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Original article

R&D collaborations along the industry life cycle: the case of German photovoltaics manufacturer

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Abstract

Industrial evolution prompts firms to enter into R&D collaborations to ensure competitiveness and substantial growth. This study expands the industry life cycle concept to include the extent and types of R&D collaborations. I analyze 6581 R&D collaborations by 60 manufacturers in the German photovoltaics (PV) industry from 1980 to 2016 using a negative binomial regression model. The results indicate that the number of R&D collaborations is higher in the post-shakeout than in the pre-shakeout period of an industry. While this is particularly true for science-based R&D collaborations with universities and public research organizations, market-based R&D collaborations evolve from predominantly competitors before an industry's shakeout to suppliers and customers after a shakeout has occurred.

JEL classification: O32, O31, L69, L14

1. Introduction

The industrial progress incentivizes firms to carry out R&D to ensure competitiveness and substantial growth. The steps and outcomes of progress and the change in firm-level capabilities can be described in an industry life cycle model (Abernathy and Utterback, 1978; Klepper, 1997; Argyres *et al.*, 2015). As an often-confirmed life cycle model, Klepper (1997) depicts the pattern of industry entries and exits over time and its determinants such as a firm's innovativeness. Innovation and R&D collaboration have become increasingly important in the industrial dynamics literature in recent years (Bhaskarabhatla and Klepper, 2014; Agarwal *et al.*, 2015; Carlsson, 2016). R&D collaborations indicate a firm's external relationships with other actors that mutually commit to exchange resources and particularly knowledge for the creation of new or improved products or processes (Un *et al.*, 2010).

The R&D management literature has extensively investigated the motives and performance outcomes of R&D collaborations (Un *et al.*, 2010; Un and Asakawa, 2015; Wu *et al.*, 2015). It distinguishes between R&D collaborations with science-based partners (i.e. public research organizations/PROs and universities) and market-based partners (i.e. suppliers, customers, and competitors) (e.g. Tether, 2002; Belderbos *et al.*, 2004; Du *et al.*, 2014). A handful of studies relate the importance of these types of R&D collaborations to their occurrence in the course of a technology life cycle (e.g. Cainarca *et al.*, 1992; Lecocq and Van Looy, 2009; Kapoor and McGrath, 2014; Vanhaverbeke *et al.*, 2015). However, the technology life cycle only describes an industry's underlying technologies while neglecting more mature stages in which technologies are substituted, the hazards of exit increase and a shakeout occurs (Klepper, 1997). Thus far, both literature streams ignore how R&D collaborations evolve along the industry life cycle. This lack of research might be due to the kind of information on former collaborations that is sometimes hard to find, deleted or nonexistent because firms might exit the industry at a certain point in time. Because of the growing relevance for firms to stay competitive during the industrial progress, more light must be shed on how the change in the structure of industries influences the extent and tendencies to collaborate.

In this article, I aim to extend the industry life cycle concept with the notion of R&D collaborations to explain the evolution of their number and types during industrial progress. Building on arguments from the industry life cycle literature (e.g. Klepper, 2007; Peltoniemi, 2011; Agarwal *et al.*, 2015), I propose that the change in the structure of industries drives firms' tendencies to engage in R&D collaborations. Therefore, I hypothesize that the number of R&D collaborations is higher in the post-shakeout than in the pre-shakeout period of an industry. Moreover, since the types of collaboration partners differ in their capabilities and risks, I expect that the extent of R&D collaborations with science-based and market-based partners varies in the course of an industry's structural change.

The background of this article is the German photovoltaics (PV) industry from 1980 to 2016. The PV industry is one of the fastest growing markets worldwide that created many new opportunities for firms to engage in R&D and push policy makers to support innovation and growth toward a desirable energy transition (Jacobsson *et al.*, 2004). As in many other science-based industries that favor large incumbents and a coherent identity (e.g. automobiles, biotechnology, semiconductor), innovation policy is a continuously used tool to reap positive externalities for society (Georgallis *et al.*, 2019). R&D and collaboration are important for PV manufacturers to enhance innovative capabilities and to remain competitive on a market for which cost disadvantages to traditional energy sources exist (Dewald and Fromhold-Eisebith, 2015). Because of high R&D intensities (Quitzow, 2015), firm dynamics (Hoppmann, 2018) and the industry's broad sectoral configuration (Hipp and Binz, 2020), R&D collaborations by German PV manufacturers are of particular interest. I use information on the development of 97 PV cell and module manufacturers, of which 60 firms engaged in 6581 science-based and market-based R&D collaborations from 1980 to 2016. I apply a negative binomial regression model to understand how the dynamics of the PV industry shape the engagement in the different types of R&D collaborations.

The findings point to increasing R&D collaboration efforts after the industry has experienced a shakeout. While this is particularly true for science-based R&D collaborations with universities and PROs, market-based R&D collaborations evolve from predominantly competitors before the industry's shakeout to suppliers and customers in the post-shakeout period. This study contributes to the debate over who to collaborate with during industrial evolution by extending the industry life cycle theory with the notion of R&D collaborations (e.g. Klepper, 1997; Carlsson, 2016; Esteve-Pérez *et al.*, 2018). It enriches our knowledge on R&D collaborations during the technology life cycle (e.g. Vanhaverbeke *et al.*, 2015) by providing a conceptualization and empirical evidence on how their extent and types change along the industry life cycle. To the best of my knowledge, I am the first to explain how the industry life cycle determines a firm's tendencies to collaborate. Many R&D collaboration studies focus on specific technologies or mature industries using either survey or conference data (e.g. Belderbos *et al.*, 2004; Lööf, 2009; Kapoor and McGrath, 2014). This analysis uses a novel set of firm-specific, industry-level and collaboration data from a comprehensive range of sources. It provides policy recommendations to sustain firms' competitiveness by tailoring the support for specific types of R&D collaborations before and after an industry's shakeout.

The remainder of this article is structured as follows. Section 2 presents the conceptual background and the hypotheses on the role of R&D collaborations along the industry life cycle. Section 3 contains information on the development of German PV manufacturers and their engagement in R&D collaborations. Section 4 explains the data and the statistical methods used. Section 5 presents the results and Section 6 concludes with a summary and discussion, limitations, and guidance for further research.

2. Theory and hypothesis

2.1 The industry life cycle and innovation

The literature on the industry life cycle describes how the structure of industries changes over time using a life cycle model (Klepper, 1996, 1997; Klepper and Simons, 1997; Agarwal *et al.*, 2015; Esteve-Pérez *et al.*, 2018). Widely discussed in this literature, Klepper's life cycle model (1997) suggests that an industry evolves from a high rate of firm

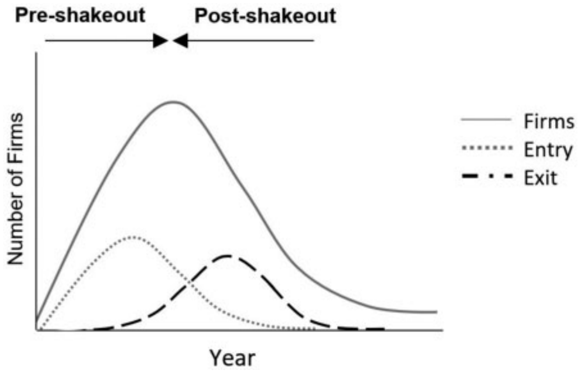

Figure 1. Stylized industry life cycle in line with Klepper (1997).

entries and increasing levels of competition to a shakeout in which firm exits exceed the number of entries. Two major phases characterize this life cycle, the "pre-shakeout" and the "post-shakeout", often referred to as the "formative era" or the "era of ferment" and the "era of incremental change" or the "era of mass production" (Peltoniemi, 2011; Huenteler *et al.*, 2016; Hipp and Binz, 2020). An industry emerges when large incumbent firms and entrepreneurs from other sectors enter a small niche market to diversify their activities into new technological fields. In this "pre-shakeout" period, firms develop a new product of a simple design and low production outputs using unspecialized techniques while facing high uncertainty regarding customers' needs (Williamson, 1975). A variety of different product designs emerges to attract new buyers (Clark, 1985). Many new and specialized firms enter this niche to seize new market opportunities through product innovations (Klepper, 1996). As soon as a dominant product design has emerged, price-based competition intensifies and the hazards of industry exit increase. A shakeout occurs as more firms exit than enter the industry, even though the output continues to grow. In this "post-shakeout" period, firms engage in process innovation to meet the growing demand through a larger output that allows for economies of scale on a mass market. A few remaining firms will dominate the industry with specialized processes, specific applications or niche products, grow in their size, and share an oligopoly (Klepper, 1997). Figure 1 depicts the typical shape of an industry life cycle. Table 1 provides an overview of the key characteristics of its major phases.

Empirical evidence on this life cycle was provided for different industries in the United States, such as automobiles, tires, televisions, and penicillin (e.g. Jovanovic and MacDonald, 1994; Klepper and Simons, 1997; Klepper, 2002; Peltoniemi, 2011). Recent research also transfers this life cycle to other countries (e.g. Cantner *et al.*, 2009; Tan and Mathews, 2010; Furr and Kapoor, 2018). Some industries, however, show different life cycle patterns since submarkets can emerge that prevent an industry's shakeout (e.g. as for lasers) (e.g. Buenstorf, 2007).

