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Who innovates longer? - Survival of innovators in the German photovoltaic industry.

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Abstract

The crucial role of innovation for welfare and economic success is widely acknowledged at the economic level as well as on the and firm level. Innovation is considered as a driving force for national and regional competitive advantage and for long-term firm survival. Thereby, innovation activities of firms build on knowledge from different technological areas. The quantity of a firm?s technological knowledge at a point t in time finds it expression in the technological knowledge stock. The accumulation of this technological knowledge stock fol-lows a successively, path depended and firm specific learning process. This raises fundamental imitation barriers for competitors and facilitates long-term success.

The impact of technological knowledge on innovation performance in special and on a firms? overall performance in general is traditionally addressed by technology management literature. This research stream builds primarily on resource based arguments and concepts (e.g. Garcia-Vega 2006, Thornhill 2006, Leten et al. 2007). In our study we change the perspective and combine arguments form industrial dynamics literature and research on firm survival de-terminants. Whereas research in the field of industrial dynamics focus on the whole industry and all firms within this industry, our research abstracts from this view. Innovators as a special group of firms within an industry are highlighted. Technological knowledge as important determinant for the survival of innovators is analyzed. To keep market and industry specific influences constant, we focus on the German photovoltaic (PV) industry. Since the early be-ginning of the worldwide PV industry, German innovators have been playing a dominant role for technological development and technological dynamics. In an innovation based competi-tive environment, German firms successfully defended their worldwide position as leading innovators and pioneers in several photovoltaic technologies.

Besides the pioneering role of German innovators, the industry focus of this study is further-more motivated by a special characteristic of the German PV industry: Public support schemes aim to intensify innovation based competition by demand inducing and R&D enhancing policy instruments.

The objective of the present paper is to analyze the determinants of the survival chances of German innovators within the German PV industry. A focus is on technological knowledge and technological dynamics as a crucial success factor for innovation activities. An innovative methodological approach is adopted to differentiate types of technological knowledge according to quantity, quality and time specific characteristics.

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Abstract

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1. Introduction

The crucial role of innovation for welfare and economic success is widely acknowledged at the economic level as well as on the and firm level. Innovation is considered as a driving force for national and regional competitive advantage and for long-term firm survival. Thereby, innovation activities of firms build on knowledge from different technological areas. The quantity of a firm's technological knowledge at a point t in time finds it expression in the technological knowledge stock. The accumulation of this technological knowledge stock follows a successively, path depended and firm specific learning process. This raises fundamental imitation barriers for competitors and facilitates long-term success.

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Besides the pioneering role of German innovators, the industry focus of this study is furthermore motivated by a special characteristic of the German PV industry: Public support schemes aim to intensify innovation based competition by demand inducing and R&D enhancing policy instruments.

The objective of the present paper is to analyze the determinants of the survival chances of German innovators within the German PV industry. A focus is on technological knowledge and technological dynamics as a crucial success factor for innovation activities. An innovative methodological approach is adopted to differentiate types of technological knowledge according to quantity, quality and time specific characteristics.

The paper proceeds as follows: chapter 2 summarizes the history of the German PV industry. Milestones for industry evolution in general and innovation dynamics are emphasized. In chapter 3 theoretical arguments from industrial evolution concepts are combined with previous empirical observations from the German PV industry for hypothesis development. Data description and the applied innovative methodical approach are introduced in chapter 4. Chapter 5 is dedicated to the discussion of the estimation approach and the presentation of the empirical results. Hypothesizes are answered and results are discussed. Finally, chapter 6 draws a conclusion and discusses the limitation of our work.

2. Historical Background and Evolution of the German PV-Industry

The origin of the photovoltaic industry can be traced back to the early 19th century. A milestone in the evolution of the photovoltaic industry was the invention of the solar cell in the U.S. Bell Laboratories in 1954 (Perlin 1999). The cell itself is based on the photoelectric effect, which was discovered by the physicist A.E. Becquerel in 1839, but also the invention of the transistor triggered the evolution (Lewerenz/Jungblut 1995).

Solar cells basically consist of semiconductor materials, especially silicon. A semiconductor wafer is used to generate an electric field with a positive and a negative pole. When light energy falls on the solar cell, electrons within the semiconductor material start to move freely. An electrical circuit is created by the connection of electrical conductors to the positive and negative pol. In this way electrons can be transformed into electricity. On a larger scale, a photovoltaic module exits of several photovoltaic cells, electrically connected by a special support structure. In common, modules supply electricity at a certain voltage.

Based on the definition of submarkets in general by Klepper and Thompson 2006, Blankenberg and Dewald (2013) argue that different submarkets of the photovoltaic industry can be defined according where the technology is applied. The on-grid market and the off-grid market can be seen as the major submarkets. On-grid PV systems are connected to the utility grid. Electricity is generated by solar modules, converted by one or several inverters and fed in to the grid by a grid connection system. On-grid systems exist in different scale from small scale rooftop systems up to large scale solar power stations. Off-grid systems are not connected to a grid. They provide stand-alone systems for electricity generation and distribution. Mainly they are used to provide a smaller community with electricity, e.g. in developing countries. Off-grid systems often include a battery solution to store excess electricity for future consumption. In the early years of the PV industry between 1957 and 1973 off-grid applications dominated. Off-grid systems had been applied almost exclusively in the aerospace industry as main source of power generation in the space. Research and Development in the early phase was predominatly conducted by large firms (Pfisterer/Bloss 1989). During the 1970s the oil shocks lead to an increase of the public and political awareness concerning energy provision and security. Public promotion schemes and funds had been donated for research on non-fossil fuel technologies. Consequently, the public research activities within the area of power generation from renewable resources increased (Braun et al. 2010). Driven by these developments, especially the off-grid-submarket experienced a strong growth between 1973 and 1995. Off-grid systems had been expended to large scale, centralized applications out of the space. This expansion did not yield in the end of one of aerospace applications, both applications fileds exist in parallel.

Since the 1990s a shift from public research funding to public demand funding is observable. One important Milestone in this context is the "Electricity Feed-in Act" (Stromeinspeisegesetz/StrEG) and the 1000-roofs program from 1991. These public support schemes triggered the demand for standardizised, decentralized small-scale on-grid PV-systems for private households, mainly in terms of grid-connected roof-top-systems.[1] The introduction of the 100.000-roof program in 1999 as well as the Renewable Energy Sources Act (EEG) as follow up program of the StrEG in 2000, secured stable investments for a period of 20 years. Demand for on-grid systems, industry growth and technological advantage experieced further stimulation. The EEG created a competitive environment without the exclusion of any technology design. Firms had free choice regarding the technological design of their products (Jacobsson et al. 2004).

Besides the evolution of submarkets, the technology itself experienced several developments. Basically it is possible to distinguish crystalline and thin film technologies (Goetzberger & Hoffman 2005). Both technologies have different advantages. E.g. thin-film experienced a strong cost reduction but it is also confronted with a lower effiency. Technological progess and innovation occurred within both technologies. Especially innovations and enchancements within system solutions and material systems of cells were realized. New material compositions were developed and advancements of existing materials were made. Technological progress was accompanied with an increasing degree of vertical integration and a decrease in prices. Between 2006 and 2011 alone prices dropped by 52 percent (Grau et al. 2012).

