsche Cell	1098,5	**4**	85	**3**
First Solar	1011,5	**5**	128	**2**
Sovello	485	6	2	33
Conergy	460	7	23	8
Azur Space Solar Power	390	8	14	14
Sunways	375,5	9	6	24
Solibro (Q-Cells)	164	10	10	19
Arise Technologies	130,8	11	7	21
Würth Solar	129,145	12	11	17
Inventux Technologies	117,01	13	9	20
Schüco TF	112	14	30	6
Malibu	90	15	4	28
EPV	70	16	2	34
Masdar PV	68	17	2	35
Shell Solar	63,8	18	18	10
Soltecture (Sulfurcell)	52,8	19	16	13
Evergreen	49,8	20	29	7
Avancis	48	21	6	25
Global Solar	47	22	11	18
Scheuten Solar	43	23	4	29
Solarwatt	31	24	18	11
Antec Solar	27	25	7	22
Odersun	26	26	5	27
Calyxo (Q-Cells)	19	27	13	15
Signet Solar	15	28	3	32
Centrosolar	14,1	29	0	37
CSG-Solar	7,2	30	12	16
Bosch Solar CISTech GmbH	6	31	0	36
Eco Europe	6	32	0	38
Sontor (Q-Cells)	4,6	33	0	39
Nanosolar	4,01	34	4	30
Solarion	0,219	35	18	12
IXYS	0,101	36	0	40
PV-Flex Solar	0,1	37	7	23
Siemens Solar	0	38	82	**4**
Innotech Solar	0	39	4	31
CTF Solar	0	40	0	41
Heckert	0	41	0	42
AEG	0	42	6	26
Heliotronic	0	43	0	43
MBB	0	44	0	44

Tab. 9: Patent & Output data for all firms

Tab. 8 & 9 show that large firms have comparatively more patents and according to this, more innovations. This can be shown in total and furthermore over time. Prediction 6 can be proofed true.

The predictions concerning the model are supported by empirical results. The tested predictions 4, 5 and 6 indicate that it is possible to use the model of Bhaskarabhatla & Klepper (2011) to explain the evolution of the photovoltaic industry in Germany.

6 Discussion and conclusions

The photovoltaic industry, a high technology industry, in Germany offers the great opportunity to observe the evolution of a specific industry in real time. Through the lens of industry-life-cycle theories, to date the evolution as well as the emergence of new technology-based industries is seen as the result of technological change. We considered five different theory approaches about how industries evolve. The photovoltaic industry shows an arrested development. In the years between 1950 and 1990 a lot of research funding was made. But it took more than 40 years to start the real industrial life cycle as it is predicted by the theories. As reflected by the foundation of the cell producers, neither the invention nor the research funding triggered the evolution. But at a certain point of time politics shifted away from standard science-based and technology-push mode of foundation. Since 1990 the policy makers realized a failing of hitherto approaches and designed different funding schemes with a focus on the demand side. Currently the photovoltaic industry is a high technology industry whose evolution was at least by large triggered by public policy, especially the EEG. So at least the model of Bhaskarabhatla & Klepper (2011) is applicable to explain the evolution of the photovoltaic industry in Germany with an extension. What drives exogenous the growth in the submarkets and leads furthermore to the new technology that triggers finally the shakeout is public policy.

Until 2011 the output of the German cell producers shows a continuous growth. But compared to the worldwide output it is observable that the German output capacity is getting less important in relative terms. Although there is a steady growth, growth in other countries is higher. An interesting question for further research is how a country that had a first comer advantage for a long time and was also an example with its laws for other countries could become so less important in the worldwide market. Several mechanisms serve as a possible explanation. First, German companies did not adequately build up R&D-competencies in times of high profits and are now not able to keep a technological leadership. Second, cheaper modules from Chinese production flood the German market and squeeze German producers. Third, the market changed from a seller's market to a buyer's market. Consequently, firms of limited size and with inappropriate cost structure were not able to compete anymore. Evidence for validity of all these explanations is that restructuring and consolidation concerns all types of companies from all core stages of the value chain. Start-ups with sophisticated but challenging and small-scale thin-film production concepts are as well affected as large producers of standard solar modules. Beside restructuring or shutdown of operations other trends are in the offing. Industry giant Bosch started a shopping spree and integrated a number of different producers with different technological backgrounds. Chinese solar company LDK took over cell and inverter producer Sunways, a photovoltaic pioneer. Furthermore, companies move downstream into project development (Dewald, 2012). But are these possible explanations right? This is an interesting question for further research.

The findings of this paper are limited to one industry and so it needs further research to proof if these results are also applicable for other industries. At least we can say that the evolution of this industry was not triggered by technological change but mainly by public policy. So we can add public policy to the list of reasons which can influence the nature of submarkets.

Acknowledgments

We thank Tobias Bauckloh for his help concerning the provision in patent classification. Thanks to Guido Bünstorf for many useful comments over all the time. Thanks also due to Thomas Brenner, Koen Frenken, Jackie Kraftt and Simone Borghesi for helpful comments.

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