A firm's innovativeness plays a key role for the industry life cycle and industrial dynamics (Klepper, 1997; Bhaskarabhatla and Klepper, 2014; Agarwal *et al.*, 2015). In his early work, Schumpeter (1911) argues that entrepreneurial profits in an industry are spurred by innovation. Later, Abernathy and Utterback (1978) propose that an industry's structural change determines the different types of product and process innovation. Product innovation relates to a new product or to improvements of its components (Henderson and Clark, 1990). Process innovation, in contrast, refers to more efficient methods of production (Klepper and Simons, 1997). Many empirical studies highlight the importance of innovation for the industry life cycle and a firm's survival (e.g. Cefis and Marsili, 2005; Klepper and Simons, 2005; Cantner *et al.*, 2009).

2.2 Innovation, R&D collaborations, and the technology life cycle

As a complement to internal innovation activities in an industry, a firm can engage in R&D collaborations with other organizations to enhance its capabilities and achieve a competitive advantage (Teece, 1986). The motives and outcomes of R&D collaborations have been deeply examined in the R&D management literature. This literature describes the access to new resources, learning, and risk and cost sharing as key motives to engage in R&D collaborations, which considerably increase a firm's innovativeness and survival in an industry (e.g. Mitchell and Singh, 1996; Powell *et al.*, 1996; Walsh *et al.*, 2016). R&D collaborations diverge from other collaborative forms such as

Table 1. Key characteristics of the industry life cycle

	Pre-shakeout	Post-shakeout
Rate of entry	High	Low
Competition	Increasing	High
Type of firm	Incumbent	Specialist
Type of innovation	Product	Process
Product design	Various	Dominant
Market	Niches	Mass
Output	Small	Large
Rate of exit	Low	High

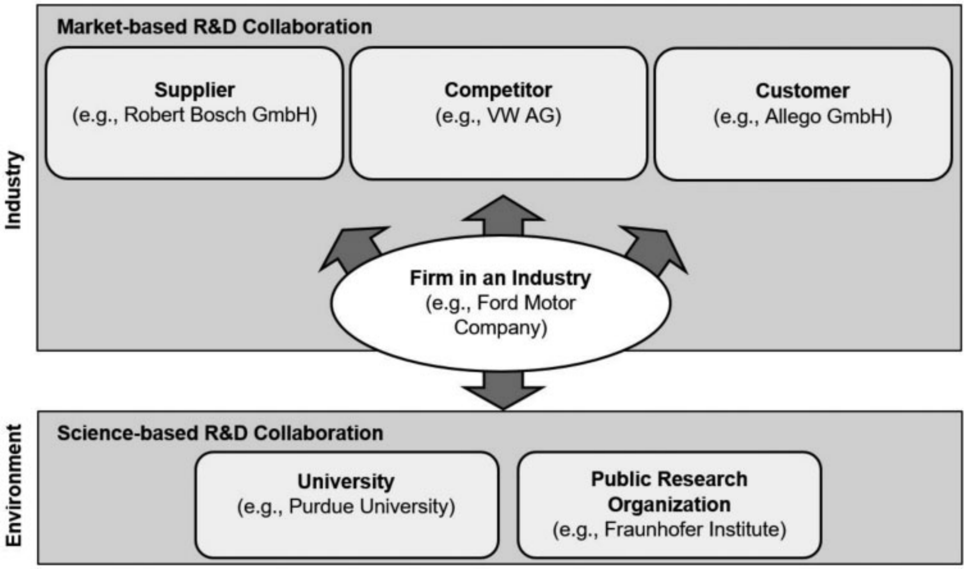

Figure 2. Types of R&D collaborations.

commercial, financial, or productive collaborations that target at different outcomes than the creation of new products or technologies (i.e. their commercialization, financing, or production) (Croonen, 2004; Wandfluh *et al.*, 2016). However, some R&D collaborations bear risks, such as involuntary spillovers or resource misappropriation (Belderbos *et al.*, 2004). Cassiman and Veugelers (2002) show that the likelihood of spillovers is greater when firms collaborate with particular types of R&D partners. The presence of involuntary spillovers can cause firms to invest less in R&D collaborations because they cannot fully appropriate all returns. A plethora of empirical studies underlines the presence of spillovers from R&D collaborations (e.g. Belderbos *et al.*, 2004; Lööf, 2009; Du *et al.*, 2014; Hottenrott and Lopes-Bento, 2014).

The R&D management literature basically distinguishes between science-based and market-based types of R&D collaboration depending on a partner's position in or outside of an industry (Tether, 2002; Miotti and Sachwald, 2003; Belderbos *et al.*, 2004; Du *et al.*, 2014). Science-based R&D collaboration includes a manufacturing firm from an industry and at least one university or PRO as a partner from the industry's environment. Market-based R&D collaboration consists of a manufacturing firm from an industry and at least one supplier, customer, or competitor as a partner positioned within an industry. Figure 2 depicts the types of R&D collaboration.

Science-based R&D collaborations with universities and PROs deliver new knowledge from the technological frontier in multidisciplinary areas (Tether, 2002; Miotti and Sachwald, 2003). Universities target exploratory knowledge creation with a long-term focus on basic research without the need to apply or commercialize products

(Giannopoulou *et al.*, 2019). PROs are highly specialized in technical fields and mainly intend to commercialize products developed in the R&D process (Readman *et al.*, 2018). In many science-based industries, manufacturers (e.g. Ford Motor Company) frequently collaborate with universities and PROs (e.g. Purdue University, Fraunhofer Institute) to generate and test product ideas and create new technologies such as for mobility or transportation purposes (Perkmann and Walsh, 2009).

In market-based R&D collaborations, suppliers are integrated in the upstream part, competitors belong to the core part, and customers are positioned in the downstream part of an industry (Stephan *et al.*, 2017). While suppliers deliver components for integration into a market-related core product, customers bring the core product into a usage context (Miotti and Sachwald, 2003). Competitors, in contrast, produce similar core products (Hamel *et al.*, 1989). For instance, Ford recently collaborated with its supplier Robert Bosch GmbH to integrate automotive solutions, its competitor VW AG delivers knowledge on autonomous driving, and customers such as Allego GmbH provide charging stations for electric vehicles and contribute to their operation.

Recent studies show that the types of R&D collaborations vary along the life cycle of a technology in an industry. The concept of the technology life cycle describes the progress of a specific technology in a typical s-curve that evolves from an initial stage of emergence, through its growth, into maturity in which technological limits are reached (Christensen, 1992). Cainarca *et al.* (1992) provide the first evidence in their sample on information technologies from 1980 to 1986 that the propensity to collaborate on R&D changes along the technology life cycle. Using a panel of 197 regions in the EU-15 and Switzerland from 1978 to 2001, Lecocq and Van Looy (2009) investigate the impact of R&D collaboration types on a region's technological performance in the field of biotechnology. Recently, Kapoor and McGrath (2014) use an archival dataset on technical conferences to analyze how the types of R&D collaborations evolve along the technology life cycle of the deep ultraviolet technology from 1990 to 2010. Vanhaverbeke *et al.* (2015) show that the number of R&D collaborations changes during the technology life cycle of application-specific integrated circuits from 1987 to 2000. Even though these studies explain how the extent and the types of R&D collaborations vary along the technology life cycle, their evolution along an industry's life cycle remains an unexplored issue.

2.3 R&D collaborations along the industry life cycle

2.3.1 Number of R&D collaborations

The engagement in R&D collaborations is driven by the structural change of industries. An industry emerges when a few large incumbents enter a niche market to gain profits from a new technology (Klepper, 1996). The level of competition as well as the output is low, but the incumbents face high uncertainty regarding the new technology's characteristics and customer needs and start to engage in in-house R&D (Klepper and Simons, 1997). Due to activities in other business areas, they got in touch with other firms and learned to trust their partners (Deeds and Hill, 1996). R&D collaboration allows for the exploration of new technological knowledge (Tether, 2002), the creation of new product designs (Song and Parry, 1997), and the introduction of product innovations (Un *et al.*, 2010). Moreover, it reduces transaction and contractual costs (Williamson, 1975) and enables risk sharing when conducting R&D activities (Das and Teng, 2000). Incumbents are more committed to their partners (Kale *et al.*, 2000) and easily enter into new R&D collaborations (Belderbos *et al.*, 2004). They prefer to collaborate with new firms to be closer to new technological knowledge required on a niche market (Bond and Houston, 2003). In turn, new firms tend to collaborate with incumbents to overcome initial resource constraints and to share the high risks and costs inherent in the R&D process (Okamuro, 2007).

Empirical evidence shows that R&D collaborations increase in the course of a technology life cycle. For instance, Cainarca *et al.* (1992) show that the majority of firms engaged in R&D collaborations during early technology stages. Kapoor and McGrath (2014) found that R&D collaborations increased along the technology life cycle. Vanhaverbeke *et al.* (2015) support these findings, but they observe a shrinking number of R&D collaborations as the technology has matured.

In line with the findings on the technology life cycle, I argue that R&D collaborations increase before an industry experiences a shakeout because firms seek to gather new knowledge, share risks and costs, and create new product innovations as technological uncertainties and market opportunities are high.