On a global level, German innovators played besides Japan the leading role for innovation and technological progress within the worldwide PV industry, resulting from strong public

[1] Since 2009/2010 adittionally the submarket for on-grid large scale power plants emerged.

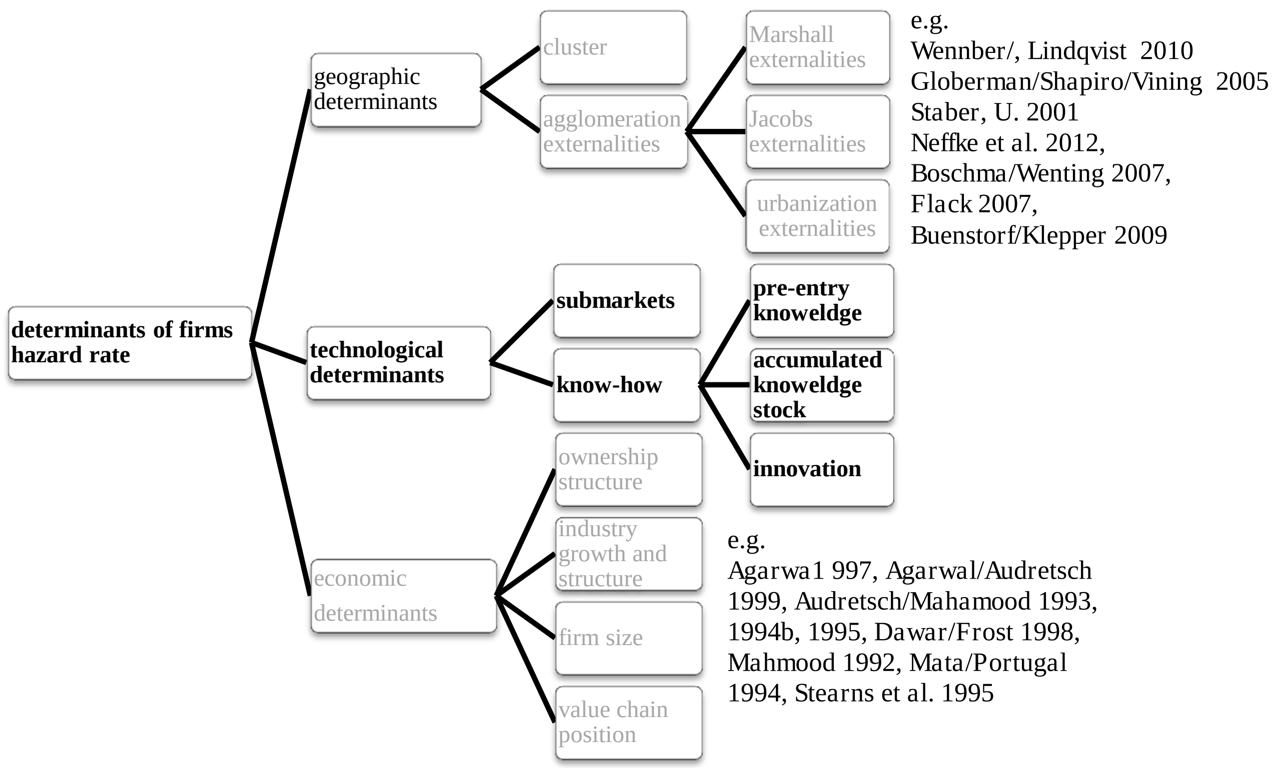
support schemes (Braun et al. 2010). Despite significant technological dynamics, the photovoltaic technology has not reached the maturity stage so far. Electricity produced by photovoltaic technology is still expensive and not competitive yet. However, there is a large potential for further innovations in cost reduction and efficency enhancement.

To deepen the understanding of innovation dynamics and firm behavior within the German PV industry, this paper addresses the general research question which determinants drive the survival of innovators.

3. Theoretical Arguments on Survival of Innovators and Hypothesis Development

Intrasectoral and intersectoral industry studies emphasize the dominant role of several determinants for firm survival. In general geographic, technological and economic determinants can be differentiated. Figure 1 gives an overview.

Figure 1: Determinants of firm survival



In the following study the survival of innovating firms within the PV industry is analyzed. Therefore, we concentrate primarily on technological determinants since technological dynamics, technological knowledge and resources are on the core of successful innovation activities.

Methodically, the focus on innovators limits the generalizability of our study. Since innovation activities per se are expected to have an impact on firms' survival, results are valid only for firms which pursue innovation activities within the PV industry. More technically, our applied innovator sample is characterized by left truncation since only firms which conduct innovation are considered. Estimation results are not generalizable for the whole PV industry.

Pre-entry knowledge and innovators survival

According to prior research, the knowledge stock of a firm at the time where it enters a market, drives firm survival (Agarwal et al. 2002, Helfat/Liebermann 2002). This argument is based on the condition that pre-entry knowledge can be leveraged into new market environments and utilized for business activities with no or less additional costs. Several differentiations of prior knowledge can be found. Chatterjee and Wernerfelt (1991) distinguish between specialized knowledge and generalized knowledge. Generalized knowledge is characterized by a broad applicability within different environmental settings, for example financing capabilities, production and management routines and the capability to efficiently coordinate diverse business activities. Specialized knowledge is associated to specific application settings, for example knowledge in specific technologies and markets. A second, procedural oriented differentiation distinguishes technological knowledge and market knowledge Wiklund/Shepherd 2003). Technological knowledge belongs to specific technologies and technological areas and is associated to the input side of the firm. Market knowledge belongs to marketing and sales activities and is associated to the output side of the firm.

Since competition of innovators is primarily based on technological knowledge we focus on pre-entry technological knowledge. Crucial when considering the impact of prior technological knowledge on innovators survival is the level of synergies between prior knowledge and the knowledge needed for innovation activities in the new industry. If potential for synergies exists, the firm can redeploy and leverage existing technological knowledge into new technological fields. Synergies facilitate knowledge spillovers which may enhance the likelihood of an innovator to survive. In fact, such spillovers in specific technological knowledge have occurred in the photovoltaic industry. Braun et al. (2010) emphasize the synergetic potential within the photovoltaic industry by the example of Japanese PV firms. The authors attribute the concentration of Japanese firms' innovation efforts on PV technologies within renewable energy technologies to the transfer and exploitation of technologies and process knowhow already developed within the silicon, semiconductor and consumer electronics industry.

Potential for synergies is reflected by the degree of technological relatedness of technological knowledge domains. Especially in terms of innovation activities where competition is based on specific technological knowledge, non-related knowledge seems to be not sufficient to drive long term firm performance. Pre-entry unrelated technological knowledge allows for leveraging some generable parts of the existing knowledge stock to the new technological area. However specialized technological knowledge, which is crucial for innovation-based competition has to be developed from the beginning. Therefore we propose:

H1. The mere possession of pre-entry technological knowledge is not sufficient to enhance the survival chances of innovators within the German PV industry. Prior related technological knowledge drives the survival chances of innovators.