The tendencies to collaborate will change when the industry matures and a shakeout occurs, in which the number of exits exceed the rate of entries into the industry (Klepper, 1997). As a dominant product design has emerged, firms must either specialize in certain applications, niches, or processes to achieve economies of scale, or they fail and leave the industry (Klepper and Simons, 2005). R&D collaborations can involve risks such as involuntary spillovers, opportunistic behavior, or a misappropriation of resources (Vanhaverbeke *et al.*, 2015). Moreover, coordination and management costs rise with the number of collaborations (Deeds and Hill, 1996). However, collaborating partners share great loyalty and trustworthiness and their resource interdependencies and complementarities increase over time, which minimizes collaboration risks (Nohria and Garcia-Pont, 1991). Furthermore, firms become increasingly embedded in collaboration networks, which eases the continuity or renewal of former as well as the entry into new relationships, particularly if firms have gained a central network position (Gulati, 1995). The reputation of central network actors in turn incentivizes new firms to enter into R&D collaborations to gain access to superior capabilities (Powell *et al.*, 1996). R&D collaborations help to realize efficiency gains through economies of scale, knowledge accumulation, and cost sharing (Das and Teng, 2000). They further allow firms to monitor technological and market developments (Hamel *et al.*, 1989), develop industry standards (Nakamura, 2003), and achieve process innovation (Becker and Dietz, 2004). As competition intensifies, firms increase their tendencies to collaborate to shorten innovation cycles (Pisano, 1990), share costs and market risks (Uzzi, 1997), and increase the pace of technology development (Wu, 2012).

Even though the number of firms in an industry decreases after a shakeout, firms increase their collaboration efforts to specialize, enhance the efficiency of new technology development, and achieve process innovation to reduce the high hazards of market exit. I therefore posit that the extent of collaborative R&D will be even higher after the shakeout of an industry:

H1: Ceteris paribus, the number of R&D collaborations is higher in the post-shakeout than in the pre-shakeout period of an industry.

2.3.2 Science-based R&D collaborations

As collaboration tendencies increase in the course of an industry's life cycle, access to a partner's specific capabilities takes on a crucial role. In the pre-shakeout period, firms seek to reduce high uncertainties with respect to the development and market acceptance of a new product (Klepper, 1997). Science-based R&D collaborations enable access to fundamental research when firms need to solve technical or design-related problems, re-orient R&D and develop new products (Lee, 2000). They support the exploration of new markets (Tether, 2002), provide inputs from the technological frontier (Miotti and Sachwald, 2003), and help to achieve product innovations (Belderbos *et al.*, 2004). R&D collaborations with universities in particular increase a firm's competence level and the variety and diffusion of knowledge (Ahrweiler *et al.*, 2011), form a trustful environment (Bstieler *et al.*, 2015), and ensure a high quality of the technology to be developed (Walsh *et al.*, 2016). They offer an easy access to new resources (Un *et al.*, 2010) and often allow for a firm's participation in public R&D programs (Sakakibara, 1997). Particularly large incumbents are closer to the scientific environment and tend to collaborate with universities (Beise and Stahl, 1999). They share complementary assets and costs with their scientific partners; but also new specialists can easily enter into these collaboration types (Veugelers and Cassiman, 2005).

While Kapoor and McGrath (2014) found that science-based R&D collaborations predominantly occur in a technology's emergence stage, Lecocq and Van Looy (2009) show their continued importance during the growth of a new technology.

I expect that science-based R&D collaborations increase before an industry's shakeout as they provide easy access to fundamental research on new products and enable risk and cost sharing in an environment that is characterized by a high level of technological uncertainty.

When an industry has matured and prompts into a shakeout, price-based competition becomes fierce and increases a firm's hazards of industry exit (Klepper, 2007). To stay competitive in an industry, firms must achieve cost efficiencies or serve other (sub)markets (Bhaskarabhatla and Klepper, 2014). Science-based R&D collaborations contribute to the generation of process innovation (Un and Asakawa, 2015). However, they can become less important as fewer firms enter the industry (Motohashi, 2005). Firms decrease their entry into science-based collaboration types as they become riskier in competitive environments (Hanel and St-Pierre, 2006). In particular, universities work in a rather exploratory, long-term manner, which entails a certain distance from firms; this approach does not explicitly target a product's improvement or its transfer into an application context (Giannopoulou *et al.*, 2019). Instead, they produce large involuntary spillovers that can strengthen a rival's market position (Belderbos *et al.*, 2004; Veugelers and Cassiman, 2005; Lööf, 2009). Only when firms explore new submarkets, scientific partners again gain in importance for providing key inputs for new technical solutions that can enable an industry's revitalization (Bhaskarabhatla and Klepper, 2014).

However, the long-term nature of fundamental research and large involuntary spillovers might reduce firms' intentions to engage in science-based R&D collaborations after an industry's shakeout. I therefore hypothesize that the number of science-based R&D collaborations becomes less during the post-shakeout period:

H2: Ceteris paribus, the number of science-based R&D collaborations is lower in the post-shakeout than in the pre-shakeout period of an industry.

2.3.3 Market-based R&D collaborations

As opposed to science-based partners, market-based R&D collaborations provide knowledge on similar technologies and markets (Cainarca *et al.*, 1992; Tether, 2002; Miotti and Sachwald, 2003). However, R&D collaborations with competitors, suppliers and customers differ in their motives and the kinds of knowledge to be transferred. A firm's motives to enter into competitor R&D collaborations can be complex; for example it may seek to learn about a rival's knowledge (Hamel *et al.*, 1989). Emerging niche markets are mostly served by large incumbents before new firms enter the industry and create various product designs until one dominant design arises (Klepper, 1997). Competitor R&D collaborations provide a resource pool that influences the creation of new product standards and the regulatory environment (Tether, 2002). They usually involve large incumbents that possess the necessary resources to address major technological challenges and advance technologies (Gnyawali and Park, 2011). Competitor R&D collaborations contribute to product innovation (Miotti and Sachwald, 2003) and process innovation to increase a firm's product sales and growth (Belderbos *et al.*, 2004).

Lecocq and Van Looy (2009) underline the relevance of competitor collaborations in early technology stages, but Kapoor and McGrath (2014) observe their continued occurrence along the technology life cycle.

Since firms intend to pool their complementary knowledge on new products for the creation of a dominant design, I expect that the number of R&D collaborations with competitors increases before the shakeout of an industry.

When firms follow a dominant design, price-based competition becomes fierce and firm exits increase, inducing an industry's shakeout (Klepper, 2002). Intense competition and high hazards of exit reinforce collaboration risks such as opportunistic behavior (Das and Teng, 1996). R&D collaborations between competitors increase the risks of resource misappropriation and involuntary spillovers (Belderbos *et al.*, 2004) as well as the risks of being acquired from their partners (Mitchell and Singh, 1996). Coopeting firms therefore need to consider a product's appropriability to avoid involuntary spillovers (Laursen and Salter, 2014). In contrast, the probability of entering into supplier–customer R&D collaborations increases with the degree of appropriability (Cassiman and Veugelers, 2002). They entail lower risks than competitor collaborations (Tether, 2002) and mainly target the improvement of a product's characteristics to better serve customer needs (Rosenberg, 1963). By sharing knowledge about markets, R&D collaborations with suppliers and customers support the improvement of a product's components (Miotti and Sachwald, 2003). Over time, suppliers and customers become specialists that can easily integrate components into the product architecture or bring them into a usage context (Kapoor and McGrath, 2014). While R&D collaborations with customers in particular increase the chances of a product's market acceptance through application (von Hippel, 1976), suppliers provide easier knowledge access (Un *et al.*, 2010) and closer contextual knowledge to the collaborating firm to achieve process innovation (Un and Asakawa, 2015).

Due to their market-related knowledge on how to improve a product's features and its production processes and the lower risks of resource misappropriation, firms may prefer supplier–customer R&D collaborations over competitor R&D collaborations as the level of competition and the hazards of exit increase after the shakeout of an industry. Thus, I hypothesize the following:

H3: Ceteris paribus, the number of market-based R&D collaborations evolves from predominantly competitors in the pre-shakeout to suppliers and customers in the post-shakeout period of an industry.

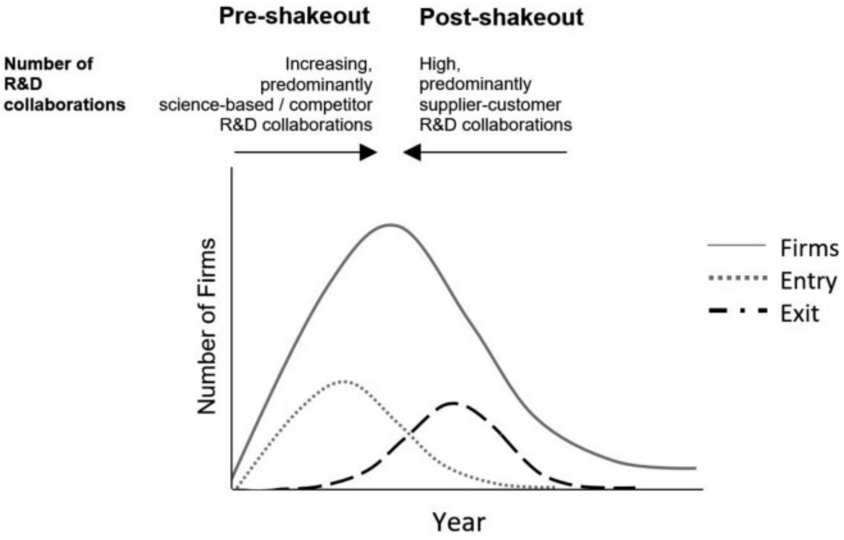

Figure 3. Conceptual framework on R&D collaborations along the industry life cycle.

Figure 3 summarizes the derived hypotheses in a conceptual framework.

3. The German photovoltaics manufacturing industry and R&D collaborations

The German PV industry is a representative case of a global science-based industry because it was leading in PV production and installation for many years (Binz *et al.*, 2017). It is largely known as an emerging industry as installed capacities continue to grow on a global scale (Hoppmann *et al.*, 2014). However, a look at the supply-side indicates that the PV industry experienced a recent shakeout in which more firms exited than entered the industry (Dewald and Fromhold-Eisebith, 2015; Furr and Kapoor, 2018; Hipp and Binz, 2020). I focus on firms that produce wafer-based crystalline silicon (c-Si) as the market leader for PV technologies (Hoppmann, 2018).[1] A crystalline PV manufacturer (e.g. Bosch Solar Energy AG) casts polysilicon into ingots, slices the ingots into wafers, coats the wafers for cell production, and interconnects, encapsulates and fixes the cells into modules (Kalthaus, 2019). The German PV industry has its origin in the 1960s with only a few large incumbents such as AEG Telefunken AG that early diversified with new c-Si-related product innovations of low production volumes and a simple design to be used for satellites (Bruns *et al.*, 2009). Niche markets for off-grid or small-scale on-grid applications existed only in fractions (Dewald and Truffer, 2012). Apart from the few incumbents, new and specialized firms such as Concentrix Solar GmbH only entered the industry from the 1990s onward, which increased competition between the active firms (Dewald and Fromhold-Eisebith, 2015). In this “pre-shakeout” period, the extent of innovative activities and in particular the number of product innovations, mostly in form of PV patents, increased considerably (Binz *et al.*, 2017). New product innovations addressed various cell and module product designs (Huenteler *et al.*, 2016). The necessity to increase cell efficiencies, reduce material and production costs, and support the application of PV enabled a shift to process innovation (Bruns *et al.*, 2009). A mass market for a dominant cell design emerged with decreasing prices for end-consumers (Huenteler *et al.*, 2016). Until 2009, price-based competition around this dominant design intensified and more firms exited than entered the industry, which induced a shakeout (Hipp and Binz, 2020). Since the beginning of this “post-shakeout” period, the German PV industry is marked by continued firm exits and a shrinking global share of product innovations (Binz *et al.*, 2017). The remaining PV cell and module producers became highly specialized

[1] Even though other PV technologies such as thin film and organic compound gained in efficiency and increasingly replace crystalline silicon (e.g. Li *et al.*, 2018), I exclude them from the analysis because of their different technology architecture and underlying industry dynamics.

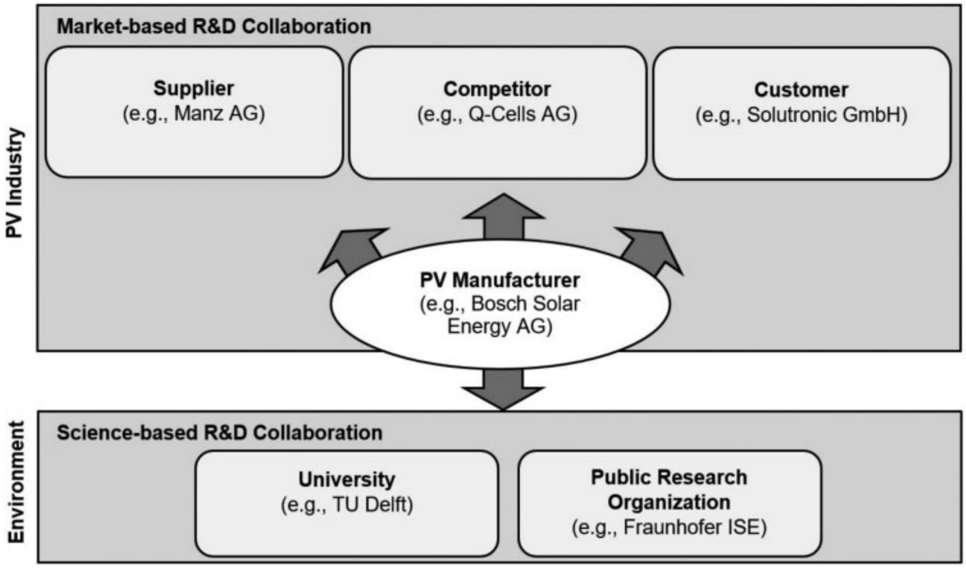

Figure 4. R&D collaborations in the PV industry.

and mostly engage in the development of process innovation that results in a continued increase of technological efficiencies and the production output (Fraunhofer ISE, 2014).

R&D collaborations have gained in importance for German PV manufacturers since the 1980s. Science-based R&D collaborations involve either universities that mainly engage in basic research on PV (e.g. TU Delft) or PROs with a focus on applied PV research (e.g. Fraunhofer Institute for Solar Energy Systems/ISE). During the early stages of PV, some PROs were founded but did not play a crucial role for collaborations, similar to universities. Due to continuing initiatives from firms and environmental associations since the end of the 1990s, the EU and the German government have introduced a mix of innovation policies to enable the expansion of renewable energies and particularly PV (Jacobsson *et al.*, 2004). This policy mix included demand-pull instruments to create a market for PV (e.g. the 100,000 Roofs Program) and technology-push instruments to support joint technology development (e.g. R&D collaboration programs) (Cantner *et al.*, 2016). The scientific infrastructure was expanded and allowed for science-based R&D collaborations (Jacobsson and Lauber, 2006). Since then, firms could finance R&D collaborations either with their internal budget or bank loans or receive public funding (Quitzow, 2015). Today, public funding for R&D represents an important and continuous source of financing the development of PV technologies (Fraunhofer ISE, 2014).

Market-based R&D collaborations include different partners from the PV industry. The strong sectoral configuration of the PV industry enables a clear distinction between the types of market-based partners based on their position in the industry (i.e. suppliers, competitors, and customers) (Hipp and Binz, 2020).[2] In the core part of the PV industry, competitors develop products in the same market segment, that is cells and modules (e.g. Q-Cells AG). In the upstream part of the PV industry, suppliers deliver highly specialized technological inputs, such as manufacturing equipment or semiconductor materials, or automated production lines to manufacture cells and modules (e.g. Manz AG). In the downstream part of the PV industry, customers engage in mounting the core product into a final operational system such as a solar system or provide features for its application such as electrical wires or charge controllers (e.g. Solutronic GmbH) (Malhotra *et al.*, 2019).[3] Figure 4 depicts the types of R&D collaborations in the PV industry.

[2] Collaboration partners are assessed by their position in the industry and not by their geographic location. Thus, they may have headquarters in another country (e.g. SunPower Corp. in the United States).

[3] A customer is defined here as a producer in the downstream part of an industry as opposed to Du *et al.* (2014), for example, who refer to end-customers in the using part of a product.

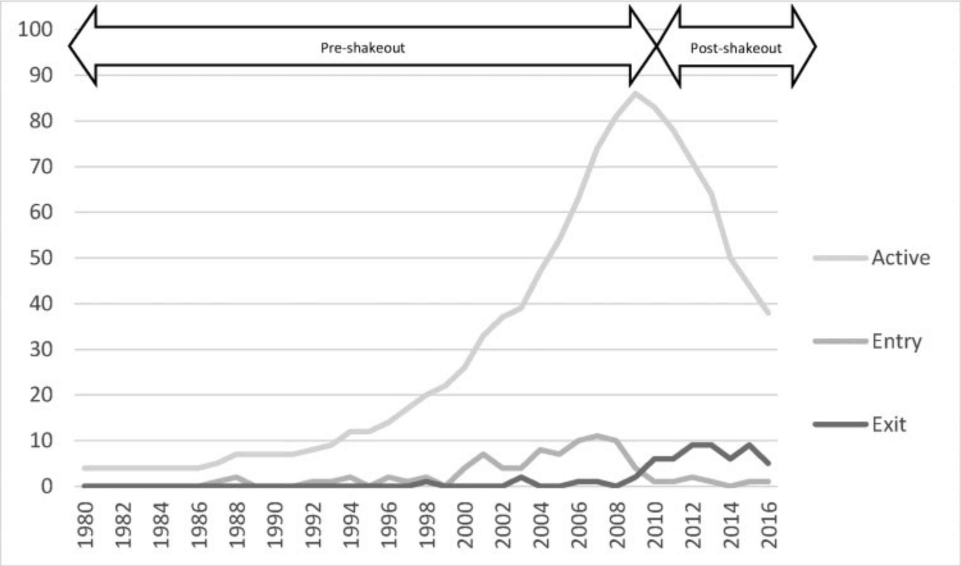

Figure 5. The life cycle of the German PV manufacturing industry.