Past entry knowledge and innovators survival

The impact of past entry knowledge on firm survival is a traditional concern of the industrial dynamic research. The amount of knowledge and experience which is collected by a firm after its entry in a new industry is widely proven to reduce firm's hazard of market exit. Once a firm entered a market the company successively accumulates knowledge and experience regarding technologies, innovation activities, production, distribution, market conditions and dynamics, competitors' and customers behavior of the new industry. The entrance initiates a continuous learning process; the longer a firm is active within the market the higher is the accumulated past entry knowledge stock (Hall 1987). This kind of first mover advantages is based on the realization of economies of scale and scope and results in more efficient processes and in lower costs for innovation and business activities (Jovanovic/MacDonald 1994, Utterback/Suàrez 1993, Klepper/Simons 1997, Klepper 1996, Klepper 2002a,b, Agarwal/Gort 2002, Thompsen 2002).

If competition is primarily based on innovation, technological knowledge is crucial for a sustainable competitive advantage. Innovation can be viewed as a problem solving activity which draws upon firms' accumulated technological knowledge stock. From an evolutionary perspective, the accumulation of firms' technological knowledge occurs successively since the initial start of innovation activities. The technological knowledge and is characterized by a path depended development and accompanied by a dynamic learning processes. Innovators gradually learn about efficiency of innovation actives, technological opportunities, challenges and boundaries as well as complex and dynamic technological contexts. The earlier an innovator starts innovation activities within PV technologies, the earlier the efficiency enhancing learning process and the technological knowledge accumulation process is triggered. An early entrance leads to knowledge advantage which should allow firms to be ahead of late innovators.

Braun et al. (2010) provide some indirect empirical indications concerning the influence of past entry knowledge on innovators survival in the worldwide PV industry. On a global level the authors' emphasize, that in the 1980s PV innovators from the US lost their position as technological leaders besides Japan and Germany. This development was a consequence of the substantial decline in public R&D support for PV technologies under the Reagan administration, resulting in a considerable reduction of private innovation efforts and market exits of US innovators at the global level. Despite of the (re-)introduction of strong research support schemes in later years, US innovators could not manage to catch up the technological gap and to recapture a position as technological leader. Past entry learning processes and technological knowledge accumulation was interrupted by changes in the public support schemes. At the same time dynamic learning and knowledge accumulation continued for Japanese and German PV innovators under the condition of stable support schemes. This resulted in technological progress and competitive advantage which remained unattainable for US innovators in later years.

Based on the theoretical arguments and empirical indications we hypothesize that first mover advantages can be realized by early innovators of the German PV industry. Therefore we propose:

H2. Post entry stock of knowledge positively influences the survival chances of innovators within the German PV industry. An innovator which enters early the German PV industry has a lower hazard to exit than an innovator which enters later.

Innovation submarkets and innovators survival

Klepper and Thompsen (2006) develop a model in which the process of evolving and declining submarkets drives industry evolution and survival of individual firms. According to this model, an industry is built up of different submarkets. Submarkets of an industry are defined by different determinants e.g. the geographic dimension or the applied technology. In an emerging industry, firms are specialized within one submarket. Over time, new submarkets develop and old ones decline. Firms possibly engage in different submarkets. Their survival is related to the number of submarkets in which they are active. Based on these considerations, Baskarabathla and Klepper 2014 argue that in consequence, an industry can evolve through the creation and destruction of submarkets without a significant decrease in net entry rates for the overall industry.[2] A shakeout within the industry only occurs if the growth rate regarding the creation of new submarkets decreases. One important trigger of submarket dynamics is the exploitation of economies of scale and scope on the firm level, especially resulting from leveraging of exiting knowledge and resources.

Arguments of traditional submarket theory are strongly market and firm level output oriented. Given the assumption of a homogeneous demand; product differentiation and demand fragmentation are assumed to be causal for the creation and destruction of niches which prevents shakeout (Baskarabathla/Klepper 2014). Consequently, from the input perspective of innovators it can be argued that different submarkets for technological knowledge and innovation may exist. Thus, evolution of innovation submarkets is primarily driven by technological progress, new technological opportunities and application fields. If an innovation submarket declines, technological knowledge associated to this innovation submarket becomes increasingly obsolete within this submarket setting. Innovators can ensure persistent innovation activities by a successive shift of their innovation activities into new innovation submarkets with promising future potential. Also on the input level, the realization of economies of scale and scope can be seen as crucial for innovation submarket dynamics. The general existence of submarket dynamics is proven for several industries like the laser, disk drive, automobile and tire industry (Buenstorf/Klepper 2010). For the German PV industry no empirical evidence for submarket dynamics exists so far. For the German PV industry no empirical evidence for submarket dynamics exits so far. Within this industry no shakeout was observable for more than 35 years. In fact, in 2011/2012 the shakeout finally started (Blankenberg/Dewald 2013). Since the competition in the overall PV industry was determined by innovation and technological progress for a long period, innovation submarkets may play an important role for the survival of PV firms in general and especially for innovators. Therefore we propose:

H3: The existence of innovation submarket dynamics influences the survival chances of innovators within the German PV industry. Innovators which spread their innovation activities across different innovation submarkets over time, survive longer.[3]

[2] Net entry rate is defined by the number of new entrances minus the number of exiting firms within one year leading to a consolidation and concentration within the industry. It declines strongly as shakeout occurs. After the shakeout the entire industry output is produced by the most efficient early entrants.

[3] Hypotheses H3 presupposes the existence of innovation submarkets. This assumption is empirically tested in chapter 4.3.

4. Data and Methodology

4.1. Identification of Innovators and Data Collection

Patents are used as proxy for innovation activities and technological knowledge in order to identify innovating firms within the photovoltaic industry. This approach is accompanied by some limitations which should be kept in mind (Griliches 1990). First, patents cover only technological inventions with a certain degree of novelty. Second, patents are characterized by some intrinsic variability. Patents can differ considerably in their technological and economic value. Third, as an output indicator, patents are characterized by a time lag. Several months passes by between the initial invention and the final patent application or grant. A further shortcoming of patent indicators is more strategically than methodological in nature. Some firms may consciously abstain from patenting and pursue alternative means to protect their innovations, like a lead-time strategy or secrecy. This is especially true for firms in volatile high tech industries where very short technological life cycles lead to a fast obsolesce of knowledge. Furthermore process innovations are less likely to be protected by patents (Levin et al. 1987, Archibugi and Pianta 1996). In the context of these shortcomings of patent based innovation indicators some alternative indicators are suggested in the literature like R&D expenditures (Audretsch/Mahmood 1994), number of R&D workers (Agarwal/Audretsch 2001) or innovation lists (Klepper/Simons 2005). For firm level analysis all these indicators lack a sufficient degree of disaggregation at the firm level or general accessibility, especially in the context of long-term observations. For our research purpose such innovation indicators are not suitable. Instead there are some arguments reducing the shortcomings of patent based innovation indicators in the given research setting. Our research interest is on survival of firms which pursue technological innovation activities. By legal definition, obtaining a patent requires novelty and technological inventiveness. Patents are a strong and frequently employed source of data for measuring technological innovation. Additionally the intrinsic variability does not affect the validity or reliability of our methodological approach. Patents are used only for the differentiation between innovating and non-innovating firms and the neutral differentiation of technological knowledge areas. To reduce the time lag between invention and patent, patent applications are used regardless if the patent is granted or not. This also guarantees the consideration of all innovation activities of firms independently if they yield in economic success. Furthermore the methodological approach applied for the classification of different innovator types takes sufficiently a possible time gap between invention and patent application into consideration. Last, patents are considered as a highly relevant strategic mean to protect inventions in the PV industry (Braun et al. 2010, Breyer 2012). Additionally, process innovation is especially relevant in late phases of the industry whilst product innovation is dominant in early phases (Utterback/Albernathy 1975, Klepper 1996a). Since the PV is evidently still in an early stage, the bias from unrecognized, not patent protected process innovation in the German PV industry is regarded as very low. Consequently, innovators within the PV industry are defined by a market oriented, patent based demarcation according to the Green Inventory (GI) Scheme developed by the WIPO. The GI scheme proposes an approach to differentiate Environmentally Sound Technologies (ESTs) by an assignment of different IPC classes. The GI scheme has a hierarchical structure and differentiates several main and sub technologies for every form of alternative energy production. The field of solar technology is differentiated into the main technologies Photovoltaics (PV), Use of solar heat and Propulsion of vehicles using solar power.[4] Our study focuses on PV. Relevant firms of the PV industry were identified by a patent inquiry on PATSTAT. All European and German patent applications of German applicants which are assigned to the PV IPC-classes were selected. A refinement of the results was obtained by including technological or photovoltaic related key words in the patent search. Key words were defined by expert interviews at the Helmholtz Institute for Silicon Photovoltaics.[5]

For each German applicant the first solar patent application in firm's history was defined as the start of innovation activities within the solar industry (entry time).[6] Only private firms with at least four PV-patents were included in the sample.

The final sample comprises (so far) 291 innovators within the German PV industry. It covers the whole evolution of patenting activities of the German PV innovators, starting with the first PV patent in 1964 until the end of the year 2011.[7] Patent data was completed with data gained by an extensive review of the historical background of all sample firms. We identified the year of foundation for every firm, connections to other firms as well as all relevant changes within a firms' evolution: changes in the name, the legal status, the location, the ownership structure. Companies which changed their names or head quarter within Germany during the whole observation period were treated as continuing entities. Furthermore, the date and type of exit was collected, when appropriate. Exit is defined by different events. We distinguish voluntary liquidation, bankruptcy as well as Mergers and Acquisitions. The data was obtained

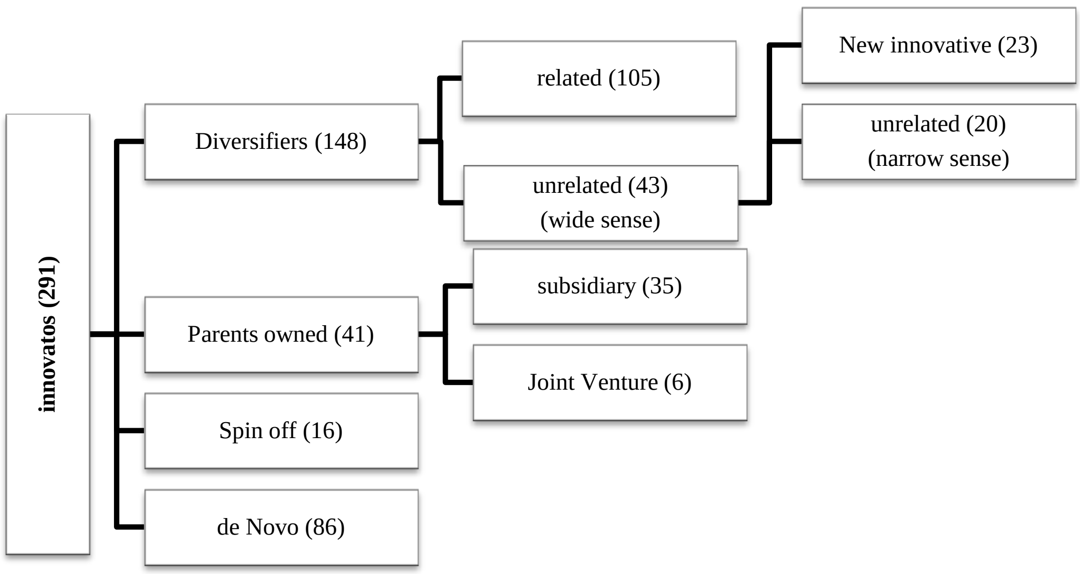
[4] See Appendix for the detailed hierarchical structure
[5] See Appendix for the key defined words. Key word search was applied to the whole patent document.
[6] For the case of co-applications every German co-applicant is considered independently. Applicant data was carefully cleaned by hand to prevent discrepancies, which may result from different spellings of the same applicant.
[7] German PV innovators are all firms with a head quarter in Germany during the whole period under consideration.

by a variety of secondary sources, primarily official trade registers and trade publications, commercial firm registers like Hoppenstedt, Buergel and LexisNexis, web material and the BSW member list. In terms of exit we additionally checked if the initially defined innovators remain active within the PV industry. For all exiting firms with no PV patent application six years before exit and for all survivors with no PV patent six years before the end of the observation time firm's latest PV patent plus six years was considered as year of diversifying out. For all firms, a continuous innovation strategy was assumed and firms where kept as surviving innovators in the sample.[8]

4.2. Types of Innovators and Pre-Entry Knowledge

Based on quantity and quality of the patent stock four main types of innovating firms (diversifiers, parents-owned, spin off, de Novo) are distinguished by their pre-entry technological knowledge. Figure 3 shows the innovator types within the German PV industry. The number in parentheses represents the number of sample firms associated to the different innovator types.

Figure 3: Number of innovator types within the German PV Industry



(1) Diversifiers are all established firms which fulfill two criteria: (1) the firm starts innovation (patenting) activities within PV technologies at least five years after foundation, (2) at least one non-PV patent was applied before the first PV patent application. Within the group

[8] Please note: This paper is still a working paper version. Diversify out is not yet considered within the estimation.

of diversifiers a finer differentiation based on pre-entry knowledge characteristics is pursued. The first subgroup is the related diversifiers. Related diversifiers have at least one patent in a PV technology related technology before applying for the first PV patent. A patent is considered as technological related to PV technologies when one (or more) of its associated IPC classes falls at least into one technological field which also comprises at least one IPC class which is defined as PV technology by the GI. Technological fields are differentiated by the ISI-OST INPI classification developed by the WIPO (Schmoch 2008). This concordance scheme associates IPC classes to five technological sectors. These sectors are further differentiated into 35 technological fields. Related diversifiers possess PV related technological knowledge when starting innovation activities within PV technologies.

The second subgroup of diversifiers, the unrelated diversifiers in the wide sense, is consequently defined as firms which diversify innovation activities into PV technologies. Before they start patenting within PV technologies, these firms have no patent within PV related technologies. Unrelated diversifiers in the wide sense are further differentiated into new innovative firms and unrelated diversifiers in the narrow sense. Firms of the latter subtype have one or more patents before they start innovating within PV technologies but these are not associated to PV related technological fields. New innovative firms start to patent at least five years after their foundation and their first patent is associated to a PV technology.