4. Data

4.1 Sample

To analyze how the life cycle of the German crystalline PV industry determines the number and types of R&D collaborations, I collected a novel set of firm data that includes the development of 97 cell and module manufacturers, of which 60 firms engaged in 6581 R&D collaborations from 1980 to 2016. This dataset offers several advantages in the study of collaborative R&D as it allows to investigate the change in the different types of R&D collaborations that are located within and beyond an industry. The German PV industry has experienced a shakeout in the last decade, which enables an examination of the entire life cycle (Hipp and Kalthaus, 2018).

I collected information on the industry entries and exits using Germany's common register portal (Handelsregister). In contrast to other statistical classification systems that aggregate and anonymize firm-level information in different sectors (e.g. NACE or SIC), the Handelsregister provides detailed information on all firms in Germany and their activities, such as the day and type of entry, the corporate objectives, the position in the industry, and, if applicable, the reason why they exited the market. It has archived firm information since 1820, long before the first PV manufacturer entered the industry. Moreover, it provides information on all changes in a firm's activities, making it a suitable data source to investigate a firm's past developments. To identify all firms in the industry, I applied a keyword approach (Kapoor and McGrath, 2014) using technology-specific terms such as "solar", "PV", "cell" and "module". To assure representativeness of the sample, I extensively searched for additional information from PV associations (e.g. Bundesverband Solarwirtschaft), PV exhibitions (e.g. SNEC), PV magazines (e.g. PV Magazine), and newspaper articles (e.g. Handelsblatt).[4] I received a final sample of 97 manufacturers that were active in the German PV industry between 1980 and 2016.

Figure 5 depicts the evolution of the number of active firms, their entries into and exits from the German PV industry. Only a few manufacturers were active during the 1980s, and many new firms entered the market from the 1990s onward. The number of active PV manufacturers grew rapidly until it reached a peak in 2009. In 2010, the industry experienced a shakeout with more firms exiting than entering. Since then, the number of active PV manufacturers has steadily decreased. The development of the German PV industry shows a typical life cycle pattern.

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[4] Operating firms and service providers are excluded from the manufacturer sample because they do not engage in PV production and only focus on trade and installation of PV technologies or execute solar parks.

I started to collect data on R&D collaborations from the full sample of German PV manufacturers by using Nexis to identify their private collaborations along the industry's life cycle. Nexis is a commonly used research tool that entails a broad range of historic information in text form from international news, firms, and industries since the 1970s. For selecting the R&D collaborations, I used keywords that relate to the name of all 97 PV firms (e.g. "Bosch Solar Energy" or "Bosch Solar") and their engagement in R&D (e.g. "develop" or "technologies"). Supplementary Table A1 provides an overview of the keywords. I classified an announcement as an R&D collaboration program when it included at least one of the related keywords (e.g. "collaborate" or "work together"), which produced a sample of 443 private R&D collaboration programs. Programs with no identifiable date or partner seized 167 observations and were excluded from the analysis. Furthermore, I eliminated the duplicates, which accounted for 48 observations, leading to a sample of 228 private R&D collaboration programs. Since firms usually collaborate with different organizations in an R&D program at the same time, I coded each type of partner and defined it as an R&D collaboration, which is in line with recent research (Miotti and Sachwald, 2003; Belderbos *et al.*, 2004; Kapoor and McGrath, 2014). For instance, if a firm announces an R&D program with two universities, one PRO and one supplier, the collaboration is categorized as three science-based collaborations and one supplier–customer collaboration. The sample of private R&D programs thus include a total of 430 R&D collaborations by 53 PV firms.

In addition to private collaborations, I collected data on publicly funded R&D programs, which is a common approach in collaboration studies (e.g. Hagedoorn, 1995; Powell *et al.*, 1996; Ahuja *et al.*, 2012). The motives to engage in public R&D programs and their innovation outcomes are similar to private collaborations (cf. Sakakibara, 1997; Hottenrott and Lopes-Bento, 2014). Both the EU and the German government provide detailed information on their funded R&D collaboration programs, such as the period of funding, the type of technology developed, and the participants. There is a wide range of continued programs available since the 1990s (e.g. Spitzencluster Solarvalley; Framework Programs FP1–FP7; Horizont 2020) with the aim of increasing technological research and international competitiveness. All firms are eligible and free to apply. A few programs favor startups and small and medium-sized firms due to their high innovativeness and financial restrictions, and some of the EU-funded programs require a minimum number of three participants.[5] They can attract the participation of universities and PROs since they receive full funding for the R&D collaboration in contrast to the usual 50% funding of a firm's expenses. The EU has documented funded R&D collaborations in the database of the Community Research and Development Information Service (CORDIS).[6] After scrutinizing all German PV manufacturers in CORDIS, I received information from 24 firms that participated in 108 EU-wide programs, representing 1095 R&D collaborations. The German government also runs a public database (Förderkatalog) on more than 110,000 current and completed R&D collaboration programs since 1960. After applying the same procedure as described above, I found that 28 PV firms participated in 160 German programs by pursuing 669 R&D collaborations.

I added the overall 1764 public R&D collaborations to the 430 private ones, which produced a sample of 2194 collaborations by 60 firms that participated in 496 R&D programs. I assessed the duration of each R&D collaboration and calculated the sum of all running collaborations of each firm in every year.[7] The final sample counts 6581 R&D collaborations. I then classified each R&D collaboration by its type, which resulted in 2754 R&D collaborations with universities and PROs, 1760 R&D collaborations with competitors, and 2067 R&D collaborations with suppliers and customers.

Figure 6 depicts a firm's average number and sum of R&D collaborations along the life cycle of the German PV industry. Firms increasingly engaged in R&D collaborations between 1980 and 2011, after which this trend reversed.

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[5] The analysis controls for the impact of a firm's size on its collaboration efforts and accounts for the larger number of participants in EU-funded programs in a robustness test.

[6] The CORDIS database aims to bring together R&D activities of the European community, using up-to-date research findings to diffuse new knowledge and increase the EU's competitiveness and innovativeness through collaborative projects.

[7] The duration of each public R&D collaboration is documented in the project description. Information about the duration of private R&D collaborations is however missing. I therefore assumed a duration of 2.86 years, which is equal to the average duration of public collaborations.

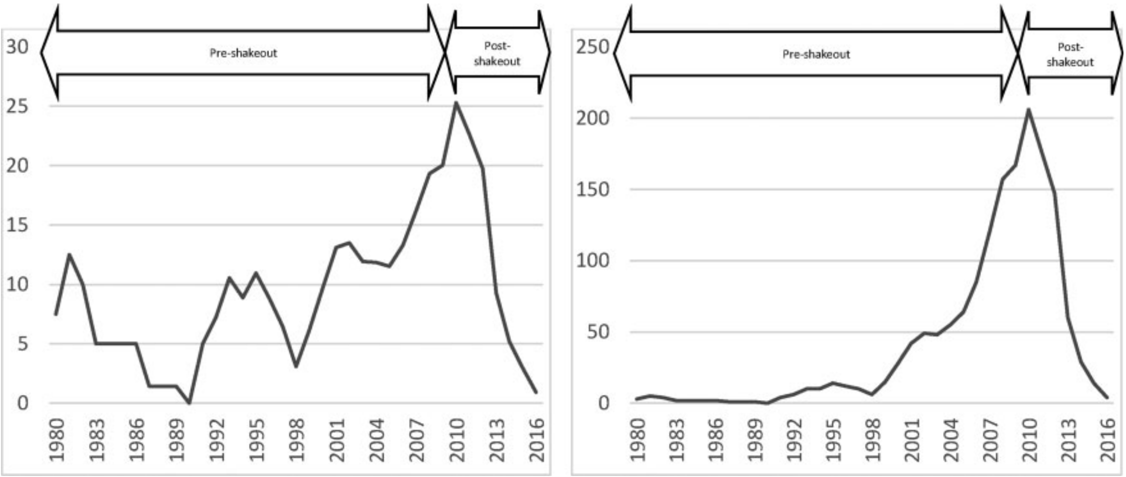

Figure 6. Average number and sum of R&D collaborations per firm along the PV industry's life cycle.

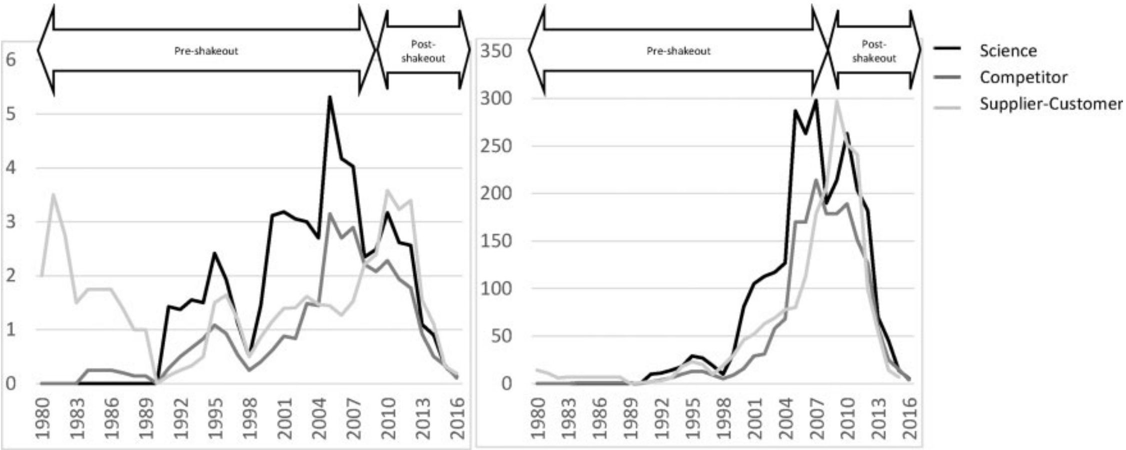

Figure 7. Average number and sum of R&D collaboration types per firm along the PV industry's life cycle.