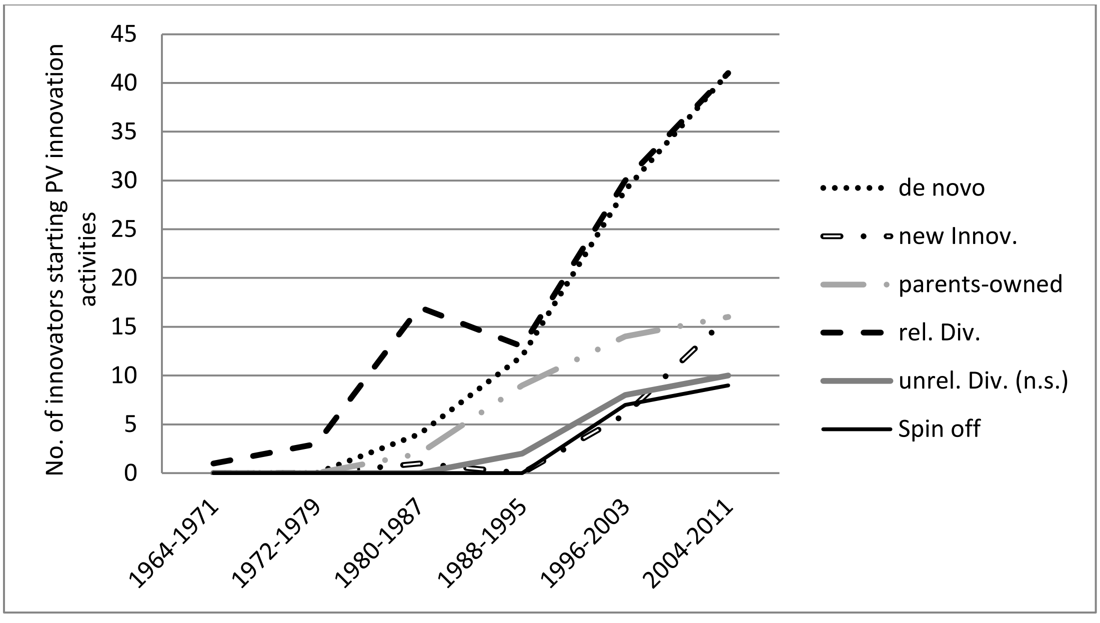
(2) Parents owned innovators are all firms which are legally independent but economically dependent on an established firm. This innovator type comprises joint ventures and subsidiaries.[9] Between parents owned innovators and their linked established firm, multiple connections exists. Through these, parent’s technological experience, tacit and explicit knowledge as well as other resources can be transferred (Audretsch 1995). The initial quantity and quality of the parents owned innovators’ technological knowledge stock is hard to determine. It depends on the extent to which the parent firm transfers tacit technological knowledge in form of personnel, experiences or organizational systems as well as explicit knowledge in form of physical assets and technologies at the time of foundation. But in general, the parent owned innovator has frequently access to the parent’s resources such as technological knowledge and management routines for the creation of innovation. When starting innovation activities within PV technologies, parents owned companies can be assumed to possess managerial and/or technological knowledge which contribute to the successful generation of innovations within PV technologies.

[9] Based on our sample no other types are relevant.

(3) Spin offs are all academic and private spin offs. Recent research in industrial organization highlights the important role of spin offs for innovation dynamics within industry evolution. In general spin offs exploit knowledge and expertise of their founders to generate innovations. Founders accumulate knowledge and expertise from R&D and marketing of their parents during their prior employment which builds the basis for the spin offs innovation activities. Moreover, Spin offs are characterized by organizational and flexibility advantages over incumbents. Those foster the development of a spin offs' capability to generate radical innovation. Initially, the spin off will use the same core technological knowledge and the same technologies as the parent firm to create new technological knowledge which challenge incumbents competencies (Franco/Filson 2000).

(4) De novo innovators are all firms which start patenting activities within PV technologies within the first five years after their foundation. Since these firms are start-up companies, they are assumed to possess no prior knowledge and expertise on which innovation activities can build on. Figure 4 shows the number of firms starting innovation activities within PV technologies, differentiated by different time periods.

Figure 4: Number of firms starting PV technology patenting



4.3. Technological Application Fields and Technological Submarkets

The Green Inventory (GI) distinguishes seven PV technologies according to their primarily field of application: (1) Assemblies of a plurality of solar cells, (2) Charging batteries, (3) Devices adapted for the conversion of radiation energy into electrical energy, (4) Dye-sensitised solar cells (DSSC), (5) Electric lighting devices with, or rechargeable with, solar cells, (6) Regulating to the maximum power available from solar cells, (7) Silicon; single-crystal growth.

To test if this application-based differentiation of PV technologies is suitable to the submarket concept and fulfills the properties of innovation submarkets a X^2 test is performed. By definition, submarkets evolve over time. If one submarket gets destroyed, firms become more and more motivate to move to upcoming submarkets. From a conceptional point of view if innovation submarkets dynamics exits, innovation actives within PV technologies should also follow an evolving pattern. The X^2 tests the null hypotheses of equal distribution of initial innovation activities within the seven PV technologies. To test the hypothesis, following Klepper and Thompson (2006) and Bhaskarabhatla and Klepper (2014) five-year intervals are built. In the context of statistical tests, this interval length ensures a sufficiently large subsample for each time period. The analysis periods starts with the first PV technology patent in 1964. Table 1 shows the number of innovators which initially start their innovation activities within the different PV technologies during, differentiated by eight periods.

Table 1: Number of innovators initially starting innovation actives by PV technologies

	PV technologies p										
Period t	(1)	(2)	(3)	(4)	(5)	(6)	(7)	Tot t		Df	c
1964-1969	2	0	3	0	0	0	3	8		0	26,82
1970-1975	1	0	2	0	0	0	1	6		6	38,99
1976-1981	4	1	7	1	0	1	5	20		12	52,75
1982-1987	6	10	10	1	3	1	2	33		18	137,84
1988-1993	18	6	28	2	1	3	6	63		24	139,26
1994-1999	44	8	55	2	0	7	9	125		30	140,83
2000-2005	62	4	75	4	1	2	5	153		36	142,03
2006-2011	74	9	108	2	1	6	9	209		40	142,78
Tot p	211	38	288	12	6	20	40	615			821,31

As the tables indicates, the total number of firms starting innovation activities within each PV technology varies highly by technology, reflecting possibly seven different innovation submarkets within the PV industry and different sizes of these submarkets. In a next step, we test the null hypothesis using the test statistic $c=\Sigma_{p,t}$ $[(I_{pt} – Tot_t* \Sigma tTot_t /Tot_p)/ Tot_t* \Sigma tTot_t /Tot_p]^2$, where I_{pt} is the actual number firms starting innovation activities in PV technology p in time interval t and $Tot_t* \Sigma tTot_t /Tot_p$ is the expected number of initial innovators under the null hypothesis. Thus, executed t-test takes possible differences in the general patent intensity and the size of the single PV technologies into account. The two right columns of table 1 represent the degrees of freedom (df) and the calculated test statistic c for every period t under consideration and for the whole observation time. In every column the test statistic is significantly different from 0 at the 0.001 level. The null hypothesis of no significant clustering of innovation activities by initial innovators in the PV industry is rejected. In consequence, the seven PV technologies can be interpreted as differentiable technological submarkets for innovation.

5. Survival in the PV Industry: Estimation Approach and Empirical Results

5.1 Estimation approach

To analyze the role of different knowledge characteristics of innovators in the PV industry with regard to their performance, the time period of firm survival is taken as firm performance measure. The methodological approach of survival analysis is adopted. The basic idea of a survival analysis is the approximations of a survival function and hazard rates based on survival durations. Survival duration for an individual starts with being at risk for the first time. In our research setting, survival duration starts with the first innovation activity within PV technologies. The survival duration ends with a failure event, e.g. death. In our study, we define bankruptcy and voluntary liquidation as failure event. Following Schary (1991) Mergers and Acquisitions are treated as exits, but not as failure events. M&A'S are connected with a profitability of the target and the aim of the acquirer to integrate and use material and immaterial assets of the target in order to realize synergies. Moreover, in some high tech industries, acquisition by an incumbent is an intended exit strategy for startup and spin of firms (DeTienne 2010). In a similar vein the legal reintegration of parents-owned innovators within the parent's organization is treated as exit, but not as failure event.

A survival analysis calculates the hazard of an individual to suffer a failure event at time t, conditional on the fact of survival until t. Survival analysis models also allow to integrate a vector of explanatory variables. In the subsequent study, a semi parametric Cox-regression model and a parametric Gompertz proportional hazard model is applied. Both models are characterized by different advantages and disadvantages. In general, the cox regression model specifies parts of the hazard rate conditional on the vector of explanatory variables. A proportional hazard rate is used and no assumption concerning the functional form of the baseline hazard is made.[10] Formally, the hazard function of the cox specification can be expressed as:

$$h(t_i) = h_0(t_i) \cdot e^{\beta_1 x_{i1} + \cdots + \beta_k x_{ik}}$$

[10] Cox regression is semi parametric since the parametric part of the hazard rate is estimated independently of the functional form or estimation of the non-parametric part of the hazard rate(=baseline hazard). A cox model is estimated by a partial likelihood estimation (Kiefer 1988).

Since the hazard rate is strongly positive, an exponential transformation is carried out. The survival duration is expressed by t. t is influenced by k explanatory variables of the firm i. The influence of the explanatory variables values $x_{i1},\ldots,x_{ik}$ on the hazard rate $h(t_i)$ represented by the parameters $ß_1,\ldots,ß_k$. $h_0(t_i)$ represents the baseline hazard. No assumptions concerning the functional form of $h_0(t_i)$ are made. The partial likelihood function allows for an parameter estimation of $ß_1,\ldots,ß_k$, independently of the baseline hazard specification and estimation.

The Gompertz model requires the complete functional specification of the likelihood-function. The Gompertz specification considers k explanatory variables $x_{i1},\ldots,x_{ik}$ and l explanatory variables $z_{i1},\ldots,z_{il}$. Compared to the Cox model, the Gompertz model estimates the value of the constant β_0. Furthermore, the hazard rate can be divided in two estimation parts. The first part of the hazard rate estimates the influence of the explanatory variables ß at the time where the firm starts to be at risk (e.g. market entry). The second part of the hazard rate estimates the chance of this influence depended on the survival time (represented by the parameters γ). Both parts are multiplicatively related. This lead to a lower robustness of the estimation results, but if the functional form of the hazard rate is sufficiently specified, more precise estimation results are obtained.

$$h(t_i) = e^{\beta_0+\beta_1 x_{i1}+\cdots+\beta_k x_{ik}} \cdot e^{(\gamma_0+\gamma_1 z_{i1}+\cdots+\gamma_k z_{il})\cdot t_i}$$

In analyzing or hypothesizes, both models are applied to check the robustness of the estimation results. The proportional-hazards assumption underlying both specifications was tested on the basis of Schoenfeld residuals. The proportionality assumption holds for the entire models as well as for individual explanatory variables.

5.2 Empirical Results

H1. Prior Technological Knowledge

Table 1 shows the estimation results for hypothesis one. Values represent coefficients. Different innovator types according to their type of prior knowledge are considered. Pre-entry knowledge is successively refined. Furthermore, the age at entry is included in every model as a variable to control for age specific influences on the firms survival duration. This variable considers the phenomenon of liability of newness which describes the fact of lower survival chances for younger firms (Stinchcombe 1965). Robust standard errors are used to adjust for heterogeneity in the model.

In Model one and four, we differentiate between experienced and de novo firms by dummy variables. Experienced innovators are all firms with some pre-entry knowledge and experience, thus all sample firms which are not de novo. The coefficient indicates a significant lower hazard for experienced innovators to fail compared to unexperienced de novo innovators. In general, innovators with prior knowledge and experience are more successful than firms without. To refine this result, model two and five differentiate experienced innovators into the innovator types related diversifiers, unrelated diversifiers, parents owned and Spin offs. Unexperienced de novo innovators are kept as base category. Compared to de novo innovators the estimated coefficient of spin offs (-37.79) and related diversifiers (-35.40) show the weakest risk of failure.

Table 2: regression results – hypothesis 1

	Cox			Gompertz		
	(1)	(2)	(3)	(4)	(5)	(6)
age	-0.0649*** -4.40	-0.0858** -2.28	-0.0805** -2.16	-0.0721** -4.39	-0.0950** -2.07	-0.0899* -1.94
Experience	-1.1252*** -2.98			-1.1524*** -3.01		
related DIV		-35.4037*** -57.28	-38.5384*** -61.57		-17.4333*** -23.82	-15.3565*** -20.60
unrelated DIV w.s.		0.4861 0.91			0.5291348 0.93	
new innovative			0.6982 1.21			0.7058 1.14
unrelated Div n.s.			-0.0658 -0.08			0.0255 0.03
Parents owned		-1.8068** -2.39	-1.8097** -2.39		-1.8381** -2.43	-1.8392** -2.43
Spin off		-37.7850*** -120.50	-40.838*** -111.22		-19.9629*** -55.05	-17.9643*** -49.80
Cons				-3.3729*** -14.56	-3.3943*** -12.74	-3.3820*** -12.83
No. Firms	291	291	291	291	291	291
Time at risk	2947	2947	2947	2947	2947	2947
Ll	-173.25277	-163.1683	-162.69419	-107.32463	-96.667901	-96.292598
Wald chi2	36.41***	22422.80***	27005.96***	35.45***	5178.72***	4214.08***