Figure 7 shows a firm's average number and sum of R&D collaboration types along the PV industry's life cycle. Firms predominantly collaborated with universities and PROs and competitors before the shakeout of the industry, but they changed their tendencies towards collaborations with suppliers and customers during the post-shakeout period.[8]

4.2 Dependent variables

The dependent variable *R&D Collaborations* is operationalized as the overall number of R&D collaborations in which a firm engages in a given year of the industry life cycle. *Science Collaborations* indicates the number of universities and PROs that engage in a collaborative R&D project with a firm in a given year. *Competitor Collaborations* counts the number of competitors (i.e. cell and module manufacturers) positioned in the same part of an industry that engage in a collaborative R&D project with a firm in a given year. *Supplier–Customer Collaborations* is the

[8] The dominance of supplier-customer collaborations during the 1980s can be explained by the low number of PROs, universities, and competitors available for R&D collaborations in the field of PV. The regression models account for the number of available partners in each year.

number of suppliers and customers positioned in different parts of an industry that engage in a collaborative R&D project with a firm in a given year.

4.3 Independent variable

The hypotheses concern the evolution of R&D collaborations along the industry life cycle. The stages of the industry life cycle are categorized by the number of firm entries and exits from the industry (Klepper, 1997). *Pre-shakeout* is characterized by an increasing number of entries from 1980 until 2009 when the number of active firms reached a peak (Figure 5). From 2010 onward, the rate of firm exits exceeded the market entry and the industry experienced a shakeout. A shakeout is characterized by more firms exiting than entering the market (Klepper, 2007). I thus set *Post-shakeout* as equal to 1 for those years, which are marked by more firm exits than entries in the German PV industry (2010–2016) and 0 for the years in which the number of active firms in the industry continues to grow (1980–2009). This classification scheme of the industry life cycle is in line with the results from recent studies on the German PV industry (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015; Huenteler *et al.*, 2016; Hipp and Binz, 2020).

4.4 Control variables

The analysis includes several control variables to account for firm-specific and industry-related influences on a firm's collaboration tendencies along the industry life cycle. First, the type of firm entry into the industry influences its engagement in R&D collaborations (Klepper, 2002). In the analysis, *New* is set as equal to 1 when the firm enters the industry as a new organization and 0 when it is affiliated to another firm. I expect that affiliates find it easier to enter into collaborations because they have gained more experience and reputation on the market. Moreover, manufacturers become increasingly specialized during an industry's evolution (Klepper, 1997). I account for this specialization by setting *Mainly PV* as equal to 1 when the firm specializes in PV and 0 when it mainly engages in other industries. I expect that the more specialized a firm is, the more it engages in R&D collaborations. Furthermore, collaborative efforts make up only a portion of a firm's total R&D activities since it can also engage in in-house R&D. As a commonly used measure that is highly correlated with internal R&D resources (Artz *et al.*, 2010), I collected data on the number of a firm's patent grants in each year using the service of the German Patent and Trademark Office (DEPATIS) and included the variable *Patents* in the analysis. The more patents a firm owns, the more innovative and engaged it is in developing new capabilities by entering into R&D collaborations (Zobel *et al.*, 2016). Related to that, the generation of product innovations shifts to a focus on processes along the industry life cycle (Abernathy and Utterback, 1978). The variable *Process* is set as equal to 1 when the firm develops process innovation and 0 when it develops product innovation. I expect that firms tend to collaborate more on process innovations over time.

The analysis also controls for various industry-level factors that influence a firm's engagement in R&D collaborations. *Competition* is operationalized as the number of active firms in the German PV industry in a given year (Klepper, 1997). I expect that the level of competition positively affects the extent of R&D collaborations. *Market Size* is proxied by the yearly amount of cumulative installed global PV capacity, which is retrieved from the International Energy Agency (IEA, 2017). I expect that the size of a market has a negative impact on R&D collaborations because of increasing global market pressures. Furthermore, *Policy* measures the number of public grants that a firm has received to finance an R&D collaboration in a given year. I expect that policy support incentivizes science-based R&D collaborations in particular. Furthermore, the availability of partners determines whether firms enter into R&D collaborations (Kapoor and McGrath, 2014). *Partner Science* is proxied by the number of international coauthors that publish in PV-related journals in a given year. This publication data is retrieved from the Web of Science's core collection by Graf and Kalthaus (2018) who report 59,681 coauthors between 1980 and 2016. I expect that the number of available partners from universities and PROs has a positive influence on a firm's engagement in science-based R&D collaborations. In parallel, the analysis includes *Partner Industry* as the average number of firms that participate in two of the largest international PV conferences and exhibitions in a given year (SNEC, Shanghai, and Intersolar, Munich) (Hipp and Binz, 2020). I expect that the number of available industry partners affects the engagement in competitor R&D collaborations. Table 2 provides an overview of the variables. Table 3 shows the descriptive statistics and the correlation matrices.

Table 2. Variable overview

Variable name	Definition	Data source
Dependent variables		
R&D collaborations	Number of a firm's R&D collaborations in a given year	Nexis, CORDIS, Förderkatalog
Science collaborations	Number of a firm's R&D collaborations with science-based organizations (i.e. university or PRO) in a given year	
Competitor collaborations	Number of a firm's R&D collaborations with organizations from the same part of an industry (i.e. competitors) in a given year	
Supplier–customer collaborations	Number of a firm's R&D collaborations with organizations from different parts of an industry (i.e. suppliers or customers) in a given year	
Independent variable		
Post-shakeout	Set equal to 1 when more firms exit than enter the German PV industry in a given year (2010–2016), 0 when the number of firms continues to grow (1980–2009)	Commercial registry
Control variables		
New	Set equal to 1 when a firm enters the industry as a new organization, 0 when it is affiliated to another organization	
Mainly PV	Set equal to 1 when a firm specializes in PV, 0 when it mainly engages in other industries	
Patents	Number of a firm's patent grants in a given year	DEPATIS
Process	Set equal to 1 when a firm engages in process innovation, 0 when it engages in product innovation	CORDIS, Förderkatalog
Competition	Number of active firms in the German PV industry in a given year	Commercial registry
Market size	Yearly amount of cumulative installed global PV capacity	International Energy Agency
Policy	Number of public R&D collaboration grants that a firm receives in a given year	CORDIS, Förderkatalog
Partner Science	Number of available science-based partners in a given year	Web of Science
Partner Industry	Number of available market-based partners in a given year	PV Conferences

4.5 Model specification

To test Hypotheses 1–3, I applied a negative binomial regression model to include the dependent variables of the number of R&D collaborations and the collaboration types. A negative binomial regression model is a generalized linear model to proceed count data and to account for its overdispersion (Cameron and Trivedi, 1990). I used robust standard errors to minimize issues of heteroskedasticity and autocorrelation. Model (1) estimates the impact of the industry life cycle on the number of R&D collaborations based on observations of all 97 firms *i* in the industry in every year *Y* at the firm level (Hypothesis 1). Model (2–4) estimates the impact of the industry life cycle on the number of R&D collaboration types, that is Science Collaborations, Competitor Collaborations, and Supplier–Customer Collaborations, based on observations of all R&D collaborations by 60 firms *i* in the industry in a given year *Y* at the project level (Hypotheses 2–3) as follows:

$$\begin{aligned} R\&D\ \ Collaborations_{iY} = {} & \beta_0 + \beta_1\ (Post - shakeout_Y) \\ & + \beta_2\ (New_{iY}) \\ & + \beta_3\ (Mainly\ \ PV_{iY}) \\ & + \beta_4\ (Patents_{iY}) \\ & + \beta_5\ (Process_{iY}) \\ & + \beta_6\ (Competition_Y) \\ & + \beta_7\ (Market\ \ size_Y) \\ & + \beta_8\ (Policy_{iY}) \\ & + \beta_9\ (Partner\ \ Science_Y) \\ & + \beta_{10}\ (Partner\ \ Industry_Y). \end{aligned}$$

Table 3. Descriptive statistics and correlation matrix for (1) R&D collaboration and (2–4) R&D collaboration types

Model (1)	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11
R&D collaborations	1.83	8.318	1										
Post-shakeout	0.19	0.392	0.092**	1									
New	0.21	0.406	0.081**	0.216**	1								
Mainly PV	0.28	0.447	0.256**	0.291**	0.668**	1							
Patents	1.54	8.242	0.316**	0.181**	0.086**	0.091**	1						
Process	0.06	0.343	0.503**	0.075**	0.163**	0.250**	0.230**	1					
Competition	30.89	27.512	0.263**	0.531**	0.441**	0.586**	0.169**	0.205**	1				
Market size	28,120.76	66,189.068	0.009	0.815**	0.138**	0.179**	0.127**	0.007	0.337**	1			
Policy	0.04	0.202	0.634**	0.053**	0.095**	0.239**	0.250**	0.515**	0.216**	−0.002	1		
Partner Science	1613.97	2139.102	0.100**	0.852**	0.279**	0.359**	0.162**	0.074**	0.642**	0.896**	0.075**	1	
Partner Industry	384.85	633.683	0.167**	0.916**	0.311**	0.424**	0.202**	0.142**	0.747**	0.680**	0.123**	0.796**	1

Model (2–4)	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12	13
Science collaborations	1.18	1.983	1												
Competitor collaborations	0.74	1.293	0.451**	1											
Supplier–customer collaborations	0.89	1.759	0.243**	0.089**	1										
Post-shakeout	0.49	0.500	−0.151**	−0.084**	0.028	1									
New	0.48	0.500	−0.010	0.076**	−0.068**	−0.022	1								
Mainly PV	0.88	0.331	−0.050	0.028	−0.128**	0.041	0.303**	1							
Patents	76.74	151.602	−0.039	0.010	0.153**	0.151**	−0.088**	−0.536**	1						
Process	0.50	0.500	0.038	−0.040	0.056*	0.121**	0.000	0.012	0.043	1					
Competition	65.15	22.082	−0.095**	0.064*	−0.025	0.524**	0.055*	0.220**	−0.001	0.232**	1				
Market size	48,983.15	57,268.922	−0.153**	−0.076**	0.012	0.720**	−0.010	−0.001	0.130**	0.070**	0.268**	1			
Policy	0.54	0.499	0.223**	0.004	0.069**	−0.113**	−0.042	−0.141**	0.037	0.029	−0.250**	−0.099**	1		
Partner Science	2577.45	1409.626	−0.078**	−0.001	0.041	0.608**	0.022	0.082**	0.057*	0.102**	0.370**	0.864**	−0.140**	1	
Partner Industry	1074.19	761.113	−0.160**	−0.048	0.026	0.872**	−0.007	0.106**	0.119**	0.177**	0.754**	0.564**	−0.167**	0.516**	1

Table 4. Descriptive trends of R&D collaborations along the industry life cycle

Phase	R&D collaborations	Science collaborations	Competitor collaborations	Supplier–customer collaborations
Pre-shakeout	65% Total # 4264 Mean 0.88	72% Total # 1971 Mean 0.41	68% Total # 1191 Mean 0.25	53% Total # 1102 Mean 0.23
Post-shakeout	35% Total # 2317 Mean 3.41	28% Total # 783 Mean 1.15	32% Total # 569 Mean 0.84	47% Total # 965 Mean 1.42
Industry life cycle	Total # 6581 Mean 1.19	Total # 2754 Mean 0.49	Total # 1760 Mean 0.32	Total # 2067 Mean 0.37

The development of manufacturers largely affects the number of R&D collaborations in the PV industry. However, a manufacturer's age and size have a decisive influence on its engagement in R&D collaborations (Stuart, 2000).[9] Moreover, each year of the industry life cycle is characterized by different risks such as business cycles or financial crises that influence firms' decisions to collaborate. This unobserved heterogeneity between the firms and each year would lead to biased and inconsistent estimates. I therefore included fixed effects in the analysis to account for the systemic differences between the firms and the years.[10] The Hausman test confirms that a fixed effects model is more appropriate than a random effects specification (Chi-square $= 14.24$, $P < 0.05$).

5. Results

5.1 Descriptive results

Table 4 provides the descriptive trends of the firms' engagement in R&D collaborations along the life cycle of the German PV industry. Before the shakeout of the industry (1980–2009), 65% of all PV firms engage in a total of 4264 R&D collaborations. While the sum of R&D collaborations decreases to 35% or 2317 R&D collaborations after the industry's shakeout, a firm's average number of R&D collaborations increases from 0.88 to 3.41. This provides the first evidence that firms increasingly engage in R&D collaborations after the shakeout of the industry (Hypothesis 1). The sum of science-based R&D collaborations decreases from 72% or 1917 collaborations during the pre-shakeout to 28% or 783 R&D collaborations after the industry's shakeout. However, a firm's average number of science-based R&D collaborations increases from 0.41 to 1.15 after the shakeout of the industry (contrary to Hypothesis 2). Regarding market-based R&D collaborations, the share and mean of firms' competitor collaborations (68%/0.25) outweigh that of supplier–customer collaborations (53%/0.23) before the industry's shakeout. This trend reverses in the post-shakeout phase in which supplier–customer collaborations (47%/1.42) prevail over competitor collaborations (32%/0.84). Indeed, the number of supplier–customer collaborations diminishes after the industry's shakeout, which is similar to competitor collaborations.[11] Nonetheless, the descriptive analysis indicates that a firm's number of market-based R&D collaborations evolves from predominately competitors during the pre-shakeout to suppliers and customers after the shakeout of the industry (Hypothesis 3).

[9] 9 For example, AEG Telefunken AG, an experienced and large industry incumbent, has had many opportunities to collaborate, resulting in a higher number of R&D collaborations than that of smaller firms, such as Sunfilm AG, which entered the industry at a later stage.

[10] I used each year of the observation period as well as a firm's age and its size as fixed effects. A firm's age relates to the number of years since foundation. A firm's size is categorized by the number of employees in accordance with the commonly accepted EU classification scheme as follows: $1 =$ small firm < 50 employees, $2 =$ medium-sized firm < 250 employees, and $3 =$ large firm ≥ 250 employees.

[11] Note that this cycle is not completed yet; the number of R&D collaborations with suppliers and customers in particular may still grow during the forthcoming years.

Table 5. Regression results of R&D collaborations

Model Dependent variable	(1) R&D collaborations	(2) Science collaborations	(3) Competitor collaborations	(4) Supplier–customer collaborations
Intercept	-4.907^{***}	-1.986^{***}	-1.041	-6.655^{***}
Post-shakeout	1.172^{***}	0.472^{***}	-0.658^{***}	0.411^{*}
New	-0.564^{***}	0.027	0.377^{*}	0.352^{***}
Mainly PV	1.791^{***}	-0.312	-0.548	-1.303^{***}
Patents	0.034^{***}	0.000	0.000	-0.001^{**}
Process	0.540^{***}	-0.098	-0.677^{***}	0.160
Competition	0.042^{***}	0.021^{***}	0.015^{***}	0.005
Market size	-0.006^{***}	-0.004^{***}	0.002	-0.001^{***}
Policy	2.639^{***}	0.173^{**}	-0.143	0.116
Partner Science	1.890^{***}	1.799^{***}	0.322	2.495^{***}
Partner Industry	-1.939^{***}	-1.668^{***}	0.400	-0.329
Log-likelihood	-2757.111	-1359.983	-494.511	-998.066
Chi-square	4057.097^{***}	65.626^{***}	41.284^{***}	95.675^{***}
BIC	5598.54	2792.802	1053.491	2068.923
Fixed effects	Incl.	Incl.	Incl.	Incl.
# Observations	6581	496	496	496

Pre-shakeout is the reference phase.
$^{***}P < 0.01$; $^{**}P < 0.05$; $^{*}P < 0.10$.

5.2 Regression results

Table 5 reports the regression results on how the industry life cycle influences a firm's tendencies to engage in R&D collaborations. Similar to the descriptive trend, the coefficient of *Post-shakeout* is positive and significant in Model (1). This finding supports Hypothesis 1 that the number of R&D collaborations is higher in the post-shakeout than in the pre-shakeout period of an industry. The coefficients of *Mainly PV*, *Patents*, *Process*, *Competition*, *Policy*, and *Partner Science* are positive and significant, indicating that a firm's specialization in PV, its innovativeness and engagement in process innovation, higher levels of competition, policy support, and the availability of scientific partners positively affect its number of R&D collaborations. The coefficients of *New*, *Market Size*, and *Partner Industry* are negative and significant, implying that new entries, a growing market, and the number of available industry partners negatively affect a firm's engagement in R&D collaborations. New firms face higher barriers to find collaboration partners whereas the latter findings can be explained by growing global market pressures and a rising number of international competitors after the industry's shakeout.

The coefficient of *Post-shakeout* is positive and significant in Model (2). This finding implies that the number of science-based R&D collaborations is higher in the post-shakeout than in the pre-shakeout period of an industry, which is in contrast to Hypothesis 2. The coefficients of *Competition*, *Policy*, and *Partner Science* are positive and significant, the coefficients of *Market Size* and *Partner Industry* are negative and significant, and *New*, *Mainly PV*, *Patents*, and *Process* are nonsignificant.