Since both coefficients are close to each other a t-test to check the equality of coefficients was performed. The null hypothesis of equality was rejected at the 0.001 level. Spin offs are the best performing innovator type in the PV industry. This result suggests furthermore that related technological knowledge is a critical success factor for the survival of innovators in the PV industry and that this advantage is largest for spin offs which can not only assesses prior related technological knowledge of the parent company but also core PV knowledge, expertise and resources. Furthermore, in line with prior empirical work on spin offs, these innovator type might be more successful because of organizational and flexibility advantages over larger innovators which pursue a related technological diversification strategy. In the spin off literature it is discussed that spin offs often face a competitive disadvantage because of a lack of market oriented knowledge like customer needs and competition dynamics. This is especially for spin offs with an academic background. With regard to this critical point in research literature, our results suggests, that the in the case of innovators of the German PV industry, initial technological capabilities of spin offs seem to be sufficient to overcome the lack in market knowledge. This is in line with the general finding of Bruederl et al. (1992). The authors give empirical evidence for a lower exit hazard of new firms which are initiated by entrepreneurs with prior industry experience, compared to other de novo firms (Bruederl et al 1992). For the unrelated diversifiers no significant difference in the hazard compared to de novo firms is identified. Obviously, prior knowledge and expertise is not sufficient for long term survival per se. Crucial for the survival of diversifying innovators within the PV industry is the stock of related and core technological knowledge at the time of entry. Generable and complementary knowledge e.g. in managing multiple projects, managing distribution networks and customer relationships or production skills (Chatterjee/Wernerfelt 1991, Carroll et al. 1996, Helfath/Lieberman 2002) are not essential for the survival of diversifying innovators. The last innovator type is the parents owned innovators. Compared to de novo innovators, parents owned innovators have a significant lower hazard to fail, but a much higher risk than related diversifiers and spin off firms.[11] The influence of prior technological knowledge on the hazard rate of this innovator type is more difficult to predict. In general, parents owned innovators have initially success to parent's knowledge and resources. The intensity and the type of parents' knowledge and resources are hard to determine. At least, compared to spin offs, it can be assumed, that the quantity of transferred core technological knowledge is much more limited (Helfat/Liebermann 2002).[12]

Based on the criterion of prior technological knowledge, the innovator type of unrelated diversifiers is refined in Model 3 and 6. Even in a more detailed analysis of unrelated diversified innovators, no significant change in the hazard rate, compared to de novo innovators, becomes evident. In the German PV industry it obviously does not matter if a new innovator possess prior unrelated technological knowledge (diversifiers in the narrow sense) or just generable non-technological knowledge (new innovative firms), it faces a similar hazard of failure like de novo innovators. In Conclusion, our results give empirical support for hypothesis

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[11] A t test is performed to test the null hypotheses of coefficient = 0. The null hypothesis is rejected at the 0.01 level.

[12] No differentiation between parents active within the PV industry and parents which are not active within the PV industry is made.

one. Innovators with prior core and related technological knowledge outperform innovators without. Our results remain stable under the Gompertz specification as well as under the Cox specification.

H2. Entry Time and Post-Entry Knowledge

In a next step, the influence of the knowledge stock accumulated after innovators entrance into the PV industry on firm survival is estimated. In order to differentiate entry cohorts, innovation relevant characteristics of the PV industry are taken into account. Methodologically, the approach by Klepper (2002) was followed. Klepper suggest a critical number of at least 15 firms which survived at least 15 years to balance the cohorts with respect to an entry time dependent changing number of observations within every cohort. In all estimations, the age at entry is included as control for age specific influences on the firm's survival duration. Results are presented in table 3.

Table 3: survival regression results – hypothesis 2

	Cox		Gompertz	
	(7)	(8)	(9)	(10)
Age	-0.0974*** -4.24	-0.0958*** -4.28	-0.0980*** -4.28	-0.1010*** -4.39
E1a: 1964-1991	-2.4564 ** -2.49		-2.5970 *** -3.62	
E1b: 1964-1987		-2.7046*** -2.79		-3.263005*** -3.49
E2b: 1988-1999		-1.6274*** -3.44		-1.612496*** -3.82
cons			-3.8669 *** -13.11	-3.6127*** -12.64
No. Firms	291	291	291	291
Time at risk	2947	2947	2947	2947
Ll	-171.04651	-167.88579	-102.32547	-100.5598
Wald chi2	28.43***	47.42***	45.46***	56.22***

In a first step, we distinguish two entry cohorts. Referring to Johnstone et al. (2008, 2010) who emphasize the substantial role of policy instruments for encouraging innovation in renewable energy technologies, the cutting point is defined by the year 1991. In 1991 the Electricity Feed-in Act in combination with the 1000-roofs program was introduced and incentives for innovation changed. The selection of the 1991 cutting point takes a possible distortion of public funding on the survival of later entering innovators into account. The period from 1992 to 2011 acts as base category. Results indicate significant lower hazard for early innovators, despite the introduction of the Electricity Feed-in Act and the 1000-roofs program. This holds true for the Cox as well as for the Gompertz specification. Obviously the influence of the new public support measures did not affect advantages of early innovators like economies of scale or economies of scope. In a second step, three entry cohorts are differentiated. The first entry cohort represents all innovators starting innovation activities within PV technologies between 1964 and 1987. The second entry cohort covers the period from 1988 to 1999. The period from 2000 to 2011 is considered by the third entry cohort, which builds the base category within the regression models. Compared to the last entry cohort, the first entry cohort shows the lowest hazard. For the second entry cohort, the hazard increases, but is still lower than for the latest entry cohort. [13] Again, these results hold under the Cox and the Gompertz specification. These results strongly support hypothesis two.

H3. Innovation Submarkets

The influence of innovation activities within several submarkets on innovator's survival is tested by the variable No.SM. This variable is a simple count of the number of different PV innovation submarkets in which an innovator is active. Thus, the value range of this variable is one to seven. Furthermore a dummy variable DivSM is introduced to take a possible bias from endogeneity into consideration.[14] It takes the value of zero if an innovator conducts specialized innovation activities within one innovation submarket and the value of one if innovation activities are spread over more than one submarket. This dummy variable is characterized by two properties. First, it correlates with the endogenous explanatory variable, conditional on the other explanatory variables. Second DivSM is not correlated with the error term, conditional on the other explanatory variables. Interaction effects for all inventor types are introduced to test for a joint effect of pre-entry knowledge and the number of innovation submarkets on firm survival. Results are presented in table 4.

In model 11 and 14 the main effect of the number of innovation submarkets on innovators survival is tested. Both model specifications reveal a significant lower hazard for firms conducting innovation within an increasing number of innovation submarkets. Coefficients are significant at the 0.01 level. Considering possible problems from endogeneity, model 12 and 15 confirm significant lower survival chances for innovators which focus innovation activities

[13] The equality of coefficients for E1b and E2b was performed. Equality is rejected at the 0.01 level.

[14] The number of submarket in which a firm conducts innovation can also be assumed to be influenced by the survival duration of innovators. The longer an innovator is active within the market, the higher is the expected number submarkets in which the innovator is active. The explanatory variable correlates endogenously with error term which leads to inconsistent estimation results. This special issue of reverse causality can be solved by the usage of an instrument variable.

on one innovation submarket. Significance level drops to 0.05, which can still be accepted for statistical evidence given the sample size. Joint effects of pre-entry knowledge type and number of innovation submarkets are considered within models 13 and 16. Positive interactions are proven for related diversifiers, spin offs and parents-owned firms. The highest interaction effect is realized for related diversifiers. The effect of pre-entry related knowledge on firm survival increases significantly with the number of innovation submarkets in which the related diversifier performs innovation activities. The second highest interaction effect is proven by spin offs. The effect of a spin offs pre-entry knowledge on its survival chances also increases with the number of innovation submarkets in which the spin off is active. The joint effect of parents-owned firms and innovation submarket is considerable lower but positive and still significant at the 0.1 level. The joint effect is not as unambiguously as the joint effects realized by related diversifiers and spin offs. One possible explanation for the gained results could be the realization and exploitation of multiple synergies within the knowledge base of related diversifiers and spin offs during the exploration of new innovation submarkets.