The coefficient of *Post-shakeout* is negative and significant in Model (3) and positive and significant in Model (4). Taken together, I find support for Hypothesis 3, which is that the engagement in market-based R&D collaborations evolves from predominantly competitors during the pre-shakeout to suppliers and customers after the shakeout of an industry. Both models show positive and significant coefficients of *New*, while the coefficients of *Policy* and *Partner Industry* are nonsignificant. The coefficient of *Competition* is positive and significant for competitor collaborations and nonsignificant for supplier–customer collaborations. The coefficient of *Partner Science* is positive and significant for supplier–customer collaborations and nonsignificant for competitor collaborations. The coefficient of *Process* is negative and significant for competitor collaborations and nonsignificant for supplier–customer collaborations. The coefficients of *Mainly PV*, *Patents*, and *Market Size* are negative and significant for supplier–customer collaborations and nonsignificant for competitor collaborations.

5.3 Robustness check

The findings are tested for their robustness by applying several tests. First, I checked whether the engagement in R&D collaborations differs in its determinants during the life cycle using a Chow test to account for an industry's structural changes (Chow, 1960). The results confirm the explanatory power of the industry life cycle phases (see Supplementary Table A2). The robustness of the industry life cycle can be further supported by including a squared term for the age of the industry instead of its phases. However, we need to interpret this variable with caution because the industry life cycle is not a symmetric curve, even though I receive similar findings (Supplementary Table A3).

Second, I analyzed the similarities between the evolution of private R&D collaborations and public R&D collaborations and the impact of the industry life cycle on the tendencies to engage in private collaborations. The tests lead to qualitatively similar results (Supplementary Table A4). Moreover, one could argue that in large projects not every partner collaborates with all other project members but exclusively with the project coordinator. Therefore, I assumed for projects with more than five partners that a firm only collaborates with the coordinator by setting the number of any other partner to zero. I rerun the analysis and observe similar tendencies to collaborate (Supplementary Table A4).

Last, I checked whether the occurrence and not the number of R&D collaborations is influenced by the industry life cycle. In line with previous approaches (e.g. Kapoor and McGrath, 2014), I included binary variables for the R&D collaboration types and applied a logistic regression model. The results of the logit models hold for the magnitude of the life cycle coefficients and confirm the observed trends for the number of R&D collaborations (Supplementary Table A5).

6. Discussion and conclusions

This article attempted to contribute to the debate about how R&D collaborations evolve during the industrial progress. It offers a conceptualization and empirical evidence on the extent and types of R&D collaborations and extends the industry life cycle theory with their evolution from the period before to the aftermath of an industry's shakeout. The industry life cycle is characterized by the pattern of firm entries and exits over time that explains the two major stages of pre-shakeout and post-shakeout, providing different opportunities and risks for R&D collaborations (Agarwal *et al.*, 2015; Carlsson, 2016; Esteve-Pérez *et al.*, 2018). The analysis shows that the tendencies to collaborate with universities and PROs, competitors, suppliers and customers are influenced by the opportunities and risks from this long-term change in the structure of industries.

The empirical context of this article is the German PV industry, in which 60 out of 97 manufacturers engaged in 6581 R&D collaborations from 1980 to 2016. This industry experienced considerable dynamics in the number of manufacturers, which have largely driven firms' tendencies to collaborate (Jacobsson and Lauber, 2006; Quitzow, 2015; Cantner *et al.*, 2016). The German PV manufacturing industry follows a typical life cycle pattern (Klepper, 1997) in which a shakeout occurred in 2010 that pushed many firms out of business. I used Germany's common register portal to reproduce the pattern of industry evolution. Further firm-specific, industry-level, and collaboration data was collected using a new and comprehensive set of data sources.

Before the shakeout of an industry, firms increasingly join R&D efforts to seize new opportunities in a market in which uncertainties about technological developments and customer needs are high (e.g. Teece, 1986; Powell *et al.*, 1996; Kapoor and McGrath, 2014). These industry dynamics drive the number of R&D collaborations in general and R&D collaborations with universities and PROs as well as competitors in particular because they offer new technological knowledge and enable risk and cost sharing in the development of various product designs. After the industry's shakeout, the number of R&D collaborations becomes even higher because it contributes to the development of new technologies and process innovation despite of high hazards of market exit. Against my initial assumption, this holds true for science-based R&D collaborations with universities and PROs, which can be explained by the necessity to develop new products in submarkets (Bhaskarabhatla and Klepper, 2014). In contrast, as R&D collaborations with competitors bear higher risks of resource misappropriation and involuntary spillovers (Belderbos *et al.*, 2004), their number is lower in the post-shakeout period than in the pre-shakeout period. R&D collaborations with suppliers and customers entail lower risks of opportunistic behavior and provide easy access to market-related knowledge that adds to product and process improvements (Tether, 2002; Miotti and Sachwald, 2003). This results in the evolution of market-based R&D collaborations from predominantly competitors before the shakeout to suppliers and customers after the shakeout of an industry.

Furthermore, I find that a firm's characteristics, the types of innovation activities, and industry-related factors influence the evolution of R&D collaborations. New firms face disadvantages in the entry into R&D collaborations in general and only engage in competitor and supplier–customer collaborations. This can be explained by the organizational proximity between market-related partners (Balland, 2012). Even though a specialization in PV and patents drive R&D collaborations in general, more diversified and less innovative firms tend to engage in supplier–customer R&D collaborations. I relate this finding to particular types of collaboration, for which specialization and innovativeness matter more or less (Argyres *et al.*, 2015). Moreover, process innovations trigger the engagement in R&D collaborations in general, but not in competitor collaborations. This finding can be referred to Un and Asakawa (2015), who observe that some types of R&D collaborations support process innovation, while others seem to be detrimental. Due to increasing market pressures from global price-based competition (Quitzow, 2015), the size of the market and the number of international competitors exert a negative influence on most of the R&D collaboration types. In contrast, the size of the national firm population, policy measures, and a scientific infrastructure increase the tendencies to collaborate, which highlights the growing opportunities from a firm's diverse sources of innovation activities (e.g. Cantner *et al.*, 2016).

Overall, the findings show that the dynamics of an industry's structure influence the patterns of R&D collaborations. Thus far, the industrial dynamics literature has focused on the evolution of R&D collaborations during the development of a specific technology and largely ignored how they will change in more mature industry stages in which some technologies are replaced, firm exits increase and a shakeout occurs. The results support recent studies that describe the evolution of R&D collaborations along the technology life cycle (e.g. Cainarca *et al.*, 1992; Lecocq and Van Looy, 2009; Kapoor and McGrath, 2014; Vanhaverbeke *et al.*, 2015). However, I go beyond the focus of these studies and shed light on how the extent and types of R&D collaborations evolve after an industry has experienced a shakeout. I extend the frequently confirmed industry life cycle model (Cantner *et al.*, 2009; Tan and Mathews, 2010; Furr and Kapoor, 2018) and contribute to recent studies in this field (Peltoniemi, 2011; Agarwal *et al.*, 2015; Argyres *et al.*, 2015) by explaining how the change in the industry structure determines the opportunities and risks of engaging in R&D collaborations with universities and PROs, competitors, suppliers and customers. Finally, I extend the predominant use of single and public data sources in the literature (e.g. Hagedoorn, 1995; Ahuja *et al.*, 2012; Kapoor and McGrath, 2014) with a novel dataset that integrates diverse types of R&D collaborations.

The findings have important implications for policy makers. The analysis shows that the number of R&D collaborations is higher in the post-shakeout period than in the pre-shakeout period of an industry. I recommend that policy makers provide sufficient public R&D collaboration programs during an industry's evolution to allow firms to transfer knowledge, share risks and costs, and achieve innovation. Since firms increase their R&D collaborations with universities and PROs along the industry life cycle, policy should be to invest early and continuously in a country's scientific infrastructure to ensure transfer of fundamental knowledge and new product innovations. Because R&D collaborations with competitors receive considerable attention before the industry's shakeout, I recommend that policy makers incentivize firms to enter into coopetitive relationships early to engage in resource pooling and product standardization. After a shakeout has occurred, policy makers can promote R&D collaborations with suppliers and customers to achieve product improvements and process innovation.

Although I applied the highest standard of accuracy to the analysis, some aspects must be taken with caution. This article builds on Klepper's industry life cycle concept (1997), which suggests a measurement of the life cycle stages based on the number of firm entries and exits from a national, conventional industry. As further studies in this field, I used a single industry case to investigate life cycle dynamics. The life cycle dynamics of the German PV industry can be transferred to many other science-based industries, such as consumer electronics, pharmaceuticals, or software coding; indeed, other industry types with more complex technologies can evolve in a different way (Binz and Truffer, 2017). Furthermore, I aimed to present a complete picture of the firms, but some information such as market shares or R&D expenses were impossible to obtain. The same holds true for the categorization of the collaboration types that is based on a partner's position in or outside of an industry (i.e. their core capabilities) because hints to specific responsibilities in the R&D collaboration were missing. Last, despite its frequent use to track historical events, information in Nexis is based on announcements and some collaborations may not be made public. The sample includes more public than private collaborations due to continuous policy support like in many other science-based industries (Georgallis *et al.*, 2019).

In sum, this study examines how the extent and types of R&D collaborations evolve along the life cycle of an industry. Further research might extend the analysis by investigating the dynamics of global, more complex industries, such as wind energy, and find more data on each partner's responsibilities, in particular in private, confidential R&D collaborations. Since the analysis focuses on a national, science-based industry, the results must be generalized to other environments.

Supplementary Data

Supplementary materials are available at *Industrial and Corporate Change* online.

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