Table 4: survival regression results – hypothesis 3-1

	Cox			Gompertz		
	(11)	(12)	(13)	(14)	(15)	(16)
age	-0.099831*** -4.37	-0. 100336*** -4.43	-0.09212** -2.16	-0.107641*** -4.50	-0.109069*** -4.49	-0.1003015** -1.96
DivSM		-0.7521748** -2.26			-0.7243474** -2.11	
No.SM	-0.704137*** -3.38		-0.44473* -1.83	-0.6919197*** -3.35		-0.416613* -1.83
related DivxTF x No.SM			-36.044*** -39.25			-13.40015*** -12.58
new innovativex No.SM			0.46030 1.64			0.4496923 1.51
unrelated DIV n.s. x No.SM			0.0890 0.21			0.1307143 0.30
Parents owned x No.SM			-0.67339* -1.95			-0.6917047** -2.00
Spin off x No.SM			-20.4483*** -95.15			-9.459685*** -45.50
cons				-2.336904*** -5.02	-3.113793*** -8.34	-2.620088*** -4.89
No. Firms	291	291	291	291	291	291
Time at risk	2947	2947	2947	2947	2947	2947
ll	-171.66179	-174.91023	-160.40367	-105.59082	-109.1032	-94.153366
Wald chi2	26.42***	22.10***	13479.88***	27.96***	22.89***	2759.37***

To deepen the understanding of innovation submarkets and innovators survival in a next step, a tobit model is applied to test the determinants of innovation submarket entry.

Results of the tobit estimation illustrate that innovators of the early entry cohort (1964-1991) perform innovation activities within a higher number of different innovation submarkets, compared to innovators which start PV innovation activities later (between 1992-2011). The coefficient is significant at the 0.01 level. This result seems intuitively evident since per definition submarkets evolve sequentially over time. Innovators which enter late the PV industry may miss innovation within one innovation submarket because this submarket is decreasing or already destroyed.

Table 5: tobit regression results – hypothesis 3-2

	tobit	
	(14)	(15)
E1a: 1964-1991	1.02039 *** 7.06	0.9477208 *** 6.59
related Div		0.3264662*** 2.66
new innovative		-0.1643697 -0.84
unrelated Div n.s.		0.0337973 0.16
parents-owned		0. 4096212 *** 2.59
Spin off		0. 5561833** 2.45
Cons	2.004 *** 36.95	1.818817 *** 20.04
No. Firms	291	291
ll Pseudo R2	-368.17278 0.0588	-359.51208 0.0810

The type of pre-entry knowledge also seems to influence the number of innovation submarkets of an innovator. Taking de novo innovators as base category, we found a positive and significant effect for parents owned innovators, spin offs and related diversifiers. All three innovator types are associated with a certain stock of PV technology related knowledge before starting innovation activities within PV technologies. This again emphasizes the possible relevance synergies in form of economies of scale and especially economies of scope when leveraging knowledge from one application setting to another.

6. Discussion and Conclusion

The present study focuses on the survival of German innovators within the German Photovoltaic industry. Three hypotheses were developed by combining theoretical arguments. General research on firm survival and several streams of industrial evolution research are considered. Furthermore, practical arguments based on empirical observations within the German PV industry are included. The relevance of different types of technological knowledge on innovators survival is tested. The definition of different technological knowledge types is based on an innovative technology-based differentiation of innovator types. Therefore the Green Inventory scheme and the ISI-OST INPI classification; both developed by the WIPO, are applied to the sample firms patent portfolio and combined with comprehensive firm level data collected from several database and sources. De novo innovators, related diversifying innovators, new innovative diversifiers, unrelated diversifying innovators, parents-owned innovators and spin offs are distinguished and goes far beyond prior research. A total number of 291 German PV innovators are considered.

By applying survival estimation models, we found empirical evidence for all of our three hypotheses. First, for long term survival of German innovators within the German PV industry, prior related and prior core technological knowledge at the time of entering the PV industry as innovator is a crucial factor. Generable and unrelated technological knowledge are not sufficient. Second, the technological knowledge stock which an innovator collects after its entry as an innovator in the German PV industry lowers the hazard of exit. Third, we give empirical evidence of innovation submarket dynamics within the German PV industry. We show that German innovators which spread their innovation activities across different PV innovation submarkets over time, survive longer than innovators which are specialized within one PV innovation submarket. These results contribute to existing work by focusing especially on the research gap concerning innovation and technological knowledge as drivers of firm survival in dynamic industries. Also practitioners can benefit from our results. Before pursuing new firm formation or diversification strategies, de novo innovators as well as established innovators should precisely consider their technological competencies and knowledge as well as the technological knowledge stock of incumbent competitors. For innovators within the German PV industry, technological knowledge confers a competitive advantage which is not easily to overcome by competitors.

We applied an innovative methodological approach within a unique research setting. Nevertheless our research is not free of limitations. First, by applying a patent based definition of PV technologies and PV innovators, innovators which don't pursue patenting activities, remain unconsidered. As pointed out, there are several reasons which allow assuming a very low bias from this approach, given the empirical framework and the characteristics of the German PV industry. Furthermore, we consider only firms with at least four PV patents. On the one hand, this ensures the intrinsic validity of our study since innovators with random PV innovations are excluded from the sample. On the other side we may lose especially younger innovators, which started innovation activities in PV technologies short before the end of the observation time. The appearance of right truncation is common in survival analysis and has no significant influence on the robustness and significance of our results given our research setting (Cleves et al. 2010, p. 36). Last, we assume persistency within a firm's innovation strategy. If a firm starts to be an innovator, it is assumed that there will be no change in this strategic orientation, for example a shift to an imitator strategy within the PV industry.

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Appendix

A1. Keywords

“solar", ”module” “panel", "stirling", "photovoltaik", "inverter", "silicium", "wafer", "heterojunction", "polycrystalline", "silicon", "radiation", "photo electronic", "thin-film", "photo electric", "photo electrically", "photoelectronic", "photoelectrical", “photovoltaic”, “cell”.

A2. Green Inventory

No.	Photovoltaics (PV)	IPC
1	Devices adapted for the conversion of radiation energy into electrical energy	H01L 27/142, 31/00-31/078
		H01G 9/20
		H02N 6/00
2	Assemblies of a plurality of solar cells	H01L 25/00, 25/03, 25/16, 25/18, 31/042
3	Silicon; single-crystal growth	C01B 33/02
		C23C 14/14, 16/24
		C30B 29/06
4	Regulating to the maximum power available from solar cells	G05F 1/67
5	Electric lighting devices with, or rechargeable with, solar cells	F21L 4/00
		F21S 9/03
6	Charging batteries	H02J 7/35
7	Dye-sensitised solar cells (DSSC)	H01G 9/20
		H01M 14/00